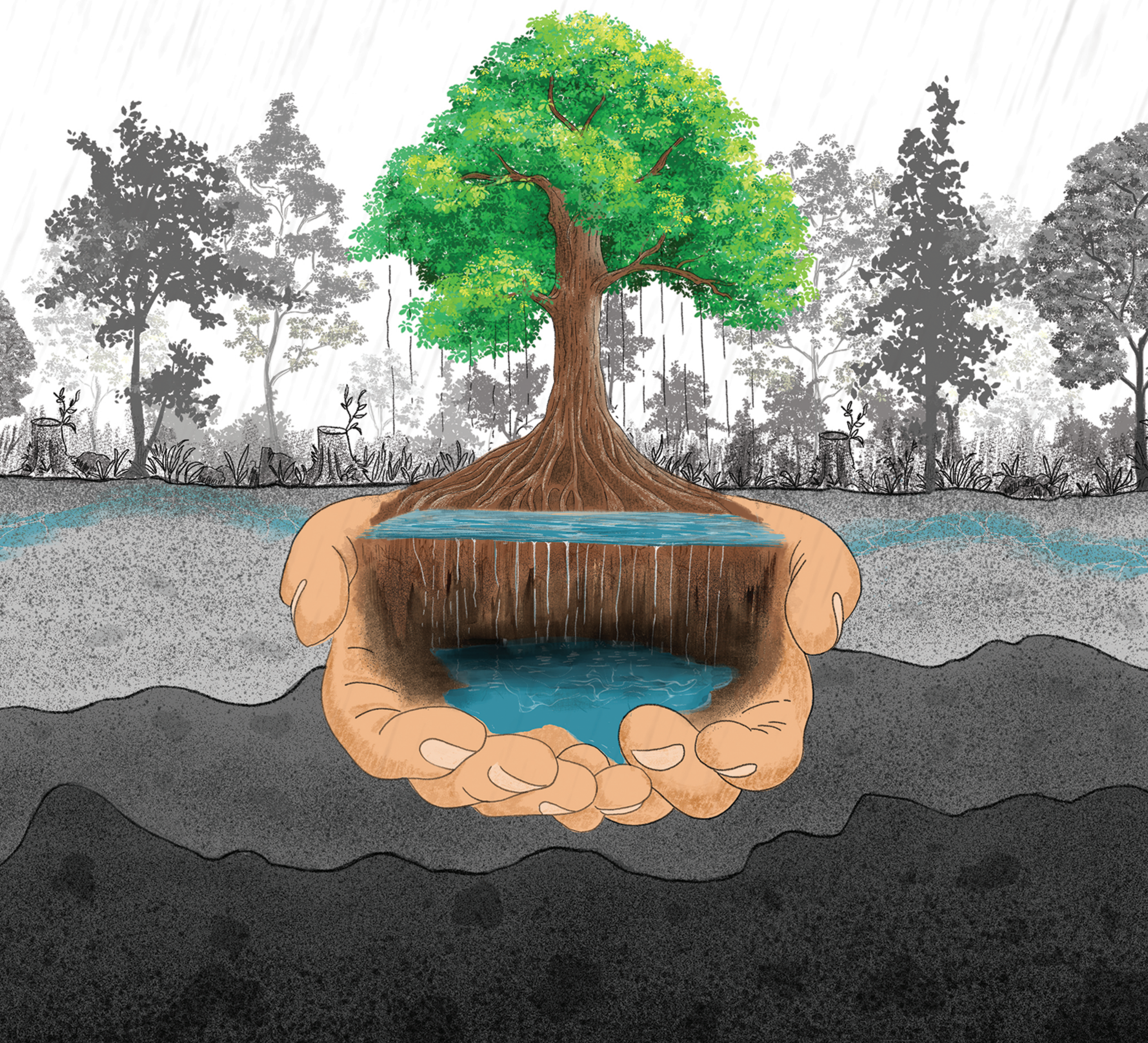
Human Appropriation of Water Resources in a Multifunctional Landscape : Issues, Models, Games and Responsibilities

Lisa Tanika



Propositions

1. The main challenge for the implementation of integrated water management is that everybody looks for their best solution.
   (this thesis)
2. Power and status within social hierarchies break down the circularity between participation and shared understanding in participatory water management.
   (this thesis)
3. Many restoration strategies focus on symptoms rather than pressures and drivers.
4. The long-term benefits of scientific research are undervalued.
5. Frequent drip-feeding knowledge is needed to influence people's cast-in-stone mind-set.
6. Approaching life as a serious game allows focusing on the goals.

Propositions belonging to the thesis, entitled

'Human Appropriation of Water Resources in a Multifunctional Landscape: Issues, Models, Games and Responsibilities'

Lisa Tanika

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Human Appropriation of Water Resources in a Multifunctional Landscape:
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Lisa Tanika

Thesis committee

Promotors

Prof. Dr Marielos Peña Claros
Personal Chair, Forest Ecology and Forest Management
Wageningen University & Research

Prof. Dr Meine van Noordwijk
Special Professor, Agroforestry
Wageningen University & Research

Co-promotor

Dr Erika N. Speelman
Associate Professor at the Laboratory of Geo-Information Science and Remote Sensing
Wageningen University & Research

Other members

Prof. Dr Martine van der Ploeg, Wageningen University & Research
Dr Bruno Verbist, KU Leuven, Belgium
Dr Robert-Jan den Haan, Universiteit Twente, Enschede
Dr Cora van Oosten, CIFOR-ICRAF, Bogor, Indonesia

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Lisa Tanika

Thesis

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In loving memory of my mom, who was always by my side in this journey

“A life that is not fought for will never be won”

Sutan Syahrir (1909-1966)

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Chapter 1: General Introduction

1.1. Evolution of Human Appropriation of Water Resources

The relationship between humans and nature has a long history of change, reciprocal influence and continuity, culminating in the 'Anthropocene', the first geological era dominated by a single species (Crutzen and Steffen, 2003). Avoiding harm and using opportunities to benefit were probably survival strategies for early humankind. These were supported by describing what could be observed, understanding what could be inferred and testing the response to activate interventions. While nature gradually became separated from people, the knowledge and power to intervene in nature also led to responsibility (Pascual et al., 2023). The relationship between humans and nature as a form of human appropriation of natural resources (Fig. 1.1) has been described as four phases of a 'spiritual forest transition' (Roux et al., 2022): (1) nature is powerful and humans adapt to natural conditions to survive; (2) taming of nature when technology emerges and allows humans to reduce dependence on, or even dominate over, nature, (3) rational management of nature when the science of resource depletion and planetary boundaries becomes a basis for management of natural resources, and (4) reconnection with nature by exploring other related services values of nature with greater appreciation for diversity of needs, knowledge and preferences within human societies. These phases coexist and overlap in space and time, and can be used for understanding the debates on the relations of humans with natural resources, including water (Roux et al., 2022). In this thesis, I use these four phases of a 'spiritual forest transition' to describe the relationship between humans and water resources and the multiple ways this can be understood in a society rather than necessarily as a uni-directional historical sequence.

In the first phase, humans have limited capacity to intervene and must adapt to natural conditions and the variability it implies, often interpreted in a religious respect for supreme powers. In this phase, humans tend to be passive and prefer to adapt to the current water resource conditions. In the second phase humans tend to see nature as a product created for humans to exploit. In this phase, humans manage their environment to get the benefits or services they need (Millennium Ecosystem Assessment, 2005b), e.g., in agriculture, water regulation, irrigation, flood control. The objective of the land and water management in this phase is solely to make it easier to access water resources and minimize hydrological hazards, i.e., have sufficient fresh water for all uses, reduce flooding and limit water pollution to the natural cleaning capacity. The third phase develops in response to over-use of resources and represents the modern view of stewardship where humans see nature as a provider of 'instrumental' values that can be managed technically to balance current and future human needs. In the context of water resources, it involves the understanding that water resources can be fully understood and technically managed to meet society's needs (Ramawadh et al., 2023). For example, the main function of an upstream area can be seen as a water harvesting area, so this area needs to be managed to increase infiltration and groundwater supply. In the fourth phase, the relational value with wider (incl. 'cultural') ecosystem services becomes a reason for people to treat nature more wisely (Hendee and Flint, 2014; Roux et al., 2022; Pascual et al., 2023). In water-related contexts, this phase includes water management for human spirituality, pleasure, recreation, comfort and aesthetics. If in the first phase humans depend still on nature, in the second and third phase, human appropriation of water resources becomes more intense and clearly visible for how water security is perceived, and in the fourth phase stewardship and responsibility go beyond direct human needs.

In the context of human appropriation of water resources, water-related problems arise when the condition of water resource does not meet people's expectation. To reduce the water problems there are three options commonly used by human: (1) influence the 'source' of water sources, (2) adapt by adjusting to available water sources (e.g., from groundwater to surface water), and (3) restore harmony with nature. There are several ways to restore harmony with nature, i.e., by choosing methods with minimal impact on nature in carrying out crucial sectors for human welfare and carrying out integrated development together with conservation (Ferreira and Leitão, 2007; Dewi et al., 2013; Coles et al., 2018; Tengberg et al., 2021). These efforts also refer back to the human-nature relationship (Fig. 1.1). The socio-hydrological problems occur when in addressing water-related problems, humans need to influence other humans to meet their needs. The efforts to address the socio-hydrological problem require managing and arranging the landscape as a spatial unit where various levels of human activity meet and interact jointly with the physical character of the environment (van Noordwijk et al., 2013).

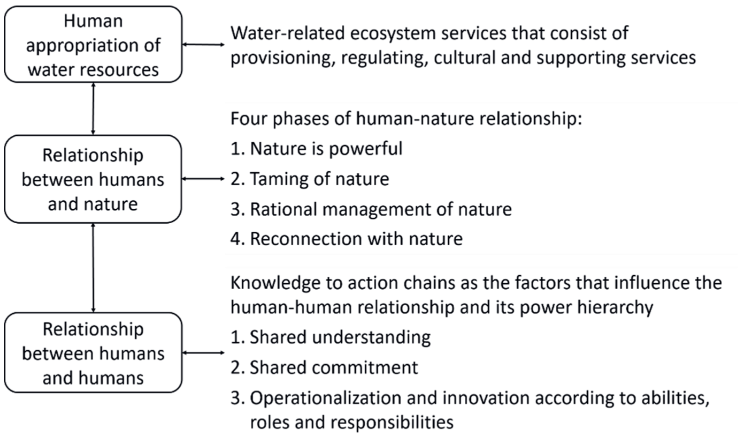


Figure 1.1. Human appropriation of water resources varies with the relationship between humans and nature, which affects and depends on the human-to-human relationships.

1.2. Multifunctional Landscapes for Sustainable Water Resources

Multifunctional landscapes are heterogeneous mosaics of lands used for a variety of purposes (e.g., agriculture, forestry, settlements and conservation areas) that provide a large diversity of ecosystem services (e.g., water quality and quantity, biodiversity) needed to guarantee human welfare (Minang et al., 2015; Fagerholm et al., 2020). The multifunctional landscape management approach sees the landscape as one unit and seeks to use the landscape conditions efficiently, through integrated planning, to fulfil many functions (Landscape Institute, 2009; Selman, 2009; Sayer et al., 2013; Minang et al., 2015). In socio-hydrological systems, stakeholders often have their own needs that are fulfilled by certain hydrological functions, resulting often in the degradation of other functions (Neyret et al., 2023, Van Noordwijk et al., 2002). Consequently, when managing water resources in multifunctional landscapes, it is necessary to consider various levels and types of hydrological functions (Hölting et al., 2020; Manning et al., 2018).

Developing a multifunctional landscape is difficult because the contribution of each stakeholder needs to be identified, from the landscape down to the local level (Fagerholm et al., 2020). During the development process of such an approach, one needs to identify who are involved, how and in what ways, where, and when are they involved, who gain and lose, and what is their motivation (van Noordwijk et al., 2013). This identification process requires understanding from each stakeholder regarding the type of environmental function they need, as well as the factors that cause and disrupt the function.

There are at least three groups of stakeholders in a multifunctional landscape, namely: local stakeholders, public stakeholders and researchers (Jeanes et al., 2006). Local stakeholders are communities who make a living in the area, with various degrees of tenurial security derived from settlement history and formal land classification. Public stakeholders are people from national, provincial or district governments, or other institutions who have influence in policy-making process in the area, such as private companies and NGOs. Biophysical or social researchers, who are from research centres or universities who are conducting research in this area. These three groups differ in their type of ecological knowledge: Local Ecological Knowledge (LEK), Public Ecological Knowledge (PEK), and Modeller/Researcher Ecological knowledge (Jeanes et al., 2006). Local ecological knowledge refers to the knowledge related to the relationship between humans and the surrounding environment that is passed down from generation to generation or obtained from long experience of living in the area (Davis and Wagner, 2003). PEK provides ecological knowledge from a policy perspective and its dynamics, while MEK provides ecological knowledge based on a scientific perspective which is carried out based on research or reviewing existing theories (Jeanes et al., 2006; van Noordwijk, 2014). Based on the main thoughts in the four phases of the spiritual forest transition' (Roux et al., 2022), LEK is connected to the first and second phase, PEK contributes to the second and third phase and MEK contributes to the third phase. The fourth phase is a combination of LEK, PEK and MEK.

1.3. Socio-hydrological System, Hydrological Models and Serious Games

Implementing a multifunctional landscape approach for sustainable water management requires mutual understanding and commitment from stakeholders. To achieve this, it is required that four knowledge-to-action chains converge (van Noordwijk, 2018), those are: understanding, commitment, operationalization, and innovation (Fig. 1.1). The first step for designing a multifunctional landscape is developing a shared understanding among stakeholders. The shared understanding refers to the understanding of the current socio-hydrological problem, and how ecosystem structures and climate generate the hydrological functions and underpin ecosystem services. Once stakeholders have a shared understanding of the hydrological function and its impacts, it will be harder for them to neglect the consequences of the degradation of the system. In this phase, the stakeholders' commitment will arise, so they can engage and cooperate in managing the landscape. The challenge that arises when building a shared understanding is that each stakeholder already has their own knowledge according to their interest in the landscape management and of the background. This problem can be exacerbated when the stakeholders (e.g., researchers) do not accommodate their knowledge and/or use language to the needs of other stakeholders (Gober and Wheater, 2015). Currently, there are a lot of research to bridge the differences and needs of each knowledge type, which indicates that these three knowledge systems complement each other in answering socio-hydrological problems (Wesselink et al., 2017; Ahlborg et al., 2019; Kumar et al., 2020).

To overcome the knowledge gaps between stakeholders due to differences in viewpoints (i.e., science-based knowledge by researchers, limited 'logic' with sectoral interest by government and other public stakeholders, and often-neglacted local knowledge), we need tools that can help facilitate the sharing and transfering knowledge to encourage mutual understanding by showing environmental issues faced by each stakeholder. This mutual understanding could then be turned into shared commitment towards more tangible action where each stakeholder acts according to his/her abilities, roles and responsibilities within the framework of the multifunctional landscape (Fig. 1.1). In addition, the tools should be inclusive and participatory, and should have three functions: strengthening knowledge, sharing knowledge and facilitating the collaborative-collective decision-making. Finally, to find the optimal model of multifunctional landscape out of many potential models, these tools should also be able to assist stakeholders in exploring various landscape management scenarios. Hydrological models and serious games are the tools commonly used to increase the understanding of the complexity of socio-hydrological systems (van Noordwijk et al., 2020).

This thesis uses a socio-hydrological system concept to describe systems where human appropriation of water resources occurs (i.e., interaction, dynamics, impacts, behaviour, response) (Blair and Buytaert, 2016). I classified the socio-hydrological system as a wicked system since many studies described socio-hydrological problem as a wicked problem because it included planning that had social value (Rittel and Webber, 1973; Reed and Kasprzyk, 2009; Markowska et al., 2020). As a wicked system, socio-hydrological systems have many interactions among components, which bring a high level of uncertainty (Rumeser and Emsley, 2019). To get a better understanding of socio-hydrological systems, I simplified it into a cascade model that provided a logical approach to the relationship between nature and humans by distinguishing biophysical structures providing functions and functions that serve human welfare (Haines-young and Potschin, 2010) (Fig. 1.2). Consequently, I divided the understanding of socio-hydrological systems into: 1) understanding effect of changes in landscape condition on hydrological functions and the provision of hydrological services (Fig. 1.2 to the left), and 2) understanding the human responses to (changes in) the hydrological services (Fig. 1.2 to the right; (Kumar et al., 2020). In this thesis, I used a hydrological model to simulate the effect of changes in landscape conditions on hydrological functions and a serious game to simulate the relationship between hydrological functions and human responses.

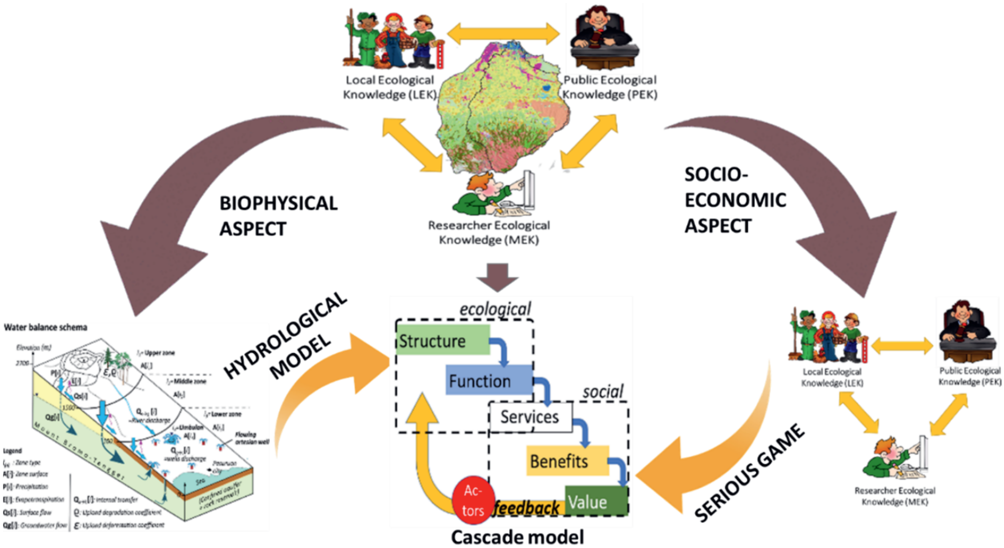


Figure 1.2. The cascade model (in the centre) is the initial step to simplify the socio-hydrological system that consists of biophysical aspects (e.g., topography, soil type, land cover, water body) and social aspects (i.e., stakeholders who have an interest in the landscape). The hydrological model is used as a tool for understanding biophysical aspects, while the serious games are used to understand human interactions among stakeholders and with landscapes.

Hydrological models can function as explanatory tools or discovery tools (Jakeman et al., 2006; Pianosi et al., 2016; Mozafari et al., 2023). As an explanatory tool, a hydrological model explains hydrological behaviour of the landscape under certain conditions, while as a discovery tool, the model is used to identify characteristics that cause this behaviour. Similarly, serious games are widely used to increase shared understanding of how a system works and to promote awareness raising (Ferguson et al., 2020; Feng et al., 2018; Rossano et al., 2017) and to provide a safe environment for the participants to explore many difference strategies and build a collaboration model through interaction among players a collaboration model (Janssen et al., 2023; Laucelli et al., 2019; Speelman et al., 2019; Fasce, 2015).

One of the challenges in using models and games are reusability and adaptation. To be able to contribute to actual planning, the models and the games need to be developed to a level of accuracy acceptable to the users (Costanza et al., 2014). Although the basic hydrological equations used in hydrological models are similar, at finer resolution there are unique characteristics associated with the location characteristics that affect the output and acceptance by users (Fenicia et al., 2011). Similarly, serious games with the aim of contributing to decision making for planning need to also consider the uniqueness of the area being simulated through game design and development (Flood et al., 2018). Therefore, developing models and games to be general enough to allow users to make modifications according to their needs might be a way to facilitate the wider application of these tools.

1.4. Summary of Problems, Objective and Research Questions

1.4.1. Summary of Problems

In this thesis, I address four problems related to socio-hydrological understanding of human appropriation of water resources in a multifunctional landscape to improve decision making in water and landscape management. Those problems are:

Problem 1: To meet needs and improve welfare, human appropriation of water resources has occurred in all aspects of water resources (e.g., quality and quantity of groundwater and surface water), and often these interventions have repercussions on humans and nature. Therefore, it is necessary to identify in more detail the human impact on water resources as an effort to restore the hydrological function as well as to maintain human welfare.

Problem 2: Socio-hydrological systems are complex due to the diversity of socio-hydro-physical characteristics, which are exacerbated by the fragmented understanding of what stakeholders have from the system. Therefore, it is necessary to select priority issues and their related elements through a participatory process as the initial step for the simplification of the socio-hydro-physical system to be portrayed into models and serious games.

Problem 3: Hydrological conservation and restoration can get inspiration from different areas facing similar socio-hydrological issues. Therefore, providing a clear framework and approach to address these issues will help the replication and adaptation process of it.

Problem 4: Designing a multifunctional landscape to restore the hydrological functions without neglecting the economic conditions requires shared understanding and commitment from all major stakeholders. Therefore, inclusive and participatory tools will encourage shared understanding among stakeholders.

1.4.2. Objective and Research Questions

The general objective of this thesis is to develop a fuller understanding of socio-hydrological systems for sustainable water resource management in multifunctional landscapes by integrating information from different knowledge systems and perspectives of different stakeholders.

Therefore, I address the following research questions:

RQ1. What are the impacts of human actions on water resources at various spatial scales?

RQ2. How can the socio-hydrological system be simplified into hydrological models and serious games?

RQ3. How can the models and games be adapted and replicated?

RQ4. To what extent do games and models contribute to decision making in restoring the hydrological functions?

To answer the research questions, I explore LEK, PEK and MEK based on literature reviews, interviews and discussions with stakeholders, and carry out field measurement and hydrological modelling to assess and predict the hydrological functions. I structure the LEK, PEK and MEK information using Driver, Pressure, State, Impact and Response (DPSIR) and Actor, Resource, Dynamic and Impact (ARDI) frameworks to develop serious games. I evaluate the use of serious game to the changes of stakeholders' perception using the Likert and Q-methodology survey. Two study sites are used to demonstrate the adaptability of the hydrological models and the serious games.

1.5. Study Sites

This thesis explores two distinct socio-hydrological systems in Indonesia where groundwater issues are relevant in contrasting way to create the opportunity to contextualize progress along the knowledge-to-action chain. The lessons learned from these two landscapes are expected to provide a guideline for adaptation at other locations where groundwater issues are also relevant. Both landscapes, the Rejoso watershed in the Java Island and the Pawan-Kepulu peatland on the Kalimantan Island, are characterized by hydrological degradation due to forest conversion into plantations and agricultural land and massive water extraction leading to various environmental problems. However, each site has a unique socio-ecohydrological characteristic that may require different efforts or responses to restore its hydrological function.

The Pawan-Kepulu peatland is a peat area in Ketapang district, West Kalimantan Province, Indonesia. The peatland is situated between Pawan River, Kepulu River and Karimata strait, functioning as a unified hydrological system. Since 2021, this peatland has become part of the national restoration priority program because of its high frequency of fires that occur mostly during the dry season. The average monthly rainfall in the Ketapang district varies from 100 to 500 mm with the dry months between June–August (Kurnianto et al., 2019). Data on the distribution and function of peat ecosystems (Inventory of Peatland Ecosystem Characteristics (Scale 1:50.000))shows that the Pawan-Kepulu peatland covers 64,263 Ha, consisting of 58% of peat soil and 42% mineral soil. Around 60% of the peat soil (22,056 ha) is designated as a protected area, and is characterized by a peat depth of more than 3 m. The remaining 40% (15,117 ha) is covered by cultivated areas with a peat depth of less than 3 (Fig. 1.3).

Based on the 2022 land cover map by Tropenbos Indonesia (Fig. 1.3), oil palm plantations dominate this landscape. The forest area is part of a state forest managed by the Forest Management Unit and is the habitat of orangutans. Recently, some of the forested areas have been handed over to the villages as part of social forestry programs for implementation by village forest management units. Most of the oil palm area is managed by the oil palm companies and a small part by communities. The agricultural area is used for seasonal crops and belongs to the local people who are mostly migrants from other regions in Indonesia. However, due to lack of infrastructure and equipment, part of their agricultural area is still abandoned and covered by shrubs (Fig. 1.3, mixed crop and shrub). The spatial analysis result of comparing canal density and land use in this peatland indicated that the oil palm plantations and mixed cropping and shrub areas have the highest canal density (Chapter 4). The intensive agriculture and oil-palm plantation, which triggered the massive canal construction, has made peatlands dry faster during the dry season (Tonks et al., 2017).

As an effort to reduce and prevent fire hazards in the Pawan-Kepulu peatland, Peatland and Mangrove Restoration Agency (BRGM) is implementing three restoration strategies: rewetting, revegetation and revitalization of economic conditions. The district and provincial governments responsible for the spatial planning in this area have prepared a master plan for peatland management, which defines the land use according to the depth of the peat soil, water management through canal blocking, awareness raising and monitoring (Widayati et al., 2022, 2024). The master plan is expected to be a guideline for land management in the Pawan-Kepulu peatland to restore the hydrological function of peatlands and thereby prevent land fires. This thesis has contributed to the development of the master plan by providing a better understanding of the hydrological system of the Pawan-Kepulu peatland (Chapter 4) and by using tools to facilitate the improvement of and sharing of knowledge between stakeholders (Chapter 5). However, the implementation of this master plan still requires awareness and acceptance by stakeholders who live and work in this region.

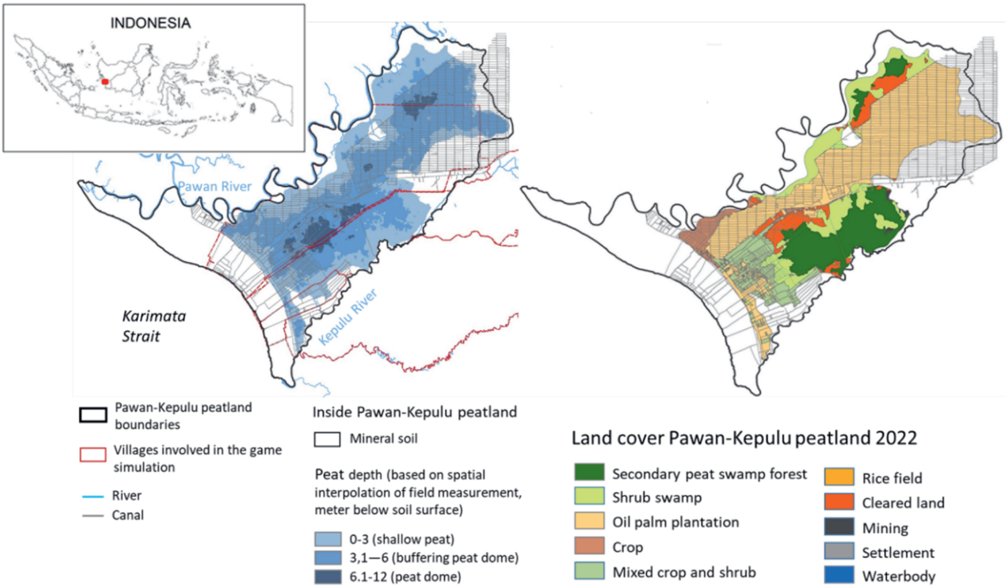


Figure 1.3. (A) Pawan-Kepulu peatland which consists of mineral and peat soil which has three classes of peat depth (shallow peat, buffering peat dome and peat dome) (source: Ministry of Environment and Forestry and field measurement in this thesis) (Left), and (B) land cover in 2022 (Source: Tropenbos Indonesia and field measurement) (Right).

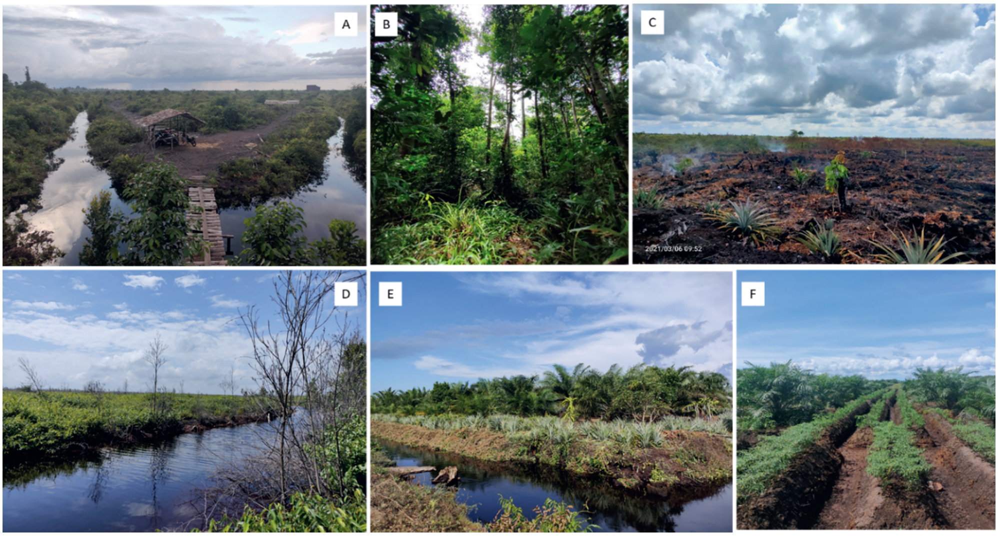


Figure 1.4. Pictures of the study area to illustrate the different land uses found in the Pawan-Kepulu peatland. (A) Canals that were made in the peatland and connected to each other, (B) secondary peat swamp forests that are home to orangutans and other animals, (C) peatlands that were currently burning, (D) areas that were burned several years ago that have become swamps shrub, (E) smallholder oil palm plantations, (F) dry land agriculture with young oil-palms.

The Rejoso watershed is a watershed in East Java which has its final outlet in the Java Sea. Most of the Rejoso watershed area is in the Pasuruan District, and the rest is in the Pasuruan City. In 2021, the President of Indonesia inaugurated the national drinking water project taken from the Umbulan spring in the downstream of the Rejoso watershed. This project has been prepared since 2016 and is part of a national strategic project targeting 4000 litre/second of water from the Umbulan spring to supply drinking water for 1.3 million people. This large amount of groundwater storage in the Rejoso watershed because of being surrounded by the active volcanos. Besides providing a large supply of groundwater, this condition also gives fertile soil. In the volcanic areas of Indonesia, most soils are formed by young soil layers, which have a high level of porosity and fertility as a result of active volcanic eruptions (Kurniawan et al., 2021). Most soil layers in the Rejoso watershed are formed from layers of ancient lava that allow many fractures to connect the surface and groundwater systems in the upstream and midstream, which produce a large supply of groundwater (Toulier et al., 2019a). The fertile soil condition supported by an abundant water supply, has made the Rejoso watershed suitable for intensive agriculture.

Based on the Rejoso watershed wide range of elevation (0-2670 m a.s.l.), some studies divided the Rejoso watershed into: downstream (0-100 m a.s.l.), midstream (100-1000 m a.s.l.) and upstream (>1000 m a.s.l.) (Fig. 1.5) (Amaruzaman et al., 2018; Leimona et al., 2018; Khasanah et al., 2021). These large elevation differences cause the Rejoso watershed to have variations in the amount of rainfall between upstream, midstream and downstream. Annual rainfall in the Rejoso watershed varies from 1655 mm during dry years to 3675 mm or even more during wet years. Even though there are different variations in the amount of rainfall, all areas have a rainy season from November to May with monthly rainfall of more than 100 mm.

Based on the 2015 land cover map produced by World Agroforestry (ICRAF), the upstream area is dominated by horticulture, the midstream area is dominated by complex agroforestry, and the downstream area is dominated by rice fields (Fig. 1.5). Based on the 1990-2015 land cover analysis, complex agroforestry was a land cover that has undergone many changes (Amaruzaman et al., 2018). Agroforestry areas were being converted into rice fields in the downstream areas and into horticulture in the upstream areas. In 2015, the area with the most remaining complex agroforestry was only the midstream area. The water conditions and the local knowledge of trees in the midstream area are the reasons why people continued to maintain agroforestry in this area. In the future, the community predicts that the dominant land cover in their area will remain the same, but the settlement area will increase due to population growth. The downstream area will still be dominated by rice fields, but the number of settlements will increase, the midstream will still be dominated by complex agroforestry, but settlements and timber plantations will increase, and the upstream area will still be dominated by horticulture.

In the downstream areas, there is competition for the use of groundwater between rice farmers and companies. The condition of the Rejoso watershed with its still active volcano means that the Rejoso watershed has a large supply of groundwater with downstream utilization areas (Toulier, 2019). Most of the rice farmers in the downstream area from the Rejoso watershed irrigate their rice fields using groundwater extracted by artesian wells (Khasanah et al., 2021). The ease of farmers in constructing artesian wells encourages competition for water use with water-based companies, especially the companies that manage drinking water supply system from the Umbulan spring.

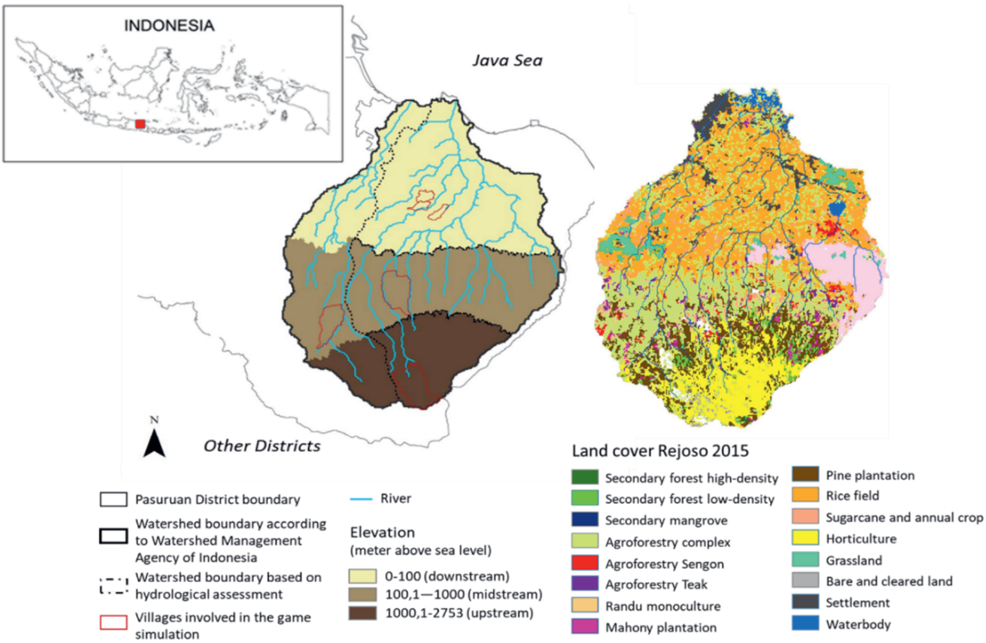
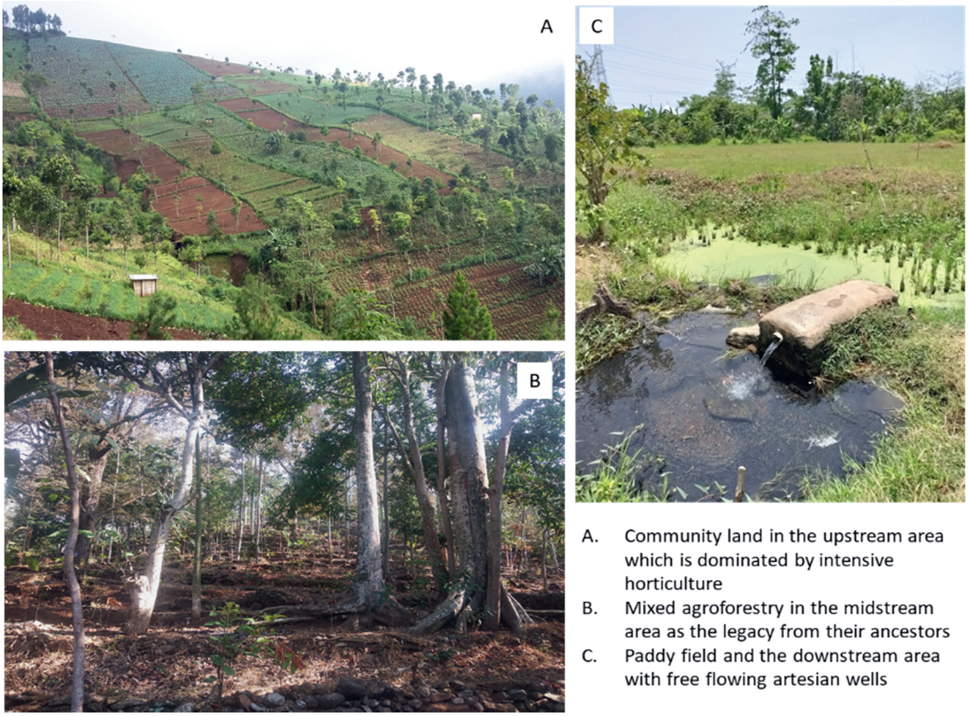


Figure 1.5. Rejoso watershed which is divided into upstream, midstream and downstream area based on elevation (left) and land cover in the Rejoso watershed in 2015 (right) (Source: Amaruzaman et al. (2018)).



A. Community land in the upstream area which is dominated by intensive horticulture
B. Mixed agroforestry in the midstream area as the legacy from their ancestors
C. Paddy field and the downstream area with free flowing artesian wells

Figure 1.6. Dominant land cover conditions in the upstream (A), midstream (B) and downstream (B) of the Rejoso watershed.

Hydrological restoration in the Rejoso watershed needs to be carried out in an integrated manner from upstream to downstream, comprising land and water use management to manage supply and demand of hydrological resources. As the groundwater recharge area, the upstream and midstream areas need land management that supports and maintains infiltration levels, without neglecting the economic functions for communities as owners and managers of the land. The study of tree and crop preferences carried out in upstream and midstream indicated that the economic value of agricultural products became the main criteria in selecting agricultural commodities (Amaruzaman et al., 2018). Good agricultural practices in the downstream area such as crop rotation and an efficient water utilization according to vegetation needs are expected to overcome the issue of groundwater demand (Khasanah et al., 2021).

To show the comparison between the conditions of the Rejoso watershed and the Pawan-Kepulu peatland, I summarized the landscape conditions and the issues in Table 1.1.

Table 1.1. The comparison of characteristic and issues of the two study sites in this research.

Parameter	Pawan-Kepulu peatland	Rejoso watershed
Area (Ha)	64,263	62,773
Area and boundaries	The hydrological area and boundary in this study is the peatland area between the Pawan River and the Kepulu River. Social data collection involved four villages: Sungai Pelang, Sungai Besar, Sungai Bakau and Pematang Gadung.	The hydrological area and boundary is the Rejoso Watershed stretched from Mt. Bromo (upstream) to Java sea (downstream). Social data collection involved five villages: Tosari, Kemiri, Galih, Kebon Candi, Penataan, and Tenggilis Rejo. In addition, secondary data collected from other villages in the Rejoso watershed was used to identify the main issues.
Climate	Average annual rainfall: 3200 mm. Rainy season from November to May and dry season from June to October.	Annual rainfall: 1655-3675 mm, and more than 5000 mm in the extreme wet year. Rainy season from December to February, and dry season from June to October.
Elevation (m a.s.l.)	0-10	0 - 2760
Landscape zoning to support management	The Indonesian government regulations divide peatland into: cultivation area in shallow peat (peat depth <= 3 m), and protected area (peat depth > 3m). This thesis divided the protected area into: buffering area of dome (Peat depth 3-6 m) and the dome (peat depth > 6m).	The Rejoso watershed was divided into (Amaruzaman et al., 2018; Leimona et al., 2018; Khasanah et al., 2021): Upstream (elevation 0-100 m a.s.l.) Midstream (elevation 100 – 1000 m a.s.l.) Downstream (elevation > 1000 m a.s.l.)
Land cover	The Pawan-Kepulu peatland is dominated by oil palm (company and small holder plantation), secondary peat swamp forest and mixed crop and shrub cover (refer to figure).	The Rejoso watershed was dominated by horticulture and pine plantations in the upstream, complex agroforestry (mixed garden) in the midstream and rice fields and annual crops in the downstream.
Population size	39,900 people	838,313 people
The importance of this area	Provide many ecosystem services (e.g., regulating water, storing carbon and maintaining biodiversity). The forest area is the home of critically endangered Bornean Orangutan (*Pongo pygmaeus).*	Supporting high quality groundwater supply for downstream industries and communities. The Umbulan spring became a national priority project because provides water to the Surabaya metropolitan area and the surrounding cities and districts.
Environmental Issues	Haze hazard during fires in the dry season and flooding during the rainy season.	Decreasing groundwater supply (6 m^3s^{-1} to 4 m^3s^{-1}) that implies a gap between groundwater supply and demand.
The purpose of this study to meet the issues	To restore the hydrological function by increasing and/or stabilizing the 'ground-water' level (or reducing the water outflow from artificial drainage), to prevent the fire hazard.	To restore the hydrological function in The Rejoso watershed by improving the ground-water management.

1.6. Structure of the Thesis

I organized this thesis into seven chapters, with the connections between chapters being shown in Fig. 1.7. Table 1.2 presents the use of ecological knowledge (LEK, PEK, and MEK) and tools (hydrological modelling and serious game) in each chapter. The seven chapters are as follows:

- Chapter 1 provides a general introduction to provide background, problems and general approaches used in this thesis. It also provides the research questions being addressed.
- Chapter 2 presents various human efforts to secure water resources on the ground by reviewing ten different efforts or factors that influence rainfall, which are believed to be the source of the water resource.
- Chapter 3 presents a simple hydrological simulation to see the impact of land use and water management on the restoration of the discharge of the Umbulan spring. It also provides a typology of rice farmers who use groundwater to understand their decisions in utilizing the artesian wells. This chapter uses water budget equations to calculate the changes of groundwater storage and interviews with rice farmers to understand their rice field management patterns.
- Chapter 4 presents the development of a process-based and semi-distributed peatland hydrological model based on field measurements to simulate the hydrological conditions as impact of land and water management. To develop a peatland hydrological model at plot and landscape level, I use both water budget equations and the Hooghoudt equation to calculate water level between two open channels.
- Chapter 5 provides a documentation of the H_2Ours game development and discusses the adaptability of serious games in allowing adjustments to local contexts for other issues or areas. I use two frameworks to sort information from the socio-hydrological system to develop the H_2Ours game: Driver, Pressure, State, Impact and Response (DPSIR) and Actor, Resource, Dynamic and Interaction (ARDI).
- Chapter 6 provides a reflection of the use of the H_2Ours game in the Rejoso watershed to develop shared understanding and facilitate transfer knowledge among game participants. I analyse the results of the H_2Ours implementation in the Rejoso watershed in terms of their decision making on and the reasons related to land use and water management during the game session and the changes in participants' perceptions before and after the game session using Q-methodology analysis.
- Chapter 7: The general discussion provides key findings and discussions referring to the general research questions. This chapter is built based on the literature review, research findings and reflections from the related chapters in this thesis.

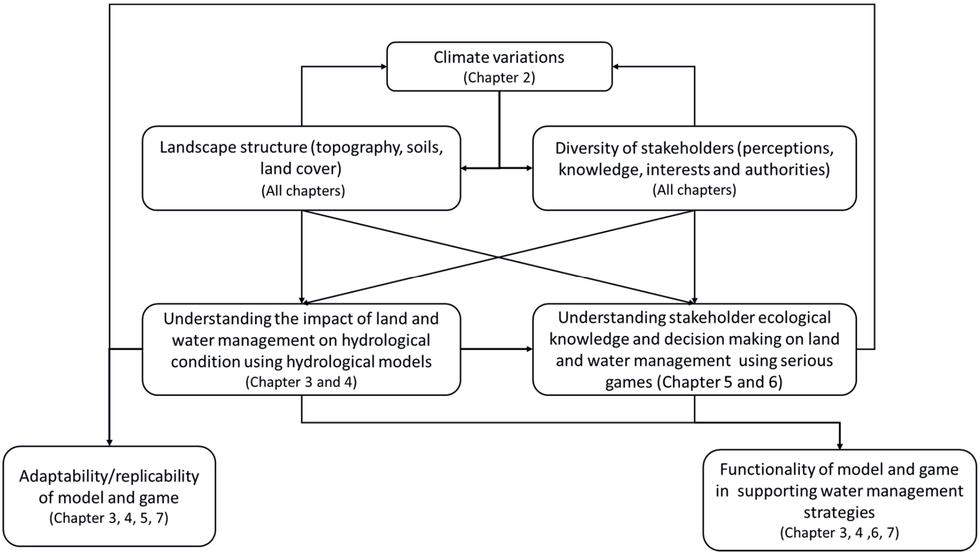


Figure 1.7. The structure of chapters in this thesis that describes the process of integrating understanding as input for the development of hydrological models and serious games to facilitate the development of shared understanding among stakeholders to support water resource management strategies in multifunctional landscapes.

Table 1.2. Structure, knowledge systems (LEK: Local Ecological Knowledge. PEK: Public Ecological Knowledge, and MEK: Modeller/researcher Ecological Knowledge) and tools (hydrological model and serious game) used in this thesis. (++: strongly or explicitly used, +: used).

Chapter	Title	Knowledge system			Tools	
		LEK	PEK	MEK	Hydrological model	Serious game
2	Who and what makes rainfall? Relational and instrumental paradigms for human impacts on atmospheric water cycling	++	++			
3	Groundwater-extracting rice production in the Rejoso watershed (Indonesia) reducing urban water availability: characterization and intervention priorities	+	+	++	++	
4	Rewetting a tropical peatland by canal blocking? Linking groundwater dynamics at plot and landscape scale in the Pawan-Kepulu peatland, Indonesia	+	+	++	++	
5	The H_2Ours game to explore Water Use, Resources and Sustainability: connecting issues in two landscapes in Indonesia	++	++	+	+	++
6	Trees and restoring groundwater flows: enhancing shared understanding through H_2Ours game in the Rejoso watershed, Indonesia	++	+			++
7	Synthesis and general discussion					

A Complex agroforestry in the midstream area of the Rejoso watershed. The area with the most trees but always suffering from water scarcity during the dry season.

Found a double rainbow during
a thesis break.

Chapter 2: Who or What Makes Rainfall? Relational and Instrumental Paradigms for Human Impacts on Atmospheric Water Cycling

This chapter was published as:

Tanika, L., Wamucii, C., Best, L., Lagneaux, E. G., Githinji, M., & van Noordwijk, M., 2023, Who or what makes rainfall? Relational and instrumental paradigms for human impacts on atmospheric water cycling. *Current Opinion in Environmental Sustainability*, *63*, 101300.

Abstract

Human impacts on water cycles (HIWC) can include modification of rainfall. Spatial and temporal variation in rainfall, with implications for 'water security', has been attributed to multiple causal pathways, with different options for human agency. Ten historical paradigms of the cause of rainfall imply shifts from 'nature controlling humans' to 'human control over nature' and 'human control over other humans'. Paradigm shifts have consequences for human efforts, interacting with social-ecological systems, to appease spirits, please rainmakers, expose 'rainfakers', protect forest, plant trees, reduce greenhouse gas emissions, apply cloud seeding, or declare rainfall modification an illegitimate tool in warfare. The 'instrumental' and 'relational' values of atmospheric water cycling depend on cognitive paradigms of rainfall causation as represented in local, public/policy or science-based ecological knowledge. The paradigms suggest a wide range of human decision points that require reinterpretation of rationality for any paradigm shift, as happened with the forest-rainfall linkages.

Keywords: Climate change; Cloud seeding; Forests; Instrumental value; Rainmakers; Relational value; Teleconnections

2.1. Introduction

Without rainfall, life on earth would be restricted to oceans, where 97% of the world's water currently resides. Evaporation of sea water started the water cycle over land, with 69% of the worlds' fresh water currently stored in ice caps, 30% in groundwater and a mere 1% in soils, lakes and vegetation (van Noordwijk et al., 2019); only 0.03% of the worlds water is at any point in time atmospheric – feeding rainfall, while evapotranspiration over both land ('short cycle') and oceans ('long cycle') replenishes the atmospheric pool. Human wellbeing depends on rain that greens the lands, allows crops to grow, and quells human thirst. Historically, the onset of the rainy season has been a period of stress, with a strong incentive for humans to control the process, with rainmakers addressing the social tension and 'buying time' until rains start. Beyond broad spatial and seasonal patterns, rainfall still has low temporal and spatial predictability, especially where modern weather forecasts and radar-based monitoring of rain-fronts is lacking. While other aspects of human impacts on water cycles (HIWC) are widely discussed, metrics such as 'footprints' consider rainfall to be 'exogenous', rather than as direct target for human action (van Noordwijk et al., 2022).

Although precipitation is one of the most relevant aspects of the climate, the UN Framework Convention on Climate Change (UNFCCC) has focused on warming as primary impact of greenhouse gas emissions, and on land cover change as emission factor, rather than as direct modifier of the climate. Current Global Circulation (or 'Climate') models have limited skill to predict changes in rainfall patterns, although improvements of the representation of vegetation feedback are a frontier in this science (Masson-Delmotte et al., 2021). Rainfall as a process is not included in the IPBES conceptual scheme of Nature's Contributions to People (NCPs) and its 18 categories (Pascual et al., 2017); nor is it listed as a Nature Based Solution (Seddon et al., 2020). However, a growing body of literature considers it an 'Ecosystem Service' (van Noordwijk et al., 2022, 2016; Ellison et al., 2017). People's worldview about who or what causes rain inform their actions. With progress in empirical and science-based understanding, concepts that were part of traditional ecological knowledge (such as 'rainmakers') can be replaced. Sometimes, however, such concepts re-emerge with a new mechanistic interpretation, as happened with 'forests' in relation to rainfall. Rainfall is subject to widely differing explanatory models or paradigms (spiritual, geographical, biological, technical, warfare, etc.). Based on a recent review (Creed et al., 2018), at least ten different paradigms have, across time and space, been used as explanatory causes of rain (Fig. 2.1).

We briefly review these ten different rainfall paradigms that currently coexist providing an overview of how humans have connected with rain throughout the history of social-ecological systems. We grouped the human-nature relations into four phases, according to a recent transition hypothesis (Roux et al., 2022): I. Nature is powerful, II. Taming of nature, III. Rational management of nature, IV. Reconnecting with nature. These paradigms suggest very different actions and operational metrics to be used as indicator (Lusiana et al., 2017) (Fig. 2.2). After reviewing the paradigms, we discuss 'how has the balance of instrumental and relational values in the human-nature relationship on rainfall changed over time and how manageable is future rainfall?'.

2.2. Rainfall Paradigms

2.2.1. Rain God(s)

Our ancestors who lived as hunters and gatherers, but also the subsequent pastoralists and their herds who followed the rains and fresh grass it generates, were not constrained by fences and borders.

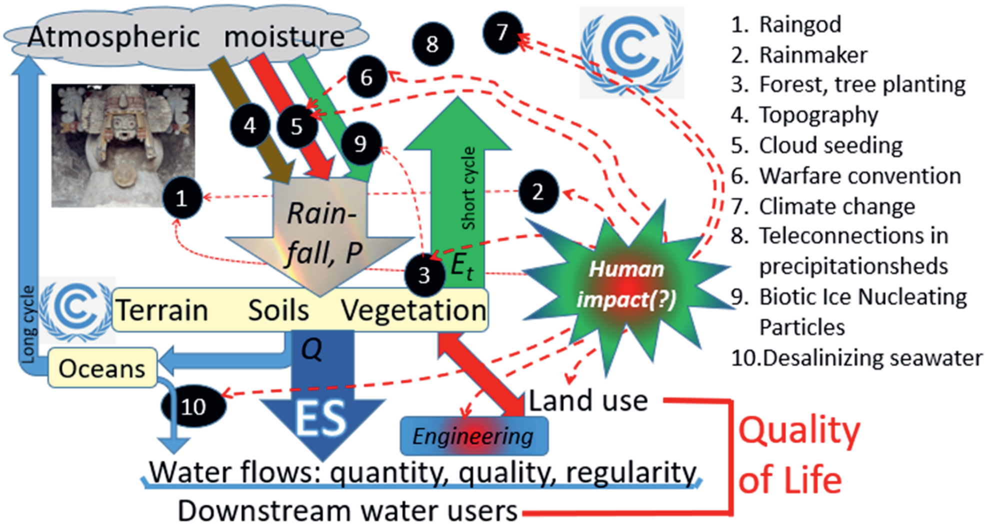


Figure 2.1. Ten paradigms of provision of water through rainfall or alternate means, with different pathways for and degrees of (presumed) human impact; ES = Ecosystem Services, P = precipitation, Q = river discharge, Et = evapotranspiration, interrupted red arrows = human impacts.

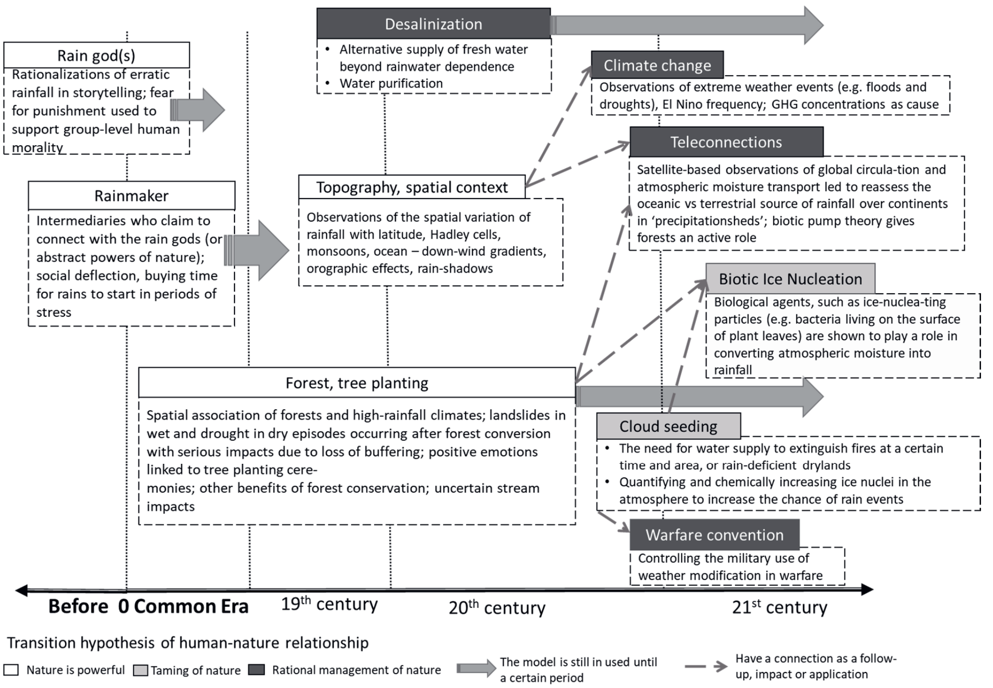


Figure 2.2. Ten paradigms of the cause of the rain according to time period and transition hypothesis of human-nature relationship.

Place-bound crop growers of the last 10,000 years had to pray for rain to arrive at the desired time to plant their seeds, for the rivers to bring water and soil fertility to flood plains, for springs to continue to flow and for pastoralists to go elsewhere. Associated with these lifestyles, spiritual and religious concepts diverged among people of different habitats (Preston and Baimel, 2021). Deities associated with water or bodies of water were important in many mythologies from the Middle East, Greeks, Romans, and American first nations (Angelakis et al., 2022). Various beliefs and rituals were performed to please the rain gods/goddesses as shown by rock art in Mexico (De La Cruz et al., 2008; Rissolo, 2020), and to attack water-dwelling companion spirits of bad-acting local rulers and settlers in Huitzilan, Mexico (Taggart, 2020). Using a worldwide, largely nonindustrial sample of 46 societies with high gods, a recent study (Ember et al., 2021) found that belief in a high god being directly involved in rainfall was more common in drier climates. The ancient Greeks often considered a king to be a magician at the service of the (water) gods. This indicates a gradual transition to paradigm 2, the rainmaker.

2.2.2. The Rainmaker

Rainmaking is surrounded by mystery and dark magic (Guthiga Paul ; Newsham Andrew, 2011), seen as exploiting clients by 'rainfaking', but also described as part of Indigenous Knowledge that needs to be studied since it affects decision-making and actions at local level (Speranza et al., 2010; Guthiga Paul ; Newsham Andrew, 2011; Martins, 2022). A real contest in faith of rainmaking occurred when Sechele, the Bakwena chief in current Botswana, had, as part of accepting the new religion brought by missionaries in the 19th century, renounced his traditional ritual functions of rainmaker (Stanley, 2014) during a continuous drought affecting his area. After conversions from African traditional religions to Christianity, the churches willingness to 'pray for rain' has been described as a slippery slope (Muller, 2017) reconciling the relational need for *communion* with the instrumental requirement of providing *explanation, prediction and control* of everyday events. Interestingly, in the humid tropics of South-East Asia, where heavy rainfall can disturb events such as weddings or motor races, the 'pawang hujan' who, after suitable ceremonies, can avoid rainfall at a specified time and place is still popular; some operate on a 'no cure, no pay' accountability clause that protects them from blame. In recognition of relational values that communities place on the rainmakers, some countries have integrated indigenous knowledge with scientific knowledge as an important component of making rain. These include the use of the Nganyi rainmakers in Kenya (Guthiga Paul ; Newsham Andrew, 2011; Zachary et al., 2021). Whether rainmakers make it rain or not, this cultural phenomenon made humans view themselves as a part of nature, thus nurturing nature instead of utilizing it for own benefits (Simonse, 2017; Molato, 2020). The rainmakers also provide a cause for endurance around drought and floods with anticipation that he/she will provide spiritual solutions to rainfall (Ogwang et al., 2014).

2.2.3. Forest

Since ancient times, humans have observed the spatial association of forests and rainfall, but debated the causality involved: forest dependence on rainfall and/or forests as rainmaker. The notion that 'forests make rain' was reinforced in the colonial era with tree planting as logical rainmaking consequence (Creed et al., 2018). Increasing evidence in the last quarter of the 20th century that planting fast-growing trees, such as *Eucalyptus* species can actually dry up, instead of return, streams casted doubt on the causal pathways involved, or at least on the relevance of spatial context and functional traits of tree species chosen. While hydrologists clarified the water balance of forests and trees, given rainfall, the focus was on evaporation, transpiration, enhancing soil infiltration and stream flow persistence. Meanwhile, statistical evidence that links long-term rainfall data sets to regional deforestation (or reforestation) has generally been inconclusive, although a recent study for Africa found significant patterns (Duku and Hein, 2021). A considerable science-policy gap arose when the general belief that there is ‘no water without forests’ and that tree planting is a solve-all intervention, was replaced by the blue-green water competition concept that more trees means less water in the streams (Creed et al., 2018). When the assumption of ‘no effects on rainfall’ was revisited, however, it became clear that forests and trees can also affect several factors required for rainfall, such as the presence of atmospheric moisture through evapotranspiration and convection processes and the local capture of atmospheric moisture at higher altitudes (cloud forests) (Makarieva et al., 2009). Current science, however, does not support a generic ‘all forests cause rainfall’ theory, but accepts that the role land cover plays in precipitation depends on location on the globe, and interacts with other factors (Browning, 1990; Old et al., 2003) that are discussed below. Reconciliation of local, public-policy and science-based knowledge is needed to guide tree planting efforts (Leimona et al., 2015).

2.2.4. Topography

Travelers, since the ancient Greeks at least, noticing dry and brown, or wet and green places started to speculate about spatial variation in rainfall and its consequences, preferentially settling where springs or rivers provided water in pleasant, not-too-humid, disease-ridden climates. Seafarers noticed winds and ocean streams, and their seasonal and latitudinal patterns. On land, travellers noticed orographic rainfall and rain shadows (Creed et al., 2018). Terrain features, as studies in topography, play an important role in determining the planet’s atmospheric circulation (Ogwang et al., 2014), hence they are an important paradigm of rainfall causation. Topography can explain the differences in spatial-temporal rainfall distribution starting from local, regional, to global levels. Land surface features produce a gradient of atmospheric and earth surface energy budget that influence precipitation in space and time (Trenberth, 2011). At the local level, rainfall distribution differs as the gradient changes from highly elevated areas e.g., mountains (characterized by high rainfall, low temperatures) to area with lower elevation e.g., lakes, oceans, arid environments. Three different types of rainfall emerge including; orographic rainfall (Rodrigo-Comino, 2021), convectional rainfall (Old et al., 2003), and frontal rainfall. At the regional level, monsoon circulations occur due to atmospheric energy differences between oceans and lands, hence seasonal rainfall variations (i.e., summer, winter, spring, and autumn seasons) (Gitau et al., 2015; Liu et al., 2020; Ramesh et al., 2021). Global-scale atmospheric convection produces Hadley cells, the salient features that control precipitation in both the northern and southern hemispheres of the globe (D’Agostino et al., 2020b; Xian et al., 2021). This type of understanding does not suggest human interventions, other than informed choices of where to settle, start water-dependent agricultural practices or engineer water flows.

2.2.5. Cloud Seeding

Naturally, water molecules need to coalesce before water droplets are formed. This process is highly dependent on the presence of particles as nuclei, without which rain fails to materialize although air is saturated with water vapour. A cloud seeding experiment in 1946 demonstrated the potential for inducing precipitation (Dennis, 1980). However, changes in cloud structure at the micro-level during the cloud seeding process were found to affect the success rate. A range of hygroscopic materials such as salt, urea, dry ice, silver iodide and potassium iodide was tested (Malik, 2018). Detailed statistical evaluation of current practice in water-scarce and arid areas in the Middle East suggests a 23% increase in annual surface rainfall over the seeded target area (Al Hosari et al., 2021). Today, cloud seeding is not only used to increase rain, but to regulate the weather such to reduce cloud cover, to clean air from pollutants, to extinguish wildfire (Al Hosari et al., 2021), and to store water as ice in the mountainous area during the snowy season (Rauber et al., 2019). Contested applications aim to shift heavy rainfall away from flood-sensitive metropoles, leading to complex 'loss and damage' claims to the areas receiving unwelcome rain. Drawbacks to cloud seeding remain the costs, atmospheric pollution, low predictability of impacts and risks of unintended damage elsewhere.

2.2.6. Warfare Convention

During the Cold War era starting in the late 1940's opportunities for Wet Warfare by inducing heavy storms at will, were explored by both sides of the military-technological arms race (Fleming, 2010). The political, military and ethical implications of geotechnical climate engineering to "control" the climate led to a public outcry in the aftermath of the Vietnam War. The United States used cloud seeding to flood northern Vietnam, to aid photoreconnaissance, to reduce enemy troop morale or damage harvests. Elsewhere, it triggered snow to expose camouflage and reveal signs of enemy activity on supply routes (Harper, 2017). As a result of the debate this sparked, an international treaty was negotiated in the United Nations and ratified on 5 October 1978 that prohibits the military or other hostile use of such environmental modification techniques (Currier, 2017). The public phase-out of military cloud seeding was discussed as an example of the social and political aspects of technologies that are rejected for adverse social or environmental effects, opening the door to new, peaceful applications (Koretsky and van Lente, 2020). The relevance of regulating the domestic use of cloud seeding, that likely will have both winners and losers in any application, is still unresolved (Williams, 2017; Hertz, 2021).

2.2.7. Global Climate Change

The increasing concentrations of greenhouse gases (GHG) in the atmosphere modifies the global atmospheric circulation affecting the intensity and frequency of precipitation (Dennis, 1980; Gordon et al., 1992; Tabari, 2020). Human climate impact was summarized by IPCC in 2021 (Masson-Delmotte et al., 2021) as already reaching a 1.5^{O}C global warming in the 2010–2019 period relative to 1850–1900, but counteracted by a 0.4^{o}C aerosol-induced cooling – based on clouds that reflect incoming radiation but do not bring rain. Global warming leads to greater atmospheric energy on the earth's surface, hence high surface evaporation on oceans and surface drying on land, affecting the intensity and duration of droughts. In line with increasing oceanic and terrestrial evaporation, globally averaged precipitation over land has likely increased since 1950, with a faster rate of increase since the 1980s. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming (Masson-Delmotte et al., 2021). A recent study identified two human fingerprints on the global climate in multiple ensembles of Earth system model simulations (Bonfils et al., 2020). The first is characterized by global warming, intensified wet–dry patterns, and progressive large-scale continental aridification. This is largely driven by multi-decadal increases in GHG emissions. The second captures a pronounced interhemispheric temperature contrast, associated meridional shifts in the intertropical convergence zone, and correlated anomalies in precipitation and aridity.

2.2.8. Precipitationshed Teleconnections

Terrestrial evapotranspiration, moisture recycling and transportation are now understood to be a major source of rainfall over continents (van Noordwijk et al., 2014; Wang-Erlandsson et al., 2018). Teleconnections link precipitation to upwind areas that contribute atmospheric moisture (Keys et al., 2012) and explain how droughts can spread from upwind to downwind areas, as has happened during the 2012 Midwest drought in the USA (Herrera-Estrada et al., 2019). Teleconnections also explain why precipitations within large basins (e.g., Amazon, Yangtze) are strongly influenced by land-use changes occurring outside the basins (Bonfils et al., 2020). They have important implications for (international) water management and governance, particularly when land-use change in a given region (e.g., deforestation, which diminishes evapotranspiration) disrupts rainfall patterns elsewhere (Spracklen et al., 2012). For example, West African rainfall depends on East African evapotranspiration (Tabari, 2020); deforestation in West African rainforest threatens food security in the Nile Basin (Ellison et al., 2018). While watersheds, rather than precipitation sheds, are still the focus of water governance (Keys et al., 2017), understanding tele-coupled patterns of land-use change and moisture recycling can support transregional water management and governance (Spracklen et al., 2012; Herrera-Estrada et al., 2019; Tabari, 2020). So far, legal and institutional implications ("moisture recycling governance") remain to be explored (Spracklen et al., 2012). One study of atmospheric recirculation (Tuinenburg et al., 2014) suggests that increased groundwater use for irrigation in India contributes to increased rainfall in Pakistan, relevant for ongoing 'Loss and Damage' debates in the UNFCCC. As Pakistan, due to its topography, appears to have a high recycling ratio (Keys et al., 2019) for its own use of groundwater (replenished in a multi-year balance), the cause-effect relations will be hard to disentangle; blaming global climate change for recent floods may be oversimplified.

A recent study (Wunderling et al., 2022) found four distinct terrestrial moisture recycling hubs in the tropics: the Amazon Basin, the Congo Rainforest, South Asia and the Indonesian Archipelago, with contrasting network patterns. The Amazon strongly relies on directed (upwind-downwind) connections for moisture redistribution, the other hubs have less-directional reciprocal moisture connections. Current debate looks at how such results relate to the 'biotic pump hypothesis' (Ogwang et al., 2014) that condensation of water vapor over forests creates horizontal pressure differences in the lower atmosphere that propel local atmospheric dynamics (Dominguez et al., 2022; Makarieva et al., 2022). Rather than generic 'forest' theories, the teleconnections suggest specific topologies shape specific effects of land-use changes on precipitation.

2.2.9. Biotic Ice-Nucleating Particles

The transition of atmospheric moisture to droplets and rainfall depends on the presence of ice nucleating particles (INPs), including abiotic dust and hygroscopic salts, and biotic volatile organics or biological cell wall material. Particularly microbial communities living on the surface of plant leaves play an important role in water cycling (Vacher et al., 2016). Bacteria such as *Pseudomonas syringae* use ice-nucleating proteins to induce ice formation at temperatures just below the ice melting point, to frost damage the plants they attack (Pandey et al., 2016). When these bacteria join the atmospheric microbiome as aerosols, they can catalyse ice crystal formation and cloud formation, generating precipitation (Morris et al., 2014; Fröhlich-Nowoisky et al., 2016). Precipitation, in turn, is beneficial for the growth of plants and associated microorganisms, forming a positive bio-precipitation feedback cycle (Fröhlich-Nowoisky et al., 2016), that may complement the biotic pump.

2.2.10. Desalinizing Sea Water

Large-scale desalination of seawater drives the main hydrological cycle, through evaporation of seawater, condensation in the atmosphere and rainfall over land (Nair and Kumar, 2013). In the past, sailors used small-scale versions of this process to provide fresh water for long distance travel; soldiers also use this desalination technique to supply water during war (Zhu et al., 2014). In the modern era, the increasing population, changing climate, human interventions and subsequent demand for freshwater has pushed humans to look for options to address scarcity of freshwater (Angelakis et al., 2021; Tsiourtis, 2001; Zheng et al., 2020). Since installation of the first desalination unit in 1885 in Scotland the technology has been refined (Lior, 2012; Curto et al., 2021) and spread to over 177 countries across world (Chenoweth and Al-Masri, 2022) with 44% of global production of desalinated water occurring in the Persian Gulf. Negative effects on local marine environments of commonly used technologies include discharges of waste water that increase salinity, temperature, and nutrient concentrations affecting marine ecosystems such as seagrass meadows, coral reefs and soft sediment ecosystem (Miller et al., 2015; Petersen et al., 2018).

2.3. Human-nature Relationship

The balance of instrumental and relational values in the human-nature relationship changed over time, as across the ten paradigms. With an increasing sense (perception) that human actions influence rainfall, either positively or negatively, (e.g., by disturbing the cosmic balance, displeasing gods, deforesting, emitting greenhouse gasses, cloud seeding) specific groups of people become status-worthy (e.g., rainmakers, tree planters, forest protectors, cloudseeders) but their power may be contested, as both evidence of effectiveness and desirability of impacts is contested. Increasing perceived control of humans over nature and biophysical processes thus shifts attention to political and social challenges of control over human actions that are understood to modify where and when rainfall occurs (Fig. 3).

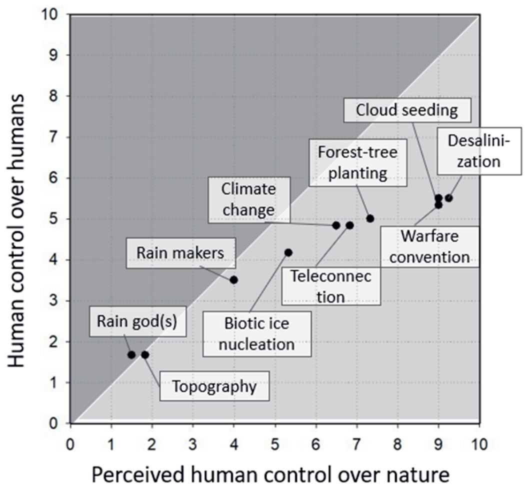


Figure 2.3. Increasing inter-human power questions when perceived human control over rainfall increases; perceived human control represents the authors' interpretation of the human perceptions, in any of the ten paradigms of the degree to which rainfall responds (positively or negatively) to human actions (0 = no control, 10 = strong control); summarizing a small survey involving all the co-authors of this paper.

According to the four stages in a transition hypothesis of human-Nature relationships (Roux et al., 2022), the ten rainfall paradigms cover the first three (Fig. 2; nature is powerful, taming of nature, rational management), as humans take control over natural processes. The fourth stage, a re-discovery of spiritual values of forests may represent a synthesis that sees rain as part of ecosystem services that need to be respected, protected and managed. The technical cloud seeding experience helped in the emergence of biotic INP theories, a newly understood role of forest and other high-water-use vegetation, beyond the presence of atmospheric moisture and its movement to places where condensation can occur. Current global circulation models are still deficient in their representation of land-cover feedbacks (Masson-Delmotte et al., 2021), a major constraint to current rainfall forecasts and restoration efforts.

Future rainfall is not manageable in the same way as other parts of the water cycle are (van Noordwijk et al., 2022), however, it is not independent of human actions either. The Harm-Care pillar of human morality in (Haidt and Kesebir, 2010; van Noordwijk et al., 2023) is directly linked to instrumental values, ecosystem services and nature-based solutions. Human capacity in engineering to 'work with nature' is possible and can make effective use of science-based understanding, if it aligns with the morality pillars of social relations: Fairness-Cheating (reciprocity), Loyalty-Betrayal (within a group), Authority-Subversion and Sanctity-Degradation (purity), that include relational values of nature to people. Attribution of flood-causing rains in Pakistan to global climate change or to land use change in a neighbouring country has huge political ramifications. The Sanctity-Degradation (purity) axis tends to be invoked in a social and political context to blame others for misbehaving ('against nature') and causing nature to be affected with disastrous consequences for all, whether disturbance of rainfall patterns or a COVID-19 pandemic. The distinction between instrumental and relational values is a gradual one, as language is full of cross-over metaphors (van Noordwijk, 2021). The analysis of social-ecological systems needs to reconcile a relational understanding of the social-political and human-nature subsystems with a mechanistic or instrumental understanding of the non-human world (IPBES, 2022). The various water-related issues, from droughts to floods are physically related through the water balance, but may socially connect in different ways, interacting with the way the nature-people relationship is perceived (van Noordwijk et al., 2020). How people understand the answers to who or what causes rainfall shapes ways to rationalize and communicate relational preferences for aspects of nature. Despite the complexity, rainfall deserves a more prominent place in efforts to better align human activity with planetary resources and boundaries and reduce negative human impacts on water cycles (van Noordwijk and Ellison, 2019; Smith et al., 2023). In the recent call to collective action by the Global Commission on the Economics of Water (Mazzucato et al., 2023), understanding of human impact on the water cycle goes beyond the allocations of a fixed water budget, as rainfall can be influenced, if not controlled.

2.4. Acknowledgements

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Mount Bromo, the upper part of the Rejoso Watershed. A famous tourist destination in Indonesia..

Participatory mapping with the downstream farmers to develop rice field typologies.

Chapter 3: Groundwater-extracting Rice Production in the Rejoso Watershed (Indonesia) Reducing Urban Water Availability: Characterisation and Intervention Priorities

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Abstract

Production landscapes depend on, but also affect, ecosystem services. In the Rejoso watershed (East Java, Indonesia), uncontrolled groundwater use for paddies reduces flow of lowland pressure-driven artesian springs that supply drinking water to urban stakeholders. Analysis of the water balance suggested that the decline by about 30% in spring discharge in the past decades is attributed for 47 and 53%, respectively, to upland degradation and lowland groundwater abstraction. Consequently, current spring restoration efforts support upland agroforestry development while aiming to reduce lowland groundwater wasting. To clarify spatial and social targeting of lowland interventions five clusters (replicable patterns) of lowland paddy farming were distinguished from spatial data on, among other factors, reliance on river versus artesian wells delivering groundwater, use of crop rotation, rice yield, fertiliser rates and intensity of rodent control. A survey of farming households (461 respondents), complemented and verified through in-depth interviews and group discussions, identified opportunities for interventions and associated risks. Changes in artesian well design, allowing outflow control, can support water-saving, sustainable paddy cultivation methods. With rodents as a major yield-reducing factor, solutions likely depend on more synchronized planting calendars and thus on collective action for effectiveness at scale. Interventions based on this design are currently tested.

Keywords: artesian wells; ecosystem services; landscape approach; *Oryza*; paddy cultivation; restoration; rodents; sustainable intensification; water balance; Mount Bromo-Tengger

3.1. Introduction

Ecosystem services are defined as benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005a), directly as goods or indirectly as regulating, cultural, and supporting services dependent on well-functioning ecosystems (Costanza et al., 1997) . There is growing evidence of significant adverse impacts from landscape degradation due to land use/cover changes, population growth, and anthropogenic pressures, aggravated by the impacts of global climate change, for example increasing variability of rainfall (Olsson et al., 2019). These issues deserve attention at the global, regional, and national levels; sustainable landscape management is needed, encompassing both upland and lowland issues, to combat landscape degradation and strengthen the resilience of communities to climate change.

Sustainable landscape management typically implies the application of a landscape-scale approach, which has increasingly been recognised as an opportunity to minimize negative trade-offs and reconcile conservation, agriculture, and rural-to-urban livelihoods (Estrada-Carmona et al., 2014; Minang et al., 2015). A 'landscape(-scale) approach' emphasises stakeholder engagement, including smallholder perspectives on the achievement of multiple objectives: maintaining ecosystem services and goods while improving livelihoods and addressing 'development deficits'. It also implies integrated assessment of upland–lowland relations and flexible implementation (Wu, 2013). Several landscape management schemes have been introduced to combat landscape degradation and to strengthen the resilience of communities, such as through ecosystem services co-investment schemes (van Noordwijk et al., 2012). However, such schemes are still in the pilot stage and usually end when external support is withdrawn. Thus, 'upscaling' technologies and sustainability of interventions is indispensable. Internalization of externalities must include the establishment of new norms of behaviour, beyond economic incentives in the initial phase. Building on the mixed success of 'scaling up' technologies that were successful in the locations where they were developed, but not as good elsewhere, Sinclair and Coe (Sinclair and Coe, 2019) identified the need for an 'option by context' approach to addressing the variability of social, economic, and ecological issues across geographies for research and development which involves smallholder farmers. Representing the context to characterize variability of farmer's practices in managing the land that is needed to operationalise the evaluation of options.

In the context of production landscapes, agriculture both depends on 'upstream' ecosystem services and influences (often negatively) services for stakeholders further 'downstream' (Díaz et al., 2019). For water-related services, the up- and downstream terminology can be taken literally (van Noordwijk et al., 2020) (i.e., as a spatial geographical location), in other services, it is used as a metaphor (i.e., upland as the supplier of ecosystem services, while lowland as the beneficiaries of such services). Land cover type and land use management, including the status of property rights (Swallow et al., 2002) in the upland and lowland determine the quantity and quality of the ecosystem services generated and utilized in the landscape. Water availability that is naturally based on a flow from the uplands to adjacent lowlands, is influenced by the capacity of the watershed to filter and buffer the flows (van Noordwijk et al., 1998, 2004) in different parts of a landscape. Landscape managers have both legal and perceived rights to modify these flows, such as by abstracting water that may reduce extractable surface and groundwater flows. This activity may affect the water supply further down in the landscape, which at the end will raise complex issues of legal and perceived water rights of the lowland communities. Thus, the understanding of the hydrological relations, is fundamental to disentangle the social interactions and find solutions that manage conflicts and adverse trade-offs. The interactions between farmer practices and ecological subsystems need to be quantitatively understood to manage the overall resource in a fair and efficient way (van Noordwijk, 2019). The scale of the overall resource availability and use needs to be connected to that of farmer decisions, i.e., access rights and appropriation, and that of collective action, essential for reliable solutions and interventions.

The Rejoso watershed in the Pasuruan District, East Java Province (Indonesia) has experienced progressive deforestation on the higher slopes of Mount Bromo-Tengger, land use/cover changes across all elevations, and unsustainable farming practices due to rapid population growth and anthropogenic pressures (Amaruzaman et al., 2018). In combination, these changes have affected the watershed's function of maintaining ecosystem goods and services, including impact on the quality and quantity of water resources, i.e., depleting the water flows, increasing risks of droughts and floods, soil erosion, and landslides according to local stakeholders (Amaruzaman et al., 2018). In addition, the government is implementing a national project to pipe the water from the Rejoso watershed, i.e., from the Umbulan artesian spring to supply the adjacent districts and cities, including the metropole of Surabaya, the 2nd largest city of Indonesia and East Java capital. Artesian conditions develop where the hydraulic head (pressure) from a confined aquifer is higher than the topographic surface, allowing the free flow of groundwater through artesian springs (and/or wells) (Toulier et al., 2019a). There are both similarities and differences with the well-documented agricultural over-use of groundwater in India, where a reduction of the energy subsidy for pumps provides at least some incentives for farmers to only use pumps when needed (Scott and Shah, 2004). The simplest forms or Artesian wells flow 24 hours per day and 365 days per year.

Figure 3.1 illustrates the upper (> 1000 m a.s.l.), middle (100-1000 m a.s.l.) and lower (<100 m a.s.l.) zones of the Rejoso watershed supplying surface flows (rivers) and groundwater flows (aquifers). Artesian conditions develop in the lowland zone, where a mostly impermeable layer inherited from volcanic processes covers and confines the underlying aquifer (water-rock reservoir). The current data shows that the discharge of the Umbulan spring has been decreased from about 5000 l/s in 1980 to 3500 l/s in 2020, with a continuous trend towards further decline (Toulier, 2019). The attribution of this decrease across the upper, middle and lower zone has triggered debates (e.g., climate change affecting all zones vs. local anthropogenic impact) that led to the current research. In the decline of 1500 L/s, lowland flowing artesian wells and reduced recharge of aquifer by reduced upper and middle zone infiltration both may play a role. Sustainable landscape management in the Rejoso watershed will depend on suitable incentives, rules and motivation across all zones, based on a detailed diagnosis and co-investment by stakeholders (Amaruzaman et al., 2018; Leimona et al., 2018).

Through diagnostic studies, broad stakeholder participation and consultations with government agencies, proposals were formulated for performance based-payment schemes. These include managing tree and grass strips in horticultural farming systems in the upland part, increasing tree density and building of infiltration/sediment capture pits in the agroforestry farming systems of midstream smallholders (Toulier et al., 2019a). Activities here target increased soil infiltration rates for groundwater recharge, control of soil erosion and increased on-site sedimentation. According to a study in the upper part of the Rejoso catchment (Suprayogo et al., 2020), increasing tree canopy cover to values > 55% in the upland and > 80% in the midstream (highest rainfall elevation) qualified as 'infiltration-friendly' land use in the watershed, respectively, and can be expected to reduce runoff below 15% of rainfall. Groundwater recharge depends mainly on the balance between precipitation, evapotranspiration and runoff in each zone, but is also influenced by the seasons (wet and dry) (Toulier et al., 2019a).

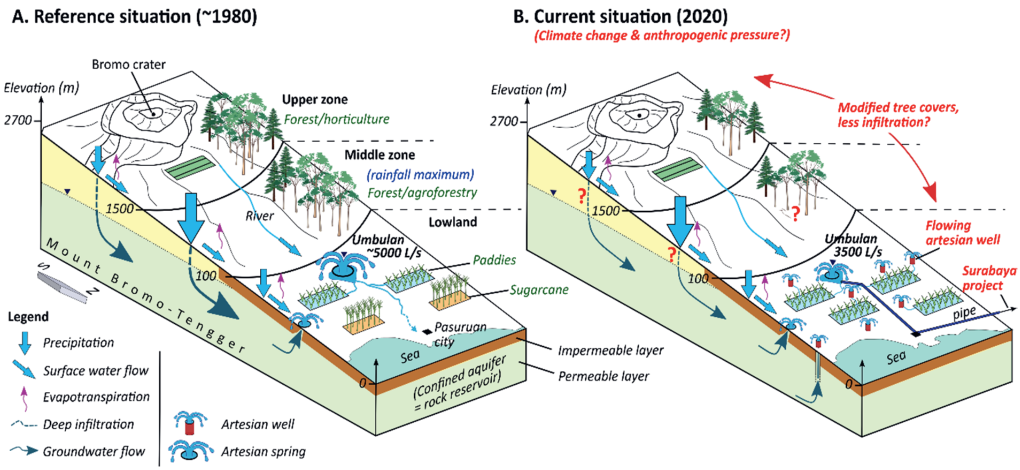


Figure 3.1. The simplified block diagram of the landscape and zone-specific water balance, illustrating A: the historical reference Scheme 1980, and B: the current situation in 2020.

In the lowland area, the Pasuruan district used to be a major sugarcane producer with good surface irrigation infrastructure, hosting since 1887 the national sugarcane research institute. However, since the last decades, most of the land has been converted to paddy fields, using additional groundwater resources mostly from flowing artesian wells (Fig. 2.1B). In this zone, reported problems include diminishing areas of fertile soil for farming (rather than for urban expansion), high intensity of pest and diseases, and low paddy productivity indicate unsustainable agricultural practices. Furthermore, intensive use of groundwater to irrigate the paddy fields decreases the aquifer pressure and then the water productivity of artesian wells and springs as the sources of agriculture and domestic water for local communities (Toulier et al., 2019a). Hence, better water management in irrigated areas is one of the targets for improved landscape-wide ecosystem services from a lowland, urban water user perspective. Five crucial root causes of unsustainable agricultural in the Rejoso watershed have been identified (Scott and Shah, 2004) as unsynchronised planting calendars, inefficient use of groundwater, high chemical inputs, imbalanced fertiliser application, and conventional, suboptimal planting patterns. The average rice yield at the district and province level is about 5.8 ton per ha (The Central Statistics Agency, 2020b), which is lower than in other provinces, i.e., Bali and Central Java. East Java Province is the second largest (with about 19%) contributor to national paddy production, with 3% of national level produced in Pasuruan District (The Central Statistics Agency, 2020a). Therefore, addressing the issues by introducing sustainable paddy cultivation (i.e., optimal use of chemical fertiliser, application of biopesticide, improved water management regimes and planting pattern) to increase productivity while reducing environmental impacts is essential. Current agricultural practices lead to high methane (CH_4) and nitrous oxide (N_2O) emissions, high intensity of pest and diseases and low agricultural yield. Water-saving techniques are expected to be financially and environmentally beneficial to smallholders by enhancing their resilience to shocks and improving the capacity of the production landscape to generate ecosystem services (Khumairoh, 2019). Nevertheless, introducing sustainable paddy cultivation beyond the current, conventional practices is a challenge, as behavioural changes and biophysical conditions vary.

Understanding the variability of farmer's practices in managing the land and cultivating paddy is, therefore, considered as an initial step towards pilot actions for the lowland zone with the potential to scale up sustainable paddy cultivation. To contextualize current practices and propose 'options in context' as restoration solutions, we thus needed a detailed characterisation of paddy farming and possible spatial patterns in cropping intensity and use of river versus groundwater for irrigation. By triangulation of quantitative spatial data analysis, qualitative insights from the participation of local farmers, communities and government agencies, and a targeted, quantitative household survey, we hoped to understand the rationale(s) of farmers for considering and choosing specific practices. Scenarios for improved resource management at landscape scale require identification of the main sustainability risks and local perspectives, at the scale required for impacts to be noticeable. Our analysis of catchment-level water balance, patterns of land and water use, and specific practices used in paddy farming tried to answer questions at three levels:

1. Is there quantitative evidence that the lowland practices are co-responsible for the decrease of the Umbulan spring's discharge?
2. Is there relevant geographic variation between villages and hamlets in the farmers' practices in managing land and water in cultivating paddy?
3. Can a participatory survey of paddy cultivation and spatial data analysis for the development of characteristic identify options by context for upscaling sustainable paddy cultivation?

We expected that the combined use of quantitative and qualitative methods, together with the participatory approach used in this study, would enable a subsequent scaling-up phase that is salient, credible and legitimate for all segments of the community at village and district levels.

3.2. Site Description and Methodology

3.2.1. The Rejoso watershed

The Rejoso watershed has an area of 62,773 ha based on the boundaries set by the Watershed Management Agency (BPDAS). It covers 17 sub-districts: Bugul Kidul, Gading Rejo, Gondang Wetan, Grati, Kejayan, Kraton, Lekok, Lumbang, Nguling, Pasrepan, Pohjentrek, Purworejo, Puspo, Rejoso, Tosari, Tutur, and Winongan, on the lower, middle and upper slopes of Mount Bromo-Tengger, East Java, Indonesia. The artesian spring Umbulan is in the lowland part of the watershed (Winongan sub-district).

Paddy fields and sugarcane plantations are dominant land covers in the lowland area, complex agroforest dominates in the mid-stream area, and horticulture and pine plantation are mostly found in the upland area of the watershed (Amaruzaman et al., 2018). *Inceptisols* are the dominant soil type in the upland, midstream to the lowland area; a small area of *Entisols* is found in the lowland area.

Complementing studies in the middle and higher zones, our study developed a characteristic of paddy farming for the lowland area of the watershed, specifically, in the eleven villages of two sub-districts (Fig. 3.2), Winongan (4,341 ha) and Gondang Wetan (2,692 ha) sub-districts (07°42'30 "–07°43'30" NL and 112°54'30 "–112°57'0" LE). The two sub-districts were selected based on parameters: the (high) number of artesian wells as one of the main sources to irrigate paddy fields, (high) area of paddy fields, and (low) yield. Artesian wells, flowing twenty-four hours per day are a specificity of the volcanic study area as the hydrogeology is represented by a shallow artesian basin.

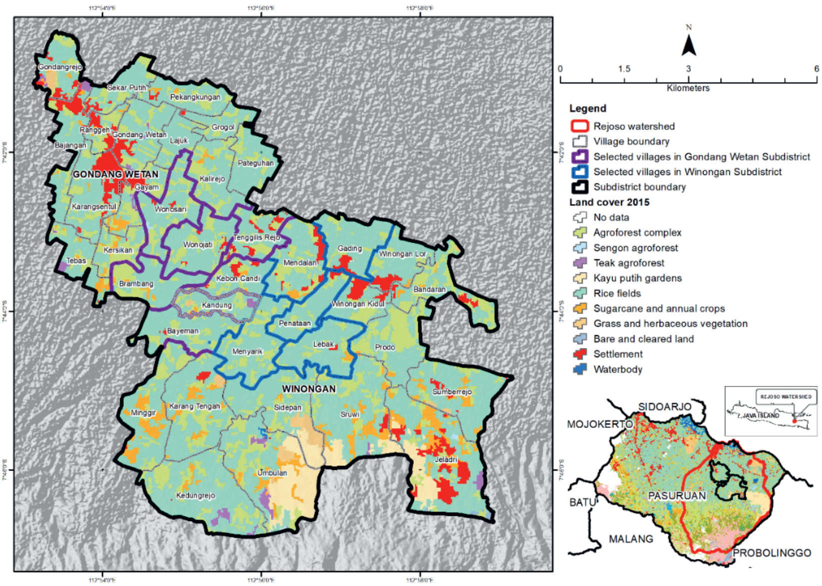


Figure 3.2. Delineation of the study area.

3.2.2. Annual water balance model of Rejoso watershed

A simple water balance has at the minimum to include precipitation (P), evapotranspiration (E), and runoff (river flow; Qs), with changes in soil moisture storage potentially negligible at annual time steps (Fig. 3.3). Evapotranspiration can be expressed as a vegetation-dependent fraction ε of the climate-driven potential value Epot and be further constrained by the fraction of P that infiltrates into the soil. Runoff can be estimated as an infiltration-limited (or Hortonian) fraction ρ of P, plus a saturation-excess amount max(0; P(1-ρ) - ε Epot). This is an alternative (first used in (Creed et al., 2018)) to the commonly used Fuh–Budyko equation, which tends to underestimate discharge under low rainfall conditions.

For the current analysis, a distinction is needed between surface flows (Q_S) and groundwater flows (Q_G) based on three possible transfers between surface and groundwater: deep infiltration (as fraction of water infiltrated, and reducing the saturation-excess river flow), seepage of water already on the river, and the resurfacing of groundwater in springs and wells. The annual water balance model (assuming no change in storage terms, expressed per unit area) linked four zones *i* (n=1 to 4), respectively, labelled Upper, Middle, Lower, and Umbulan spring zone (with areas A[*i*] in (km²)), and computed as follows:

$$Q_{Soutflow}[i] + Q_{Goutflow}[i] = P[i] - E[i] + Qs_{inflow}[i] + Q_{Ginflow}[i] \quad (1)$$

with as inputs for each zone *i*,

P[*i*] = precipitation (mm/y),

$Qs_{inflow}[i]$ = incoming surface flow (river) corrected for the relative areas of adjacent zones, defined as (A[i-1]/A[*i*]) × Q_S[*i*-1]) (mm/y),

$Q_{Ginflow}[i]$ = incoming groundwater flow corrected for the relative areas of adjacent zones, defined as (A[i-1]/A[i]) × Q_G[i-1]) (mm/y), and as outputs:

E[*i*] = evapotranspiration defined as ε[*i*] × E_{pot}[*i*] with the E_{act}/E_{pot} ratio ε[*i*] dependent on tree cover and crop type (mm/y),

$Q_{Soutflow}$[*i*] = outgoing surface flow (river) (mm/y),

$Q_{Goutflow}$[*i*] = outgoing groundwater flow (mm/y),

and as internal transfers from groundwater to surface water or vice versa:

$Q_G[i] = A[i\text{-}1]/A[i]) \times Q_G[i\text{-}1] - Q_{G \rightarrow S}[i] + Q_{S \rightarrow G}[i]$

In such a framework, we can represent "upland deforestation" as a decrease in ε and "upland degradation" as an increase in ρ. The shift from upland crops to paddy in the lowland as an increase in ε, plus wells that transfer ground to surface water. Estimates of the net transfers from surface to groundwater flows Qs➔g[i] in the Upper and Middle zone were based on measured river discharge at the transition from Middle to Lower zone. Estimates of the net transfers from groundwater to surface flows Qg➔s[i] in the Lower zone was derived from measured artesian well distribution and flow rates (Fig. 3.4).

After parameterizing this simple model (Appendix 3A), we compared five scenarios: A) a historical reference scenario, B) upland degradation, C) lowland conversion to paddy with uncontrolled artesian wells, D) combining the changes of B + C, E) a restoration scenario with agroforestry in upper and middle zones and reduced groundwater use in the lowland paddy zone (Table 3.1).

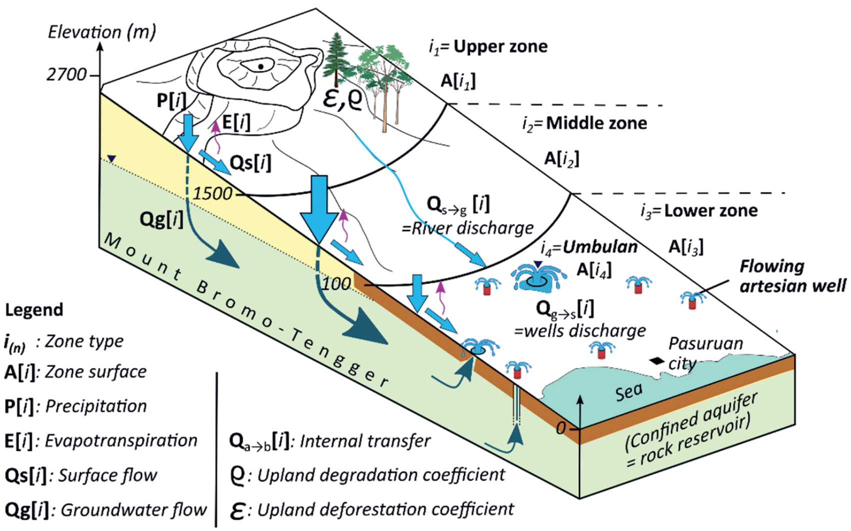


Figure 3.3. Simplified schema of the water balance components.

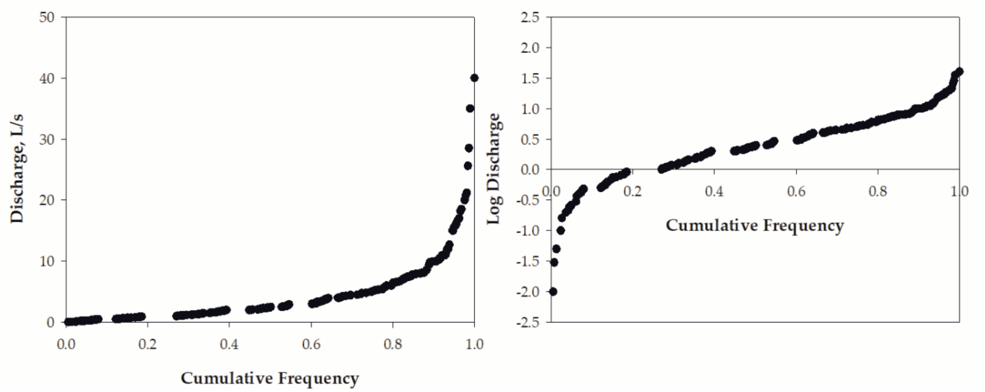


Figure 3.4. Measured flow of around 450 artesian wells in lowland Rejoso area; data source: (Toulier et al., 2019b).

Table 3.1. Scenarios of the Rejoso water balance model; t_w indicates the fraction of time the artesian wells are flowing; the evapotranspiration ratio ε was estimated from land cover composition and known temporal dynamics of Leaf Area Index of the vegetation; the ρ coefficient from existing runoff data.

Scenario, Description	Geographical zoning	ε	ρ	#Wells (number)	t_w
A. Baseline; using land cover data from 1990, before the expansion of paddy rice cultivation in the lowlands, and with a higher forest fraction in the middle and upper zone.	Upper	0.71	0.15		
	Middle	0.72	0.15		
	Lower	0.81	0.05	10	1
B. Upland degradation; keeping lowland conditions as in 1990 but reflecting the hydrological degradation in the upland and middle parts of the watershed that are caused by conversion of forest to horticulture and agroforestry.	Upper	0.71	0.23		
	Middle	0.76	0.23		
	Lower	0.81	0.05	10	1
C. Lowland dominated by paddy field and artesian wells; paddy field and unmanaged and unregulated artesian wells in the lowland, combined with upland conditions of 1990.	Upper	0.71	0.15		
	Middle	0.72	0.15		
	Lower	0.80	0.05	600	1
D. Upland degradation and intensive lowland for agriculture; using land cover data from 2015 for all zones, along with the artesian wells in the lowlands	Upper	0.71	0.23		
	Middle	0.76	0.23		
	Lower	0.80	0.05	600	1
E. Applied sustainable interventions in lowland as negotiated interventions payment for ecosystem services for tree-based farms and soil-water conservation techniques are introduced in upland and middle parts. Water efficient and low emissions paddy cultivation, and good management of artesian wells are introduced and practiced.	Upper	0.71	0.19		
	Middle	0.76	0.19		
	Lower	0.80	0.05	600	0.2

3.2.3. Selected villages for the lowland characteristic

The selection of the villages was based on the number of artesian wells, area of paddy fields and its yield, number of low-income families, and number of families with members of the family as farm labour. The eleven villages were Wonosari, Wonojati, Tenggilis Rejo, Kebon Candi, Brambang and Bayeman in Gondang Wetan Sub-district, and Gading, Mendalan, Penataan, Menyarik, and Lebak in Winongan Sub-district (Fig. 3.2). Based on data of fourteen rainfall stations, the mean annual rainfall is approximately 1350 mm with relative humidity ranges from 68% to 83%. The rainfall is distributed with a peak in January and a dry season in August, and the annual mean of maximum and minimum air temperatures are 20 ^{o}C and 34^{o}C, respectively.

3.2.4. Development of paddy farming characteristic

Figure 3.5 presents the flow of development of paddy farming characteristic. The development of paddy farming characteristic used the cluster analysis approach. A cluster analysis is a process of grouping a set of parameters in such a way that parameters in the same group (a cluster) are more like each other than to those in other groups. Twelve parameters were collected through spatial data analysis and survey of paddy cultivation that both were verified through a participatory process reflecting the variability of the paddy field, farmers characteristics and their cultivation practices in the lowland area of the Rejoso watershed. These parameters were (1) area of paddy fields, (2) density of the channel network, (3) fraction of area with crop rotation, (4) intensity of pest (rodents), (5) rice yield, (6) dose of urea (46% N) fertiliser, (7) dose of compound fertiliser (15% of N, 15% of P, and 15% of K), (8) number of pesticide types applied, (9) existence of a water regulatory officer (*ulu-ulu*), (10) number of artesian wells, (11) river as the main water source, and (12) number of water sources. The development of paddy farming characteristic emphasises on the landscape-approach as the methods applied in this study engage the direct stakeholders, i.e., smallholders with multiple objectives of positive environmental impacts with substantial livelihood improvement reflecting by the selections of identified and analysed parameters, as part of the more comprehensive picture of the Rejoso watershed.

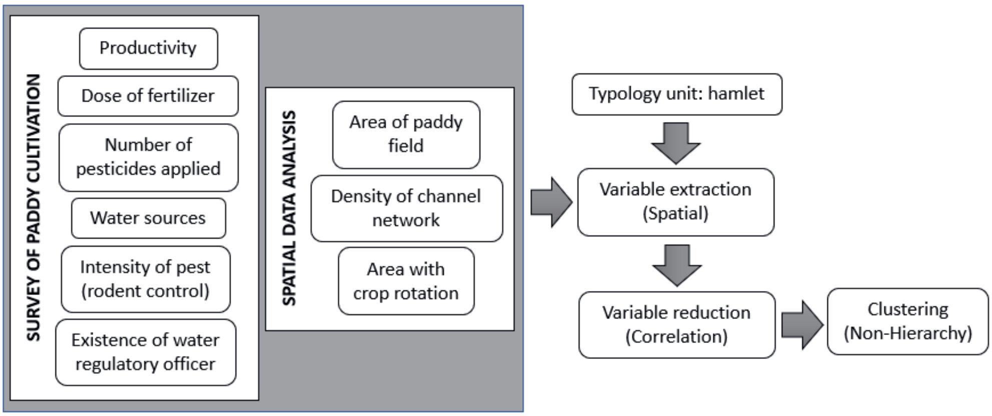


Figure 3.5. Flow diagram of cluster analysis to develop paddy farming characteristic.

3.2.4.1. Spatial Data Analysis

Figure 3.6 presents the workflow of paddy field and irrigation system mapping that consists of four main steps: (a) data gathering, (b) visual interpretation, (c) participatory mapping, (d) data analysis, and visualisation.

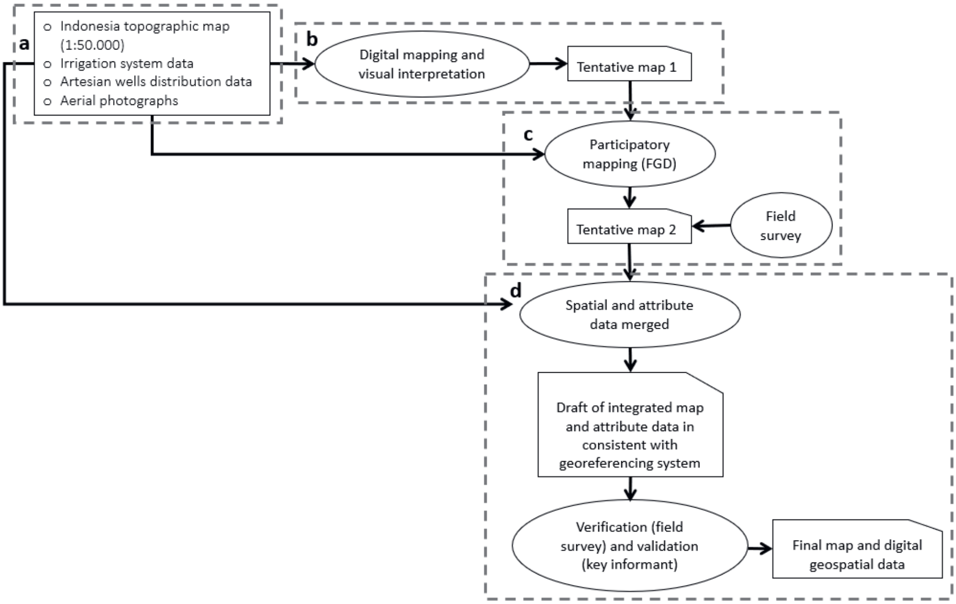


Figure 3.6. The workflow of participatory mapping scaled 2D mapping techniques.

Primary data collected through a survey and participatory approach and secondary data are two main data used for the mapping. A drone survey was conducted to obtain aerial photographs of paddy field, while focus group discussions (FGD) and key informant interviews were the approaches to obtain locations of artesian wells and detailed information of paddy fields. The secondary data were topographic maps at 1:50.000 scale, irrigation systems data (Pasuruan District Water-Related Public-Works Agency, 2019), and artesian well distribution (Toulier et al., 2019a).

Data on the area of paddy fields, the area with crop rotation, and irrigation system data were extracted from the aerial photographs through visual interpretation and convergence of the evidence approach. To correctly identify surface objects, several visual interpretation elements such as tone/colour, shape, size, pattern, texture, shadow, site, and associations were considered (Lillesand and Kiefer, 2011). Artesian wells, irrigation systems, and paddy field data were overlaid with a topographic map and visualised at the village scale to optimise the information extraction process. The result of this process led to a first tentative map that was completed and validated through FGD. The FGD was attended by 128 participants (mostly male) from eleven discussions in eleven villages.

Participatory mapping is a map-making process that attempts to make visible the association between land and local communities by using the commonly understood and recognised language of cartography (IFAD, 2009). The participatory mapping method in this study used a 2D map to allow two-way dialogues between researchers and key informants to minimise distortions of mapped information (Cadag and Gaillard, 2011). This discussion was focused on information such as the location of artesian wells, irrigation system, hamlet boundaries, paddy fields and their owners, crop rotation, and the existence of farmer groups.

Detailed information gathered from the participatory mapping was used as an input for data compilation and first tentative map improvement in digital format using GIS (Fig. 3.6). The process included (1) scanning the result of participatory mapping; (2) geo-referencing; (3) reinterpreting data; (4) and inputting attribute data. The results of this process were tentative map 2, which was then validated by eleven key informants from eleven villages. The validated spatial data was compiled as geodatabase for further analysis.

The spatial data resulted from participatory mapping were (1) hamlets boundary, (2) percentage of paddy field area in each hamlet, (3) percentage of crop rotation area per paddy field area in each hamlet, (4) drainage density in each hamlet, (5) and the number of artesian wells in each hamlet. The length of the channel network was classified by channel width. Channels with less than 1 m widths were identified as trenches, while channels with more than 1 m widths were identified as irrigation channels and rivers. The rivers that cross the study areas are Kedung River, Palembon River, Sumbermade River, and Umbulan River. Drainage density is defined as the total length of channels (trench, irrigation channels, and river) per unit area of hamlet.

3.2.4.2. Survey of Paddy Cultivation

The survey of paddy cultivation aimed to gather information about paddy cultivation practices and related issues in the eleven villages of the two sub-districts, Gondang Wetan and Winongan. The survey was conducted from August to October 2019. The survey consisted of (1) survey preparation including the development of survey questionnaire and training on interview technique, (2) respondent selection and interview process, and (3) data cleaning and analysis.

The questionnaire was designed to survey five main parameters related to paddy cultivation practices and its issues: (1) yield, (2) dose of fertiliser, (3) number of pesticide types, (4) water sources, and (5) intensity of pest (rodents). For further analysis, the dose of fertiliser was divided into (a) urea fertiliser (46% of nitrogen) and (b) compound fertiliser (15% of nitrogen, 15% of phosphate and 15% of potassium), while water source parameter was divided into (a) river as the main water source, (b) number of water resources, and (c) existence of a water regulatory officer (*ulu-ulu*).

Table 3.2 presents the distribution and characteristics of respondents by village, age, and number and size of plots/fields owned/managed. In total, there were 461 respondents, the respondent's information gathered from chairs of farmer groups, and applying a snowball technique. The age of respondents varied from 22 to 83 years old and was 56 years old on average. The respondents of this study at least owned/managed one plot. The maximum number of plots owned/managed was 25. The average area owned/managed by the respondents was 0.25 ha. The smallest was 0.05 ha, and the largest was 2.25 ha.

3.2.5. Data analysis

For paddy cultivation data, data analysis was performed after data cleaning is completed. The cleaning included filtering location of paddy field and domicile of farmers/respondents. We only considered respondents who stay and manage the farm in the eleven villages. In the data analysis process, the basic statistical analysis was used to analyse and explore the variation of the data at sub-district, village and hamlet scale. The basic statistical analysis included an average of yield, dose of fertiliser and number of types of pesticide; percent of respondents with perception on high intensity of rodent and use of artesian wells. Once the analysis completed, the result was interpreted by sub-district, village, and hamlet. Then, we used hamlet as the unit of cluster analysis considering the social characteristic

Table 3.2. Respondent distribution and characteristic of paddy cultivation survey.

Sub-districts	Villages	Number of respondents	Age distribution			Number of plots owned/managed per respondent			Owned/managed area per plot (ha)		
			Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
Gondang Wetan	Bayeman	34	80	31	59	6	1	3	0.80	0.10	0.26
	Brambang	32	70	26	51	8	1	4	2.25	0.10	0.27
	Tengglis Rejo	38	79	35	60	10	1	5	0.60	0.10	0.23
	Kebon candi	67	74	33	55	8	1	3	0.50	0.06	0.22
	Wonojati	93	83	22	54	17	1	18	2.00	0.05	0.27
Winongan	Wonosari	31	80	28	57	12	1	4	0.85	0.07	0.28
	Gading	31	70	33	55	25	1	8	0.50	0.05	0.18
	Lebak	33	73	25	51	6	1	3	1.10	0.09	0.35
	Mendalan	34	70	40	56	13	1	3	0.60	0.07	0.24
	Menyarik	32	70	29	57	6	1	2	1.33	0.08	0.20
	Penataan	36	83	32	56	5	1	2	0.60	0.10	0.26

of paddy cultivation management, the existence of farmer group and water regulatory officer in each hamlet. The information on hamlet was described on the spatial maps under the Results section.

As we worked with extensive data set, for the cluster analysis, we applied the K-means approach to cluster the data and used the elbow method to find the optimum number of clusters (Kassambara, 2017). Before we clustered the data, we conducted a correlation analysis of the twelve parameters that were extracted at the hamlet level to verify the statistical independence of the twelve parameters used (Fig. 3.5).

3.3. Results

3.3.1. Water balance

Parameters for the water balance model were adjusted to account for the approximately 5000 l/s Umbulan spring flow in reference scenario A (see results in Table 3.3). Upland degradation alone (Scenario B) would likely lead to increased river flow (due to increased runoff triggered by lower evapotranspiration in the uplands) and some decrease of the Umbulan spring flow (due to lower infiltration, i.e., lower recharge on the mountain slope). Lowland conversion to paddy with current artesian wells (Scenario C) would decrease both river flow and Umbulan spring flow.

Combining the changes of scenario B and C (Scenario D), river flow would approximate that of scenario B, but the Umbulan flow would be reduced to approximately the level currently observed (31% reduction). Attribution of this reduction (A – D), with 1.3% interaction, would be for about 15% to the middle and upper zone, and 17% to the lowland. The restoration potential in Scenario E is estimated to nearly 4500 l/s, at which the planned offtake of 4000 l/s still leaves sufficient discharge for local use.

Table 3.3. Predicted discharge of the Umbulan spring, river and groundwater flow for five land use scenarios: A) a historical reference scenario, B) upland degradation, C) lowland conversion to paddy with uncontrolled artesian wells, D) combining the changes of B + C, and E) a restoration scenario with agroforestry in upper and middle zones and reduced groundwater use in the lowland paddy zone.

Scenario	Predicted Umbulan (l/s)	Predicted mean river flow, [m^3/s]			Predicted groundwater flow, [m^3/s]		
		Upper	Middle	Lower	Upper	Middle	Lower
A	5,087	2.5	6.7	12.4	1.5	5.3	0.05
B	4,310	2.7	7.3	12.1	1.3	4.4	0.04
C	4,206	2.5	6.7	12.5	1.5	5.3	0.04
D	3,496	2.7	7.3	12.1	1.3	4.4	0.03
E	4,468	2.6	6.9	12.1	1.4	4.7	0.04

3.3.2. Area of paddy field and crop rotation

The paddy fields in eleven villages reached 980.2 ha in both targeted sub-districts, with 536.1 ha (54.7%) in Winongan Sub-district. The villages Gading, Mendalan, and Menyarik in Winongan Sub-district had the largest area of paddy fields, with 119.6 (12.2%), 118.7 (12.1%), and 118.6 (12.1%) ha, respectively. On the other hand, Kebon Candi Village in Gondang Wetan Sub-district had 56.4 ha of paddy fields, the smallest among all other villages (Table 3.4). At the hamlet level, Kemong Hamlet in Lebak Village (Winongan Sub-district) had the largest percentage of paddy fields reaching 91%, which meant that only 9% of the area was used for non-agricultural activities. Areas with smaller percentages of paddy fields were in Gondang Wetan Sub-districts, starting from 0 to 30.9% (Figure 3.7A).

Crop rotation is a vital paddy farming practice to reduce the intensity of pests and diseases, and to improve soil fertility. Different crops rotated with paddy included corn, beans, taro, chilli, and other crops. Villages in Gondang Wetan Sub-district tended toward crop rotating more often compared to those in Winongan Sub-district. The area of crop rotation reached 30.1 ha, and 26.6 ha of it (88.5%) was found in Gondang Wetan Sub-district. Brambang Village in Gondang Wetan Sub-district was the village with the largest area of crop rotation with 10.9 ha, while Penataan Village in Winongan Sub-district had only 0.34 ha, the smallest area compared to other villages (Table 3.5). At the hamlet level, Brambang Barat Hamlet in the village of Brambang had the largest area of crop rotation, reaching 34.6% of the total paddy field area (Fig. 3.7B). Hamlets in Gondang Wetan Sub-district had a percentage of area with crop rotation between 4.3–11%. Other hamlets were classified as having a low rotation area, which was less than or the same as 4.2% and it was relatively common in Winongan Sub-district.

3.3.3. Water sources and irrigation systems

Rivers and artesian wells were two primary water sources to irrigate paddy fields in Gondang Wetan and Winongan Sub-districts. Water from those two sources flowed into the irrigation channel, but in some cases, the artesian wells were located inside the paddy fields itself. The total number of artesian wells reached 318 points spread across 11 villages, and 63% of it was found in Gondang Wetan Sub-district (Table 3.4). In line with this distribution, 89% of respondents in Winongan Sub-district mentioned that the river was more dominant than artesian wells as a water source to irrigate their paddy fields, while in Gondang Wetan Sub-district, they were only 61% of respondents (Table 3.4). Brambang Village was the village with the lowest percentage of respondents that mentioned river water as the primary source. Therefore, one paddy field could use river water and more than two artesian wells (shared with other farmers) (Fig. 3.8D). At the hamlet level, most artesian wells were

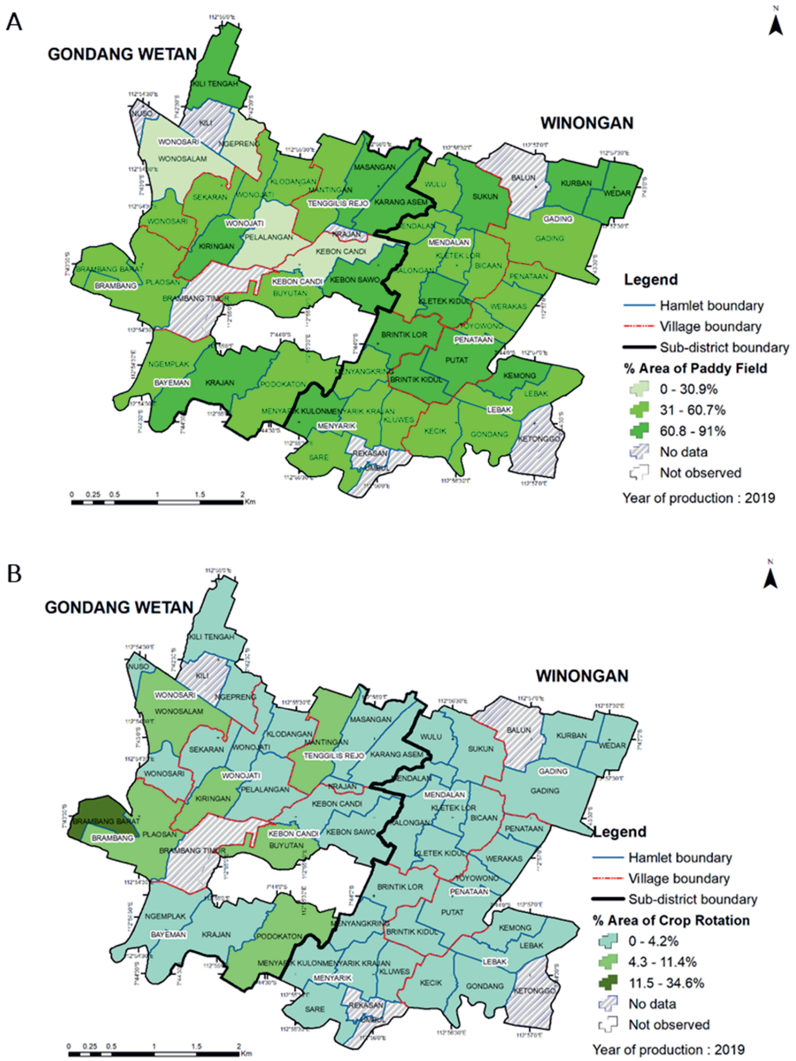


Figure 3.7. Spatial distribution of the percentage of paddy field area (A) and area with crop rotation (B) at hamlet level.

found in Podokaton Hamlet of Bayeman Village of Gondang Wetan Sub-district. Some hamlets were identified to have artesian wells between 8 to 17 wells. Other hamlets had less than eight wells. Nuso Hamlet at Wonosari Village was the only hamlet without artesian wells for irrigation, relying almost 100% on river water to irrigate paddy fields (Fig. 3.8A, C).

Winongan Sub-district had more extended irrigation channels compared to Gondang Wetan Sub-district, reaching 76.6 km in length (Table 3.4). Mendalan Village in Winongan Sub-district was the area with the most elongate irrigation channels (20.3 km). Kebon Candi Village in Gondang Wetan Sub-district had the shortest channels compared to other villages (7.27 km). At hamlet level, hamlets in Winongan Sub-districts such as Mendalan, Sukun, Kurban, Gading, Kalongan, Kletek Lor, Kletek Kidul, Putat, Krajan, Gondang, and two hamlets in Gondang Wetan Sub-district such as Karangasam and Ngemplak were classified as the highest drainage density, i.e., 8.5–11.3 km/km^2 (Fig. 3.8B).

Table 3.4. Distribution of area of paddy field (ha), the area with crop rotation (ha), number of artesian wells, and drainage density (km/km^2) in each village in two sub-districts.

Sub-dis-tricts	Villages	Area of paddy (ha)	Artesian wells per ha paddy	Artesian well water#, mm/day	Length of channels (km)	Drainage density (km/km^2)	Main water sources (% respondents)	
							River	Artesian wells
Gondang Wetan	Bayeman	97.5	0.73	17.6	13.7	7.4	58	42
	Tenggilis Rejo	80.1	0.45	10.9	11.2	7.9	46	54
	Wonosari	74.3	0.35	8.5	8.4	5.9	99	1
	Brambang	60.5	0.41	10.0	8.3	5.6	38	62
	Kebon Candi	56.4	0.41	9.9	7.3	6.1	54	46
	Wonojati	75.3	0.25	6.1	9.6	5.9	70	30
	Lebak	91.4	0.33	7.9	11.2	6.5	90	10
	Penataan	87.8	0.33	8.0	10.1	7.9	91	9
Winongan	Gading	119.6	0.18	4.2	18.5	10.4	100	0
	Menyarik	118.6	0.18	4.3	16.6	8.1	94	6
	Mendalan	118.7	0.14	3.5	20.3	10.0	67	33

#Assuming a constant (24/365) median well flow rate of 2.8 l/s.

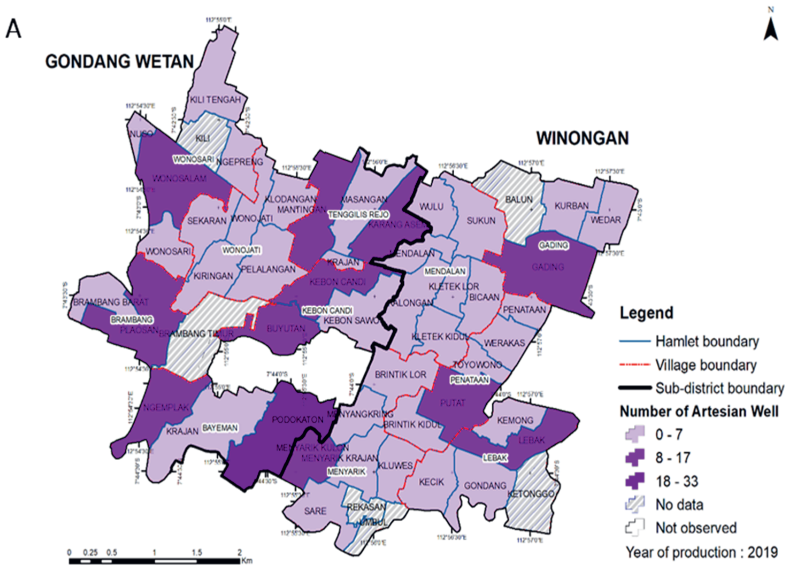
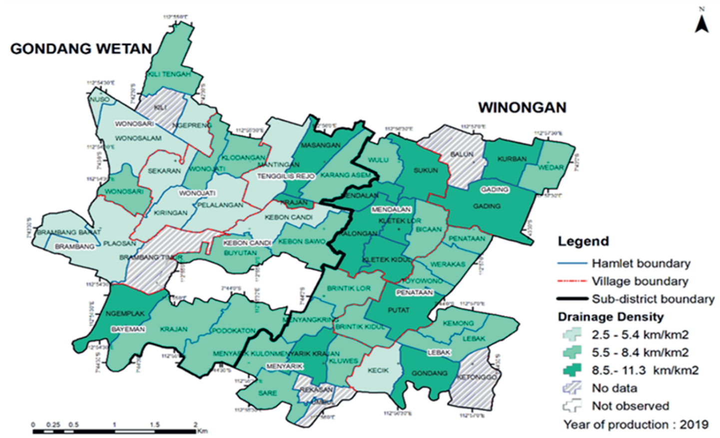
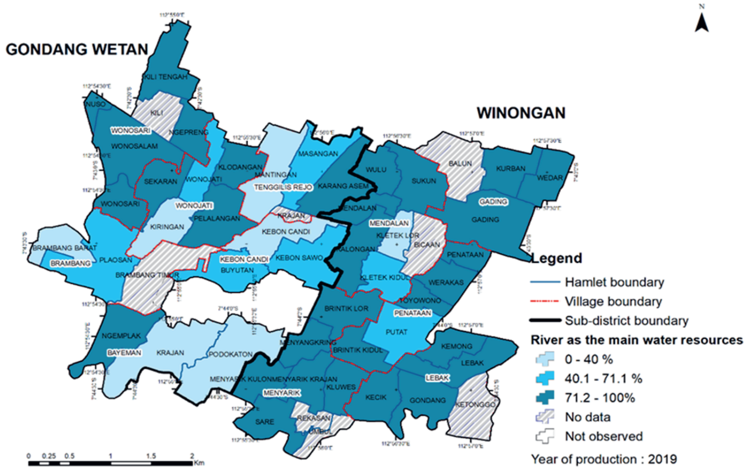


Figure 3.8. Spatial distribution of the number of artesian wells (A), drainage density (B), the hamlets that use the river as the main water resource (C), and the number of water resources (D) at hamlet level. The figure continues in the next page.

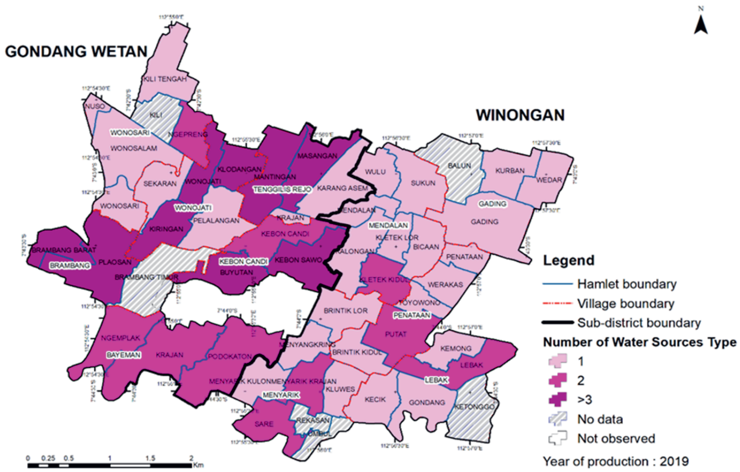
B


GONDANG WETAN
WINONGAN
Legend
Hamlet boundary
Village boundary
Sub-district boundary
Drainage Density
2.5 - 5.4 km/km2
5.5 - 8.4 km/km2
8.5.- 11.3 km/km2
No data
Not observed
Year of production : 2019

C


GONDANG WETAN
WINONGAN
Legend
Hamlet boundary
Village boundary
Sub-district boundary
River as the main water resources
0 - 40 %
40.1 - 71.1 %
71.2 - 100%
No data
Not observed
Year of production : 2019

D


GONDANG WETAN
WINONGAN
Legend
Hamlet boundary
Village boundary
Sub-district boundary
Number of Water Sources Type
1
2
>3
No data
Not observed
Year of production : 2019

3.3.4. Rice yield and fertilizer application

Farmers in Gondang Wetan Sub-district tended to apply a higher dose of fertiliser compared to farmers in the Winongan Sub-district (Table 3.5). The average dose of N fertiliser (Urea) applied by farmers in Gondang Wetan was 436 kg/ha/season and 322 kg/ha/season for compound fertiliser (NPK), while farmers in Winongan Sub-district applied N fertiliser about 343 kg/ha/season and compound fertiliser about 266 kg/ha/season. However, Gondang Wetan and Winongan Sub-districts had the same average of rice yield of 4.9 tons/ha/season, with distribution between 4.1-6.7 tons/ha/season (Table 3.5). Bayeman in Gondang Wetan and Gading in Winongan were villages that had the highest average of yield. Tenggilis Rejo in Gondang Wetan Sub-district was the village with the highest use of fertiliser, which was almost 600 kg/ha/season for N fertiliser and 370 kg/ha/seasons for compound fertiliser. It was indicated that high yield did not necessarily depend on high fertiliser rates (Table 3.5).

Table 3.5. Distribution of rice yield (ton/ha), fertiliser application (kg/ha), number of type of pesticides applied, water sources (% respondent), and intensity of rodents (% respondent) in each village in two sub-districts.

Sub-districts	Villages	Rice yield (ton/ha/ cropping season)	Fertilizer application (kg/ha)		Area with crop rotation (ha)	Number of type of pesticides applied	Intensity of rodents (% respondents)
			Urea	Compo-und			
Gondang Wetan	Bayeman	6.7	354	308	4.7	4	61
	Tenggilis Rejo	4.1	601	370	2.5	5	96
	Wonosari	5.1	375	299	2.5	5	37
	Brambang	5.1	425	315	10.9	6	27
	Kebon Candi	4.2	461	348	2.3	6	55
	Wonojati	4.5	408	293	3.9	6	36
Winongan	Lebak	4.5	257	231	1.0	5	52
	Penataan	5.0	318	252	0.3	5	71
	Gading	6.2	411	268	0.9	4	92
	Menyarik	4.7	396	309	0.4	5	70
	Mendalan	4.3	332	268	0.7	4	94

At the hamlet level, Krajan in Bayeman Village and Kurban in Gading Village were hamlets with the highest rice yield (almost 8 tons/ha/season) (Fig. 3.9A). Karang Asem and Krajan in Tenggilis Rejo Village, and Kebon Sawo in Kebon Candi Village were some hamlets with the highest use of urea (above 540 kg/ha/season) and compound fertiliser (more than 348 kg/ha/season) (Fig. 3.9B,C). Hamlets with low yield were Masangan, Karang Asem, Wulu, Bicaan, and Kebon Candi (Fig. 3.9A).

3.3.5. Intensity of pest/rodents and number of type of pesticides applied

Regarding the main problem of paddy cultivation, farmers in both Gondang Wetan and Winongan Sub-districts agreed that the high intensity of rodent attacks was the major problem in need of immediate attention. However, the respondents in Winongan Sub-district mentioned that rodents were the main problem, and their condition was worse than in Gondang Wetan (Table 3.5). Figure 3.10A shows that most paddy fields in Winongan Sub-district suffered from rodents. In Gondang Wetan Sub-district, only paddy fields in hamlets or villages next to Winongan Sub-district had a high intensity of rodent attacks, especially during rainy season. Until this study was undertaken, farmers were still struggling

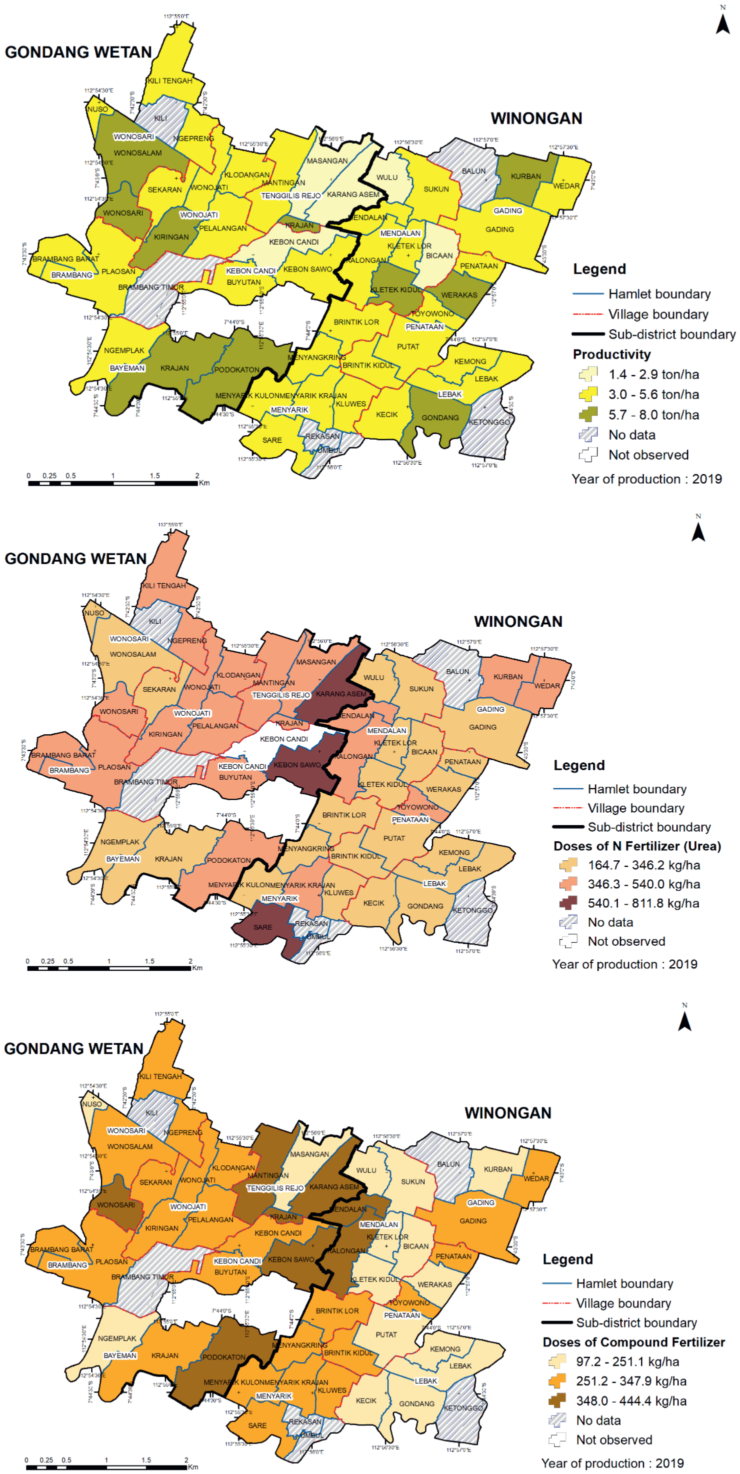


Figure 3.9. Spatial distribution of rice yield (A), urea application (B), and compound fertiliser (C) at hamlet level.

with how to deal with rodents. In terms of pests and disease control, there were more than 100 brands of pesticides used by farmers. Farmers in Gondang Wetan and Winongan Sub-districts used at least three brands, but some applied more than seven brands of pesticides in one season. In general, farmers in Gondang Wetan Sub-district applied more brands of pesticides compared to farmers in Winongan Sub-district (Fig. 3.10B).

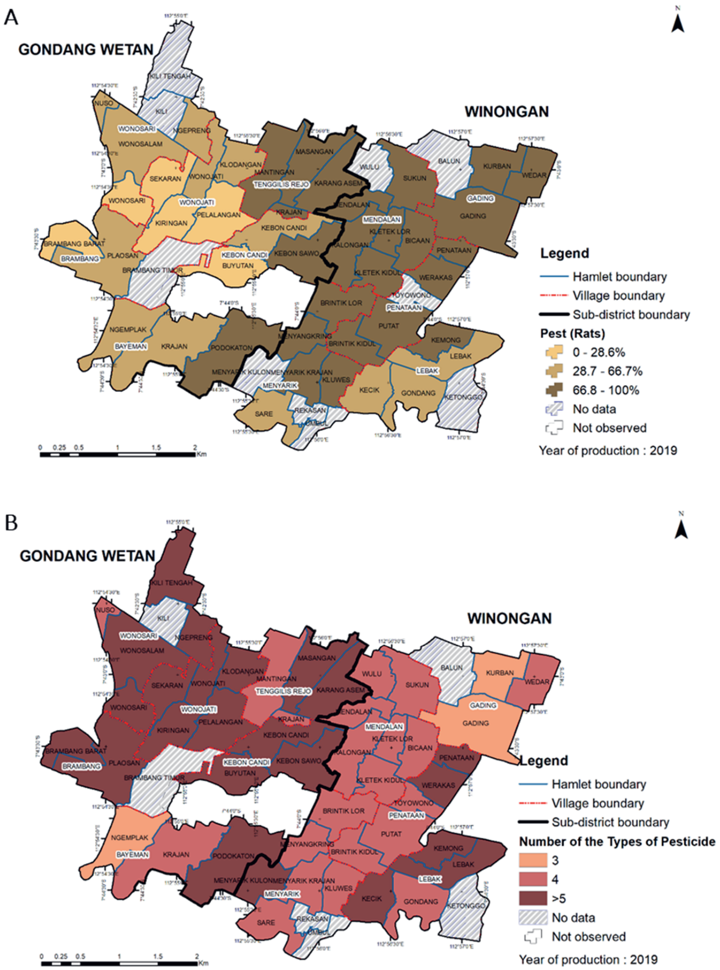


Figure 3.10. Spatial distribution of the intensity of pest/rodents (left) and number of types of pesticide applied (right) at hamlet level.

3.3.6. Characteristic of paddy farming

The twelve parameters (paddy field area, drainage density, number of artesian wells, the dose of N fertiliser, the dose of compound fertiliser, number of pesticide types, yield, the area with crop rotation, the intensity of rodent attack, number of water sources, river as the primary water source and presence of water regulatory officer) are independent to each other. The cluster analysis of the twelve parameters and the elbow method (Fig. 3.11) allows us to have five clusters of paddy fields in eleven villages of Gondang Wetan and Winongan Sub-districts. Figure 3.12 presents the map of the resulting characteristic of paddy farms in eleven villages, and Tables 3.6 and 3.7 describe the characteristics of each cluster. Cluster 1 was in Gondang Wetan Sub-district, cluster 2 was mostly in Winongan Sub-district, and cluster 5 was spread evenly in both sub-districts (Fig. 3.12). Meanwhile, clusters 3 and 4 consisted of only 1 hamlet, which was in Gondang Wetan Sub-district.

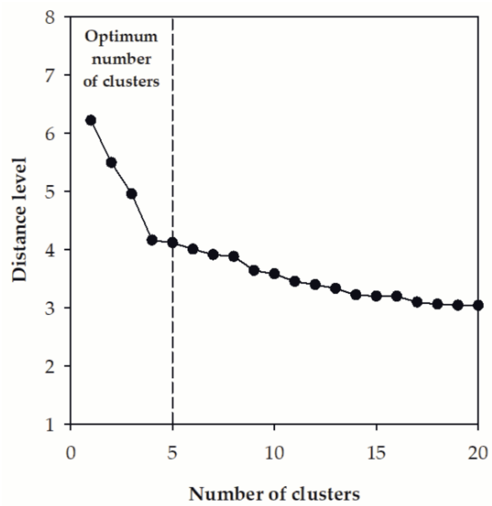


Figure 3.11. Dependence of distance level on the number of clusters as basis for elbow method of optimal cluster number to be used for the characteristic of paddy farming.

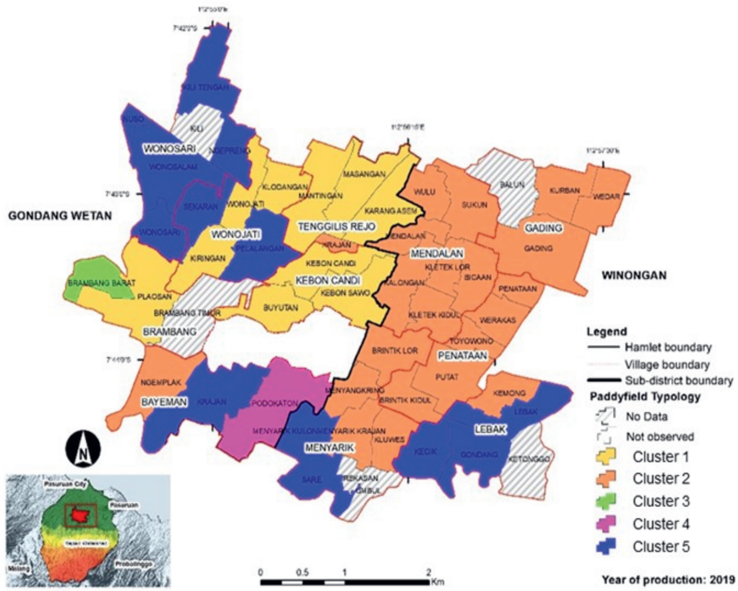


Figure 3.12. Characteristic of paddy farming in Gondang Wetan and Winongan Sub-districts.

Table 3.6. The result of cluster analysis and characteristic results for the 12 parameters.

No	Parameters	Unit	Clusters				
			1	2	3	4	5
1	Area of paddy field	%	High (218 ha)	High (407 ha)	Low (9 ha)	Low (29 ha)	Medium (230 ha)
2	Flow density (irrigation, river and trench)	km/km2	Medium	High	Low	Medium	Low
3	Area with crop rotation	%	Medium	Low	High	High	Low
4	Intensity of pest (rodents)	% respondents	Medium	High	Low	High	Low
5	Rice yield	Ton/ha	Low	Low	Medium	High	Medium
6	Dose of urea fertiliser (46% of N)	kg/ha	High	Low	Medium	High	Low
7	Dose of compound fertiliser (15% of N, 15% of P, and 15% of K)	kg/ha	Medium	Low	High	High	Low
8	Types of applied pesticide	Number	Medium	Low	Medium	Medium	Medium
9	The presence of 'Ulu-ulu' as a water regulatory officer	Existing / not existing	Exist	Not exist	Exist	Not exist	Exist
10	Artesian wells	Number	High	Medium	Low	High	Medium
11	River as the main water source	% of respondents	Medium	High	Low	Low	High
12	Types of water sources	Number	High	Low	High	Medium	Low

3.4. Discussion

3.4.1. Relevance of reducing groundwater use in lowland zone

Our first question was seeking quantitative evidence that the lowland practices are co-responsible for the decrease of the Umbulan spring's discharge. The estimated total outflow of the artesian wells (over 2400 l/s in 450 measured wells; currently there may be 600 wells) does not fully account for the observed decline in the Umbulan spring flow record (from 5000 to 3500 l/s with a declining trend). The water balance results of Table 3.3 suggest that the lowland paddy production through its reliance on unconstrained artesian wells has been the major contributor to the observed decline of the Umbulan spring, but changes in the upper and middle zone also contribute. The water balance model includes some interactions between surface and groundwater flows, but models at a higher temporal resolution that include seasonal patterns of rainfall could refine the results in future. The attribution of effects as 55% lowlands, 49% upland and 4% interaction is, at the current level of detail in the analysis, only indicative; however, it is consistent with process understanding. Models that operate on a daily time step and at higher spatial resolution will be needed (Arnold et al., 2012; van Noordwijk et al., 2017b), but tend to require parametrization efforts that challenge current data availability.

Table 3.7. Description of each paddy field type.

Clusters	Description
1	High paddy field fraction, medium drainage density, and a high number of artesian wells. The dose of application of N fertiliser is high, and use of compound fertiliser is medium, but rice yield is low. The number of pesticide types is medium. The area with crop rotation and intensity of pests (rodents) is medium. The paddy field area with rivers as the main sources of water is medium, but still have a high number of water resources. There is an 'Ulu-ulu' as the water regulatory officer.
2	High paddy field fraction and drainage density, with a medium number of artesian wells. Doses of application N and compound fertiliser are low and rice yield is relatively low. The number of pesticide types is low. The area with crop rotation is low, hence the intensity of pests (rodents) is high. The rivers have a very important role as the main water source so that the number of other water sources is low. There is no 'Ulu-ulu' as the water regulatory officer.
3	Low paddy field fraction, low drainage density, and few artesian wells. Doses of application of N fertiliser are medium and those of compound fertiliser high while yield is at a medium level. The number of pesticide types is medium. The area with crop rotation area is high, and the intensity of pests (rodents) is low. The rivers have a small role as a source of water so that the number of other water sources is high. There is an 'Ulu-ulu' as the water regulatory officer.
4	Low paddy field fraction, with medium drainage density and a high number of artesian wells. The rate of application of N and compound fertiliser is high and followed by high yield. The number of pesticide types is medium. The area with crop rotation is high, but the intensity of pests (rodents) is still high. Rivers have a small role as a source of water, but the number of other water sources is medium. There is no 'Ulu-ulu' as the water regulatory officer.
5	Medium paddy field fraction, with low drainage density and a medium number of artesian wells. The dose of application of N and compound fertiliser is low, but yield is medium. The number of pesticide types is medium. The area with crop rotation is low, hence the intensity of pests (rodents) is low. The rivers have a critical role as the main water source so that the number of other water sources is low. There is an 'Ulu-ulu' as a water regulatory officer.

3.4.2. Groundwater-wasting irrigation methods: understanding farmer decisions

The second question sought relevant geographic variation between villages and hamlets in the farmer's practices in managing land and water in cultivating paddy. The shift from rainfed sugarcane to irrigation-based paddies in Pasuruan district got a boost when relatively cheap groundwater drilling with bore holes of 10–100 m (or more) provided additional water, year-round. Without any control valve to manage the well's flow, excess groundwater was channelled back to the river and then lost to the sea. Agronomically, the water supply is considerably more than crop demand, with the average 10 mm/day of well supply per unit paddy area, two to three times the potential evapotranspiration rate, even without accounting for rainfall and river-based irrigation water. The high crop frequency, approaching three crops per year and currently reaching five crops per two years leaves short time for a break between crops. As the landscape is permanently saturated, the rice crop does not ripen off well and the harvested product is only of medium quality. Crop rotations with other crops are applied to only a small part of the area. Despite abundant water availability and intensive fertilization, however, rice yields of around 5 ton per ha in the survey were below the 5.8 ton per ha reported for the district (Leimona et al., 2018) and representing a nearly 50% yield gap relative to the potential yield for irrigated rice in Indonesia of around 9.5 ton per ha (Agus et al., 2019). Within our data, there was no indication that variation in yields were related to variation in fertilizer level (either Urea or compound fertilizer, the two were strongly correlated). Rodents were widely seen by farmers as the main yield-reducing factor, and despite ample use of pesticides, could not be controlled at farmer level. It appears that the current intensification pathway is reaching a dead end, where they produce large volumes of a medium quality product at considerable environmental costs and, even if these externalities are ignored, modest farm-gate profitability.

Investment in closing the existing wells and replacing them by wells with improved design that can be turned off when not needed appears to be a cost-effective way for external stakeholders to recover the flow at the Umbulan spring (and the millions of households that can thus be supported). In addition, the irrigation from artesian wells only during the night can avoid water wasting from evaporation process during the day. A substantial reduction of groundwater wasting seems to be feasible without risking water shortages in critical periods for the crop. However, for a free-flowing well the only decision is in its construction, whereas a controlled well requires agreements among farmers about when it will be opened.

3.4.3. Collective action aspects of solutions

The third question was whether a participatory survey of paddy cultivation and spatial data analysis for the development of characteristic can identify options by context for upscaling sustainable paddy cultivation. Sustainable agriculture within a sustainable landscape context is beyond food production, it safeguards the increasing capacity of rural people to be self-reliant and resilient when facing changes and shocks and building strong rural institutions, including landscape governance, and their economies (van Mansvelt and van der Lubbe, 1999). A well-known analysis of the Bali water temples in Indonesia, or '*subak'* in the local language, highlights the importance of local institutions that secured synchronous rice planting (Lansing and de Vet, 2012). Synchronous rice planting ensured landscape-wide breaks between cropping seasons in the traditional system, that effectively controlled rodents. When the water temples were abandoned and technical irrigation allowed for an increased cropping frequency, rodent problems came to the fore in Bali. It appears that with the unconstrained artesian wells in Rejoso, an even easier year-round availability of habitat and food supports rat populations beyond control.

Following this line of interpretation, we suggest that in the Rejoso watershed context, the lack of strong farmer institutions imply an inability to synchronise planting calendars and that this has become one of the principal causes of aggravating rodent pest attack. When farmers can collectively dry their paddy field, this cycle of fallow can reduce the rodent pressures. Thus, the management of rodent pest problems (which directly link to yield and income) can be considered as a collective driver to strengthen local institutions, which at the end leads to better water management and may allow win–win solutions of water-saving and yield increase to be feasible.

3.4.4. Sustainable paddy cultivation and its relevance to global agenda and practices

Our efforts to understand existing constraints to a sustainable production landscape in the Rejoso watershed showed that among the eleven villages in the Gondang Wetan and Winongan Sub-districts, a substantial variation in farmer's practices in managing the land could already be found. Given this variation, a one-size-fits-all solution is not likely to work. Our current understanding of such variations of the paddy field enables the landscape managers and decision-makers to identify the potential area for upscaling specific solutions and to ensure that the adoptions of interventions run smoothly because the process has embraced potential constraints and solutions according to the perspectives of smallholders and local communities.

Our approach aligns with a global agenda. The innovations of sustainable production landscape management consider the dual goals of reducing environmental impacts while increasing productivity. Discussion of the interconnected dimensions of sustainable production landscape is not new, while understandings and solutions towards actions to transform the environmentally sustainable food production systems are still unresolved (Beddington et al., 2012).

The research by Pretty et al. (Pretty et al., 2003) on the adoption of practices and technologies for environmentally sustainable with substantial benefits for the rural poor hold promising advances. The 208 projects were derived from 52 countries of the South resulted in approximately 8.98 million household farming 28.92 million ha representing 3.0% of the 960 million ha of arable and permanent crops in Africa, Asia and Latin America, adopted and practised sustainable agriculture. Knowledge from the literature confirms that increasing paddy productivity while reducing environmental impacts is doable. Likewise, it is attainable that farmers practice more efficient water use (Subari et al., 2012) and emit less CH_4 and N_2O (Cai et al., 1997; Wang et al., 2017).

3.4.5. Potential of development of paddy farming characteristic for intervention scenario and upscaling

The five clusters identified here represent variation of farmer's practices in managing the land and cultivating paddy. Each cluster provides unique information with different degrees of the constituent parameters, yet still presenting the whole targeted landscape. Intervention scenarios might include incentives for sustainable cultivation, such as insurance of stable agricultural inputs, microcredit, agricultural insurance, market transparency, and capacity strengthening in farmer group management. Table 3.8 presents the analysis and the risks for intervention and upscaling in each paddy field cluster. Clusters with high risk, when targeted for conducting innovative interventions, will provide 'gold standards' of success, compared to the ones with low risks.

The proposed characteristic of paddy farming that considers the variation of farmer's practices in managing the land and cultivating paddy corresponds to the requirement to implement an 'options by context' approach (Sinclair and Coe, 2019). Rather than selections based on proximity to the central power, or 'low-hanging fruit' ones, we expect that through the 'options by context', a more robust selection of locations and intervention scenarios allow for higher adoption rates with expected results and calculated risks of the innovations at each cluster. However, ongoing implementation efforts will have to provide the test of effectiveness. We identified some limitations in the methods applied

3.4.6. Implication for methodology

From the survey of paddy cultivation, identification of respondents by combining available information of farmer group and its member and a snowball technique is an ideal approach. However, the unavailability of up-to-date farmer group data was a challenge, and the impacts were on the length of time in finding a respondent and level of respondent representation in each hamlet. During the data analysis, the domicile of the farmer and the location of the paddy field can be unmatched. The domicile of some respondents can be outside of the eleven villages. Considering that the interventions would be delineated according to the sub-district jurisdictional boundary, the data of seven percent of the respondents who stayed outside the eleven villages were eliminated. Hence, we suggested that the filtering process in selecting respondents should be better from the beginning, and the number of respondents in each hamlet should be adequately represented if resources allow. Apart from the above limitation, we ensured that information gained from the farmer representatives were well obtained, and a structured questionnaire complemented the interviews.

Analysis of spatial data based on aerial photograph/drones produced a high-resolution image. However, the direct georeferencing method that we applied referred that orthorectification was processed without ground control point (GCP) and independent checkpoints (ICP), resulting in a mild shift of location and take effect of Root Mean Square Error (RMSE) value. Although the shifting is about

Table 3.8. Analysis and risk for intervention and upscaling of each paddy field cluster, based on feedback in local focus group discussions.

Clusters	Analysis and risk
1	**Analysis:** Cluster 1 has the potential for upscaling as there are large areas of paddy fields and high numbers of artesian wells. Another interesting fact is to understand the high level of fertiliser use, but the yield is low. The risk of technology failure due to pest is medium, and there is a potential for crop rotation to increase soil fertility. Institutionally, the potential for better water management can be explored by the presence of an 'Ulu-ulu'. **The risk for intervention and upscaling:** Medium to low.
2	**Analysis:** Like Cluster 1, Cluster 2 has the potential for upscaling. Contrary to Cluster 1, Cluster 2 is lower in yield as most of the agricultural inputs are low, but the pest prevalence is high. There is no 'Ulu-ulu' in this area. **The risk for interventions and upscaling:** High, but when the intervention is successful, this will provide a high standard for successful upscaling as well.
3	**Analysis:** With less paddy field area, low drainage density, and a low number of artesian wells, Cluster 3 might not be promising for intervention and upscaling. No obvious challenges regarding paddy cultivation. **The risk for interventions and upscaling:** Medium to low, but with a limited area of paddy field, interventions might not be attractive.
4	**Analysis:** Like Cluster 3, the size of the paddy field area is the limiting factor for upscaling. Factors contributing to high yield interesting to analyse: is it about the fertiliser? Or crop rotation? Cluster 4 may function as a learning site, especially for the application of crop rotation. **The risk for interventions and upscaling:** High to medium due to pest intensity.
5	**Analysis:** Cluster 5 can provide another option for intervention and for upscaling with average, mild conditions on several aspects of paddy cultivation. The role of 'Ulu-ulu' might be interesting to be observed. **The risk for interventions and upscaling:** Low

2–2.5 m compared to orthorectification using GCP and ICP (Widyaningrum et al., 2016), in the future, we suggested applying GCP and ICP for similar analysis to increase geometric accuracy when resources allow. Other analyses to increase the degree of spatial data accuracy focused on verification of the area of paddy fields with annual crop rotation. Multi-temporal images should be used, or a detailed survey of farmers should be conducted to obtain more accurate area estimates of paddy fields with annual crop rotation.

3.5. Conclusion

The production landscape of the Rejoso watershed has problems of unsustainable agricultural development, particularly on its lowland part, where paddy is the primary land use. The unrestricted use of artesian wells to irrigate rice paddies is reducing the pressure on and water yield of artesian wells for urban water users, while the actual rice yields achieved are below potentials achieved elsewhere. The introduction of water-saving technology, with modification of conventional paddy cultivation, and better design and management of artesian wells more control over the wells, can target yield improvement as well as positive environmental impacts. Considerable variation was found to exist within this paddy-dominant production landscape. Our analysis of the variation of farmer's practices in managing the land and cultivating paddy was based on a survey of paddy cultivation and spatial data analysis complemented and verified by the participatory approach indicating the application of landscape-approach in its development. The characteristics of paddy farming as the results reflect the requirement to implement an 'option by context' approach within a landscape for targeting effective, yet efficient, interventions and upscaling technological improvement. The characteristic of paddy farming encompassed five clusters of paddy farms. Clusters were characterised based on the relative area of paddy fields, the density of irrigation networks, area with crop rotation, rice yield, the dose of fertiliser, number of pesticide types, water sources, and the intensity of pests/rodents. Hamlets within a cluster are similar in characteristics of farmer's practices and have unique, contextual conditions. We discussed the potentials and risks of such characteristics for further implementation and upscaling. Clusters with high risk, when targeted for conducting innovative interventions, will provide 'gold standards' of success, compared to the ones with low risks. The information is expected to be useful for the landscape managers and decision-makers in targeting, considering, and budgeting the interventions that are relevant for sustainable landscape management. Future applications of a spatially differentiated intervention approach to innovate in the direction of sustainable paddy cultivation based on water saving is expected to reduce environmental impacts while increasing productivity. Tests are ongoing.

Funding: The research was funded by the Danone Ecosystem Fund through "Sustainable, Low Carbon Emissions and Water-Efficient Agriculture of Rejoso Watershed" project.

3.6. Supplementary Material

Appendix 3A. Calibrating the annual water balance model

Data for mean of annual precipitation (P) were obtained from 13 rainfall stations in lower zone (7 stations), middle zone (5 stations) and upper zone (1 station) (Table 3A.1). Precipitation for each zone (lower zone < 100 m a.s.l., middle zone 100-1000 m a.s.l. and upper zone m a.s.l.) was then generated based on correlation of elevation and annual mean of rainfall (Fig. 3A.1). Potential evapotranspiration E_{pot} were generated using Thornthwaite equation using temperature data of Accu weather (Table 3A.2).

Table 3A.1. Mean of annual rainfall for 13 rainfall stations.

Stations	Zone	Elevation (m a.s.l.)	Mean of annual rainfall (mm/year)*)
P3GI	Lower	5	1143.49
Kedawung	Lower	7	1041.40
Gondang wetan	Lower	8	1000.30
Kawis rejo- Rejoso	Lower	8	1138.33
Winongan	Lower	10	1259.06
Gading – Winongan	Lower	12	1307.53
Ranu Grati	Lower	14	1242.07
Sidepan - Umbulan – Winongan	Lower	25	652.33
Wonorejo – Lumbang	Middle	100	1590.71
Lumbang	Middle	137	1485.71
Panditan – Rejoso	Middle	600	2255.14
Puspo	Middle	640	2243.86
Tosari	Upper	1045	1539.27

*) 1990-2015

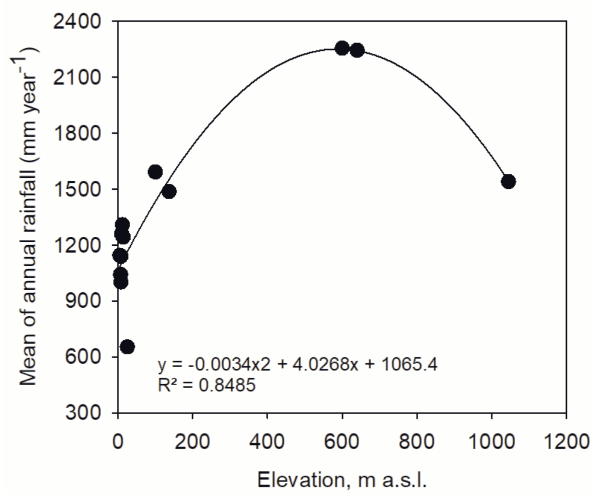


Figure 3A.1. Correlation between mean of annual rainfall and elevation of 13 rainfall stations.

Table 3A.2. Potential evapotranspiration of three zones.

Zones	Mean of annual temperature (°C)			Total potential evapotranspiration (mm year^{-1})		
	1990	2015	2020	1990	2015	2020
Upper	17	17	17	770.4	770.4	770.4
Middle	25	25	25	1367.8	1367.8	1367.8
Lower	27	27	27	1726.8	1726.8	1726.8

Parameter estimates for actual/potential evapotranspiration (ε) and runoff coefficient (ρ) were derived as area-weighted average from estimate for the specific land use types in the GenRiver model, calibrated for a number of Indonesian watersheds (Cadag and Gaillard, 2011).

Entering peat-swamp forest in Sungai Besar Village to collect peat soil data.

Chapter 4: Rewetting a Tropical Peatland by Canal Blocking? Linking Groundwater Dynamics at Plot and Landscape Scale in the Pawan-Kepulu Peatland of Indonesia

Tanika, L., van Noordwijk, M., Wijaya, K., Mariati, H., Speelman, E.N., Dohong, A., and Peña-Claros, M., Rewetting a tropical peatland by canal blocking? Linking groundwater dynamics at plot and landscape scale in the Pawan-Kepulu Peatland of Indonesia.

Abstract

Tropical peatlands are highly sensitivity to changes in climate and management, and easily lose their water buffering and carbon storage properties, becoming and become a fire risk when drained for agricultural use. Peatland degradation in Indonesia has impacts at local, national and global scales, and has triggered a national peatland restoration effort. The interactions between temporal groundwater dynamics and spatial variation in peat properties, topography, land cover and climate need to be understood when setting nationally applicable water management targets and evaluating the effectiveness of restoration. The Pawan-Kepulu peatland (64,263 ha) in the Ketapang District (West Kalimantan, Indonesia) has been degraded due to drainage, forest conversion, and fires, and has become a national priority for restoration. Dominated by oil palm and agricultural areas, the Pawan-Kepulu peatland has a high drainage density, which accelerates the decline in groundwater levels during the dry season. As a result, fires often occur, especially during El Niño episodes. Effective restoration strategies need to be built as soon as possible and require the involvement of various stakeholders. To speed of the process, a multi-level information needs to be available from the plot to landscape levels. The high spatial variation of peatland conditions makes coarse-scale hydrological modelling processes too rough to use, whereas models with fine-grained input cost time and money. The objective of this study was to explore the impact of land cover and water management on peatland groundwater level. The objective is achieved by building and simulating a process-based model that connects the plot and landscape levels of the groundwater system to improve groundwater prediction. The model used field measurements to predict the plot level groundwater and scale-up to the landscape level by taking peat depth, land cover and drain density into account. The simulation results show that the groundwater dynamics in the peatland are influenced by rainfall, land cover, peat depth and canal density. The area closer to the canal experiences a faster decline in the groundwater levels. Maintaining the ability of peat soil in storing water contributes in improving soil moisture to prevent fires. Therefore, the peatland restoration strategies need to consider the plot level variables that contribute to the landscape conditions.

Keywords: Peatland restoration, peatland hydrological model, peatland groundwater level

4.1. Introduction

Peatlands are unique ecosystems, very sensitive to changes that affect their precious water and carbon balance. The mere existence of tropical peat soils has puzzled scientists trying to understand how a long-term excess of necromass production over decomposition is possible at temperatures that favour the latter throughout the year (Kurnianto et al., 2015; Silvianingsih et al., 2021, 2022). Anaerobic conditions exist below the groundwater table, restricting tropical peatlands to poorly drained (pene)plains without elevational gradients within the humid zones, characterised by annual precipitation exceeding evapotranspiration (Gumbricht et al., 2017). Peatlands are a globally relevant carbon sink through the accumulation of necromass (Rieley, 2007; Hiller and Fisher, 2023). While intact peatlands are home to globally threatened biodiversity, they also full fill many important hydrological functions, such as storing and slowly releasing good-quality water, and buffering local climates (Belyea and Baird, 2006; Labadz et al., 2010).

The riparian transition zones between peat domes (part of peatland with a thicker peat than other areas) and rivers have a long history of settled human populations (Silvianingsih et al., 2021), with the core peat areas being used only for hunting and gathering and commercial logging. In recent decades, drainage programs were implemented to create conditions for tree plantations (Tóth and Gillard, 1988) and agriculture (including annual crops, oil palm; Harrison et al., 2020). Massive canal construction degraded the ecosystem functions of intact peatlands (Jaenicke et al., 2011; Putra et al., 2018), resulting in structural collapse and gradual subsidence of (over)-drained peatlands, and loss of water buffering and flow regulation (Loisel and Gallego-Sala, 2022). The rapid spread of fire and its persistence in a subsurface form in dry peatlands experienced in recent decades (Tonks et al., 2017), especially in El Niño years, caused smoke and haze problems affecting local health (Uda et al., 2019), the economy of neighbouring countries and the global carbon balance. The so-called ‘peatland issue’ touches on a range of morality issues in the tug-of-war between stakeholders who want to drain and those who want to rewet (Abdurrahim et al., 2023).

The 2015 fires triggered the Indonesian government to take decisive actions to restore peatlands and prevent fire episodes. A Peatland Restoration Agency (BRG) was set up, under the Presidential Regulation Number 1 of 2016, as the coordinating institution for reversing the past hydrological degradation. In doing so, a key performance indicator was needed to judge whether rewetting efforts succeeded or not. Earlier studies Wösten et al.(2008) suggested this numerical target, namely that groundwater levels should not fall below -40 cm below the surface. This target was included as a mandate in the Government Regulation number 57 of 2016 on Peatland Protection and Management. The complete blocking of main canals as the most radical intervention could lead to further problems, while a range of lightweight, partial canal blocking or thresholding (weirs) that allow overflow during high rainfall events interventions emerged as a more feasible approach (Ritzema et al., 2014). Several subsequent studies tried to link canal water level, groundwater level, canal blocking, drought, and fires to support restoration strategies (Ishii et al., 2015; Taufik et al., 2015, 2019a, b; Sinclair et al., 2020; Dohong and Tanika, 2021; Murdiyarso et al., 2021). Maintaining higher water levels in the drainage canal network will reduce the seepage of water from peat domes. However, the relevance and general applicability of the -40 cm groundwater criterion for peatland restoration remained contested.

There is a gap in the scale of understanding peatlands at the macro (global, national, landscape) and micro (plot) levels, which need to be bridged at an intermediate scale (FAO, 2020). Developing a peatland restoration strategy requires an understanding of how re-wetting at the plot level (Ketcheson and Price, 2011; Ballard et al., 2012) relate to the drainage function of a canal network during periods with an excess of rainfall over evapotranspiration, and during dry spells when the fire risk is high.

Figure 4.1 shows how key hydrological processes and their main determinants for a daily water balance can be approached at patch, transect and landscape scales. The landscape scale interventions in the canal network need to be traced back to processes in a hydraulic gradient from canal to core peat areas and to the dynamics of groundwater levels in a hydrological year. The spatial and temporal dynamics of micro-topography (Khasanah and van Noordwijk, 2019) are a challenge for groundwater-depth-based performance indicators.

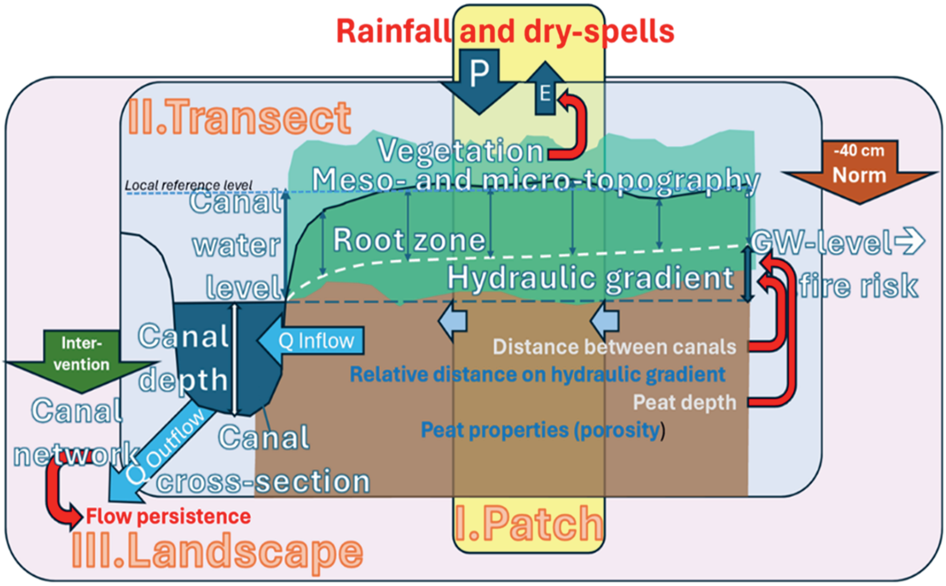


Figure 4.1. Key hydrological processes and their main determinants represented at three nested scales: I. Patch, II. Transect (hydraulic gradient), III. Landscape. E = evapotranspiration, P = precipitation, Q = discharge, GW= groundwater.

Based on fire and hotspot data obtained from the Ministry of Environment and Forestry, the Ketapang District in West Kalimantan Province has an extensive area of peatland experiencing high fire frequency. Therefore, this district became one of the target areas for the Peatland and Mangrove Restoration Agency (BRGM) and for efforts to support local governments in developing fire prevention strategies (Widayati et al., 2022, 2024). Based on our involvement in this process, we use the Ketapang area as a case study to better understand current performance targets for peatland rewetting efforts. The objective of this study is to build connectivity between the plot and landscape levels to improve peatland hydrological understanding to support restoration strategies, using the Pawan-Kepulu peatland in Ketapang as a case study. We have three research questions: (1) How do plot characteristics account for plot-level groundwater dynamics? (2) How does landscape-scale variation in properties modify plot-level groundwater dynamics? (3) How does plot-landscape management connectivity enrich the understanding of peatland management options? In this study, we used field measurements to answer the first question, and built a process-based model to simulate groundwater levels at the plot and landscape levels to answer the second question. We then construct different scenarios by varying rainfall, land cover and water management to assess the impact at the landscape level.

4.2. Methodology

4.2.1. Site descriptions: historical and future conditions

Situated between the Pawan and Kepulu Rivers, and the Karimata Strait, the 'Pawan-Kepulu' peatland in Ketapang district, West Kalimantan Province, Indonesia is recognized as hydrological unit. Since 2021, these peatlands have become part of national restoration priority because of the high frequency of fires. The Rahadi Oesman Meteorology station in Ketapang recorded that the average monthly rainfall in Ketapang varies from 100 to 500 mm, with the driest months between June–August (Kurnianto et al., 2019). Data on the distribution and function of peat ecosystems by the Ministry of Environment and Forestry of the Republic of Indonesia show that the Pawan-Kepulu peatland (64,263 a) consists of 58% of peat soil and 42% mineral soil (in riparian and coastal zones), and the peat soil is divided into 60% (22,056 ha) as the protected areas with a peat depth of more than 3 m and 40% (15,117 ha) as the potentially cultivable areas with a peat depth of less than 3m (Inventory of Peatland Ecosystem Characteristics (Scale 1:50.000)). As the reliability of national data on peat depth was questioned, a new map was created.

Based on 82 recent sampling points in this study, the peat depth in Pawan-Kepulu peatland varies from 0 to over 9 m (Fig. 4.2), with the decomposition rate varying from H1 – H9 according to the von Post humification scale. The landscape is dominated by Hemic peat (H4 and H5), but the top layer of peat soil (0-1 m) tends towards Sapric conditions with a high level of decomposition (H7), especially in oil palm plantation areas; the level of decomposition decreases with peat depth. This peat characteristic can store a lot of water but is easily disturbed by drainage which makes this area dry more quickly (Paul et al., 2021a).

Based on the 2022 land cover map by Widayati et al.(2024), oilpalm plantations dominate the land cover in this landscape (Fig. 4.2). Most of the oil palm area is managed by two oil palm companies (Abdurrahim et al. manuscript under review); although the new peat map shows many areas with a peat depth more than 3m, the land was in the past classified as non-forest zone and a smaller area by the local community. The forest area is part of a state forest managed by the Forest Management Unit, recognized as the habitat of orangutans. Recently, management of some of the forest area has been handed over to the village as part of the social forestry program. The agricultural area that is used for seasonal crops belongs to the local people, dominated by spontaneous migrants from other regions in Indonesia (Abdurrahim et al. manuscript under review). However, due to limited knowledge and capacity to convert it, part of their agricultural area is still shrub (Fig. 4.2, mixed crop and shrub).

Canals were constructed in the Pawan-Kepulu peatland in the 2000s, when local communities and oil palm companies built open drainage, unregulated canals to facilitate timber extraction and to manage oil palm and agriculture easier(Carlson et al., 2012). Therefore, the groundwater level in this area decreased rapidly and the fire frequency was high. The impact of these land fires is detrimental to both the local area and at the global level with the haze and carbon emissions (Widayati et al., 2021, 2022). NASA recorded 80 hotspots in 2015, 86 hotspots in 2018 and 155 hotspots in 2019 in the Pawan-Kepulu peatland (Fire Information for Resource Management System).

In the beginning of this study in 2020 and 2021, we met with the local communities in the villages of Sungai Pelang, Pematang Gadung and Sungai Besar and the Ketapang district government and held focus group discussions to find their understanding about their peatland and its connection with the fire issues. Local informants stated that the causes of forest and land fires in their area were long drought, lack of instruments for extinguishing fires and several issues related to humans (such as lack of awareness, lack of coordination, lack of law enforcement). For the short-term efforts, they proposed fire control and socialization about fire hazards and the early warning system. For the long-term, they proposed canal blocking (or thresholding to secure minimum water levels) and land-use management. As a result, in 2023, a master-plan of the Pawan-Kepulu peatland for fire prevention has been published containing land management, water management through canal blocking and peatland monitoring using groundwater and canal water levels (Widayati et al., 2022, 2024).

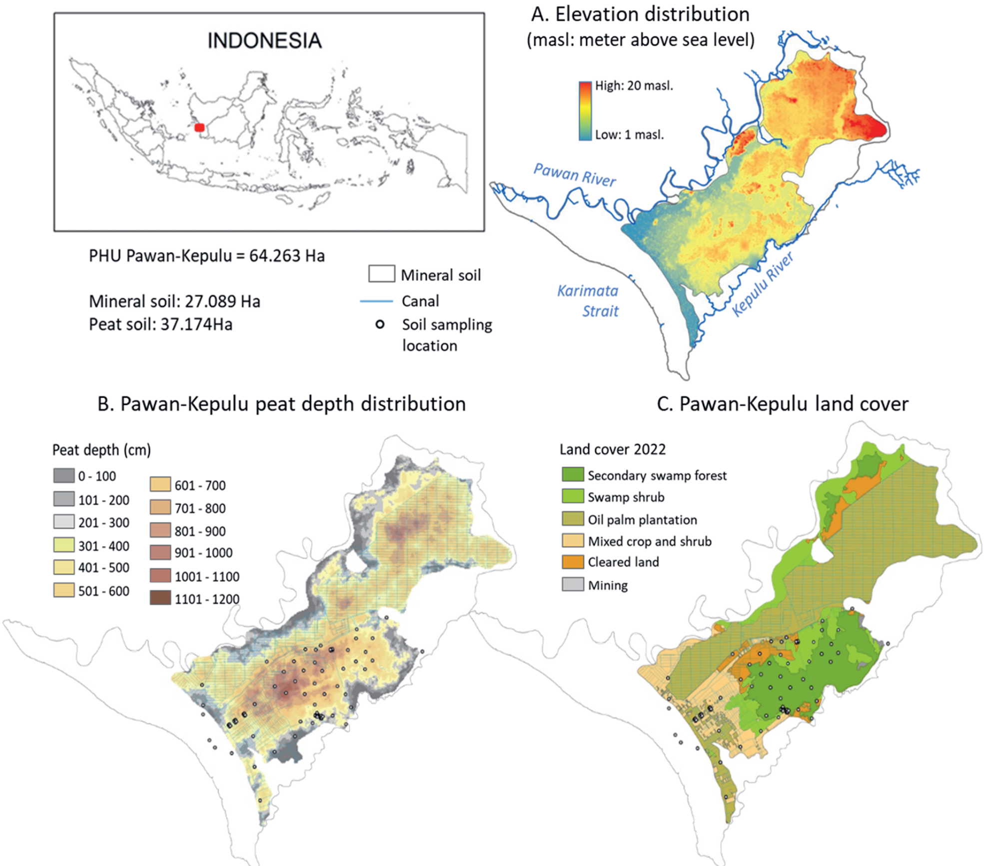


Figure 4.2. Map of Pawan-Kepulu peatland that consists of (A) Elevation based on Digital Elevation Model (Geospatial Information Agency, 2018), (B) peat depth based on interpolation of soil sampling in this study, and (C) land over variation based on Tropenbos Indonesia analysis (Widayati et al., 2024).

4.2.2. Conceptual model of peatland groundwater prediction

This study predicted groundwater levels at the landscape level through three stages which refer to the spatial scale associated with the input at each stage, namely: (A) plot measurement, (B) plot level calculation and (C) landscape simulation (Fig. 4.2). Sections 4.2.3–4.2.5 provide a more detailed explanation of the methods, input and expected output of each stage.

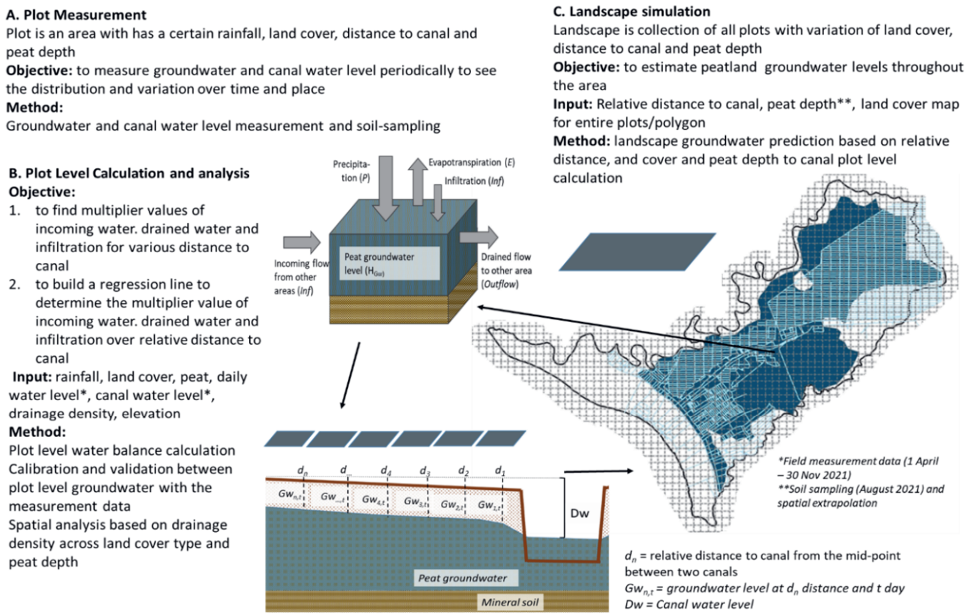


Figure 4.3. Conceptual model and stages of groundwater prediction from plot to landscape level used in this study.

4.2.3. Plot level measurement

The objective of building the measurement plots in this study was to record changes in groundwater level associated with the canal water level and the distance to the canal by constructing six measurement plots. The output from the plot measurement became the basis for developing a peatland groundwater model at the plot level. These measurement plots vary in dominant land cover (forest, shrub (mix or swamp), and oil palm) and water management (with and without blocking) (Fig. 4.4). We considered the actual conditions based on field observation, access to road to facilitate the data collection and permission from the landowner when selected these measurement plots.

Each measurement plot has 14 monitoring wells and 1 or 2 canal water meters in the canal with a design according to the presence or absence of canal blocking (Fig. 4.5). The monitoring wells were built simply by using pipes with 2"diameter and planted at the ground at depth around 3.5 m or according to the peat depth in areas with less than 3.5 m peat depth. The pipe height above the surface in the same line made even followed the 10 m pipes (Fig. 4.5). We collected groundwater level and canal water level manually every Monday and Thursday between 8-11am from April - November 2021 by 6 people divided into 3 groups. These people measured the groundwater level from the top of the pipe, while the canal water level was measured from the bottom of the canal.

This study also built two simple rainfall stations in Sungai Pelang village and Sungai Besar village to collect daily local rainfall data associated with the measurement plots. This rainfall was collected using a pipe with 4" diameter, and the data was collected every day at 7 am from 1 April – 30 November 2021. The furthest distance from these two rainfall stations to the measurement plot is 12 km to Plots 1 and 2, and the closest distance is 3 km to Plots 6 and 7, which is 3 km.

Plot	Dominant land cover based on field observation	Canal blocking	Elevation (masl.)	Peat depth (m)
Plot 1	Secondary forest	Yes	6	0.65 – 5.79
Plot 2	Secondary forest	No	6	1.00 – 2.97
Plot 3	Swamp shrub	Yes	5	5.71 – 6.66
Plot 4	Mixed between shrub & crop	No	4	7.4 – 8.92
Plot 5	Oil-palm	Yes	1	1.98 – 3.97
Plot 6	Oil-palm	No	2	4.69 – 9.81

masl = meter above sea level

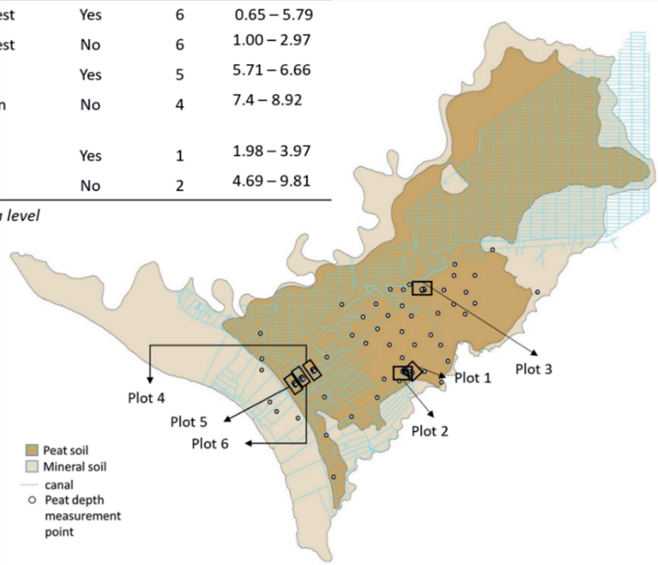


Figure 4 4. Location of the six measurement plots in the Pawan-Kepulu peatland and of the peat depth measurement points. The table provides general information on each plot. Groundwater and canal water level was collected for eight months (April 1^{st,} 2021–November 30th, 202. 1, and the soil sampling was carried out in August 2021. The blue grid represents the canal grid established in the area.

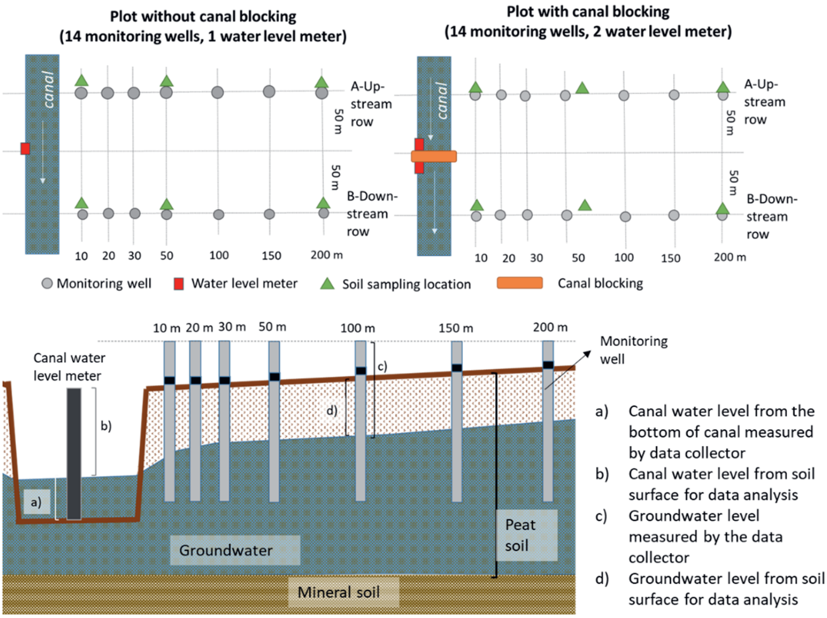


Figure 4.5. Design of measurement plots for collecting data on groundwater level and canal water level.

The analysis process of measurement data used groundwater level from the soil surface and canal water level from the top edge of the canal as local reference level. The groundwater level from the soil surface is calculated by subtracting the measurement data with the height of the pipe above the soil surface. Meanwhile, the canal water level from the top of the canal is calculated by subtracting the height of the canal bank with the water depth in the canal.

We analysed these measurement data to see the pattern and variation associated with land cover, peat depth, presence of canal blocking and distance from canals. We used box plots to see the distribution and interval of groundwater at each measurement monitoring wells. The results of these measurements was used to calibrate and validate groundwater measurements at plot level (Section 4.3.2) and landscape level (Section 4.3.3).

4.2.4. Plot level calculation

Several studies use the water budget equation to calculate changes in groundwater levels to simplify the complexity of groundwater calculations (Grant et al., 2012). This study calculates groundwater at the plot level using a simple water budget equation (Eq.1) which is then converted to Eq. 2.

$$\Delta S = inflow - outflow \qquad (1)$$

$$Gw_t = Gw_{t-1} + (Inf_t + Inc_t) - (Drained_t + E_t) \qquad (2)$$

Where, ΔS = the changes of groundwater storage which represent the changes of groundwater level (cm), Gw= groundwater level (cm), Inf = infiltration (cm), Inc = incoming water from other plots (cm), E = Evapotranspiration (cm), $Drained$= drained water to other plots or canal (cm), t = day.

This study assumes that the amount of Inf and Inc depend on the rainfall (P), so that the amount of infiltration and incoming water was calculated using the Eq. 4 and 5, wheref_{Int} and f_{Inc} are multipliers that determine the amount of rain which vary depend on the land cover and distance to canal. However, the amount of Inf and Inf received by the plot depends on the soil capacity according to micro-topography and the peat depth (Bechtold et al., 2019). The amount of groundwater that drained to other places $(Drained)$ depends on the different between groundwater level and canal water level, and was calculated using Eq. 6 and 7, where f_{Low} and f_{High} are multipliers that determine the amount of groundwater when it is above or the critical line(cl). Meanwhile, the evapotranspiration (E) was calculated based on the relationship between changes in groundwater level (ΔS) and rainfall (P) for each type of land use (Fig. 4.6) in each measurement plot. More detailed explanation of the calculation for each water balance component is given in the Appendix 4A as part of documentation of the Re-PEAT model for this study.

$$Inf = f_{inf} \times P \qquad (4)$$

$$Inc = f_{inc} \times P \qquad (5)$$

$$Drained_t = (Dw_t - Gw_{t-1}) \times f_{low} \qquad when\ Gw_{t-1} > Dw_t\ and\ Gw_{t-1} < cl \qquad (6)$$

$$Drained_t = (Dw_t - Gw_{t-1}) \times f_{high} \qquad \text{when } Gw_{t-1} > Dw_t\ and\ Gw_{t-1} > cl \qquad (7)$$

Plot level parameterization was carried out to adjust some parameters in the model that were difficult to measure in the field or to get from references. We parameterized by comparing the predicted result with the measured data. This model parametrized f_{inf} , f_{inc}, f_{low} and f_{high} to make the predicted groundwater level closed to the measured data. To calculate the predicted groundwater, we used the measured rainfall and evapotranspiration according to the observed land cover. We used the Nash-Sutcliff Efficiency (NSE, Eq. 8) as the statistical criteria to evaluate the performance of the predicted result to its measurement data. We used Solver analysis tools in MS. Excel in each monitoring points to find the combination of those multiplier that resulted with the high NSE.

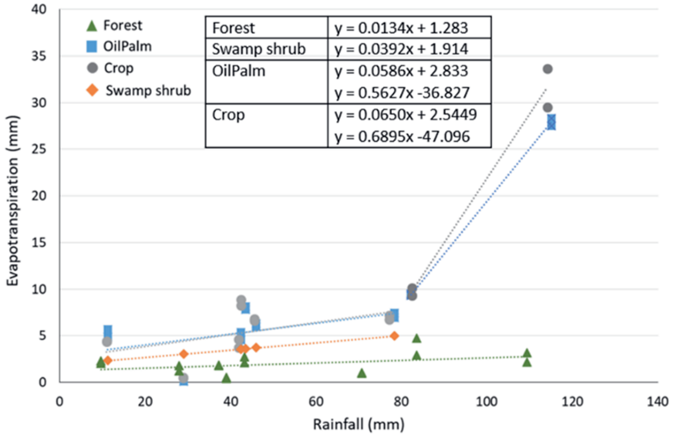


Figure 4.6. Biplot showing the relation between evapotranspiration (mm) based on the amount of rainfall (mm) for each land use type included in this study. Regression equations are provided for each land use type in the inserted table.

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Gw_t^0 - Gw_t^m)}{\sum_{t=1}^{T}(Gw_t^0 - Gw_{Avg}^0)} \qquad (8)$$

Where, Gw_t^0 is the measured groundwater level at t day, Gw_t^m is the predicted groundwater level at t day, Gw_{Avg}^0 is the average of the measured groundwater level, T = total data.

According to Fig. 4.3, the objective of plot level analysis is to build the Eq. 9-16 (Section 4.3.2) to estimate multipliers based on distance to canal. These equations were built by regressing the relative distance of each measurement point with the multiplier value resulting from the plot level parameterization. The regression between variations in these values and the relative distance to the canal was aimed to get the elliptical shape between two open water (canal or river) of Hooghoudt's equation (Belyea and Baird, 2006; Ritzema, 2006; Grant et al., 2012). During the analysis, we found that there were a correlation between f_{High} and f_{Low} with the elevation of each plot, we normalized the f_{High} and f_{Low} values to the elevation of Plot 4 (4 m a.s.l.) to eliminate the elevation factor between multiplier value. The regression between relative distance and f_{High} and f_{Low} were carried out after revising these values with elevation. The f_{Inf} and f_{Inc} values are not corrected for elevation because there was no correlation between these values and elevation.

4.2.5. Landscape level simulation

This is study, we assumed a landscape as the combination of plots with a various combination of land cover type, peat depth, and relative distance to canal (Fig. 4.3C). Mimicking the relationship between plot and landscape, this model developed groundwater level at the landscape level by combining all calculated groundwater from the plot level. We used GIS to overlay all spatial inputs (land cover, peat depth and distance to canal) and divided the Pawan-Kepulu peatland into 92,076 polygons that have different combinations of land cover, peat depth and relative distance. Because the number of polygons is quite large with daily time-steps, we used R Software to calculate and simulate daily groundwater of all plots.

The landscape simulation used several inputs issued by government agencies and organizations working in the Ketapang district, especially in the Pawan-Kepulu peatland. We used Peatland Hydrological Unit (PHU) map and soil map (mineral and peat) from the Ministry of Environment and Forestry, Digital Elevation Model (DEM) from Indonesia Geospatial portal (Geospatial Information Agency, 2018), and 2022 land cover map and canal network map from the Tropenbos Indonesia. Meanwhile, the Pawan-Kepulu peat depth distribution was estimated using Kriging interpolation based on soil sampling and the daily rainfall used the rainfall measurement data from Sungai Pelang and Sungai Besar. We used the 2022 land cover map as a replacement for 2021 land cover map because it was the closest cover map to 2021.

Model validation at the landscape level was carried out by comparing the average groundwater level in each measurement plot with the simulated groundwater level. We used the average of simulated groundwater that has the same land cover, relative distance and peat depth as the measurement plot as the predicted groundwater. Line 1:1 was used to evaluate the bias between predicted and measured groundwater.

The analysis of landscape groundwater analysis is to see the impact of changes in rainfall, land cover and water management on groundwater conditions at the landscape level. We carried out this analysis by simulating the groundwater levels using a combination of different scenarios of rainfall, land cover and water management, namely: 3 rainfall scenarios (wet year, dry year and normal year), 3 land cover scenarios (Forest, oil palm and crop) and 2 water management scenarios (with and without blocking). We evaluated the impact on the changes in groundwater levels between scenarios by comparing the daily average groundwater throughout the area and the annual average distribution of groundwater in the landscape.

Three rainfall scenarios were constructed by referring to the number of dry days and annual rainfall from 2019 (dry year = 2366 mm, dry day = 231 days), 2021 (wet year = 4156 mm, dry day = 175 days) and 2023 (normal year = 3273 mm, dry days = 180 days). We generated these three daily rainfalls using the Rainfall Simulator model (Tanika et al., 2013) based on monthly rainfall data and the number of rainy days at the Ketapang Statistics Agency, Indonesia.

We built the land cover scenarios based on community preferences during the livelihood and tree preferences survey in December 2021 involved four villages, namely Sungai Pelang, Sungai Besar, Pematang Gadung and Sungai Bakau. The survey results showed that the community prefers oil-palm as the source of the long-term income because it is more suitable to the peatlands and more resistant to drought and flooding compared to other trees. As a short-term income and daily consumption, people choose seasonal crops (chili, pineapple, corn, cucumber, eggplant). However, because it is difficult to clear land for seasonal agriculture, some areas still have shrubs. This study added forest as the ideal condition for comparison. In the land cover scenarios, we converted the entire landscape to the certain land cover to get the extreme impacts.

The water management scenarios adopted two conditions: all canals without blocking and with blocking. For the scenario with canal blocking, this study assumed that all canals are blocked according to the number, distance and quality of canal blocking to reduce canal flow. The scenario for canal conditions with blocking refers to the results of measurements on the level plot with canal blocking.

4.3. Results

4.3.1. Groundwater measurement

The results of groundwater measurements from April-November 2021 showed that Plot 1, Plot 2 and Plot 3 have a tendency of groundwater to be above -40 cm, while Plot 4, Plot 5 and Plot 6 to be below -40 cm of the soil surface (Fig. 4.7). The condition of Plot 1 and Plot 2 with shallow peat and near to the Kepulu river make the groundwater level in this area is above -40 cm. While in the Plot 3, after the ground checking with the local people, we found that there is a canal that connects this area to the oil palm company which enters directly to the Pawan River. As the result, the groundwater in the surrounding area of Plot 3 is drained towards this point. Plots 4, 5 and 6 are mostly located in the deep peat and the canal was constructed to cut the contour. This condition causes groundwater to drain easily and enters the canal, which has more discharge velocity to the primary canal which is directly connected to the river or sea.

According to the groundwater analysis results with the distance to the canal, we found that the further away from the canal, the groundwater level increases. This shows that the closer area to a canal, the groundwater is easier to flow into the canal. However, in Plot 4 and Plot 6, the groundwater level decreased at the measurement point 200 m from the canal. Based on the canal distribution map, the distance between canals in Plot 4 and Plot 6 are 388 m. It means that the measurement point 200 m from the measured canal is closer to another canal. Therefore, the decline in peatland groundwater is related to the relative distance to the mid-point between the two canals of an area.

To find how many consecutive rainy days affected the changes in groundwater levels, we also analysed the correlation between measured rainfall and the groundwater level. The result found that the best correlation is between groundwater with the four consecutive days of the rainfall with the average of correlation value is 0.43 for Plot 5-7 and less than 0.1 for Plot 1-3. Using this result for the rest of the simulation, we used a sum of 4 days rainfall to calculate the daily groundwater level.

4.3.2. Plot level groundwater calculation

Optimization of NSE from the comparison between predicted and measured groundwater using Solver in Ms. Excel produced multipliers that determines the amount of infiltration (f_{Int}), incoming water (f_{Inc}) and the drained water (f_{High} and f_{Low}) (Table 4.1). The parameterization and NSE results show the groundwater prediction is close enough to the groundwater measurement (Fig. 4.8). Plots without canal blocking resulted multiplier that produce more groundwater to be drained into the canal compared to areas with canal blocking. The relatively high of infiltration multiplier (f_{Int}) and/or incoming water multiplier (f_{Inc}) in all plots indicate that the soil still has the capacity to receive water. There are two possible situation that led to this condition. First, this large capacity can come from the hydro-physical properties of the peat soil in Pawan-Kepulu peatland with a low to medium level of the decomposition. Second, this areas are unable to hold water because the groundwater drains quickly to the canal. Figure 4.10 show more subtle relationship between multiplier and distance to the canal, and a comparison between areas with and without canal blocking.

The calibration quality of these multipliers resulted NSE more than 0.5 except for Plot 2 (row: upstream) (Table 4.1). According to the NSE efficiency indicator, this value can still be categorized that the calculation results were still acceptable to describe actual conditions. While in the Plot 2, all measurement points have NSE values less than 0.5, except for the measurement point 10 m from the canal with NSE 0.69. Therefore, we assumed the multiplier values from the parameterization process can still help calculate groundwater levels at other measurement points.

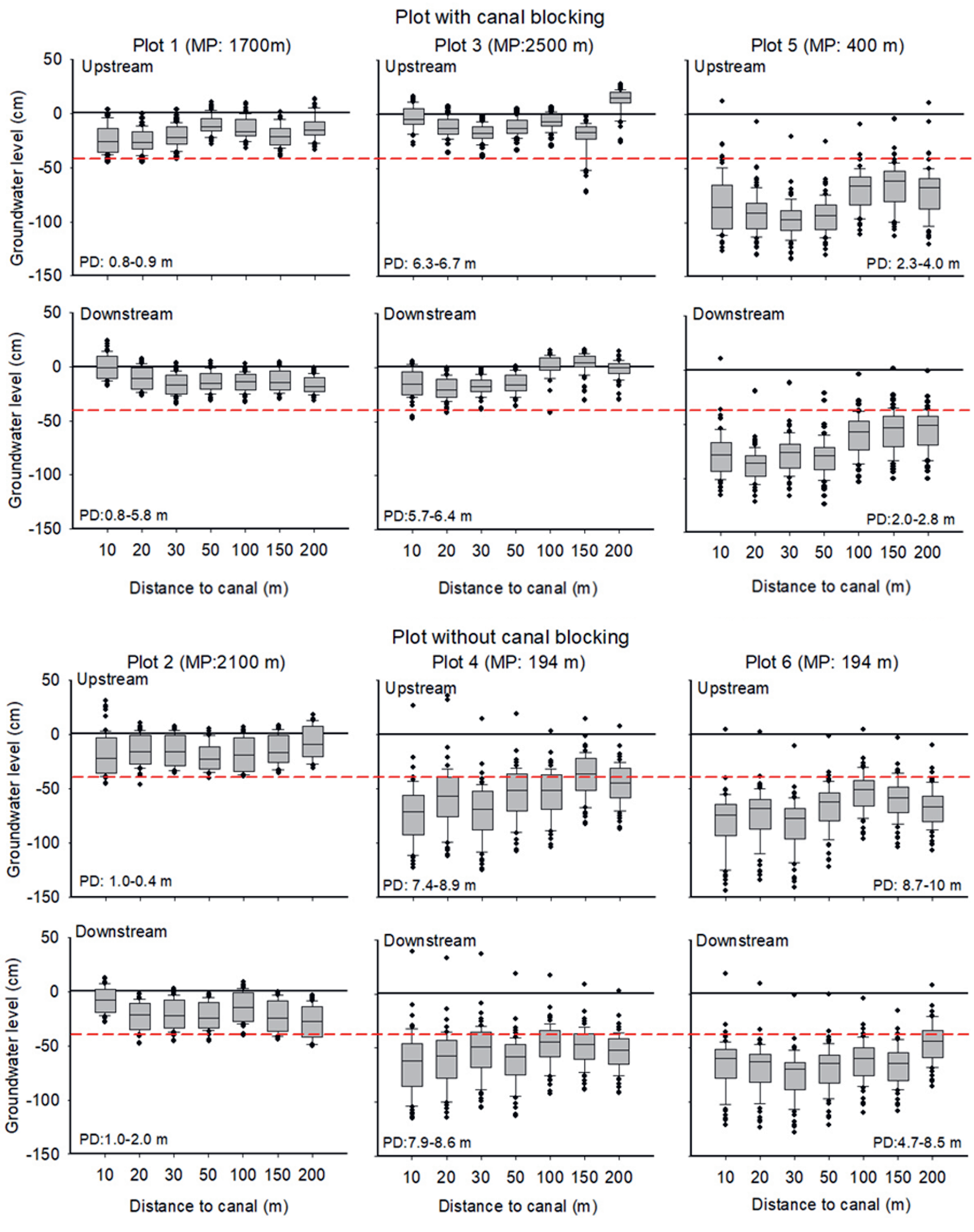


Figure 4.7. Distribution of groundwater measurements in six measurement plots with and without canal blocking, monitored for eight months (April to November 2021). Red line is the 40 cm below the surface as the indicator for fire vulnerability threshold by regulation, PD = range of peat depth based on soil sampling, MP = Mid-point of between canals in each plot based on canal network map.

Table 4.1. Characteristics and conditions of the measurement plots and the Nash Sutcliffe Efficiency (NSE) value that shows the performance of the model. NSE was calculated based on 69 measurement days from April-November 2021 (f_{Int} and f_{Inc} are multipliers that determine the amount of rain that varies depending on the land cover and distance to canal, f_{Low} and f_{High} are multipliers that determine the amount of groundwater when it is above or the critical line(cl)).

Plot with canal blocking						
Average	Plot 1		Plot 3		Plot 5	
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
f_{High}	0.143	0.080	0.055	0.062	0.469	0.241
f_{Low}	0.001	< 0.001	0.001	0.001	0.066	0.037
f_{Inf}	0.417	0.479	0.305	0.286	0.211	0.252
f_{Inc}	0.484	0.409	0.506	0.494	0.339	0.349
NSE	0.250	0.567	0.706	0.730	0.588	0.505
Plot without canal blocking						
Average	Plot 2		Plot 4		Plot 6	
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
f_{High}	0.366	0.325	0.261	0.252	0.468	0.406
f_{Low}	0.049	0.044	0.028	0.018	0.026	0.022
f_{Inf}	0.361	0.413	0.387	0.532	0.321	0.404
f_{Inc}	0.719	0.597	0.278	0.361	0.639	0.572
NSE	0.639	0.639	0.649	0.614	0.690	0.723

By converting the distance to the canal in each measurement plot into a relative distance, we got a smoother relationship between the multiplier of each water budget component and the relative distance to the canal (Fig. 4.9). The closer to the canal, the greater f_{High} and f_{Low} and the smaller f_{Int}. This represents the pattern of the measured groundwater level across to the distance to the canal (Fig. 4.7). From Figure 4.9, we also found that the most significant change in the multiplier value is at a relative distance < 0.4, so the area with a relative distance between 0-0.4 is the most affected area from canal water level. However, this still requires further study.

Based on the regression of all multipliers to relative distance (*d*) to the nearest canal in each plot (Fig. 4.9, we obtained Eq. 9-16 to generate the multiplier value for all areas in the landscape with and without blockings. These equations make it possible to calculate groundwater levels at all locations on peatlands with variations in land cover, peat depth, and relative distance to canal using the Eq. 2 and Eq. 4-7.

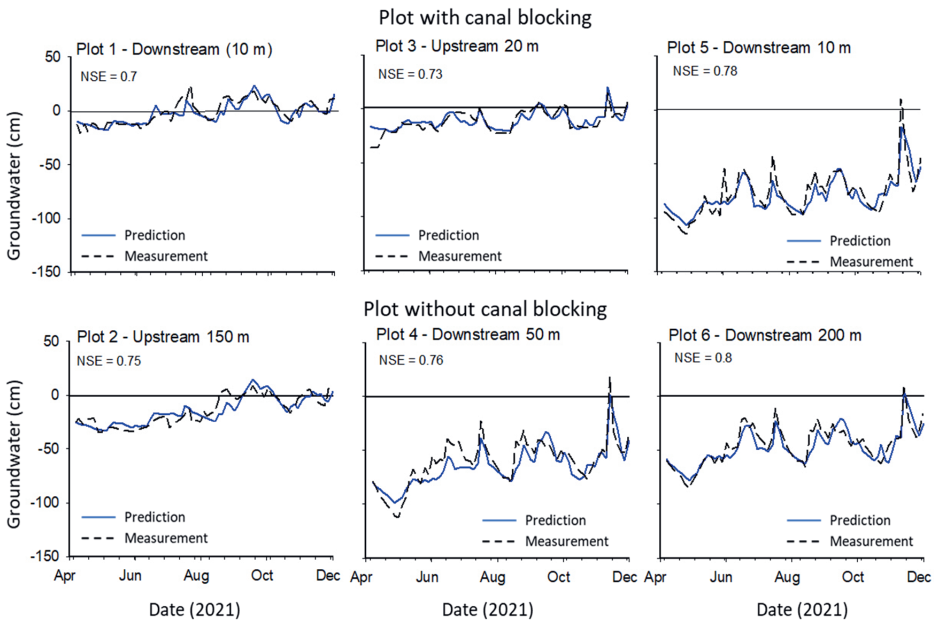


Figure 4.8. Some comparison of groundwater level between plot measurement (April-November 2021) and plot level calculation.

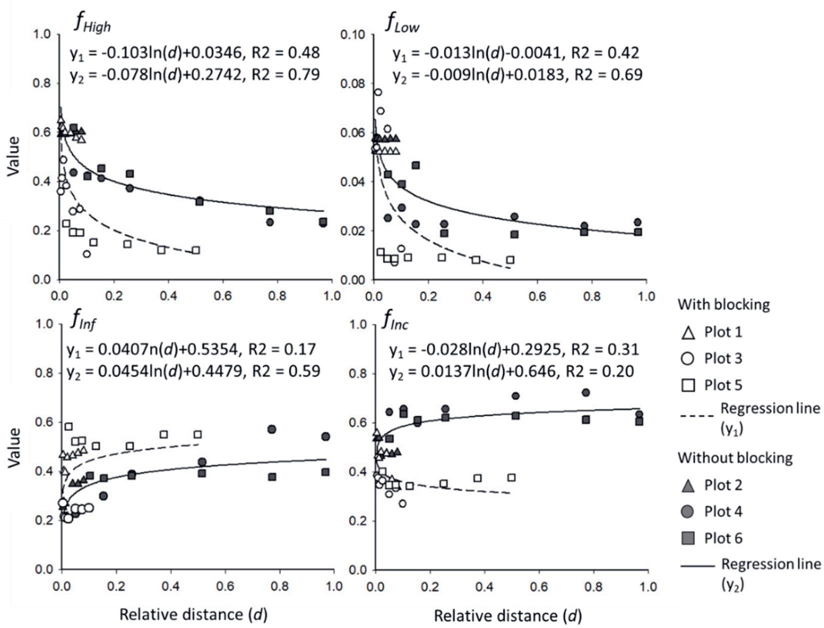


Figure 4.9. Multiplier value generated from plot level calibration to estimate drained water ($Drained$), infiltration (Inf) and incoming water (Inc).

Drained water multiplier above cl (>=-40 cm):

$f_{High} = -0.078\ln(d) + 0.2742$, when the canal does not have blocking (9)

$f_{High} = -0.103\ln(d) + 0.0346$, when the canal has blocking (10)

Drained water multiplier below cl (<-40 cm):

$f_{Low} = -0.009\ln(d) + 0.0183$, when the canal does not have blocking (11)

$f_{Low} = -0.013\ln(d) - 0.0041$, when the canal has blocking (12)

Infiltration multiplier:

$f_{Inf} = 0.0454\ln(d) + 0.4479$ when the canal does not have blocking (13)

$f_{Inf} = 0.0407\ln(d) + 0.5354$, when the canal has blocking (14)

Incoming water multiplier:

$f_{Inc} = 0.0137\ln(d) + 0.646$ when the canal does not have blocking (15)

$f_{Inc} = -0.028\ln(d) + 2925$, when the canal has blocking (16)

4.3.3. Landscape groundwater distribution

Comparison between measured and predicted groundwater level found that some areas overestimated and some underestimated (Fig. 4.10). Plot 4 (elevation 4 m a.s.l.), which is a mixture of crops and shrubs without canal blocking, is the only area with predicted results that are close to the measurements. Plot 1 and Plot 2 (elevation 6 m a.s.l.), which are dominated by forest cover with a shallow peat, predicted lower groundwater levels than its measurement of around 0-12 cm, and the highest bias at a measurement point 10 m from the canal. Plot 3 (elevation 5 m a.s.l.) with swamp shrub and canal blocking, also predicts 3 times lower than the measurement. Plot 5 and Plot 6 (1 and 2 m a.s.l) which dominated oil palm with and without canal blocking, predicted groundwater level higher than the measurements.

When we looked again at the measurement data and plot level analysis, we suspected that the elevation or other factor might influence the groundwater prediction results, which need further study. The analysis of groundwater level measurements in each plot only considered the micro-topographic, but not the topography at landscape level. The effect of elevation disappeared when we revised the f_{High} and f_{Low} multipliers when combining all multipliers together to get the Fig. 4.9. As explained in sections 4.2.4 and 4.3.2, we normalize f_{High} and f_{Low} against the elevation of Plot 4. Therefore, Plot 1 and Plot 2 predict lower groundwater, Plots 5 and 6 predict higher groundwater, while Plot 4 predicts groundwater closer to its measurement. Meanwhile, the conditions in Plot 3 may be caused by other factors that require further study.

The simulation results at the landscape level produced daily groundwater level predictions through various combinations of daily rainfall, land cover, relative distance to canal, peat depth, and water management with or without canal blocking in the Pawan-Kepulu peatland (Fig. 4.11). Using the same land cover combination, the daily groundwater level changes according to daily precipitation and the presence of canal blocks. In conditions without canal blocking, the average groundwater level is close to -100 cm during the dry month (April) and above -40 cm during the wet month (November). With the canal blocking, the deepest average groundwater is -80 cm during the dry month (April) and also above -40 cm in most of the areas in November. This shows that canal blocks can increase groundwater levels both during the dry season and during the rainy season, but some are still below -40 cm even with canal blocking during the dry season. Figure 4.11 also illustrates areas that are relatively close to the canal have lower groundwater levels than areas far from the canal. Therefore, the higher the canal density, the faster the groundwater level decreases compared to areas without canals. When entering the rainy season, areas with a higher canal density increase groundwater levels more slowly compared to areas without canals. The existence of canal blocks slows down the decline in groundwater levels during the dry season and accelerates the rise in groundwater levels during the rainy season.

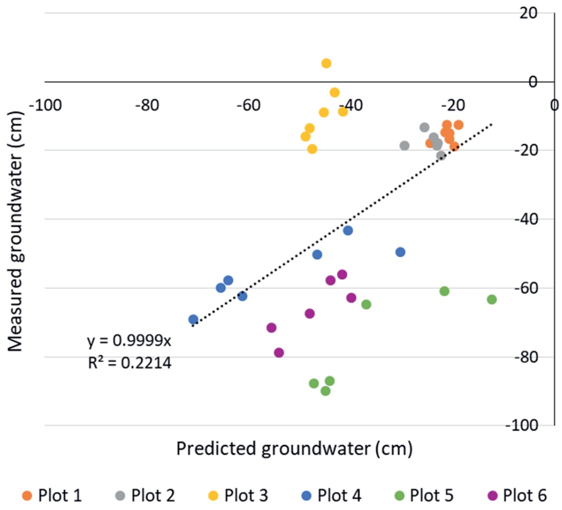


Figure 4.10. Comparison of average groundwater level between plot level measurement and landscape simulation associated with the same relative distance and peat depth.

The differences in the amount of rainfall during wet, dry and normal years gave different distributions on a daily average landscape groundwater (Fig 4.12B) and the yearly average groundwater distribution in the landscape (Fig 4.12C). During dry months (2019 and 2023) and without canal blocking, the groundwater level reached around -125 (Fig. 4.12B, 2019 and 2023, without blocking). Based on landscape distribution, some areas of the Pawan-Kepulu peatland have consistency groundwater below -40 cm and above -40 cm, but with different groundwater ranges (Fig. 4.12C, 2019 and 2023, without blocking). During the dry season but in the wet year, the groundwater level of Pawan-Kepulu peatland is between -50 to -80 cm and above -40 cm in the wet months (Fig. 4.12B, 2021, without blocking) and almost all areas in Pawan-Kepulu peatland have groundwater levels above - 40 cm (Fig. 4.12C, 2021, without blocking).

The canal blocking (thresholding) showed more effect on groundwater levels in the dry season than in the rainy season (Figure 4.12B,C). The existence of canal blocks raises the average groundwater level by around 20 to 75 cm. Meanwhile, during the rainy season, groundwater levels with and without blocking are relatively almost the same. This shows the function of canal blocking in slowing down the decline in peat water levels during the dry season.

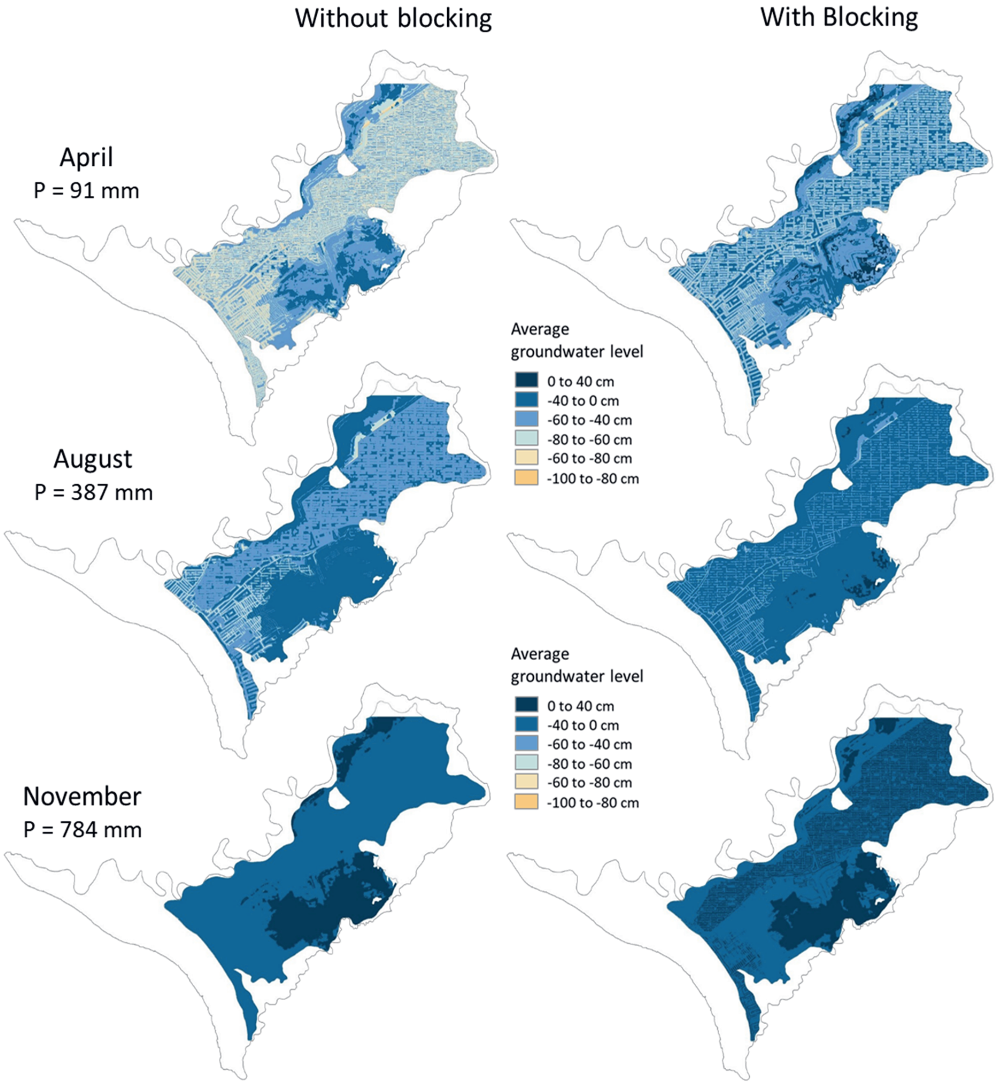


Figure 4.11. Comparison of monthly groundwater distribution with and without blocking in the Pawan-Kepulu peatland based on 2021 rainfall and 2022 land cover as the result of landscape simulation using Re-Peat model.

Simulation results with some extreme land cover scenarios show that forest produces the highest groundwater level compared to oil palm and crop land cover (Fig. 4.13). During the dry season, oil palm and crop decrease groundwater level faster than forests (Fig. 4.13B) and almost the entire Pawan-Kepulu peatland area has groundwater below -40 cm (Fig. 4.13C). On the other hand, forest land cover slows down the decline in groundwater levels and maintains groundwater levels above -40 cm in most of the Pawan-Kepulu peatland area (Fig. 4.13B,C). This simulation shows that land cover also influences the water level conditions of peatlands besides canal blocking.

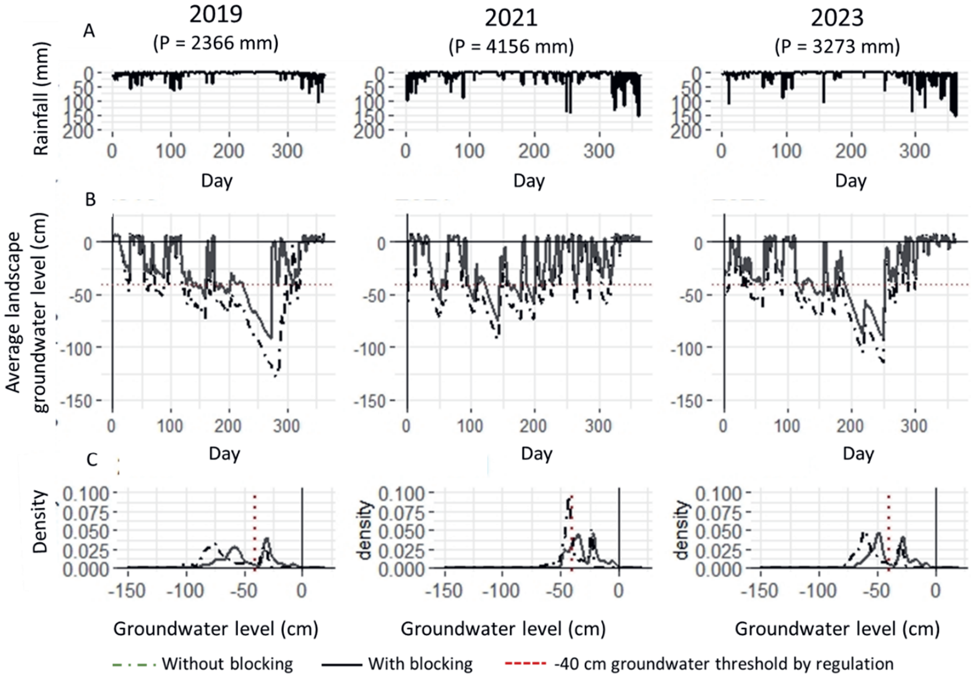


Figure 4.12. The comparison of groundwater distribution at the landscape level between with and without blocking when facing three rainfall condition (dry, wet and normal year). (A) Distribution of rainfall during dry year (left), wet year (middle) and normal year (right). (B) Distribution of groundwater level in the landscape over different annual rainfall. (C) density of area in the landscape that have groundwater level below and above -40 cm.

4.4. Discussion

4.4.1. Groundwater level and plot management

The peat hydro-physical characteristics (e.g., bulk density, soil porosity, hydraulic conductivity, peat decomposition rate) are needed to calculate the groundwater level at the plot level (see equation 2). These peat-characteristics determine the soil water storage capacity, water infiltration, and the lateral water movement between plots, from plots to canals, or from canals to plots (Schouwenaars, 1988; Tonks et al., 2017; Liu and Lennartz, 2019; Krüger et al., 2021), while the land cover influences the amount of evapotranspiration. Several studies mentioned that the evapotranspiration in peatlands is influenced by solar radiation (Hirano et al., 2015; Takahashi et al., 2021). Another component at the plot level that influences the groundwater level is the plot distance to the canal. The field measurements show that the closer the plot to the canal, the closer the groundwater level is to the canal water level (Fig. 4.7),. The distance to this canal affects the groundwater level through the hydro-physical characteristics of the peat. Another study in Central Kalimantan also found that the closer to the canal, the lower the groundwater level (Sinclair et al., 2020). This research also found that in the top layer of peat soil until 60 cm below the surface and close to the canal, the bulk density value is almost the same value as the degraded peatland. We suspect that this 60 cm is related to fluctuations in the canal water level or the cl value in Eq. 7 and 8.

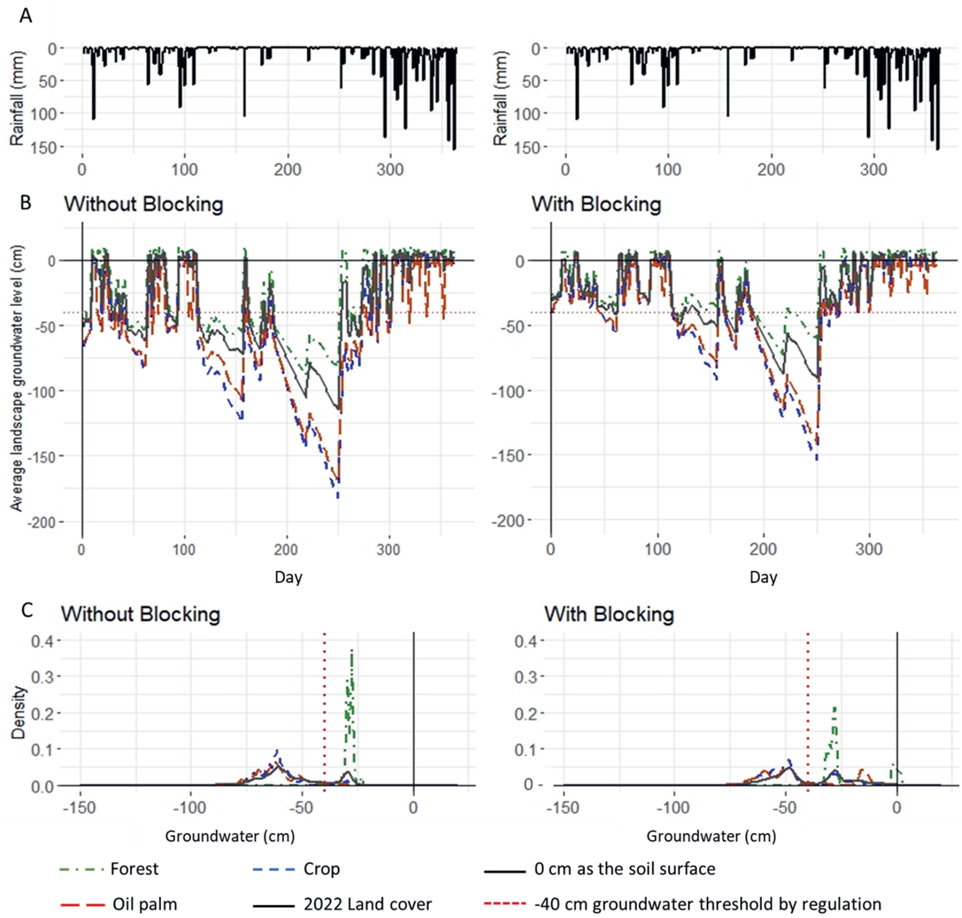


Figure 4.13. The comparison of groundwater distribution at the landscape level as the impact of different land cover (forest, crop and oil palm) between without blocking (left) and with blocking (right). (A) Rainfall pattern used in this simulation (rainfall = 3273 mm). (B) Daily average groundwater level based on land cover scenarios. (C) Density of area in the landscape that have groundwater level below and above -40 cm.

The multipliers $f_{High}, f_{Low}, f_{Int}$ and f_{Inc} in this study represent the hydro-physical properties of peat soil. The calibration of these multipliers $f_{High}, f_{Low}, f_{Int}$ dan f_{Inc} by comparing the predicted groundwater using Eq. 2 with the measurement data can replace the hydro-physical soil properties. By correlating these values with various distances to the canal, the groundwater level with its various variations can be calculated from the difference in water flow entering and leaving the peatland.

4.4.2. Understanding groundwater from plot to landscape level

The results of the groundwater level calculations at plot level and model simulations at landscape level provided a different understanding the relationship of groundwater systems between plot and landscape levels (Fig. 4.9). For example, the results of measurements and calculations at the plot level show that the closer to the canal, the lower the groundwater (Fig. 4.7 and 4.11), with implies that the higher the canal density at the landscape level, the more area there is close to the canal. This means that more and more peat areas will be degraded (Sinclair et al., 2020; Price et al., 2003). These two types of understanding complement each other and allows building an understanding of the entire peatland hydrological system.

Hydrological models are commonly used to understand hydrological systems as they can function as explanatory tools or discovery tools (Jakeman et al., 2006; Pianosi et al., 2016; Mozafari et al., 2023). The simplest hydrological model relates the discharge Q(t) in a river or canal system to that on the day before Q(t-1), incoming rainfall, and a 'flow persistence' index Fp (van Noordwijk et al., 2017a). It suggests a direct link between the effectiveness of drainage in dealing with rainfall excess, and negative impacts on subsequent drought. Where undisturbed peat domes may have an Fp of 0.95 or more, drainage designs for oil palm plantations reduce Fp to 0.5 or less. Canal management may target an intermediate level of flow persistence, but the link between plot and landscape-level processes needs further scrutiny, and flow persistence may be variable within a landscape and vary with time.

The challenges in using models to understand or assess the condition of peatlands is in determining the scale of input. The input scale for modelling needs to consider the variations of the actual conditions. The improper scale makes the model hyper-resolution so that it cannot capture important elements or makes the model too rigid so that we lose focus on the important elements (Horton et al., 2022; Weiler and Beven, 2015). In order to support strategies that can be implemented at the local level, the accuracy of the model requires inputs that are applicable to local conditions (Bechtold et al., 2019). Therefore, combining information at the landscape level (e.g., remote sensing) field monitoring data can improve the level of roughness of assessment results, and is more effective than just relying on field assessment (FAO, 2020).

The Re-Peat model is developed based on process-based model through links between plot and landscape level. In the development proses of the Re-Peat model, we to clarify the relationship between the plot and landscape levels to identify the required plot level input that have significant contribution to landscape level. At the same time, these plot level input should be easy to collect and monitor so that it can be replicated to cover a wide area of the landscape. The Indonesian government through the Ministry of Environment and Forestry and the Peatland and Mangrove Restoration Agency has built the peatland monitoring system SIPALA (https://dw.sipalaga.brg.go.id/) and SIMATAG-0.4, which is used by private companies or NGOs working on peatlands as part of the mandatory or voluntarily monitoring system to support peatland management in Indonesia. The availability of this data makes it easier for us to access information at the local level and combine it with the wider-scale information to improve the accuracy of peatland conditions and in real-time. Even though this study builds a model according to a particular area, this model is still consistent with basic theories that are widely used (Clark et al., 2015), such as water balance, water budget equation, water flow between canals. Therefore, our model can easily be applied to other areas.

4.4.3. The impact of plot and landscape management on groundwater to support peatland restoration strategies

Based on the plot level results and the groundwater distribution at landscape level, we found that land cover, canal density and peat depth influence the groundwater behaviour in peatlands (Fig. 4.11-4.13). The model includes these parameters independently in the calculations, but they are interconnected. For example, some studies indicated that canals were built to lower the groundwater levels, so that land becomes more productive and/or to transport agricultural crops or harvested timber. As part of the land preparation, people built canals to convert unproductive to productive area in agricultural terms (Carlson et al., 2012). Apart from that, canal density is also positively correlated with peat depth

(Fig. 4.2B and C). The deeper the peat, the more water needs to be drained to stabilise the condition of the land so that it is easier to cultivate. Therefore, decision making regarding land use at a certain peat depth automatically influences canal density.

The results of the simulation with the rainfall scenarios (Fig. 4.12) show there are still areas in the landscape that have a tendency for groundwater levels to be below -40 even though implementing canal blocking and land cover management. The existence of canals has changed the hydro-physical properties of peatlands so that it is difficult to expect peatland to work like the condition before it was cut by canal even though we closed all the canals (Schouwenaars, 1990). Modelling results from Wösten et al. (2008) in tropical peatland in Central Kalimantan using the SIMGROW hydro-pedological model also showed that some areas of peatland will still have a value below -40 cm during the rainy season. The study said that the -40 cm below the soil surface was to ensure the success of replanting, which is part of the restoration activities of burnt peatlands (Wösten et al., 2008; Schouwenaars, 1988). This value is not directly correlated to peatland conditions, which are vulnerable to fires when the groundwater is below the -40 cm.

In degraded peatlands, the top soil layer (up to a peat depth of 50 cm) tends to have a high level of decomposition, reducing the soil's ability to store and infiltrate water vertically and laterally, and as a result this layer experiences a decrease in soil moisture (Word et al., 2022). In the long period of degradation, peat soil becomes hydrophobic and irreversibly dry because it loses its ability to store water (Loisel and Gallego-Sala, 2022; Yuwati et al., 2021). This explains how peatlands that have not been degraded still have high soil moisture, even though the groundwater level is below -40 cm. Therefore, if the surface soil moisture of the peat soil is maintained, the threshold of -40 cm can still be the next indicator after soil moisture. Based on the results of measurements of soil conditions in the Pawan-Kepulu peatland, an increase in the level of decomposition occurred in the top layer of the oil palm plantations, which explains why fires still occur even though the groundwater level is above -40 cm, as happened in 2023 based on the results of groundwater monitoring and fire incidents by Tropenbos Indonesia. Therefore, restoration strategies need to consider efforts to maintain the soil moisture (Word et al., 2022), especially for areas that have groundwater levels below -40 cm during the dry season.

Stakeholders involved in developing peatland restoration strategies need to know the groundwater level distribution throughout the landscape. This is to find out where the critical areas need to be restored and where the areas need to be conserved. Apart from that, the distribution of groundwater levels at the landscape level also shows the areas that will be economically and environmentally impacted by certain decisions so that these areas can be supported to reduce risks. To identify these areas, we need information from the plot level. Therefore, the top-down and bottom-up approach in peatland management involves management at the landscape level and at the plot level.

4.5. Conclusion

The plot level information related to hydro-physical soil characteristics, distance to canal and land cover influence the groundwater recharge and discharge at the plot level. Replacing these inputs with some values that are easily derived from plot level information but are easy to measure (e.g., groundwater level and canal water level) can improve the accuracy of the landscape level simulation.

The groundwater at the landscape level adopts variations in plot level groundwater behaviour that are influenced by land cover, peat depth and (local) rainfall, and connect all plot level through canal distribution. The canal distribution is translated into distance to canal at the plot level and canal density at the landscape level.

Presenting groundwater distribution at the landscape level supports restoration strategies by making it easier for stakeholders to see the overall variation in groundwater level at the landscape level. The result from various scenarios improves stakeholder's understanding of the character of their peatlands. This condition allows stakeholders to formulate more realistic restoration targets and strategies apart from standard criteria that are too general or specific.

4.6. Supplementary Material

Appendix 4A. Re-PEAT model

The objective of this model is to calculate groundwater levels at the plot and landscape levels because of rainfall, land cover, canal distribution and peat characteristics. In general, this model is built involving two spatial scales: plot level and landscape level, as well as three stages: plot measurement, plot level calculation and landscape simulation (Fig. 4.4).

The objective of plot level modelling is to calculate the groundwater levels that can accommodate various variations at the landscape level. The main input of plot level calculation consists of rainfall, groundwater level and canal water level, while the supporting input consists of land cover type, peat depth, distance to the canal. The main input is the input used for calculating groundwater level, while the supporting input is the information needed to see the representation of variations in the calculation at the plot level regarding landscape conditions. Apart from groundwater, the output from plot level calculations are several equations to estimate multiplier values to calculate the amount of infiltration, drained water and incoming water based on distance to canal.

Simulation at the landscape level is a combination of all plot level calculations by accommodating all variations that exist at the landscape level and connect it through canal distribution. The main inputs of landscape simulation are land cover, canal density and peat depth. Equations for calculating multipliers based on distance to canals obtained from plot level simulation that will be used to generate all multiplier values required at landscape level. Evapotranspiration at the landscape level can be obtained using references, evapotranspiration calculation equations or the relationship between evapotranspiration and rainfall for each type of land use at the landscape level. Using this information, the groundwater level at the landscape level can be calculated by counting all plot level groundwater their variations.

Below is the documentation of the groundwater level calculation at the plot and landscape level:

A. Groundwater level at the plot level

This model predicted groundwater levels using a simple water budget equation, where changes in groundwater storage (ΔS) over time depend on the amount of water recharge and discharge (Eq. A1). By defining ΔS as the change in groundwater level over time, and separating recharge and discharge into some water balance components, then Eq. A1 becomes Eq. A2 which become the basis of groundwater calculation.

$$\Delta S = inflow - outflow \quad \text{(A1)}$$

$$Gw_t = Gw_{t-1} + (Inf_t + Inc_t) - (Drained_t + E_t) \quad \text{(A2)}$$

Where, Gw_t = today groundwater level (cm), Inf = infiltration (cm), Inc = incoming water from other plots (cm), E = Evapotranspiration (cm), Out = drained water to other plots (cm), t = day

Below is the calculation of each component that makes upEq. 2:

1. Inflow from Infiltration from rainfall and Incoming water flow from other plots

The recharge water comes from infiltration and incoming water from other plots but is limited by the current soil capacity (Eq. A3). Soil capacity (SC) to receive infiltration and incoming water depends on micro-topography (MT) which is built from hummocks and hollows and the previous day's groundwater level (Gw_{t-1}). The potential infiltration (Inf) and incoming water (Inc) depend on the precipitation (P) and the value related to soil characteristics and the relative distance to canals

$(f_{Inf}\ and\ f_{Inc})$ (Eq. A4 and Eq. A5). The values of $f_{Inf}\ and\ f_{Inc}$ are between 0-1 and vary depending on the relative distance to canal (Eq. A15-A18).

$$Inflow_t = Min(MT - Gw_{t-1},\ Inf_t + Inc_t) \quad \text{(A3)}$$

$$Inf = f_{inf} \times P \quad \text{(A4)}$$

$$Inc = f_{inc} \times P \quad \text{(A5)}$$

2. Outflow as the drained water to canals $(\boldsymbol{Drained_t})$

The difference between groundwater level (Gw) and drainage water level (Dw) affects the lateral movement of water to or from the canal. When $Gw > Dw$, the water will flow from the peat into the canal, while when $Gw < Dw$ the water will flow from the canal into the peat. The amount of water that moves from the peat to the canal or vice versa depends on the difference in groundwater level and canal water level $(Dw_t - Gw_{t-1})$ (Fig. 4A.1) and the critical level (cl) of groundwater levels. When the groundwater level is greater than the drainage water level, but below than the critical level, then less groundwater flows out than when the groundwater level is above than the critical level (Eq A6 and A7). In the case of Pawan-Kepulu peatland, the critical level uses the average groundwater level in -40 cm. The f_{High} and f_{Low} values are between 0-1 and vary depending on the relative distance to canal (Eq. A11-A14).

In this model, the water level in the canal is assumed to always be less than or equal to the groundwater level because the water in the canal flows into rivers or the sea. In canal with blocking, the same assumptions are still used, but with smaller f_{High} and f_{Low}values than in canal without channel bulkheads.

$$Gw_{t-1} > Dw_t\ and\ Gw_{t-1} < cl, Drained_t = (Dw_t - Gw_{t-1}) \times\ f_{low} \quad \text{(A6)}$$

$$Gw_{t-1} > Dw_t\ and\ Gw_{t-1} > cl, Drained_t = (Dw_t - Gw_{t-1}) \times\ f_{high} \quad \text{(A7)}$$

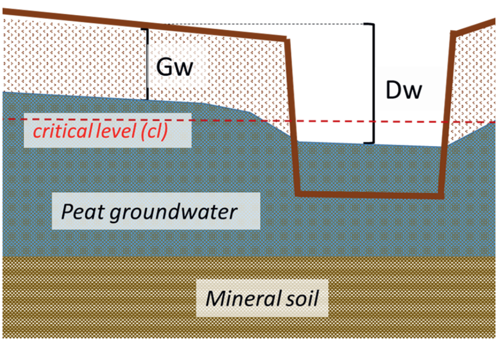


Figure 4A. 1. The illustration of the groundwater level (Gw) and the canal water level (Dw) that influence the water movement from peatland to canal, and vice versa.

3. Estimation of canal water level $(\boldsymbol{Dw})$

According to the Hooghoudt equation, the canal water level influenced by the groundwater level of the area between the two canals and the difference in height between the groundwater level and the canal water level (Fig. 4A.2). With d as the relative distance to the nearest canal, the hydraulic gradient (H) is defined as the change in the groundwater table between the canal to the mid-point over relative distance. Eq. A8 shows the relationship between canal water level, groundwater level and the hydraulic gradient.

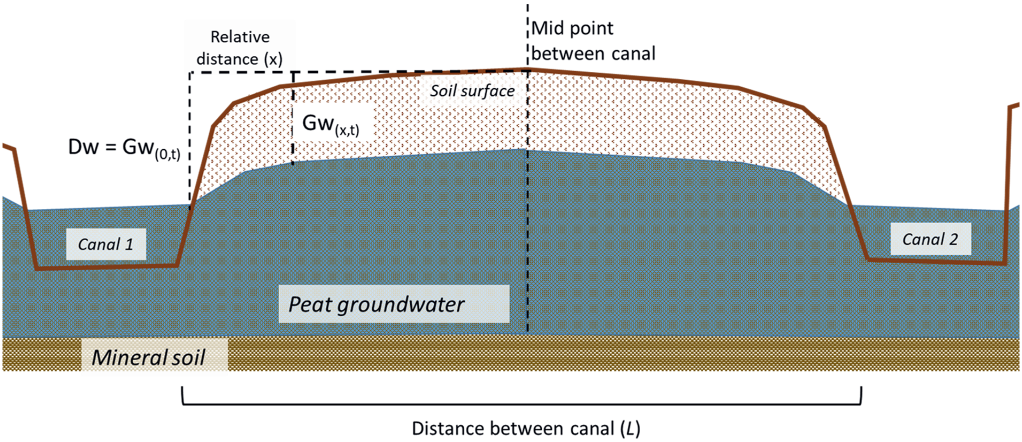


Figure 4A.2. Groundwater level in the area between to canal based on Hooghoudt equation.

$$Gw_{(x,t)} = H\ d + Dw_t \tag{A8}$$

Canal water level (Eq. A9) is predicted based on the combination of Eq. A2 and Eq. A8

$$Gw_t - Gw_{t-1} = Inflow_t - f \times (Dw_t - Gw_{t-1}) - E_t = (H_t\ d + Dw_t) - (H_{t-1}\ d + Dw_{t-1})$$

$$Inflow_t - f(Dw_t - Gw_{t-1}) - E_t = (H_t\ d + Dw_t) - (H_{t-1}\ d + Dw_{t-1})$$

$$Inflow_t - f(Dw_t - Gw_{t-1}) - E_t = (H_t - H_{t-1})d + Dw_t - Dw_{t-1}$$

$$f(Dw_t - Gw_{t-1}) = -\Delta H\ d - Dw_t + Dw_{t-1} - E_t + Inflow_t$$

$$f(Dw_t - Gw_{t-1}) = -\Delta H\ d - Dw_t + Dw_{t-1} - E_t + Inflow_t$$

$$Dw_t = \frac{-\Delta H\ d + Dw_{t-1} - E_t + Inflow_t + f\ Gw_{t-1}}{f+1} \tag{A9}$$

Where, ΔH is the changes of hydraulic gradient and $Inflow_t$ came from the infiltration and incoming water from other area.

4. Changes of Hydraulic gradient ($\Delta \boldsymbol{H}$)

Changes of hydraulic gradient ($\Delta H = H_t - H_{t-1}$) is the changes in H in Eq 8 over time. Fig. 4A.3 illustrates changes in H over day from the measurement data. This model assumes the hydraulic gradient changes with precipitation. By regressing daily precipitation and daily changes in hydraulic gradient, we obtain the regression line equation to calculate the changes of hydraulic gradient over rainfall for an area with certain land cover type. By making ΔH over rainfall for different type land cover, then we can estimate ΔH for any type of land cover.

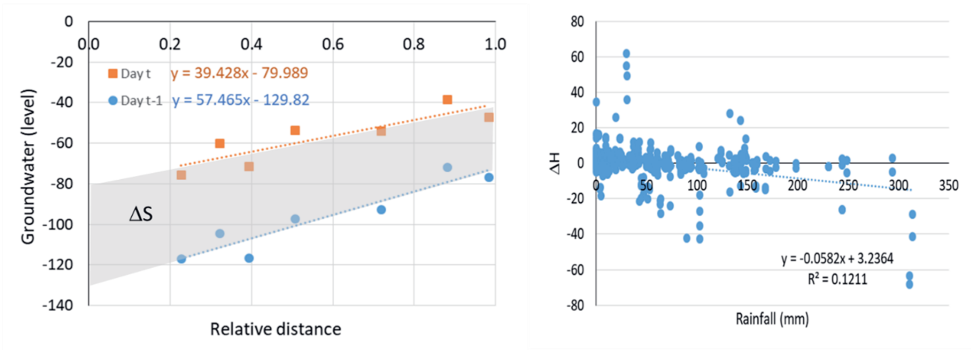


Figure 4A.3. Illustration of H, Dw_t (or $Gw_{(0,t)}$) and ΔH based on Eq. 8 over time and relative distance to canal (Left) and relationship between rainfall and ΔH (Right).

5. Evapotranspiration (E)

Based on Fig. 4 (left), the changes of groundwater level (ΔS) is the area between H_t and H_{t-1} (Eq. A10)

$$\Delta S = 2\frac{\Delta H}{3} + \Delta Dw \quad \text{(A10)}$$

Referring to Eq. 2, with the assumption that no water enters the system, the change in groundwater level because of water outflow as drained water and evapotranspiration (E). The regression between ΔS and daily average rainfall provides the variation in evapotranspiration over daily rainfall. Figure. 4.7 is a regression between daily rainfall and evapotranspiration for different land covers used for the Pawan-Kepulu peatland simulation model. Swamp forest evaporation uses an average between shrub crop and forest.

6. Calculation of f_{High}, f_{Low}, f_{Inf} and f_{Inc}

For each measurement plot, the multiplier values of $f_{Inf}, f_{Inc}, f_{High}$ and f_{Low} are calculated by comparing the predicted and measurement groundwater level. We can use Nash Sutcliffe Efficiency (NSE) or other statistical evaluations to find optimal values for these values which provide the closest calculated groundwater values to the measurements. Next, we regress these values against the distance to the canal (or relative distance to canal) to obtain an equation that can be used to calculate infiltration, incoming water and drained water for various distances to the canal that required for landscape level simulation. Equation A11-A18 is the result of the regression between the values of $f_{Inf}, f_{Inc}, f_{High}$ and f_{Low} with the relative distance to canal from the measurement level plot in the Pawan-Kepulu peatland.

Drained water multiplier above cl (>=-40 cm):

$f_{High} = -0.078\ln(d) + 0.2742$, when the canal does not have blocking (A11)

$f_{High} = -0.103\ln(d) + 0.0346$, when the canal has blocking (A12)

Drained water multiplier below cl (<-40 cm):

$f_{Low} = -0.009\ln(d) + 0.0183$, when the canal does not have blocking (A13)

$f_{Low} = -0.013\ln(d) - 0.0041$, when the canal has blocking (A14)

Infiltration multiplier:

$f_{Inf} = 0.0454\ln(d) + 0.4479$ when the canal does not have blocking (A15)

$f_{Inf} = 0.0407\ln(d) + 0.5354$, when the canal has blocking (A16)

Incoming water multiplier:

$f_{Inc} = 0.0137\ln(d) + 0.646$ when the canal does not have blocking (A17)

$f_{Inc} = -0.028\ln(d) + 2925$, when the canal has blocking (A18)

B. Groundwater level at the landscape level

Groundwater at the landscape level is a combination of all the results of groundwater calculations at plot level that accommodate variations in land cover, distance to canal, and peat depth in the landscape. The simulation steps of groundwater calculation at landscape level are as follows:

1. Using spatial analysis, create a polygon (or raster) containing a combination of variations in land cover, peat depth and distance to closest canal at landscape level.
2. Use the calculation equation at plot level to calculate groundwater from each polygon in the landscape
3. Repeat step number 2 for different rainfall values. To get daily groundwater distribution, you need daily rainfall data and repeat this step as many times as you have daily rainfall data
4. Return the calculation results from all polygons to spatial analysis to obtain groundwater distribution at landscape level.

Simulating a negotiation between multi-stakeholder forum and the local communities to encourage collective actions in the Pawan-Kepulu peatland. .

Debriefing after the game trial with students from the Tanjungpura University, Pontianak, West Kalimantan. We discussed peatland ecosystem and their management.

Chapter 5: The H_2Ours Game to Explore Water Use, Resources and Sustainability: Connecting Issues in Two Landscapes in Indonesia

This chapter is accepted with corrections:

Tanika, L., Sari, R.R., Hakim, A.L., van Noordwijk, M., Peña-Claros, M., Leimona, B., Purwanto, E., and Speelman, E.N., 2024, The H2Ours game to explore Water Use, Resources and Sustainability: connecting issues in two landscapes in Indonesia, *Hydrology and Earth System Sciences*

Abstract

Restoring hydrological functions affected by economic development trajectories faces social and economic challenges. Given that stakeholders often only have a partial understanding of the functioning socio-hydrological systems, it is expected that knowledge sharing among them will help to be better aware of the consequences of the land use choices and ways to manage water. To facilitate the collective learning, a tool is needed that simplifies the social-hydrological system but still accommodates the crucial social and technical aspects. However, data-driven simplification can lead to very site-specific models that are difficult to adopt for different conditions. To address these issues, this study aims to develop a highly adaptable serious game based on process-based understanding to make it easily applicable to any situation and to facilitate co-learning among stakeholders regarding complex socio-hydrological problems. We designed a 'serious' game that revolves around a simple water balance and economic accounting, with environmental and financial consequences for land-users. The game is based on process-based understanding of the system, allowing for both relevant site-specificity and generic replicability. Here, we describe the development of the game and explore its capacity to visualise, discuss and explore Water: Use, Resources and Sustainability ('H_2Ours') issues at the landscape level. The H_2Ours game was designed using a combination of the Actors, Resources, Dynamics and Interaction (ARDI) and Drivers, Pressure, State, Impact, and Responses (DPSIR) frameworks. The design steps for constructing the game led to a generic version, and two localised versions for two different landscapes in Indonesia: a mountain slope to lowland paddy landscape impacting groundwater availability in East Java, and a peatland with drainage-rewetting, oil palm conversion and fire as issues triggering responses in West Kalimantan. Based on an evaluation referring to credibility, salience and legitimacy criteria, the H_2Ours game met its purpose as a tool for knowledge transfer, learning and triggering action. We discuss the steps that can lead to re-designing and adaptation of the game to other landscapes and policy-relevant issues

5.1. Introduction

A recent call for collective action by the Global Commission on the Economics of Water (Mazzucato et al., 2023) asked for a turning of the tide, shifting from exploitation, overuse and waste of freshwater resources to stewardship, wise use and socio-hydrological restoration. To achieve this shift, better understanding is needed of the relations within and between the social and hydrological subsystems of a landscape, and how these relations vary over time and space (D'Odorico et al., 2019). For example, many locations experience hydrological problems due to changes in the use of land and water to meet food production, and other domestic and industrial needs (Djuwansyah, 2018). These uses often affect negatively the ability of water systems to retain their hydrological functions such as the buffering of floods and the gradual release of water in dry periods, which results in an increase in water demand for irrigation (Rosa et al., 2018), leading ultimately to degradation of the water system. Consequently, hydrological restoration aims to re-establish or restore key hydrological functions such as buffering, and to avoid further hydrological degradation by managing water resources sustainably and/or eliminating the causal factors of degradation (Zhao et al., 2016).

Four interacting knowledge-to-action steps are needed for public policy decisions that can achieve soci0-hydrological restoration (van Noordwijk, 2018). These steps are understanding (technical agenda setting based on the social relevance of environmental issues, appreciation of trends and patterns, shared ideas on 'how things work'), commitment to goals (coalitions of social understanding of urgency), operationalisation of means of implementation based on a common but differentiated responsibility (in its socio-ecological context) and innovation for better solutions (through monitoring and learning). Consequently, the first step for any restoration planning is developing a shared understanding of how the above- and below-ground ecosystem structure and the climate generate the hydrological functions and underpin the range of ecosystem services provided (van Noordwijk et al., 2022). Furthermore, the interactions between ecological and technical aspects and socio-economic conditions in a landscape (e.g., land tenure, the existence of regulations and incentive-disincentive mechanisms) make the socio-hydrological systems even more complex. Unfortunately, lacking knowledge transfer between and within different groups of stakeholders often blocks the commitment, operationalisation, and innovation stages of successful restoration (Creed et al., 2018).

Learning leads to gaining new information, knowledge, predictive ability, and ultimately to scenario development and knowledgeable decisions. However, providing information alone is not a catalyst that can trigger the associated knowledge to action chain (Marini et al., 2018). Therefore, 'services' that facilitate active learning and 'experiences' that provide a social context for technical aspects are needed for collective learning beyond knowledge transfer. In the 'learning' literature, there is a consensus that people learn more quickly through experiential learning where they can actively explore, engage with processes and then reflect on what happened during the exploration (Kolb and Kolb, 2005; Fanning and Gaba, 2007; Kolbe et al., 2015). Thus, we need tools that can show how a socio-hydrological system works as a whole and allow people to see and experience the consequences of decisions made, in order to strengthen knowledge sharing and to facilitate collective decision-making. Two tools are being increasingly used in this context: hydrological modelling (Guo et al., 2021; Tsai et al., 2021) and serious gaming (Rossano et al., 2017; Feng et al., 2018; Ferguson et al., 2020). Hydrological modelling focuses on converting data to information, knowledge and understanding of technical aspects, and it is used to simulate various relevant land-use change scenarios and to quantify the likely consequences of various water management practices (Singh and Kumar, 2017). In contrast, serious gaming focuses on relating knowledge and understanding of social and technical aspects to emotions to enhance the credibility and legitimacy of decisions made. The basic elements of gaming are challenges, rewards, experiences, strategies and emotions, to allow stakeholders to safely explore management options (Fleming et al., 2014, 2016).

Although one can see all models as games, and all games as models, these conceptually related tools have developed as separate communities of practice (van Noordwijk et al., 2020). Games are models as they are succinct and often stylised representations of a more complex reality, and models are games as they allow the exploration of alternative strategies. In addition, both approaches require one to break down a complex system into several pieces, which is challenging as not all elements of the real conditions can and should be included in the models and/or games. Several considerations can serve as a guide to the simplification process from reality to model and game simulation (Medema et al., 2019), such as what knowledge we want to share with participants, what we want them to learn, and what changes/responses we expect from them.

Socially interactive games and models that explore larger spatial and temporal horizons have complementary strengths. As reviewed in Villamor et al., (2023), games and models can 1) seek a conceptual triangulation representing the processes behind complex realties, 2) strive for numerical consistency between games and empirical models, 3) use games in the development of scenario models, or 4) use models in the design of games that trigger players to learn by experiencing manageable complexity. As an example of the letter, Lohmann et al. (2014) designed and tested model-based role plays with Namibian land reform beneficiaries, simulating 10 years of rangeland management. In this paper, we explore the feasibility of transforming a hydrological model into a serious game to provide socio-hydrological dynamics to stakeholders with diverse backgrounds to develop restoration plans.

Simplifying the complexity of the system and highlighting the socio-hydrological issues from a hydrological model to a socio-hydrological game will facilitate knowledge transfer among stakeholders and offer a better decision-making tool (Savic et al., 2016). However, such a simplification process can lead to serious games that are very specific to a given local context, making it difficult for the game to be applied to other places. For that reason, the elements and rules of the game should be easily adapted to other locations, or at least there should be guidelines on how the game can be applied elsewhere. Therefore, the objectives of this study are to develop a serious game that is adaptable to different socio-hydrological contexts and issues, and to evaluate the quality of the game in terms of credibility, salience and legitimacy. To achieve our objectives, we developed a generic game with two adaptations to two different locations in Indonesia differing largely in hydrological characteristics. First, we developed the H_2Ours game based on the socio-hydrological characteristics of the Rejoso watershed in East Java. Then, we modified the H_2Ours game according to the conditions of the Pawan-Kepulu peatland, West Kalimantan. The qualities of the game were assessed based on several criteria representing credibility, salience and legitimacy which were included in the game development process and the post-game assessment

We organised the paper by presenting as a method the stages of how we prepared, designed, tested, implemented and evaluated the two variants of the H_2Ours game. The game itself is the primary 'result', illustrated by the game dynamics during test settings and early applications with local stakeholders. Feedback from game participants is presented as an evaluation of the current games. We close by discussing the simplification process from reality to game, effectiveness of the game in achieving the goals set, and the lessons learned.

5.2. Methodology

This study consists of four stages from the diagnosis of the study area to the evaluation of the game (Fig. 5.1). The different stakeholders involved in each stage are also provided.

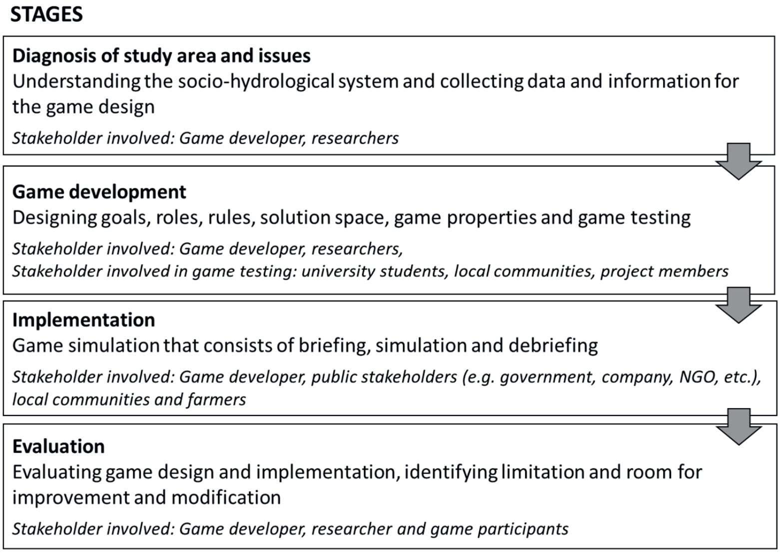


Figure 5.1. Stages undertaken from the preparation to the evaluation of the H_2Ours game, including stakeholder involvement across the different stages of this study.

5.2.1. Study areas

The two study areas used in this research, i.e., the Rejoso watershed and the Pawan-Kepulu peatland (Fig. 5.2), differ in their physical characteristics (hydrological system, land cover, soil type), but they experience similar socio-hydrological problems (lack of coordination and collective action). In the Rejoso watershed, the hydrological restoration was conducted under the '*Rejoso Kita*' project in which World Agroforestry (ICRAF) was responsible for research and development of conservation and restoration strategies, while in the Pawan-Kepulu peatland, the hydrological restoration was conducted by Tropenbos Indonesia through the '*Working Landscape*' project and '*Fires*' project. Both areas have environmental problems because of the disruption of the buffering peak flow that contribute to floods due to lack of infiltration, which in turn is key to the supply of groundwater. To restore those hydrological functions, understanding about the relationship between land-use and (surface-ground) water management and water balance at the landscape level is crucial before developing a joint strategy (IPBES, 2018).

The Rejoso watershed (1600 km^2) is in the Pasuruan district, East Java, Indonesia. Based on the elevation and the hydrological system, we can divide the Rejoso watershed into three areas: downstream (<100 m a.s.l. (meter above sea level), midstream (100-1000 m a.s.l.) and upstream (>1000 m a.s.l.). This watershed is a national priority because the Umbulan spring is used, through a recent pipeline, to supply water to 1.3 million people in the surrounding metropolitan area. Land conversion from agroforestry to intensive agriculture in the recharge areas (>700 m a.s.l. upstream and midstream area) and massive groundwater extraction for rice fields using artesian wells in the downstream area were understood to cause the reduced average discharge of the Umbulan spring, from 5 m^3/s (1980s) to 3.5 m^3/s (2020) (Leimona et al., 2018; Amaruzaman et al., 2018; Toulier, 2019;

Khasanah et al., 2021). As the declining spring discharge is disrupting the water supply for drinking water, agriculture and industries, stakeholders in the Rejoso watershed need to develop strategies to restore the hydrological function of their watershed through land-use management in the recharge area and groundwater utilization in the downstream to maintain the continuity of water supply in the Umbulan spring (Khasanah et al. 2021).

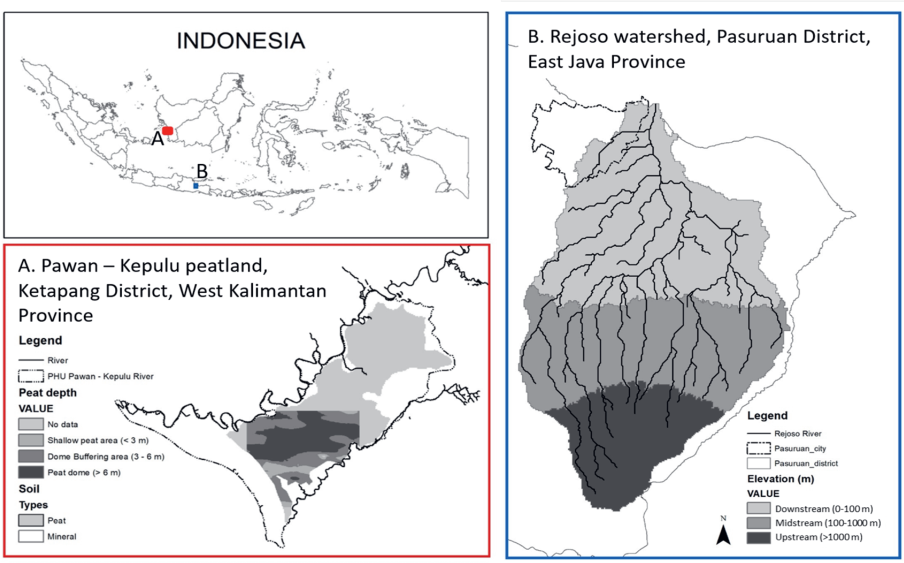


Figure 5.2. The two study areas of this study: A. Rejoso Watershed that consists of upstream (elevation >1000 m above sea level (m a.s.l.)), midstream (elevation 100–1000 m a.s.l.) and downstream (elevation < 100 m a.s.l.), and B. Pawan-Kepulu peatland that consists of peat dome (peat depth > 6 m), peat buffering dome (peat depth 3–6 m) and shallow peat (peat depth <3 m).

The Pawan-Kepulu peatland is in the Ketapang district, West Kalimantan Province, Indonesia (Fig. 5.2A). This peatland is a peat area between the Pawan and Kepulu Rivers, functioning as a unified hydrological system. Based on the mapped peat depth, we divided the Pawan-Kepulu peatland into a relatively shallow peat area (peat depth <3 m), a dome buffering area (peat depth 3–6 m) and a dome (peat depth >6 m). In the 2000s, local communities and oil palm companies started to build canals for artificial drainage to facilitate timber extraction and for facilitating the management of oil palm and other forms of agriculture (Carlson et al., 2012). However, during the dry season, the canals cause a decrease in the groundwater level so that the peatland becomes drier and more vulnerable to fire. Land fires are detrimental to both the local area and the global level with haze and carbon emissions (Widayati et al., 2021). Therefore, there is interest in restoring the hydrological function of peatlands to prevent or reduce land fires (Murdiyarso et al., 2021).

5.2.2. Diagnosis of the study areas and issues

For systems diagnosis and developing the H_2Ours game, the minimum required information composed of: hydrological information (to define boundaries of the hydrological system), hydrological problems and efforts that may control the causes and overcome impacts of the problems, rainfall, potential evapotranspiration, land cover information (typology, main locally relevant types, recent land cover change and life-cycle profitability estimates), and socio-economic information (village conditions, socio-economic issues, alternative livelihood options, institutional conditions). These information were collected using the Rapid Hydrological Appraisal (RHA) approach, which has been used and tested in a number of South-East Asian countries (Jeanes et al., 2006; van Noordwijk et al., 2013). In this approach, the information was grouped based on local ecological knowledge (LEK), public ecological knowledge (PEK) and modeller/scientist ecological knowledge (MEK). Mapping these different knowledge systems showed overlap, gaps and contrasts that provided starting points for further exploration.

To make it easier to describe the interactions between the components of a socio-hydrological system, we structured the socio-hydrological condition of the study area based on the Dynamic, Pressure, State, Impacts and Responses (DPSIR) and Actors, Resources, Dynamic and Interaction (ARDI) frameworks. The DPSIR framework is widely used to carry out hydrological assessments because of its comprehensive connections between various components in a socio-hydrological system (Sun et al., 2016; Lu et al., 2022). We used the DPSIR to trace the causes of problems, including interactions and relationships between social and hydrological components and to further explore various responses to socio-hydrological problems (Sun et al., 2016). The ARDI framework is widely used in companion modelling approaches to guide system diagnosis as a first step towards designing serious games (Etienne et al., 2011). We used the ARDI framework to identify main stakeholders involved in water management, main resources, main processes that affect changes in resources, and the interaction between stakeholders and resources (Villamor et al., 2019).

5.2.3. Game development

In this step, we transformed the information from the DPSIR and ARDI analyses into components needed in the game design: goals, roles, rules, and solution space (Fig. 5.1).

1) Scope and objective

The first stage in designing a serious game is to determine the scope and objective of the game (Silva, 2020; Mitgutsch and Alvarado, 2012). The scope of the game refers to the problem or issues to be addressed. The objective of the game refers to the kinds of knowledge, new insight or impacts are expected to be obtained by players after participating in the game. We determined the scope and the objective of the game based on the socio-hydrological problem defined in the previous stage (Sect. 5.2.2).

2) Roles

According to the ARDI framework (Sect. 5.2.2), we defined the roles based on the main stakeholders involved in water management in each study area. Most of the players were asked to be a villager, representing the largest stakeholder group, but others had specific roles as agents trying to influence villager decisions. Related to these roles, we designed goals that players must achieve during each simulation based on discussions and interviews with the related stakeholders according to their actual goal. Before the game started, we asked each group to choose a leader to facilitate discussion within the internal team and to represent the group when communicating with other groups.

3) Rules

According to the ARDI and DPSIR frameworks (Sect. 5.2.2), we transformed the interaction between actors and resources into the rules of the H_2Ours game. To show the dynamics of changes in resources and the impact of human decisions, the game's rules consist of a set of values attached to each decision's type of land-use and water infrastructure that describe both the economic and the water balance components. The economic component consists of the production costs/capital required to manage a certain land-use type and the income derived from that land-use. The water balance component consists of surface flow and infiltration of each land-use type and water infrastructures.

The values used as rules for the economic component referred to research findings by ICRAF and Tropenbos Indonesia (Sec. 5.2.1). For the water balance component, the Rejoso watershed data were obtained from the hydrological modelling and field measurement (Leimona et al., 2018; Suprayogo et al., 2020), while the Pawan-Kepulu peatland data was based on field measurement (Tanika et. al, manuscript in prep.). Several local communities then validated the values through a process of discussion and game testing (Sect. 2.3.6). We simplified the values for each land-use type as a ratio between land-uses to make the quantification process easier during the simulation process. A simple guideline for developing or modifying rules can be seen in Appendix 5A.

There are two conditions that are used to mark the positions of the participants regarding their goals in the game, namely economic and environmental conditions. We derived the economic conditions based on a simple profit calculation equation, where profit is revenue minus all financial expenses (taxes, cost, incidental cost, etc.). The underlying economic analysis applied a lifecycle perspective to the various land-use systems, annualizing discounted future cost and benefit flows. At the sub-landscape level (e.g., upstream, dome), total profit is the difference between total revenue and total production costs. While the environmental indicators were derived based on a simple water balance model implemented in the Generic River Flow (GenRiver) model (https://www.worldagroforestry.org/output/genriver-generic-river-model-river-flow) (van Noordwijk et al., 2017b). Consequently, the relationship between the two conditions allowed us to describe the socio-hydrological system of each study area.

4) Game solution space analysis

The purpose of the game solution space is to define the envelope of possible outcomes within the rules of the game, considering all possible choices made by players in the game (Speelman et al., 2014). In a random-walk any sequence of steps has equal probability, blind to where it may lead. The solution space of the H_2Ours game was explored based on the average of economic and environmental outcomes obtained with a random generator deciding choices for every step. We mapped the estimated solution space after 3, 10, 30, 100, 300 and 1000 random-walk iterations to obtain a reference for the trajectories observed in a limited number of actual, real-player games. The random-walk conditions were generated in R, then simulated using an Excel spreadsheet representation of the H_2Ours game and its economic and environmental performance indicators. The 1000 random-walk data set was used to assess the probability density function of outcomes within the solution space. The economic and environmental performance indicators of actual game implementation refer to player's land use decisions from four different game sessions in the Rejoso watershed which are calculated using the same Excel spreadsheet.

5) Game properties

The purpose of game development is to bring the game design into a real form that players can play or touch such as a game board, various required tokens, and other attributes that support the simulation of the game. We developed the game to be close to the perceived reality, so that players can relate their decisions with the consequences obtained during the game session with the impacts that they have experienced or will experience with the similar decisions. The game board, the game's land-use options, and water simulation miniature are the key elements of recognition for players. Therefore, we adapted these elements to the conditions of each study area.

6) Game testing

The purpose of game testing is to assess the game's playability and dynamics. We tested the game in two ways: checking all the quantification systems using an Excel spreadsheet and checking the complexity through role-playing testing. In the role-playing testing, we tested the game several times with different participants: members of the project, undergraduate students and non-targeted farmer groups. During the role-playing testing with project members, we checked the suitability and the game elements with the reality; with the students, we calibrated and validated the rules and feedback system in the game; and finally with the farmer groups, we checked whether the rules of the game were sufficiently clear.

5.2.4. Game implementation

In this study, we executed ten game sessions with a total of 93 people participating, with five sessions in each of the study areas. All game sessions in the Rejoso watershed were held in October 2021, while in the Pawan-Kepulu peatland were held in August 2022. In each study area, a first one game session was organised with members of a multi-stakeholder forum consisting of representatives of governments, NGOs, private sectors, and universities to get ideas about regulations and programs that would be offered to farmer communities, and four game sessions were organised with farmer groups to explore the implementation of the regulations and programes resulting from the game session with the multi-stakeholder forum.

For each game session, we invited a total of 9-12 representatives of farmer groups from the upstream, midstream and downstream villages in of the Rejoso watershed, and 12-16 representatives of four villages in the Pawan-Kepulu peatland. In the invitation, we let the group determine who would attend the simulation, provided that the group representatives were willing to hold discussions and exchange information with participants from other villages. For the four sessions with farmer groups, we grouped participants according to different criteria to get a variety of decisions. For the Rejoso watershed, we conducted two sessions with participants who had experience with the recent Payment for Ecosystem Services (PES) program (Leimona et al., 2018) and two sessions with participants from neighbouring villages where the PES program was not active. For the Pawan-Kepulu peatland, we conducted a game session with members of the village forest management unit, a session with members of an active farmer field school, and two sessions with people who are not members of the village forest management unit or the farmer field school. Game sessions took place in a central location in each of the landscapes to allow easy access for all the participants. During the game session, the participants were asked we asked to play the game with the role of a farmers from their location within the landscape.

Each game session required half a day of implementation (briefing, simulation and debriefing), excluding game preparation and participant surveys for further research. We started the session with a briefing of around 10–15 minutes to help participants connect with the game by introducing the environment, setting goals, and clarifying the roles and rules of the game (Rudolph et al., 2014). At the end of playing the game, we did a debriefing of around 30–40 minutes to allow participants to reflect on what they experienced and learned during the game (Crookall, 2023; Kim and Yoo, 2020). To maintain consistency of H_2Ours for different game sessions, we used the game session guideline provided in Appendix 5B.

The game explores the trade-off space between economic and environmental outcomes, with the responses from players during the debriefing adding further insights. The economic and environmental outcomes were calculated based on the average economic and environmental conditions because of decision-making regarding land use combinations during a game simulation over 10 rounds. We present these results together with the results of the solution space analysis to show the position of players' decisions compared to random decision-making. During the debriefing, we asked the participants several questions such as whether they enjoyed the game, what knowledge they gained from the game, how they responded to government regulations of the type included in the game, how they felt seeing other group decisions and (for study case Pawan-Kepulu peatland) their strategies as a member of multi-stakeholder forum.

5.2.5. Game evaluation

The aim of the evaluation stage is to assess the game session process and the quality of the game as the bases for the game's performance to fulfil its objectives. The game session process was evaluated based on game performance criteria in the forms of rules that can be understood, fun and playability over time. While the quality of the game is assessed based on the scientific logic and reliable knowledge used to build the game (credibility), its relevance to societal issues (salience) and its acceptance by its game participants (legitimacy) (Cash et al., 2002; van Voorn et al., 2016). For the effectiveness of the assessment, we followed input-output assessment process, which evaluated the input used in the game during the development process and the output after the game session (Bedwell et al., 2012). We followed the latter approach and carried out the evaluation based on several criteria that refer to credibility, salience, and legitimacy (Table 5C.1 in Appendix 5C), using some criteria developed by Belcher et al. (2016).

Because Belcher's long list of criteria (Belcher et al., 2016) was originally used to assess the quality of the research, for this study we chose several criteria that were relevant to the game quality. Each of these criteria was measured during the game design process and after the game implementation. We measured these criteria by how it was associated with the condition and diagnosis of the study area (Section 5.2.1 and 5.2.2) and game development process (Section 5.2.3). Please see Table 5C.1 for the parameters and sections associated with each criteria. A rapid evaluations were conducted after the game session to assess the process and quality of the game session. We converted those game performace criteria and creadibility, salience and legitimay criteria into Likert used questions and asked all game participants to fill in the survey. In the Likert survey, we used five-point scales (strongly disagree, disagree, neutral, agree, and strongly agree) in six statements to ask the participants about their feelings during the game, their understanding of the rules of the game, the length of the game simulation, new knowledge that they got from the game, and implementation the game to their reality.

5.3. Results

We organised these results side by side between the Rejoso watershed version and the Pawan-Kepulu peatland to make it easier to see the similarities and differences even though the Pawan-Kepulu peatland version of the H_2Ours game was developed after the Rejoso watershed version.

5.3.1. Diagnosis of the study areas and issues

Based on the results from the DPSIR and ARDI analyses, we found that the Rejoso watershed and the Pawan-Kepulu peatland have similarities in the socio-hydrology contexts (Table 5.1). Expectations on better economic conditions led local communities to changes in land cover, and excessive extraction of water resources (groundwater) caused disruption of the water balance. This disruption resulted in local communities and multi-stakeholder forum experience various hydrological problems, such as water shortages (or decreasing the groundwater level) and flooding. However, these two sites are also different regarding their hydrological contexts, such as hydrological boundaries, topography, and water management and interactions between stakeholders and the landscape (Fig. 5.3, Fig. 5D.1). Two proposed solutions (responses) were identified by ICRAF and Tropenbos Indonesia based on their research findings to restore hydrological functions in watersheds and peatlands, namely better land use management and (ground) water management (Table 5.1; component 7-Response).

Table 5.1. Framing problem definition for the Rejoso watershed and Pawan-Kepulu peatland, Indonesia. Problem definition was done the using Driver, Pressure, State, Impact and Response (DPSIR) and Actor, Resource, Dynamic and Interaction (ARDI) frameworks, based on ICRAF and Tropenbos research findings.

	COMPONENTS	REJOSO WATERSHED	PAWAN-KEPULU PEATLAND
1	Hydrological boundary/ landscape	Watershed (and/or groundwater catchment)	Peatland hydrological unit
2	Zone partition	Upstream: elevation >1000 meter above sea level (m a.s.l.) Midstream: elevation 100-1000 m a.s.l. Downstream: elevation <100 m a.s.l.	Dome: peat depth > 6 m Buffering area: peat depth 3-6 m Shallow peat area: peat depth <3 m
3	Driver	To get a better household income and livelihood	
4	Pressure	Land-use conversion to a non-tree-based system in the recharge area (upstream and midstream). Massive artesian well construction for a paddy field (downstream area).	Land-use conversion to oil palm (dome and buffering area). Massive canal construction to drain peatland water.
5	State	Increasing runoff and reducing infiltration (upstream and midstream). Increasing groundwater uptake (downstream).	Increasing water outflow from peatland and decreasing peatland water level. This condition makes peatland become drier during the dry season.
6	Impact	Decreasing groundwater supply in the Umbulan spring. Floods (during the rainy season).	Peat fires (during the dry season) and Floods (during the rainy season).
7	Response	Land-use/cover management Better groundwater management through artesian well management.	Land-use/cover management Better groundwater level through canal blocking management/ distribution.
8	Actors	Multi-stakeholder forum and farmers/local communities	
9	Resources	Money Water balance (especially groundwater and surface water)	Money Water balance (especially groundwater and surface water)
10	Dynamic	Land-use/cover change Water management (artesian well management)	Land-use/cover change Water management (canal blocking management)
11	Interaction	Fig. 5.3	Fig. 5D.1

The interaction between stakeholders and the landscape is represented by the type of decisions regarding their landscape taken by the multi-stakeholder forum and local communities. Local communities (farmer from upstream, midstream, and downstream village in the Rejoso watershed and farmers from neighbouring villages: Village 1-Village 4 in the Pawan-Kepulu peatland) have the authority to make decisions regarding their land which consists of land-use types and water management types (artesian wells in the Rejoso watershed and canal blocking in the Pawan-Kepulu peatland). Multi-stakeholder forums have authority over regulations and programs applied to local communities to achieve their goals. Multi-stakeholder forum can refer to their existing or potential regulation and program.

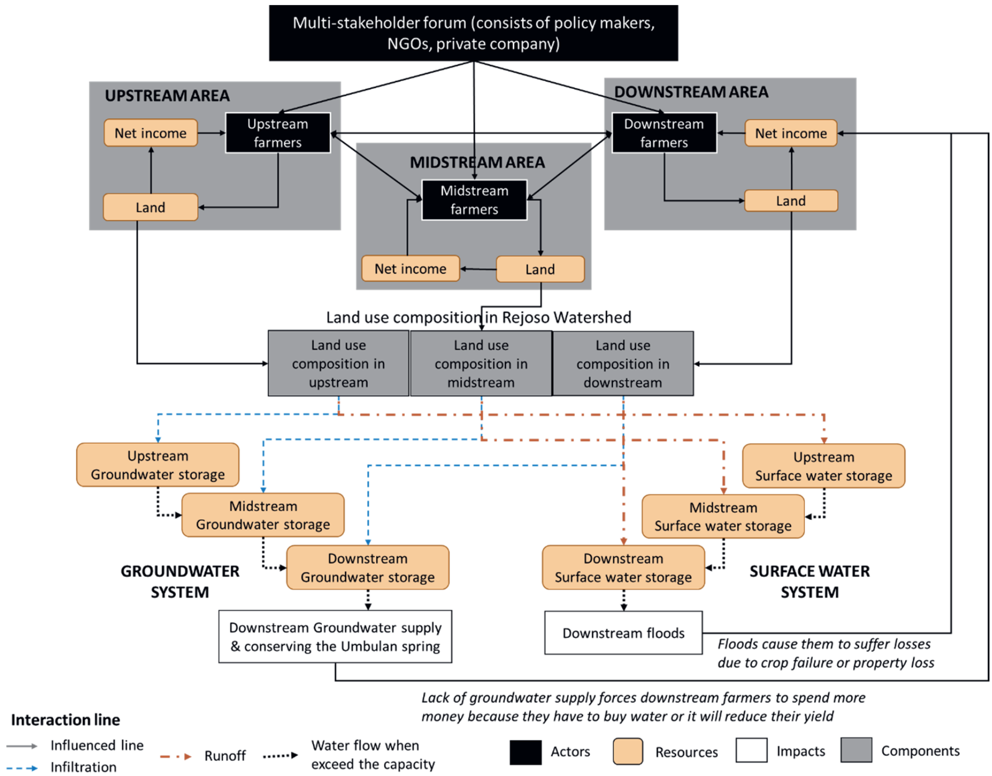


Figure 5.3. Socio-hydrological model for the Rejoso watershed, defined using the ARDI framework. Interactions among actors and between actors to landscape influence land-use composition. The land composition affects the hydrological and economic situation, which influences back to the interactions. A similar socio-hydrological model with some adjustments for Pawan-Kepulu peatland was also developed (Appendix 5D).

5.3.2. Game development: H_2Ours game

1) Scope and objective of the game

As a serious game, the H_2Ours game has the objective of becoming a tool to help sharing knowledge and building collaboration between stakeholders to restore hydrological functions in a landscape. Based on Table 5.1, we determined the goals for H_2Ours game simulation in those two study areas are for knowledge sharing and facilitating collaboration, specifically for groundwater water restoration and flood prevention. However, the H_2Ours game in the Rejoso watershed addressed the supply and utilization of deep groundwater, while in the Pawan-Kepulu peatland it addressed peatland's groundwater as an indicator of the wettability of peatlands and its vulnerability to land fires.

2) Roles

Based on the stakeholder identification survey in the Rejoso watershed and the Pawan-Kepulu peatland, we defined two key roles for this game, namely a multi-stakeholder forum and local (or farmer) communities. The goal of the multi-stakeholder forum is to prevent natural disasters meaning water scarcity and floods in the Rejoso watershed, and fires and floods in the Pawan-Kepulu peatland. In the Rejoso watershed, local communities can be grouped into people who live in the upstream village, midstream village and downstream village based on the village elevation. Meanwhile in the Pawan-Kepulu peatland, local communities can be grouped into four groups of people living in four neighbouring villages (Village 1 – Village 4). Local communities represent landowners. Their goal is to fulfil their household needs (food and taxes). The H_2Ours game brings the various interests of these actors together and shows how they make their decisions regarding the management of land and water resources to meet their economic and environmental expectations.

3) Rules

At the start of the game, players (i.e., multi-stakeholder forum or local communities) received a limited amount of play money. Community members were asked to manage their land to meet their household needs by arranging the land-use type combination and water management in their area with the play money provided, while multi-stakeholder forum was asked to run programs or to help reduce a local community's financial problems. Once players decided on how they would manage their land or community programs, the economic and environmental rules linked to those land-use decisions were applied (see Table 5.2). These rules then defined the dynamics of the economic and environmental conditions (Table 5.2, and Table 5D.1 and 5D.2 for the Pawan-Kepulu peatland).

Table 5.2. Economic and environmental impacts as the rules of the H_2Ours game in the Rejoso Watershed. The variation of environmental components resulting from different land-use options in the upstream and midstream depends on the ability of the land-use options to infiltrate water, while the variation of environmental components downstream depends on the use of water based on farmers' perceptions. The rules of H_2Ours game in the Pawan-Kepulu peatland are in the Appendix 5D. (AF= agroforestry).

Land-use	Production cost (unit money)	Income/year (unit money)		Environment impacts during wet year (ml)			Environment impacts during dry year (ml)		
		Wet year	Dry year	Runoff	Infiltration	Water use	Runoff	Infiltration	Water use
UPSTREAM AND MISTREAM									
All crop	12	25	13	40	0	0	0	0	5
Mixed AF low density	9	17	9	30	10	0	0	0	5
Mixed AF moderate density	6	9	6	20	20	0	0	0	0
Mixed AF high density	3	6	4	10	30	0	0	0	0
All trees	1	0	0	0	40	0	0	0	0
DOWNSTREAM									
Paddy	12	12	25	0	0	10	0	0	15
Maize	9	15	18	0	0	5	0	0	10
Orange	7	11	15	0	0	0	0	0	5
Cucumber	9	15	13	0	0	2.5	0	0	7.5
Banana	5	10	10	0	0	0	0	0	0

When during the rainy season the total surface water in the downstream area of the Rejoso watershed and in the shallow peat of Pawan-Kepulu peatland exceeds its capacity (>800 ml), it caused flooding. When the groundwater exceeds its capacity (>700 ml), the excess water flows to the Umbulan springs in the Rejoso watershed and to the sea in the Pawan-Kepulu peatland. But, when the groundwater was less than <200 ml, it caused water shortages for agriculture in the Rejoso Watershed and made peat soil dry which triggered fires in the Pawan-Kepulu peatland. These environmental impacts decreased the overall community income. As the consequence of this situation, the players might not have enough money to manage their land, buy food or pay taxes in the next round of the game. The multi-stakeholder forums with their limited budget could then choose to help them by providing financial help or making regulations/programs to prevent these environmental problems. Through this gameplay, we aimed to stimulate players to collaborate to achieve their goals. In addition, the economic and environmental conditions are also influenced by the yearly weather (wet year of dry year). In each round, participants decided on land-use without knowing whether the next round would be a 'dry' or 'wet' year (and rounds did not simply alternate).

4) Game solution space analysis

From the comparison results between 3, 10, 30, 100, 300 and 1000 random-walk iterations, we found that the shape and distribution of economic and environmental outcomes began to stabilize at 300 iterations. Therefore, we used 300 games with random conditions as the basis for the solution space of this research. As reference for the player-based game runs, in 300 game runs with a random decision-making process, the groundwater distribution varied depending on the location, while the distribution of surface water in the upstream and midstream is almost the same, and in the downstream is wider (Fig. 5.4A and Fig. 5.4B). Upstream and midstream had almost the same frequency distribution of surface water flows while runoff from the upstream and midstream areas was dominated by wet years, which then may potentially cause flooding downstream in the same year. Contributions of groundwater from upstream and midstream also responded to wet years, but groundwater utilization by downstream occurs mostly during the dry years. Therefore, the frequency distribution of groundwater contributions was wider than those for surface water.

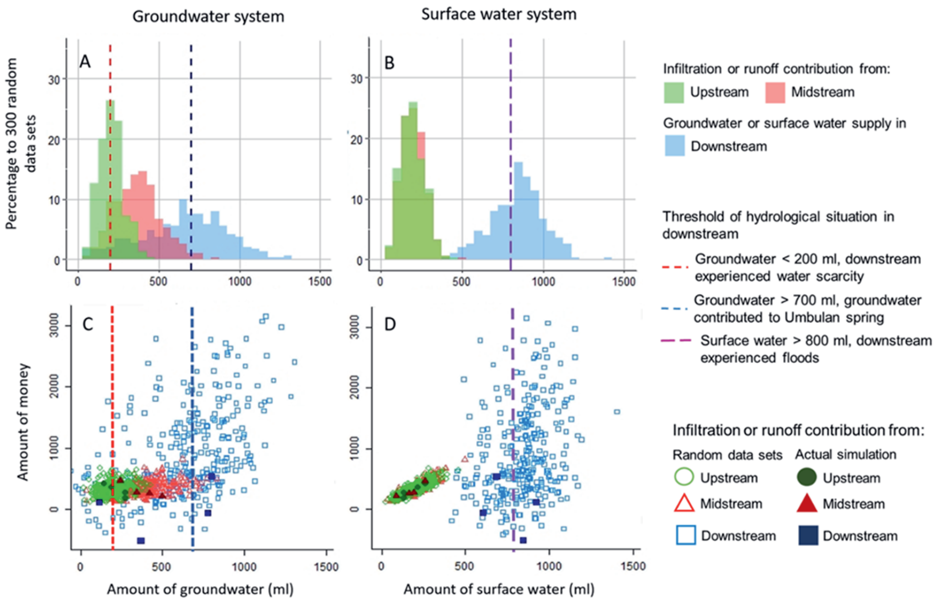


Figure 5.4. Simulation of hydrological and economic situation in H_2Ours game using random value (N = 300) and game actual simulation (obs.) results (N = 4) for the Rejoso watershed. A. Distribution of infiltration contribution from upstream and midstream and groundwater supply in downstream based on simulation with the random value; B. Distribution of runoff contribution from upstream and midstream and surface water accumulation downstream based on simulation with the random value; C. Groundwater situation and economic situation based on random value simulation and actual simulation; D. Runoff situation and economic situation based on random value simulation and actual simulation. Appendix 5E provides a further analysis of the solution space.

Related to the economic outcomes (Fig. 5.4C and Fig. 5.4D), efforts to increase infiltration in the upstream and midstream have not contributed much to increasing the income of the community. However, the efforts of farmers in the upstream and midstream areas to improve their economic conditions resulted in increased runoff, which causes flooding in the downstream areas. Therefore, for the downstream area, the relationship between environmental and economic conditions varies because of the influence of upstream and midstream conditions.

The presence of relationship values between humans and nature and between humans and other humans (relational values) influences decision making regarding natural resource management (van Noordwijk et al., 2023, 2020). Therefore, the decisions made by the players during the game are influenced by various factors (e.g., interactions between players, game settings, level of player ecological knowledge, etc.) (Rodela and Speelman, 2023), whereas random decision making is used to build solution space. For example, when the upstream and midstream groups decided to maintain and improve their economic conditions, they caused a reduction in groundwater supply and increase flooding for downstream area, which caused the downstream group to pay for the losses it experiences. Apart from that, during the game session the facilitator also provided PES scenarios (Appendix 5B, Game Play number 9: repeat step 6 for the rest of the rounds with additional scenarios such as providing payment for ecosystem services). This scenario offers downstream groups to contribute a certain amount of money to maintain more trees in the upstream and midstream. Therefore, the downstream player groups always spend more money than the mid- and upstream player groups either as a loss due to the environmental consequences (floods or water scarcity) or due to their efforts to prevent negative impacts by joining the PES program.

5) Game properties

To make the game engaging, we prepared game materials such as a game board to represent the landscape, land-use tiles according to the existing and future land use types, play money token, and water infrastructures token (Fig. 5.5). We also created water balance miniatures (Fig. 5.6) to demonstrate how surface water flows and leads to floods and water infiltration increases ground water supply. Each round after calculating the economic condition and environmental conditions based on Table 5.2, we asked players to pay production costs, taxes, etc. and get income, incentives, etc. using play money. The water balance was shown using a miniature with real water according to the produced surface water and groundwater.

6) Game testing

From the results of checking the game calculation in Excel, we adjusted the values used in the rules to ensure that these values are sensitive enough to changes in strategy by players, i.e., the initial money given to players, as well as the initial water for groundwater and surface water. The role-playing testing with project members allowed us to validate the game scenarios that would be applied in the game implementation; with the university students, we adjusted the flow of the game, the number of rounds to 8-10 rounds, and the length of simulation time to two hours; and with the local communities (non-targeted participants), we checked the terminology used during the simulation.

5.3.3. Game implementation

The game session with the H_2Ours game takes approximately two hours (excluding briefing and debriefing). For the Rejoso watershed version, the two hours of game session consisted of 10 rounds with 6-12 players divided into 3 groups (or 2-4 people per group) acting as local communities: upstream, midstream, and downstream. The Pawan-Kepulu peatland version, the two hours game session consisted of 8 rounds with 8-16 players divided into 4 groups, and the players werer asked to select their village name as first step of creating ownership. In both versions, an additional group of players consisting of 2-4 people can act as public stakeholders (government, companies, NGOs) and interact with the villages.

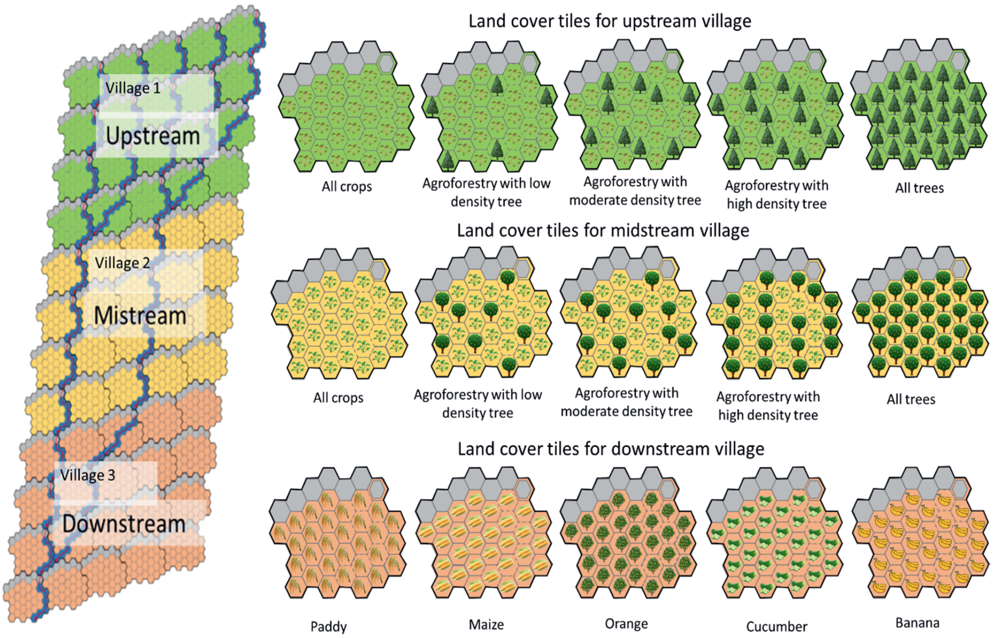


Figure 5.5. Game board and land use/cover tiles of the H_2Ours game in the Rejoso watershed. The land cover options in the upstream and midstream area varies based on their ability to infiltrate water, while in the downstream area varies based on farmer's perception on water utilization. See Appendix 5D for the game materials for the Pawan-Kepulu peatland.

Figure 5.6. Simple water balance model of H_2Ours game in the Rejoso watershed to show the dynamics of changes in hydrological conditions because of land-use change and water utilization. See Appendix 5D for the simple water balance model for the Pawan-Kepulu peatland.

During the game session, players acting as farmers/local communities tried to improve their household income and livelihood, at least to a level that would allow them to manage their household for the next year. The results of the game implementation showed that there was a trade-off between economic and environmental conditions, and among the upstream, midstream and downstream groups (Fig. 5.4, below). In the Rejoso watershed, the efforts of the upstream and midstream communities to improve their economic situation by increasing their crop area brought a negative environmental impact as flooding and water scarcity for downstream communities. The efforts of upstream and midstream communities to reduce these problems resulted in a reduction in their economic outcomes. This situation led to negotiation between those communities. In contrast, the negotiation process in the Pawan-Kepulu peatland was related to the canal blocking construction among villages and between villages with the multi-stakeholder forum. To achieve a closed hydrological system to maintain the wetness of the peatland, the construction of canal blocking must be carried out collectively by all the villages according to the location suggested by the multi-stakeholder forum. The construction of canal blocking reduced the income of farmers/local communities due to decreased yield or increased harvesting costs. Furthermore, the multi-stakeholder forum also persuaded the community by giving them some compensation to protect the peat dome area by maintaining more trees.

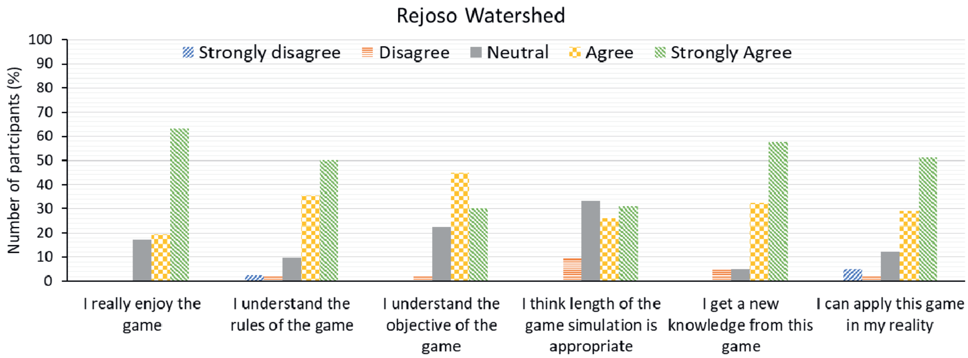
During the debriefing sessions, the participants in the Rejoso watershed and the Pawan-Kepulu peatland mentioned that the game showed that any decision at the plot level impacted hydrological function at the landscape level. They also mentioned that if they had not met their economic needs, the economic conditions became their priority. They also indicated that they would accept any regulation or program from other stakeholders if their income was not reduced significantly. But, if that happened, they hoped for compensation. From the multi-stakeholder forum's perspective, they said that it would be easier if the village knew what they wanted in advance, so that the programs and assistances would be able to match their needs. In addition, regulations should also be complemented by supporting schemes, such as compensation or incentive schemes, not just regulations issued by the government. Further analysis of these different perspectives will be presented in follow-up manuscripts (Tanika et al, in prep).

5.3.4. Game evaluation

After playing the game, the participants of both study areas were asked to fill a survey to assess the credibility, salience and legitimacy (Appendix 5C, Table 5C.1). For the credibility of the game, based on the average of Rejoso watershed and Pawan-Kepulu peatland, the survey shows that 87% of the participants indicated that they understood well and very well the rules of the game, while 78% of participants indicated to know the purpose of the game (Fig. 5.7). For the salience and legitimacy of the game, the survey shows that 92% of the participants gained new understanding and that 87% said that they were able to apply the knowledge that they took away from the game to real life. Besides the credibility, salience and legitimacy criteria, we also asked the participants about their opinion regarding the game session process. From the survey, 87% of the participants enjoyed the simulation and 79% of them feel that the length of simulation time was fair.

5.4. Discussion

To meet the first objective of this paper to develop an adaptable serious game that can represent the socio-hydrological system, we show a generic version of the H_2Ours game as a result of the development and modification process in two different landscapes in Indonesia (Sect. 5.4.1). Then, to assess whether H_2Ours games can facilitate knowledge transfer and knowledge sharing regarding water use and management and supports negotiation and coordination among various stakeholders as the second objective, we evaluated H_2Ours game based on input-output assessment according to evaluation criteria (Sect. 5.4.2).



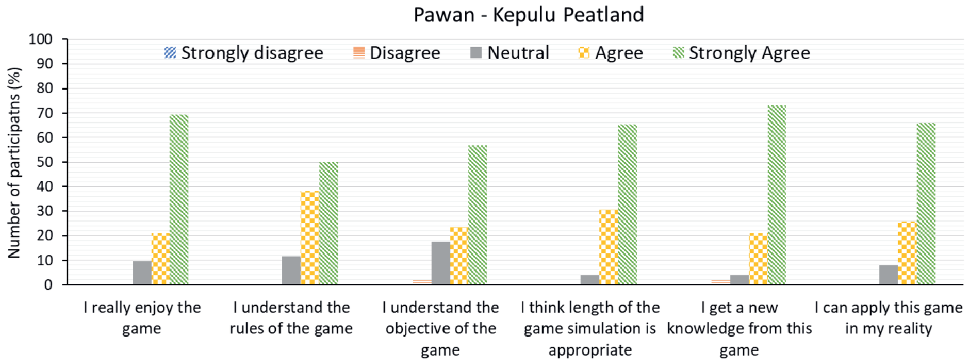


Figure 5.7. Game evaluation from the participants in the Rejoso watershed (N = 41 people) and Pawan-Kepulu peatland (N= 52 people).

5.4.1. The adaptability of the H_2Ours game allows simplifying the complexity of the socio-hydrological systems

The complexity of a system is closely related to the number of interdependent information and interactions between elements in the system (Vidal and Marle, 2008; Rumeser and Emsley, 2019). Models and games simplify this complexity by reducing the amount of information and interactions, only showing the relevant information through the holistic perspective (Strait and Dawson, 2006; Rumeser and Emsley, 2019). In the H_2Ours game, we used the DPSIR and ARDI frameworks to identify interconnections of the components of the complex socio-hydrological system of the Rejoso watershed (Table 5.1, column 3). Then we modified that version of the H_2Ours game based on the socio-hydrological condition of the Pawan-Kepulu peatland and added it to column 4 in Table 5.1. Therefore, these well-established frameworks act as a generic version of the H_2Ours game, which can easily be modified according to other socio-hydrological realities.

The two study sites experience more complex socio-hydrological problems than represented in the H_2Ours game. In our game, the water quantity issues were represented in line with national priority issues in that location, which resulted in groundwater scarcity and floods for the Rejoso watershed (Fig. 5.3) and fire and floods for the Pawan-Kepulu peatland (Fig. 5D.1). In reality, the Rejoso watershed also experience other hydrological problems, such as erosion and landslides in the upstream areas, water quality degradation due to high amount of chemical fertilizer (Amaruzaman et al., 2018; Leimona et al., 2018), while the Pawan-Kepulu peatland also experience land degradation and water contamination because of mining in the upper area of peatland (Widayati et al., 2021). The complexity in a socio-hydrological system is formed due to many relationships and interconnection of the various components (aggregate complexity), and therefore self-organization through gradual learning is the key to a better transformation (Manson, 2001). If all the real life problems are included at once in the game, the risk of confusing people, especially those without a technical educational background (Gomes et al., 2018), which would preclude their understanding of the causes and effects of the problem. Therefore, by unravelling each individual problem and showing its causes and associated-impact, players were able to expand their understanding gradually. We believe that the generic H_2Ours game creates the opportunity to explore different problems, allowing the players to gain a deeper understanding and start building connections among various problems. In this way, it is possible to create opportunities to build overall socio-hydrological understanding in the future.

By comparing the H_2Ours game in the two study areas, we found that there were game elements that remained the same while others had to be adjusted to the local situation. Game elements related to the interaction among humans or between humans and the environment (relational value) are similar in the two study areas (e.g., land-use management to maximize profits, effort scenarios to restore hydrological functions, the need for coordination and negotiation among stakeholders). As such these elements maintained the same between the locations (Driver and Pressure in Table 5.1). However, the environmental response to the drivers and pressure requires technical adjustments (State and Impact in Table 5.1) to local conditions (e.g., hydrological boundaries, land-use types and composition, water infrastructures, hydrological systems). Therefore, our generic H_2Ours game (defined using the components of Table 5.1) showed to be easy to adapt to other problems or other locations. In addition, it is expected to overcome the complexity of a system as we can choose the most important and most influential socio-hydrological problems that want to be addressed.

5.4.2. Game evaluation and lessons learned

During the game design, we evaluated the H_2Ours game using the input-output assessment process (Bedwell et al., 2012). Here, credibility, salience and legitimacy were assessed throughout the different stages of the H_2Ours game development (Fig. 5.1). During the game development of the Rejoso watershed, we accommodated the credibility of the H_2Ours game by relying on the biophysical and hydrological research, including hydrological modelling through the GenRiver model (Suprayogo et al., 2020; Leimona et al., 2018), while the Pawan-Kepulu peatland is based on the biophysical measurement and hydrological modelling (Tanika et. al, manuscript in prep.). For the salience and legitimacy, we relied on the results of participatory research done involving various stakeholders in the Rejoso watershed and the Pawan-Kepulu peatland (Widayati et al., 2021; Amaruzaman et al., 2018; Leimona et al., 2018). By considering the criteria of credibility, salience and legitimacy since the data and information collection, it was easier for the H_2Ours game to fulfil these criteria during the evaluation after the simulation.

We limit the evaluation in this study only to the quality of the game as a product. As a serious game, the H_2Ours carries certain goals that it wants to fulfil (Rodela et al., 2019), namely as a tool that can facilitate the transfer and sharing of knowledge from its players to support the coordination and negotiation process (Section 5.3.2 number 1). Evaluating the game in fulfilling its objectives is more complicated than evaluating the game session process. Ideally, the evaluation of the game in achieving its objective can be evaluated after several simulations at various levels of simulation, and should be conducted before, during and after the game sessions (Oprins et al., 2015). The evaluation of the game in meeting the objective will be carried out in the next manuscript by providing evidence of changes in participant's perceptions

As hydrological problems are usually complex and fundamental, any potential solution requires ample time for integrated planning, and requires all relevant stakeholders to understand the dynamics of the system on a large scale (Medema et al., 2019). The H_2Ours game tries to present simple representation of the landscape so that it makes it easier for players to be aware of the conditions of neighbouring players and to gain a system-level perspective of socio-hydrological issues. Improving player knowledge by looking at socio-hydrological problems in a broader context encourages responsible behaviour towards the environment which is directly proportional to commitment (Keles et al., 2023). The evaluation of the game after the simulation (Fig. 5.7) indicated that most of the participants gained new knowledge from the game which they could apply to real life. Transparency of the rules of the H_2Ours game allowed the players to see the interdependent connections between elements in the complex socio-hydrological system more clearly and made it easier for the players to explore various possibilities and to gain lessons from the reflection results (Kolbe et al., 2015; Kolb and Kolb, 2005; Fanning and Gaba, 2007). During the game session, after the players began to understand how the H_2Ours game worked, the players started to initiate communication in the form of negotiations or coordination between groups or with external parties such as multi-stakeholder forum. This is in accordance with the four interacting knowledge to action steps in restoration strategies, where commitment begins after mutual understanding has been made (van Noordwijk, 2018). One of the advantages of a serious game is that participants interact directly with the environment and get feedback as quickly as possible so that they can immediately analyse and correct unsuitable strategies (Bartolome et al., 2011; Feng et al., 2018). Moreover, during the H_2Ours simulation, players were also faced with the game situation that resemble actual situation, so they are indirectly encouraged to find possible solutions together as two last parts of restoration strategies related to operationalization and innovation.

There are several lessons learned from the H_2Ours game development and simulation process in this study. First, setting up the game material with attributes of the local context helped participants to build emotions during the simulation. Second, to maintain participant commitments on restoration after the game simulation, it is important to show that their collaborative and collective actions really work in achieving their goals in the end of the game simulation. Third, based on the evaluation and debriefing results, even if they stated they can apply the ideal collaborative actions that were explored in the game session, in real life, the enabling conditions needed to support this still required to be built (e.g., regulation, integrated planning strategies, etc.). As the game is a simplification of the real-life system, forms of collaborative action can be discussed directly by the players. In real life, the parties that are needed for successful collaboration may not easily meet each other to discuss issues openly. Therefore, it is necessary to create a condition where stakeholders can meet and explore collaboration options to jointly address issues and achieve goals. Without such encounters, the commitment referred to in the four knowledge-to-action chains cannot be attained.

The H_2Ours game clearly shows the trade-off between the economy and the environment by calculating economic and environmental performance indicators in each round after the players changed the land use combination and water management. As a result, the relational values between humans and human with nature (e.g., trees and water being inherited from their predecessors and will be a legacy for their descendants, the use of certain woods in religious rituals) sometimes becomeblurred. A very clear trade-off between the economic and environmental conditions has led players to make decisions based solely on economic value. Therefore, the cost-benefit calculation of conservation activities needs to be done carefully in this game or include social values as part of the scenario in the game.

In this research, we invited participants from the upstream, midstream, and downstream to play from the perspective of their location in the landscape. We expect that this impacted how the game was played. We intend exploring the impacts of role-switching by asking farmers to play the role of a farmer in another location in the landscape.

5.5. Conclusion

The generic version of the H_2Ours game allows for the exploration of the complexity of a socio-hydrological system. The game can easily be modified according to different needs and conditions. The complexity of the socio-hydrological system can be applied separately and/or simultaneously depending on the knowledge level of the intended participants. With an adaptable game as the one developed, the game designer can adjust the level of complexity included in the game, and even include an advanced simulation that combines all possible problems and interactions found in a socio-hydrological system.

The H_2Ours game can facilitate transfer and share knowledge and triggers collaborative actions by simplifying in time and space. The H_2Ours game saves time because the transparency of the rules allows players to see that the restoration target is something that can be achieved in the future with a clearer perspective by exploring various strategies and scenarios during the game sessions. Space simplification allows the players to see the entire landscape and the relationships between components that influence each other. In addition, they can also inventory the various enabling conditions needed to make the strategies in the game can be implemented in real terms (e.g., the need of for multi-stakeholder collaboration, restoration master plan).

5.6. Acknowledgments

We appreciate the valuable input from colleagues of World Agroforestry (ICRAF) and Tropenbos Indonesia during the H_2Ours game development and game implementation. We would like to express our deep gratitude to students of the Merdeka University, Pasuruan, East Java and Tanjung Pura University, Pontianak, West Kalimantan, and Brawijaya University, Malang, East Java, who have participated in H_2Ours game testing. This study was funded by Tropenbos Indonesia as part of the Working landscape and fires project, ICRAF as part of the Rejoso Kita project and INREF as part of the SESAM project.

5.7. Supplementary Material

Appendix 5A. H_2Ours rule development

One of the challenges in developing or modifying the H_2Ours game is to provide values for the economic and environmental impact components for each type of land-use. Here is a simple guide to modifying the H_2Ours game rules:

1. Determine the types of land-use in the landscape. If the land-use types are varied enough, take the 4-6 most dominant land covers, including the new land-use types that might be intervened in.
2. For each type of land-use, determined the amount of the economic value (production costs and income) and environmental value (runoff, infiltration, water use/utilization). The value used as a rule does not have to be the actual value. You can only use the ratio value between land-use types after setting up the maximum and minimum value. A simple method to collect this information is by conducting survey to several farmers and ask them to rank or make score the land-use type based on their economic and environmental impacts (Fig. 5A.1).
3. Determine infrastructures that will be used in games that might affect economic and environmental conditions (e.g., artesian wells for irrigation, canal blocking, water storage, etc.).
4. Determine how each of these infrastructures affects economic and environmental conditions (e.g., artesian wells: construction cost, threat, amount of groundwater extraction, etc.). You can conduct a survey to collect that information, then normalize the value following the economic and environmental value.
5. During the game testing, evaluate those values with the participant whether it is reasonable and represents their actual condition

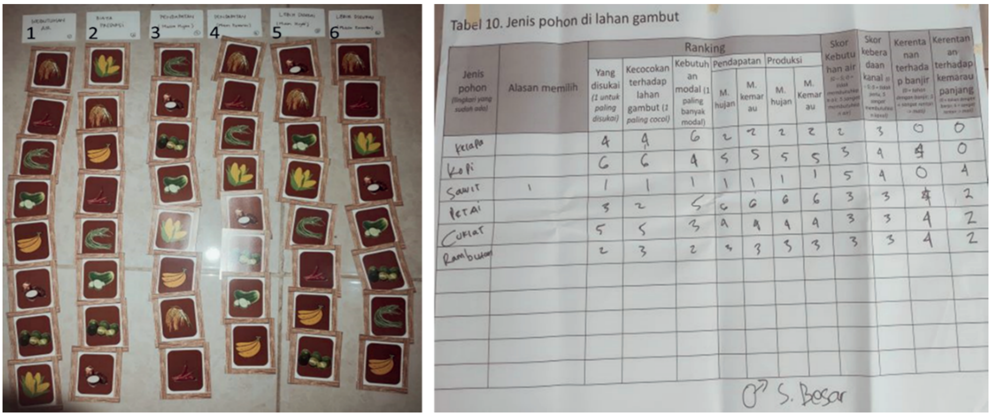


Figure 5A.1. Left: an example of the results of sorting the types of land-use in the Rejoso watershed by one of the local farmers, respectively: 1. Water use, 2. production cost, 3. income during wet season, 4. income during dry season, 5. preferences during wet season and 6. preferences during dry season. For the water balance component, we derived from hydrological model parameterization. Right: example results of scoring of land-use type during focus group discussion with some farmers in the Pawan-Kepulu peatland to collect information about preferences, suitable to peat soil, production cost, income during wet and dry season, yield during wet and dry season, water use, and dependence on the present of canal, vulnerability rate to floods, and vulnerability rate to drought.

Appendix 5B. Guideline for facilitating H_2Ours game

Overview	Simulation of the impact of land-use/cover change and water management on hydrological situation (water balance)
Objective	Knowledge sharing and decision making to support collaborative and collective actions among stakeholders
Benefits	Players can explore many scenarios of land-use/cover and water management and see its impact to their hydrological situation Players can feel the trade-off between economic and environment and explore the solutions Players can learn about negotiation and collaboration
Duration	2 hours (or around 8 – 10 rounds)
Number of players	6 – 16 players
Material	Board of the game Land-use tokens Money tokens Mini water balance simulation model Water infrastructure token (optional)

Game play

1. Welcoming all the players and give a general introduction about the workshop and game/simulation
2. Selecting 2-3 people from players to act as public stakeholders whose role is responsible for the management of the whole watershed or peatlands by providing regulations or programs to prevent various environmental problems (optional)
3. Grouping the remaining the players into 3 groups (for watershed version) or 4 groups (for peatland version) to represent the farmers from different villages. During the game simulation, their goals are to live happily by fulfilling their needs.
4. Briefing players by giving explanations/definitions about the terminology that is often used in the game and building connection between the game properties with their actual situation so the decision made by the players can be very close to their reality.
5. Introducing co-facilitator for each group who help calculation of economic resources (optional)
6. Giving initial money to players (300 – 450 per group) and initial groundwater and surface water into the water balance simulation model
7. Starting round by asking player to decide their land-use system, then calculation of the economic and environmental impact based on the (random) weather situation in that round
8. Repeat step 6 for round 2 and 3 as the warming up
9. Repeat step 6 for the rest of the rounds with additional scenarios, such as announcing regulation by government, providing payment for ecosystem program, etc. You can develop the scenarios based on the stakeholder perceptions of what they should do to restore the hydrological function through discussion or interview.
10. Debriefing session, by asking the player their strategies to achieve their goal and their feeling during the game simulation

Appendix 5C. Criteria of Credibility, Salience and Legitimacy

In this study, we refer to the criteria of credibility, salience and legitimacy by Belcher et al. (Belcher et al., 2016) in the development and evaluation process of the H_2Ours game. Table 5C.1 shows the criteria that we consider most relevant to represent the objective of the H_2Ours game to facilitate the transfer and sharing knowledge to support negotiation and collaboration among stakeholders. To use these criteria, we adjusted the definition of each criterion from the original definition (column 3) to a definition that meets the objectives of H_2Ours (Column 4). Then, how we include each criterion in the development and evaluation process of the H_2Ours game is shown in columns 5 and 6.

Table 5C.1: Criteria used to measure the credibility, salience and legitimacy of the H_2Ours game (adapted from Belcher et al. (2016). The criteria included were used to assess effectiveness in sharing understanding and encouraging collaboration for H_2Ours game development and simulation.

No	Criteria	Original definition according to (Belcher et al., 2016)	Adjustment of to meet the objective of H_2Ours game	How to include the criteria during the game design	Evaluation after game implementation
CREDIBILITY					
1	Clear problem definition	The research problem is clearly defined, researchable, grounded In the academic literature and relevant to the context	The issues handled in the H_2Ours game are relevant to the actual situation	In diagnosis of the study area and issues using ARDI and DPSIR (Sect. 5.2.2)	Likert question: the possibility to apply the knowledge from the game in the reality
2	Clear objective	Research objectives are clearly stated	The objective of the H_2Ours game is clearly stated	In scope and objective (Sect. 5.2.3. number 1)	Likert question: understanding the objective of the game
3	Suitable methods	Methods are fit to purpose and well-suited to answering the research questions and achieving the objectives.	Methods used are scientifically proven	The data and method used scientifically proven with some publications (Sect. 5.2.1 and Sect. 5.2.2)	There was no evaluation for this criterion after the game because we used scientifically proven method
4	Clearly presented argument	The movement from analysis through interpretation to conclusions is transparently and logically described. Sufficient evidence is provided to clearly demonstrate the relationship between evidence and conclusions	The rules, dynamics, and interactions in the H_2Ours game built based on logical interpretation supported by scientific data and methods	Component interaction analysis based on ARDI and DPSIR (Sect. 5.2.2 and Sec. 5.2.3)	Likert question: Understanding the rules of the game
SALIENCE/RELEVANCE					
5	Socially relevant research problem	Research problem is relevant to the problem context	The problems/issues raised in the H_2Ours game are in accordance with the issues/problems in actual conditions	The information used based on participatory approach (referring some publication in Sect. 5.2.1)	Likert question: The possibility to apply the knowledge from the game in the reality

6	Engagement with problem context	Researchers demonstrate appropriate breadth and depth of understanding of and sufficient interaction with the problem context	The H_2Ours game is built by demonstrating the interaction of various elements (physical and social, interaction between stakeholders) that are shown in actual conditions.	Problem analysis based on DPSIR (Sect. 5.2.2)	Likert question: The possibility to apply the knowledge from the game in the reality
7	Explicit theory of change	The research explicitly identifies its main intended outcomes and how they are intended/expected to be realized and to contribute to longer-term outcomes and/or impacts	H_2Ours game was built explicitly to facilitate knowledge sharing and knowledge transfer to trigger collaborative action among various stakeholders	Set the purpose of the game in the game development proses (Sect. 5.2.3. number 1)	Likert question: Gaining new knowledge from the game simulation
8	Relevant research objective and design	The research objectives and design are relevant, timely, and appropriate to the problem context, including attention to stakeholder needs and values	The objectives and design of the H_2Ours game are relevant to the problem context, including considering what the stakeholder needs and values	Based on ARDI and DPSIR analysis (Sect. 5.2.2 and 5.2.3)	Likert survey: understanding the objective of the game the possibility to apply the knowledge from the game in the reality
9	Appro-priate project implementation	Research execution is suitable to the problem context and the socially relevant research objectives	The solutions in the H_2Ours game is generated based on activities that can be implemented in the actual condition	The solutions based on the multidisciplinary research (Sect. 5.2.1)	Likert question: the possibility to apply the knowledge from the game in the reality
LEGITIMACY					
10	Effective collaboration	Appropriate processes are in place to ensure effective collaboration (e.g., clear and explicit roles and responsibility agreed upon, transparent and appropriate decision-making structures)	The H_2Ours game shows transparency of rules, responsibilities, decision-making between game participants, so the players can build collaboration between them	Simple game rules based on actual condition to facilitate participant game understanding (Sect. 5.2.3)	Using before and after survey using q-methodology to identify the change in stakeholder perception
11	Genuine and explicit inclusion	Inclusion of diverse actors in the research process is clearly defined. Representation of actors' perspectives, values, and unique contexts is ensured through adequate planning, explicit agreements, Communal reflection, and reflexivity.	Involvement of various stakeholders during the process of H_2Ours game preparation, design, implementation, and evaluation to accommodate various perspectives, knowledge, values, interests of stakeholders	Involvement of various stakeholders in this study (Fig. 5.1)	Likert survey: the possibility to apply the knowledge from the game in the reality

Appendix 5D. H_2Ours game for peatland version (case study Pawan-Kepulu peatland)

Based on some references, focus ground discussion and interview with various stakeholders in Pawan-Kepulu peatland, we found that this area experiences land and forest fires during the dry year (season) and flood during the wet year (season). Land cover conversion from forest to oil palm plantation and crop season has led massive canal construction to get better production. This situation makes this landscape drier during the dry year and vulnerable to fires.

The hydrological boundary of peatland is a Peatland Hydrological Unit (PHU) as an area between two rivers. Usually in this landscape, there is a peat dome (the deepest peat area), an area surrounding the peart dome (i.e., buffering dome area) and an area with shallow peat. Villages are spread over the peat dome and the buffer zone with villages having different proportions of peat dome and buffer zone areas. However, for simplification, peat depth (including that of the peat domes) was distributed evenly between villages (Figure 5D.1). However, for future game adaptations, the peat depth distributions in each village can be adjusted on the game board.

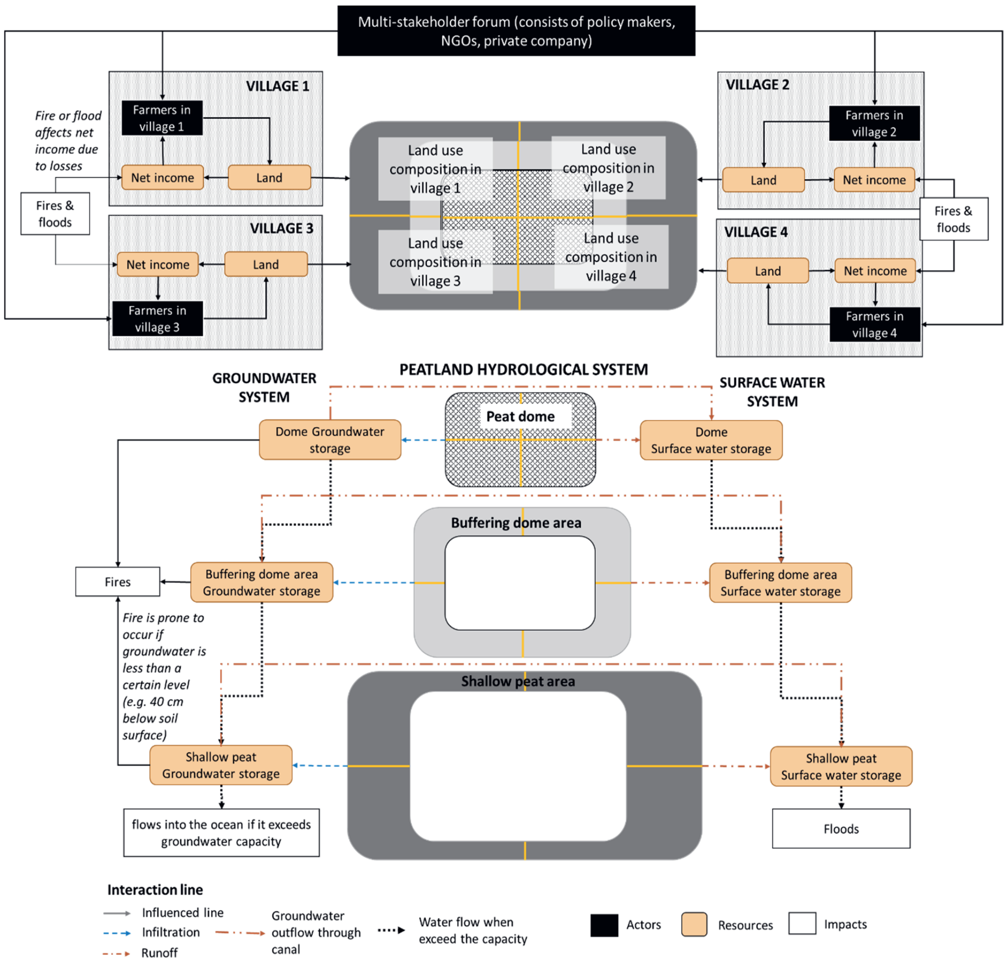


Figure 5D.1. Socio-hydrological model defined using the ARDI framework that was used to design the H_2Ours game for Pawan-Kepulu peatland. Interaction among actors and between actors to landscape influence land-use composition which affect the hydrological and economic situation, then its influences back to interaction.

Rules of game

Based on measurement data, focus group discussion with local farmers and some references, we design the rules of the H_2Ours game for peatland version by combining six land-use options (all trees, all oil palm, oil palm + trees, oil palm + crop, all crop, and shrub/burned area) and three canal density options (without canal, low- and high-density canal) (Table D1 and D2).

Table 5D.1. Economic impacts of the Pawan-Kepulu peatland version, the production cost in dome area +2/plot and in the buffering dome area +1/plot.

Land-use options	Canal density options	Production cost/year in the shallow peat area (unit: money)	Income/year (unit: money)	
			Wet Year	Dry year
All tree	Without	1	0	3
	Low	1	0	3
	High	1	0	3
All Oil palm	Without	6	6	9
	Low	9	9	17
	High	12	17	25
Oil palm + trees	Without	3	4	6
	Low	4	6	9
	High	6	9	17
Oil palm + seasonal crop	Without	5	4	8
	Low	7	7	15
	High	10	12	20
Crop	Without	4	3	7
	Low	5	5	13
	High	8	7	15
Shrub	Without	0	0	0
	Low	0	0	0
	High	0	0	0

Game Properties

The component of the H_2Ours game for peatland version is similar with watershed version with modification in the board as the landscape and the land-use options (Fig. 5D.2). The board is designed in such a way that it resembles a PHU with a dome in the middle, a buffering area around the dome and shallow peat on the outside. In the real simulation, we can add river and road to help player have a connection with their real situation.

Similar with the Rejoso watershed, the H_2Ours game for peatlands also has the same water balance miniature (Fig. 5D.3). This water balance model follows the hydrological system in Fig. 5D.1. In the groundwater system, each tank has a fire vulnerable threshold. This threshold represents 40 cm below soil surface in its actual condition as stipulated by government regulations. If the groundwater in each zone is below this limit, then the area has the potential for fires which causes harm to the local community.

Table 5D.2. Environmental impacts of the Pawan-Kepulu peatland version, we assumed during the dry year there is no runoff or infiltration (a = dome area, b = buffering dome area, c = shallow peat area, x = runoff (unit: ml), y = infiltration (unit: ml) and z = groundwater out flow through canal (unit: ml)).

Land-use	Canal density	Dry year			Wet Year								
		a	b	c	a			b			c		
			z		x	y	z	x	y	z	x	y	z
All tree	Without	0	0	0	0	20	0	2.5	17.5	0	5	15	0
	Low	7.5	5	2.5	2.5	17.5	10	5	15	7.5	7.5	12.5	5
	High	15	10	5	5	15	20	7.5	12.5	15	10	10	10
All Oil palm	Without	0	0	0	10	7.5	0	12.5	5	0	15	5	0
	Low	7.5	5	2.5	12.5	5	10	15	2.5	7.5	17.5	2.5	5
	High	15	10	5	15	2.5	20	17.5	1	15	17.5	1	10
Oil palm + trees	Without	0	0	0	5	15	0	7.5	12.5	0	10	10	0
	Low	7.5	5	2.5	7.5	12.5	10	10	10	7.5	12.5	7.5	5
	High	15	10	5	10	10	20	12.5	7.5	15	15	5	10
Oil palm + seasonal crop	Without	0	0	0	15	2.5	0	17.5	1	0	17.5	1	0
	Low	7.5	5	2.5	17.5	1	10	19	1	7.5	19	1	5
	High	15	10	5	17.5	1	20	19	1	15	19	1	10
Crop	Without	0	0	0	19	1	0	19	1	0	19	1	0
	Low	7.5	5	2.5	19	1	10	19	1	7.5	19	1	5
	High	15	10	5	19	1	20	19	1	15	19	1	10
Shrub	Without	0	0	0	20	0	0	20	0	0	20	0	0
	Low	7.5	5	2.5	20	0	10	20	0	7.5	20	0	5
	High	15	10	5	20	0	20	20	0	15	20	0	10

Figure 5D.3. Simple water balance model of H_2Ours game in Pawan-Kepulu peatland to show the dynamics of changes in hydrological conditions because of the changes in land-use and canal density. The red line in each tank in the groundwater system represent the fire vulnerable threshold.

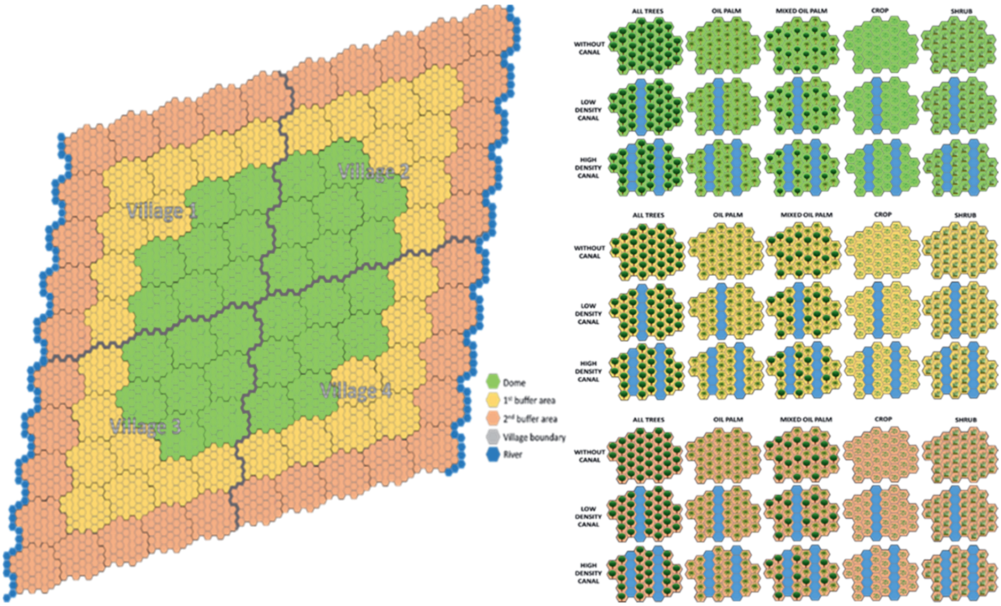


Figure 5D.2. Board of H_2Ours game for peatland version that consist of dome area, buffering dome area and shallow peat area (left); and land-use option (all trees, all oil palm, oilpalm+trees, all crop and shrub) with various canal density (without canal low canal density and high canal density) for Pawan-Kepulu peatland area (right).

In addition to the H_2Ours game for the peatland version, there is a peat infrastructure token in the form of canal blocking and fire fighters (Fig. 5D.4). In the reality, the canal blocking blocks the canal to reduce/stop the groundwater outflow. In this game simulation the canal blocking changes the land-use from high to low density canal or from low to without canal. The firefighter helps to prevent plot from fires during the dry year/season. However, providing canal blockings and firefighters cost some money.

Figure 5D.4. Additional token as canal blocking (left) and firefighters (right) for H_2Ours game.

Appendix 5E. Solution space of H₂Ours game in the Rejoso watershed

The rules of the game determine the possible outcomes or 'solution space', within which the specific choices made by game participants are located. If all choices would be random (equal probability of all choices available), without response to the outcomes so far, a substantial variation in outcomes is possible. The primary outcomes of interest are the surface water flows (rainfall not used as canopy interception evaporation or infiltration into the soil), and the groundwater flows (water infiltrating and not used for subsequent evapotranspiration), all depending on both land cover and rainfall.

A first question in defining this solution space is the number of random series that need to be evaluated to accurately estimate the frequency distributions of outcomes in various response parameters. We present data for 3, 10, 30, 100, 300 and 1000 iterations (Fig. 5E.1 – 5E.4) (each including 10 rounds and three zones, thus 30 land-use choices and 10 weather conditions (dry or wet)). The actual game simulation was only done 4 times; therefore, the closest solution space is with 3 or 10 random values, which is have not sufficiently representative the distribution. Based on Fig. 5E.1 and 5E.2, the solution space distribution pattern starts to appear in 30 random data sets. Therefore, to see the actual distribution of the farmer's decision making, at least we need 30 game simulations. Figure 5E.3 and 5E.4 show the relationship between economic conditions (money) and environment (groundwater and surface water) in the downstream area is more scatter compared to upstream and midstream. However, related to groundwater supply in downstream (Fig. 5E.3), the more groundwater supply, and the higher the economic benefits obtained. On the contrary, the more runoff obtained from upstream and midstream (Fig. 5E.4), it will decrease their economic benefits.

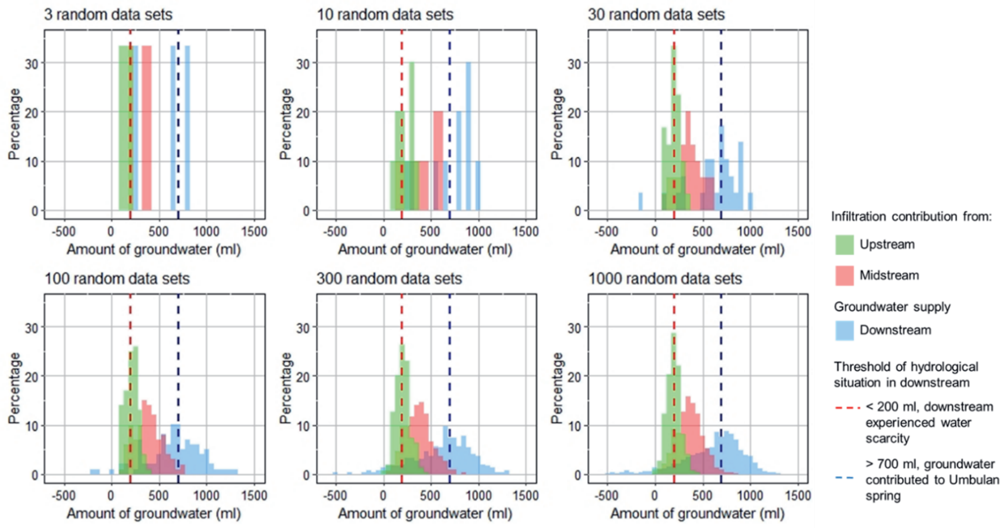


Figure 5E.1. Distribution of infiltration contribution from upstream and midstream and groundwater supply in downstream based on simulation with the random value.

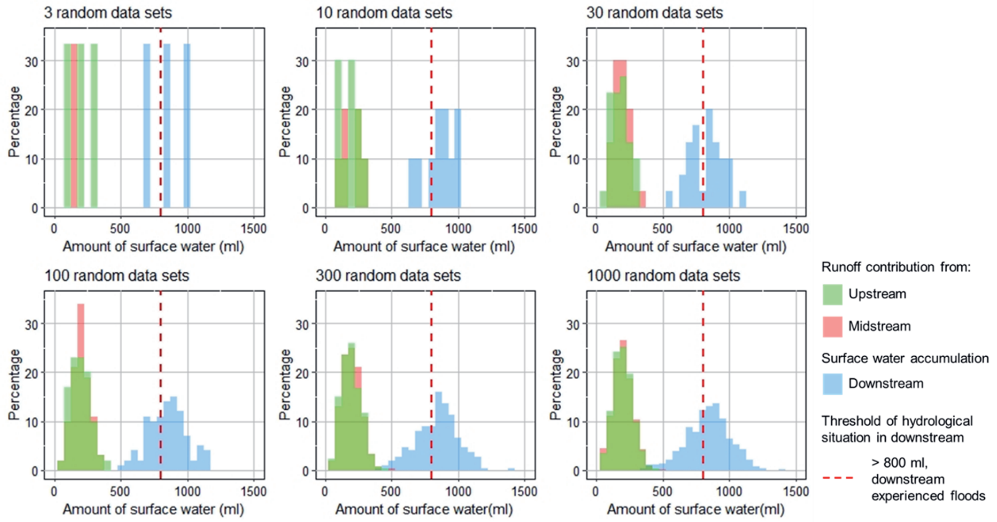


Figure 5E.2. Distribution of runoff contribution from upstream and midstream and surface water accumulation in downstream based on simulation with the random value.

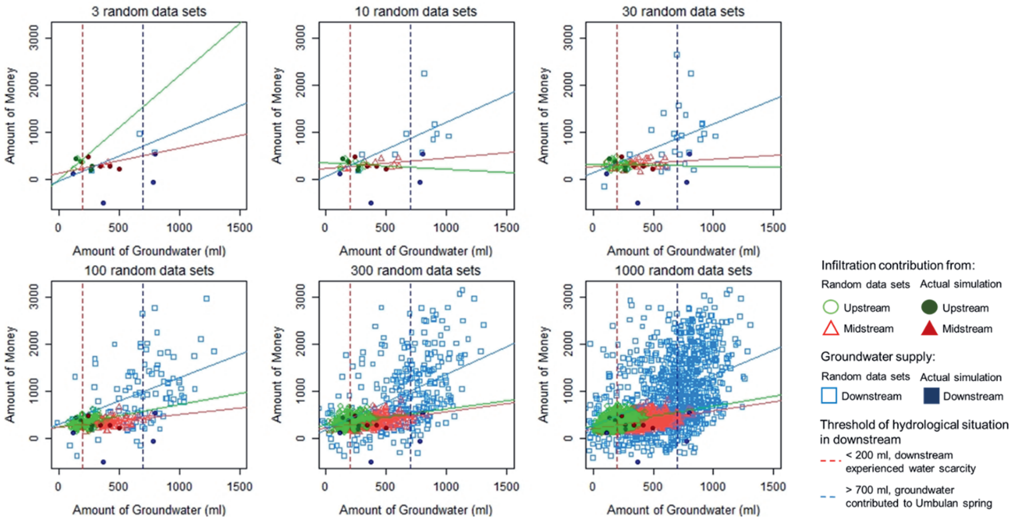


Figure 5E.3. Groundwater and economic conditions based on random value simulation and actual simulation.

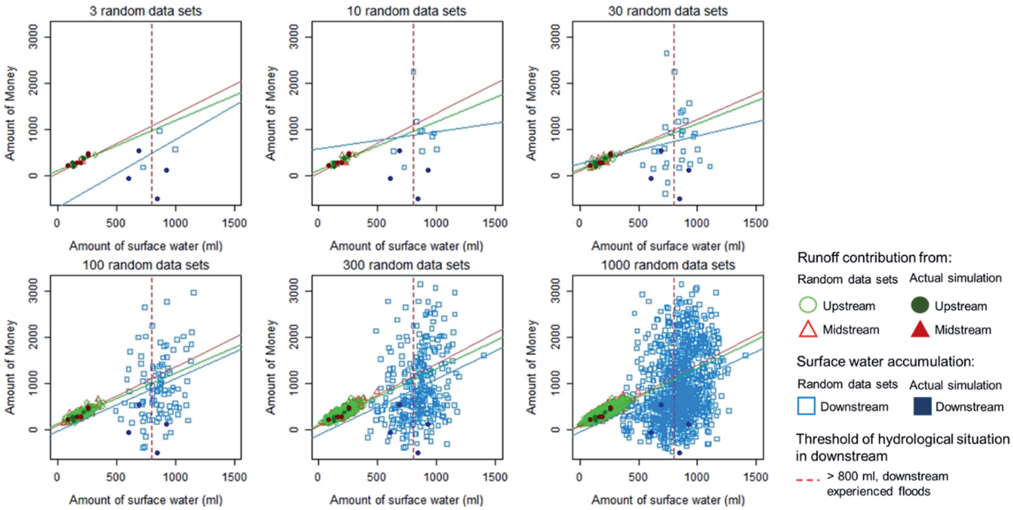


Figure 5E.4. Runoff and economic conditions based on random value simulation and actual simulation.

After calculating the environmental impacts, the game participants were waiting whether there would be a water problem or not.

In the end of the game session, the richest group who got the most profit was showing off their money.

Chapter 6: Managing Trees and Restoring Groundwater: Enhancing Shared Understanding through the H_2Ours Game in the Rejoso Watershed, Indonesia

Tanika, L., van Noordwijk, M., Speelman, E.N., Leimona, B., and Peña-Claros , M., Managing trees and restoring groundwater: enhancing shared understanding through the H_2Ours game in the Rejoso Watershed, Indonesia

Abstract

Changes in land cover and ecosystem structure affect hydrological functions, resulting in problems (disservices) or benefits (services) for people. Where the current land and water management does not sustain the desired hydrological functions, hydrological restoration can try to restore essential functions. The effectiveness and efficiency of restoration efforts requires that stakeholders have a shared understanding of the drivers of degradation and restoration options. Serious games are increasingly used to facilitate learning processes and to explore what it takes to change social norms of behaviour. This study evaluates the use of the Water Use, Resources, and Sustainability (H_2Ours) game as an exploratory tool to support restoration planning. The H_2Ours game simulates (positive and negative) impacts of stakeholder decisions on land and water use in the upper, middle and lower zones of a catchment; it can apply in different rounds according to the user choice, government regulation, and Payment for Ecosystem Services (PES) programs. In the Rejoso watershed (1600 km^2) in the volcanic area of Mount Bromo (East Java, Indonesia) groundwater flow supports the Umbulan Spring that serves drinking water to 1.3 million people in Surabaya (Indonesia's second metropole) but is also tapped by artesian wells used for lowland irrigation. The discharge of the Umbulan spring has decreased below the targeted intake, through a combination of intensifying agriculture in the recharge area (upstream and midstream) and downstream groundwater exploitation through free-flowing artesian wells. This study invited farmer groups from the upstream, midstream, and downstream of the Rejoso watershed, with and without previous exposure to a recent watershed management program, to join and play the H_2Ours game. Players' decisions and reasons regarding types of land use and water management were recorded each round to determine their land and water use decision-making patterns. Farmer perceptions on the causes of and solutions for watershed problems were quantified before and after participation in the game using the Q-methodology. Results showed that land use and water management decisions in the game reflected the players' understanding of how a landscape system works, and that the H_2Ours game changed some of the participant perceptions, filling knowledge gaps. The game supports enabling conditions needed for real-life implementation of hydrological restoration.

Keywords: Decision making, hydrological restoration, Payment for Ecosystem Services (PES), Q-methodology, serious games

6.1. Introduction

Ecosystem structures and cascading processes of water flow determine the provision of (dis) services to humans (Costanza et al., 2017; Blanco and Dendoncker, 2019), as understood in a structure-function-service-value-decisions cascade. For example, water-based ecosystem services can be traced back to hydrological processes and their structural basis in climate-vegetation-soil-geology-topography interactions (Brauman, 2015; Creed and van Noordwijk, 2018). Land cover change affects these ecosystem structures and processes, leading to changes in the provision of (dis)services. In the case of water, land cover change may lead to a reduction in freshwater availability, lower water quality, and lower water quantity regulation, resulting in droughts or flooding. These negative impacts on human health and/or economic activities may trigger action from stakeholders aiming to manage and/or restore the landscape conditions. Water management refers to long and continuous efforts to ensure water services in a cost-effective and sustainable way (Sheng, 1990; Ghebremichael et al., 2015). Integrated water management emphasizes participatory processes for decision making (Grizzetti et al., 2016; Liu et al., 2013), while restoration refers to recreating an entire system to restore or maintain certain features of an ecosystem (Jordan and Lubick, 1967). When water management has more specific goals and activities to restore the hydrological function of a degraded ecosystem mimicking the natural conditions, water management merges with restoration (Covington et al., 1999), driven by 'mimetrics' (van Noordwijk et al., 2022).

In water management and restoration, a participatory process is needed to find a 'win-win' (or at least two-way loose-less compared to status quo) solution among conflicting values, interest and needs among stakeholders (Moran et al., 2019). The participatory process expects all parties involved in management (water or other natural resources) to be actively involved in every stage of planning and implementation as a collaboration. At the beginning of this process, stakeholders usually have a different type and level of understanding, perception and assumptions about the system they live in, based on their beliefs, knowledge and interests (Muro and Jeffrey, 2012). Cooperation begins when the stakeholders can share their vision regarding the goals they want to achieve in the future (Ansell and Gash, 2008). Shared learning and reflection encourage the transformation of their knowledge (including ignorance, denial, blaming others and conspiracy theories prevailed) into a shared understanding, which then triggers the emergence of commitment, agreement and collective actions which also refer to the natural resource management cycle (Leimona et al., 2015; Moon et al., 2019; van Noordwijk, 2019). The conditions above in accordance with the six principles for successful ecosystem restoration were defined based on best practices from around the world (Metzger et al., 2017). These principles are 1) participatory, transdisciplinary and adaptive approach; 2) identify and accommodate various stakeholders' desire; 3) suitable methods for targeted outcome; 4) suitable strategies or scenarios; 5) evaluation and trade-off analysis; and 6) implementation with facilitation incorporated.

The first and second principles for successful ecosystem restoration recommend the use of participatory, transdisciplinary and adaptive approach; and the need to identify and accommodate various stakeholders' desires. Serious games that facilitate information sharing and knowledge transfer are expected to encourage shared understanding and generate commitment to achieve the restoration goals (Rodela and Speelman, 2023). Although game simulations may not predict how players act in real life, games provide information on what factors influence their decisions (Meinzen-Dick et al., 2016). Serious games, aligned with science-based understanding of underlying processes, are widely used to increase shared understanding of how a system works and to raise awareness of relevant and actionable issues (Rossano et al., 2017; Feng et al., 2018; Ferguson et al., 2020). The setting of a serious game resembles actual conditions with transparent rules so that it is easy for players to understand causal effect relationships. Once the players understand how the game works, players can safely explore and reflect on various potential solutions (Fleming et al., 2014, 2016; Janssen et al., 2023). In addition, games also can raise the value of relationships by showing conditions that may be difficult to see in real life (e.g., relationships between stakeholders, problems experienced by certain communities) (van Vugt et al., 2014; Janssen et al., 2023). Serious games that include a decision-making process need to at least consider the decision-making phase. The decision-making by players can be analysed and understood as the outcome of multiple implicit steps: problem structuring, defining objectives and attributes, developing scenarios, estimating consequences of the scenarios, evaluating trade-offs, decision selection, implementation, monitoring-evaluation (Mittal et al., 2022). In the phase of estimating consequences and trade-off evaluation, the player's subjectivity influences their decision (Moon et al., 2019) as the subjectivity is associated with their understanding of the system (mental model). Sharing knowledge to equalize perceptions or combining different knowledge from various stakeholders aims to build a mutually appreciated perception (Etienne et al., 2011).

The Water Use, Resources, and Sustainability (H_2Ours) game (Tanika et al., 2023) is a serious game that simulates the impact of land use change and water management on surface and groundwater conditions at the landscape level. The objective of this game is to facilitate knowledge sharing and knowledge transfer to support collective and collaboration actions among various stakeholders involved in water resources management. Through this game, players explore various combinations of land use and water management at the landscape level, which exposes trade-offs between economic and environmental conditions, allowing them to learn negotiation and collaboration. This game was used in the Rejoso watershed, one of the most important watersheds in Indonesia, with a national strategic project for drinking water. However, in 2020, the discharge of the Umbulan spring has decreased below the targeted amount of water (Khasanah et al., 2021). To restore the hydrological function of the Rejoso watershed, more trees are being planted in the upstream and midstream areas to increase groundwater supply to the Umbulan spring, as well as proper artesian wells equipped with valve and smart agricultural systems with crop rotation are being promoted to increase efficiency of water use. The H_2Ours game simulation in the Rejoso watershed was expected to facilitate gaps in space and knowledge between stakeholders, as well as provide input to public stakeholders on how local communities take decisions regarding their land use. Stakeholders involved in watershed management need to have space to interact and see the same space as the basis for their interactions (Mayer et al., 2021). However, beyond knowledge (cognitive aspects), the social norms of behaviour involved in the current imbalance of groundwater supply and demand and in possible solutions need attention as well.

The objective of this study is to evaluate the use of the H_2Ours game as an explanatory and learning tool to support hydrological restoration strategies. As an explanatory tool, the H_2Ours game was used to understand stakeholder decision making on land and water management and to identify the enabling conditions for real life implementation. As a learning tool, the H_2Ours game was used to contribute to the perceptions of the game participants. To address the objective, we developed three research questions: (1) How do stakeholders respond in their decision making on land and water management to possible programs and regulations to restore the hydrological functions? (2) What are their social-hydrological concerns in the Rejoso watershed?, and (3) How can the H_2Ours game contribute to the changes of stakeholder's perceptions? This study answered the first question by comparing land use combination, water management and the reasons behind these decisions between various game sessions involving different participant groups of the Rejoso watershed. We answered the second and third question through a Q-methodology perception survey before and after the game regarding factors that are needed to secure water, the causes of hydrological problems in the Rejoso watershed and the factors that determine the success of hydrological restoration.

6.2. Methods

6.2.1. Rejoso watershed

The Rejoso Watershed (1600 km^2) in the Pasuruan district of East Java Province, Indonesia, can be divided in three areas based on the elevation and hydrological system: downstream (0-100 m a.s.l.), midstream (100-1000 m a.s.l.) and upstream (>1000 m a.s.l.; Fig. 6.1). This watershed has national priority because of the Umbulan spring that is used, through a recent pipeline, to supply water to 1.3 million people in the surrounding metropolitan area (Suprayogo et al., 2023). Land conversion from agroforestry to intensive agriculture in the recharge areas (>700 m a.s.l.) in the upstream and midstream area and massive groundwater extraction using artesian wells in the downstream area for rice field is thought to cause the reduced discharge of the Umbulan spring, from 5 m^3/s (1980s) to 3.5 m^3/s (2017) (Toulier, 2019; Khasanah et al., 2021; Amaruzaman et al., 2018; Leimona et al., 2018). As the declining spring discharge is disrupting the water supply for drinking water, agriculture and industries, stakeholders to a large city, provincial and district-level authorities in the Rejoso watershed are committed to develop strategies to restore the hydrological function of their watershed through land-use management in the recharge area and more effective groundwater utilization in the downstream to maintain the continuity of water supply in the Umbulan spring (Khasanah et al., 2021).

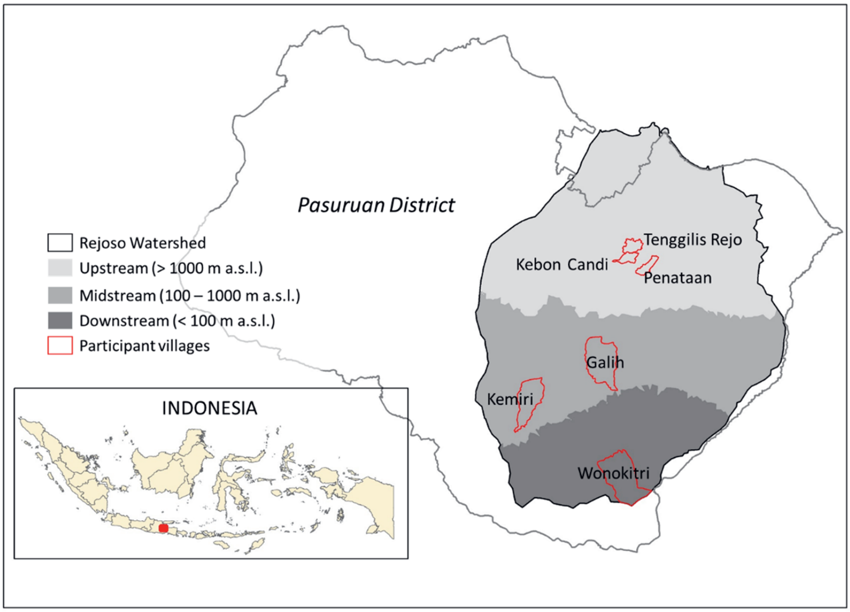


Figure 6.1. Rejoso watershed with the upstream, midstream and downstream areas, as well as villages invited to participate in the H$_2$Ours game simulation (m a.s.l.: meter above sea level).

Several hydrological studies have been carried out by various parties to assess the hydrological condition of the Rejoso watershed based on water balance and groundwater recharge areas (Toulier et al., 2019a; Khasanah et al., 2021). Surrounded by several volcanoes, the upstream and midstream area of the Rejoso watershed has very fertile soil and the downstream area has easily accessible groundwater. This condition made land conversion to intensive agriculture in the upstream and midstream, and the rice field with groundwater irrigation in downstream area profitable and attractive. As a result, water infiltration in up- and mid-stream areas was reduced (Suprayogo et al., 2020) but the downstream groundwater utilization increased, and flash-flood risk seemed to have increased. Once understood in this light, hydrological restoration of the degraded Rejoso watershed targeting recovery of the discharge of the Umbulan spring involves reorganizing land and water utilization to balance the supply and demand of groundwater.

As an effort to restore the hydrological function of the Rejoso watershed and to increase groundwater supply to the Umbulan spring, the Pasuruan watershed forum published an action plan as a guidance for stakeholders to manage land and water in the Rejoso watershed (Leimona and Khasanah, 2022). The action plans include agroforestry with more trees in the upstream and midstream areas, which are recharge areas of the groundwater (Toulier et al., 2019a; Suprayogo et al., 2020), as well as promoting proper artesian wells equipped with valve and smart agricultural systems with crop rotation and less water use (Khasanah et al., 2021).

This study involved farmer groups from five villages located in the Rejoso watershed (Fig. 6.1, Table 6.1). Upstream villages were represented by two different farmer groups from Wonokitri village, while the midstream villages were represented by farmer groups of two villages, and the downstream villages by three villages (Table 6.1). One of the farmer groups from Wonokitri and the farmer group from Galih had experience in Payment for Ecosystem Services (PES) activities in 2017-2018. Farmer groups from Kebon Candi and Penataan had experience with a project supporting 'smart' agriculture practices and water management in 2020-2022.

Table 6.1. Characteristics of the villages, farmer groups and game participants who was joining the game session of H_2Ours game to describe the variety of participants in each game session.

No	Village name	Village elevation (m above sea level)	Dominant land use	Number of game participa nts	Age range of particip ants	PES expo-sure	Smart agriculture and water manage ment	Game session
1	Wonokitri (group A)	1600-2200	Horticulture	6	24-58	Yes	No	1 and 2
	Wonokitri (group B)		Horticulture	6	18-60	No	No	3 and 4
2	Galih	300-800	Mixed agroforestry	8	24-61	Yes	No	1 and 2
3	Kemiri	700-1100	Mixed agroforestry	7	21-50	No	No	3 and 4
4	Penataan		Paddy field	3	26-59	No	Yes	2
5	Kebon Candi	15-40	Paddy field	4	46-58	No	Yes	1
6	Tenggilis rejo		Paddy field	8	36-63	No	No	3 and 4

6.2.2. H_2Ours game

To simulate the impact of land use change on hydrological conditions, the H_2Ours game adopts a simple water balance principle at the landscape level that is influenced by land cover and topography. Rain that occurs in a landscape contributes to infiltration and runoff. The amount of water that seeps into the ground and becomes surface runoff depends on the type of land cover. The topography of the region, with its elevation and river network, forms upstream, midstream and downstream areas, where the respective areas have the capacity to store groundwater and surface water. The infiltrated rainwater becomes groundwater supply that can be used by humans for various needs. Surface flow that is blocked during a rain event has the potential to become a flood if the amount exceeds the surface water capacity of the area.

A game session of H_2Ours game takes around 2 hours with approximately 8-10 rounds depending on how long it takes the players to make decisions on land and water use each round. This game consists of a game board that is the basis for the landscape (Figure 6.2A), tiles representing various types of land use (Figure 2B), tokens depicting water management infrastructure (e.g., types of artesian wells), yearly weather cards and the played-money (Figure 6.2C-E). To show the water flow from upstream to downstream and to make the game livelier, the game session can use a water balance model that demonstrates changes in surface and groundwater conditions (Figure 6.2F). The game is commonly played with 6-12 people divided into 3 groups representing farmer groups from upstream, midstream and downstream villages. The objective for these player groups is to fulfil their needs in terms of food and taxes.

The rules used in the H_2Ours game are provided in a table containing information regarding the economic and environmental impacts for each type of land use (Table 6.2). Economic impact uses money units and environmental impact uses millilitres of water (mm times area divided by game-specific scaling factor) as economic and water units that are easy to understand for people with non-technical backgrounds. At each round players defined the combination of land use and water management in each of their villages. These combinations determined their economic and environmental impacts, which are calculated based on Table 6.2. When the surface water exceeds storage capacity, the downstream group would experience flooding; conversely, when groundwater conditions are less than required, the downstream group would experience water shortages. These two conditions trigger economic losses for the downstream groups. A more detailed explanation related to the flow of the H_2Ours game can be seen in the simulation guideline in Appendix 5A (Chapter 5).

A game session consists of briefing (15 minutes), game implementation (120 minutes) and debriefing (30 minutes). In the briefing, the facilitator briefly explained the game and several terms that were often used during the game, and correlated the game components with reality to include player's emotions in the game. The game implementation comprised three phases: warm-up phase (round 1 and 2), learning phase (round 3 and 4), and exploration phase (the remaining rounds). There were three scenarios used in the exploration phase of this study: (a) regulation from the government to add agroforestry areas (round 5 and 6), (b) PES scenario to see the willingness to pay from downstream player groups and the willingness to accept from upstream and midstream player groups (round 7-9) and (c) their willingness to renew the contract after they gained PES experience (round 10). In the debriefing, players were asked to explain the strategies they used during the game implementation and their reactions to the game.

6.2.3. Data collection

This study collected three types of data, namely: (1) participant profiles collected before the game, (2) decisions regarding land use and water management collected during the game session, and (3) participants' perceptions of socio-hydrological issues in their area collected before and after the game.

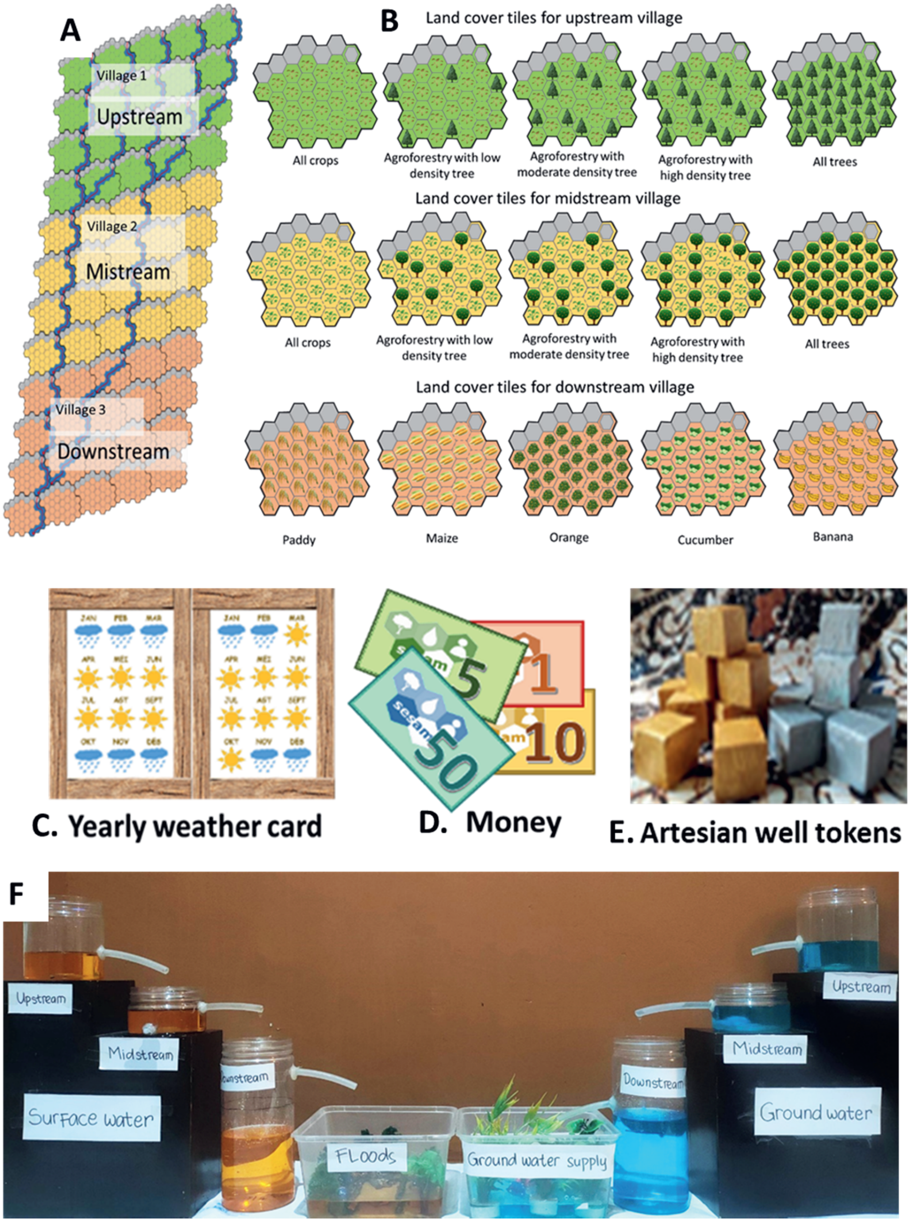


Figure 6.2. Game components used in H_2Ours in the Rejoso watershed. (A) Game board consists of upstream, midstream and downstream village, (B) land use tiles represent current and potential land use types, (C) yearly weather cards consist of wet and dry year, (D) played-money, (E) artesian well tokens consist of good/proper well and conventional well, and (F) water balance model to simulate the changes of surface water and groundwater.

Table 6.2. Economic and environmental impacts of different land uses and water management options on which the rules of the H_2Ours game in the Rejoso watershed are based. AF = agroforestry. (Chapter 5; Tanika et al., 2023).

Land-use	Production cost (unit money)	Income/year (Unit money)		Environment impacts during wet year (ml)			Environment impacts during dry year (ml)		
		Wet year	Dry year	Runoff	Infil-tra-tion	Water use	Runoff	Infil-tra-tion	Water use
UPSTREAM AND MISTREAM									
All crop	12	25	13	40	0	0	0	0	5
Mixed AF low density	9	17	9	30	10	0	0	0	5
Mixed AF moderate density	6	9	6	20	20	0	0	0	0
Mixed AF high density	3	6	4	10	30	0	0	0	0
All trees	1	0	0	0	40	0	0	0	0
DOWNSTREAM									
Paddy	12	12	25	0	0	10	0	0	15
Maize	9	15	18	0	0	5	0	0	10
Orange	7	11	15	0	0	0	0	0	5
Cucumber	9	15	13	0	0	2.5	0	0	7.5
Banana	5	10	10	0	0	0	0	0	0

Water management options for downstream village:

Type of wells	Description	Construction cost (unit money/well)	Water extraction (ml/well)
Good/proper artesian well. Construction cost: 45,	The well will take water according to the farmer's needs. The valve allows farmers to close the wells when water is not needed.	45	40
Conventional artesian wells	Each round, the well will take water based on the number of wells multiplied by 40 ml	15	40

1) Number of game session and participants

Five game sessions were organized from 13 October 2021 to 2 November 2021 with 47 people taking part. The first game session was done with a multi-stakeholder forum consisting of representatives of governments, NGOs, private sectors, and universities, to get ideas on programs that could be used as scenarios for the game sessions with farmer groups. The other four game sessions were organized with farmer groups (game session 1-4), who were invited based on their village location (upstream, midstream and downstream), and their experience with PES program for the upstream and midstream farmer group and water management for agriculture for the downstream farmer group (Table 6.1). The invitation to participate in the study was directed to groups and provided information regarding the series of activities and discussions to be undertaken with other farmer groups. The decision of who was joining the game session was left entirely to the farmer group.

Each game session was attended by 6-12 people. The game sessions with farmer groups were organized in the following way: game session 1 and 2 invited farmers from upstream and midstream had experience with Payment for Ecosystem Services (PES) programs, and participants from downstream had previously joined water management programs for agriculture, while game sessions 3 and 4 invited farmers from upstream, midstream and downstream who had never been involved in PES nor water management programs. Participant profiles were collected through short interviews with each participant after they consented to participate. This interview collected names, gender, village origin, name of farmer group, their role in farmer groups or in the village, experience involved in PES or water management. We only used this information to divide participants into each game session, anonymized this information and stored it according to data privacy regulations.

2) Decision making during the game session

Each H_2Ours game session was led by one facilitator and three co-facilitators. The facilitator handled the overall flow of the game, presenting the scenario in each round and collecting data and information related to negotiation and collaboration between groups of players. Co-facilitators in each player group calculated economic and environmental conditions and collected reasons related to land use and water management decisions within the group. All the data was recorded by the co-facilitators on a tally sheet.

We collected decision-making data on a combination of land use pattern, type of artesian wells, PES contract value and the reasons behind these decisions from each group of players in each round. At the beginning of each round, each group of players could change or maintain the condition of the land. Data from the combination of land use patterns was in the form of the amount and type of land cover chosen by the group to fill their 20 plots. Every time they had finished determining the land cover combination to be applied in that round, they were asked to provide reasons for their decision. The co-facilitator from each group recorded the combination of land use patterns and the reasons behind those decisions.

3) Q-methodology survey before and after the game session

This study conducted an initial survey to obtain participant profiles and participants' perceptions of socio-hydrological issues before the game, at the same day as the Farmer Options and its Risk in Complex Ecological-Social systems (FORCES) game sessions that were carried out several days before the H_2Ours game session. The Forces game, which is a single-player land management game at the individual farmer level, was used to provide initial knowledge regarding land management and its impact on the environment (Sari et al. 2023). Having the FORCES game sessions before the H_2Ours game sessions allowed to gradually build participants' understanding. From this setting, we expected that farmers became aware that even though they manage their land individually, they are not actually farming alone. During the H_2Ours game, farmers met farmers from other groups and villages with whom they were connected in the landscape that has a unified hydrological system.

Participant’s individual understanding of socio-hydrological issues in the Rejoso watershed was collected using the Q-methodology survey. As a systematic approach, Q-methodology combines qualitative and quantitative analysis and aims to recognize structure (‘discourses’) in the perspectives on a certain issue (Brown, 1996; Lutfallah and Buchanan, 2019). Opinions on three topics were explored in the Q-method survey through a set of three questions: (1) the factors needed to secure water (Question 1: what do you need to secure water for human needs in the Rejoso watershed?), (2) the causes of socio-hydrological problems in their area (Question 2: what are the causes of hydrological problems in the Rejoso watershed?), and (3) the factors that determine the success of hydrological restoration (Question 3: Which factors determine the success of hydrological restoration in the Rejoso watershed?). Each topic had 33 Q-statements collected from the perceptions of various stakeholders through formal or informal discussion during the landscape profiling in the Rejoso watershed by ICRAF (Amaruzaman et al., 2018; Leimona et al., 2018). During the process of developing and selecting statements, we grouped 33 statements into 3 groups for Topic 1, 4 groups for Topic 2 and 5 groups for Topic 3 (Table 6.3). The Q-methodology survey asked participants to first make the 33 statements into three piles: agree (14 statements), neutral (5 statements) and disagree (14 statements). Next, from each pile of agree and disagree, we asked participants to distribute 14 statements into very strongly agree/disagree (relevant/irrelevant) to the question (2 statements), strongly agree/disagree (3 statements), agree/disagree (4 statements), slightly agree/disagree (5 statements). Participants did the Q-methodology survey twice, answering the same questions through the same statements: after a short interview before the H_2Ours game session and after the H_2Ours game session. More detailed information regarding the three topics and their statements can be seen in Appendix 6A.

Table 6.3. Classification of statements for each topic being addressed using the Q-methodology to gather information on the individual understanding on socio-hydrological issues of farmers living in the Rejoso watershed. Number of statements per statement class is provided (See Appendix 6A for a complete list of statements for each topic and their division).

Topics of the Q-methodology survey		Statement classification		Number of statements
A	Factors needed to secure water for human need	1	Forest and trees as the key factors (A1)	11
		2	Water engineering (A2)	11
		3	Full water cycle (A3)	11
B	The causes of hydrological problems	1	Natural causes (B1)	6
		2	Human activities (B2)	9
		3	Knowledge (B3)	9
		4	Social economy (B4)	9
C	Factors that determine the success of hydrological restoration	1	Knowledge, research, and behaviour change (C1)	7
		2	Regulation and strategies (C2)	8
		3	Stakeholder involvement (C3)	6
		4	Restoration budget and financial capital (C4)	5
		5	Collaboration and collective actions (C5)	7

6.2.4. Data analysis

1) Decision making during the game sessions

We analysed the decisions by each player group (upstream group, midstream group and downstream group) based on the collected decisions data on land use pattern and water management without external forces (Round 1-4), as a response to regulation (Round 5-6) and PES program (Round 7-10). Indicator and analysis methods for each criterion are given in Table 6.4. Land use decisions and its impact on the environment and economy made in the game were compared between the three player groups (down-, mid-, and up-stream), as well as between players with and without experience with PES and water management (game session 1-2 and game session 3-4).

Differences in land use combination and its impacts were obtained by comparing the decisions among farmers based on topography (upstream, midstream and downstream) and experience with PES and water management (game session 1-2 vs game session 3-4). The differences in decision making were analysed based on the number of plots for each type of land use in each round, especially the number of plots that included trees in the upstream and midstream and use less water in the downstream. The second set of information focused on the reasons that players had to choose those combinations. The reasons why they chose these combinations were analysed based on the type of reason (environmentally related, economic-related reasons and other reasons) and frequency of appearance in each game session.

Table 6.4. Criteria, indicators and method to analyse and compare decision making between players group and game sessions.

Criteria	No	Indicators	Methods
Land use selection without external forces (Round 1-4)	(a)	Tree density in the upstream and midstream area	Compared the average of tree density score based on the land use combination. The tree density score for each land use tiles in the upstream and midstream is as follows: All trees - score 4, Mixed AF high density – score 3, Mixed AF moderate density – score 2, Mixed AF low density – score 1, All crops – score 0.
	(b)	Water efficiency in the downstream area	Compared the average of water efficiency score based on the land use combination. The water efficiency score for each land use tiles in the downstream is as follows: Banana - score 4, Cucumber – score 3, Orange – score 2, Corn – score 1, Paddy – score 0.
Water management option (Round 1-4)	(c)	The used of artesian wells with or without valve in the downstream	Compared the number and type of artesian wells by the downstream groups: (a) all wells with valve, (b) all wells without valve or (c) mixed between with and without valve
Response to regulations (Round 5-6)	(d)	Compliance with regulation scenarios	Compared whether they follow the regulation
Response to PES program (Round 7-10)	(e)	PES contract value (Round (7-9)	Compared the value of PES contract based on negotiation between upstream, midstream and downstream.
	(f)	Willingness to renewal of the contract (Round 10)	Compared whether they want to renew the PES contract or not.

2) Q-methodology analysis

The first step in the Q-methodology analysis is to determine the number of factors that represent the viewpoint patterns of the participants. There are several common criteria used to determine the number of factors, such as number of significant loading factors, eigenvalues, screen plot analysis, percentage of explained variance (Sneegas et al., 2021). Some studies even state that there is no standard method for determining the number of factors, and that the number of factors can be determined subjectively as long as the division of factors makes sense and can provide meaning (Webler et al., 2009; Sneegas et al., 2021). In this analysis, we used the following criteria to determine the number of factors: eigenvalues ≥1, around 50% of explained variance, and lack of drastic changes in the screen plot analysis (See Appendix 6A for a more detailed value of each criterion). The results of the Q-methodology survey before and after the game were analysed simultaneously to create the same number and type of factors for each of the three selected topics. Data were analysed using the Q-method coding package developed in R software (Zabala, 2014). Based on the number of factors, we extracted the significant positive and distinguished agreed statements based on their z-scores and participants' factor loadings that showed a high level of correlation with each factor (Amaruzaman et al., 2017). The positive and distinguished agreed statements were used to obtain the main socio-hydrological concerns of participants. Changes in the participant's factor loading before and after the game were used to understand how concerns changed after the game.

We grouped changes in participants' perceptions into 3 classes: became agree (more) (if the difference in factor loadings before and after was >20% of the maximum value of the difference for the same factor), (more) disagree (if the difference in factor loadings before and after <20% of the minimum value of the difference for the same factor), not changing (if the difference in factor loadings between before and after the game between 20% of maximum and minimum of the difference for the same factor).

6.3. Results

6.3.1 Land use and decision making during the game session

The results of the game session carried out together with the multi-stakeholder forum did not go as expected because they were not excited about the game simulation. During the game session with the multi-stakeholder forum, participants were only willing to show the combination of land uses they thought was the ideal one for the Rejoso watershed according to their interests (i.e., flood prevention and groundwater sustainability). This ideal combination of land use consisted of agroforestry with high tree density in the upstream area, agroforestry with moderate tree density in the midstream area and crop system with lower water use in the downstream area. However, from several discussions related to spatial planning and integrated watershed management, the multi-stakeholder forum decided to include friendly agricultural systems in the downstream and planting more trees in the midstream and upstream area in their real-life action plans (Leimona and Khasanah, 2022).

The results of the game sessions (game Sessions 1-4) showed different decisions were made by-patterns between farmer groups with experience with PES and water management (game sessions 1 and 2) or without it (game sessions 3 and 4) (Table 6.5 and Fig.6.3). At the beginning of the game (rounds 1-4) before the presence of an external scenario, game session 1 and 2 had a higher tree density and use less water than game session 3 and 4 (Table 6.5a,b), due to more plots with high density agroforestry or 'all trees' in the upstream and midstream, and fewer rice fields in the downstream (Fig.3). On the other hand, game session 3 and 4 resulted in more monoculture crops and agroforestry with less trees in the upstream and midstream, with paddy fields dominating downstream in the early rounds (Table 6.5 and Fig. 6.3). When arranged their land use, players with PES experience (game session 1 and 2) tended to give reasons that were strongly related to the environment, while players without PES experience (players from game session 3 and 4) mixed between environmental and economic reasons (Table 6.6).

In rounds 5-6, players were confronted with government regulations that demanded a minimum of 50% of the upstream and midstream areas to be at least agroforestry with moderate density, and no more artesian well constructions without valve in the downstream areas. Players in the upstream and midstream area in game sessions 3 and 4 were forced to follow the government regulations, while the players from game session 1 and 2 were not affected by that regulation because they had managed their land exceed the government regulation. With the government regulation on artesian well design, the downstream group needed to adapt their land management with the number of the existing wells for the remaining rounds of the game. All groups of players from all game sessions followed the regulation given by the government (Table 6.5d).

Table 6.5. Comparison of decision-making results between player groups and between game sessions. (Maximum of tree density score is 80 when all plots only have tress, Maximum of water efficiency score is 80 when all plots are banana, contract value based on negotiation between upstream, midstream and downstream groups.

Game session	Participant groups	Based on land use: (a) Score of tree density in upstream and mid-stream (Round 1-4)	Based on land use: (b) Score of water efficiency in down-stream (Round 1-4)	(c) The used of artesian wells with or without valve in the downstream (Round 1-4)	(d) Compliance with regulation (Round 5-6)	(e) Contract value (amount of money) (Round 7-9)	(f) Willing-ness to renewal contract (Round 10)
1	Upstream	59			Yes	Got payment 75/round	Yes
	Midstream	60			Yes		Yes
	Downstream		42.5	Mixed	Yes	Paid 60/round	No
2	Upstream	56			Yes	Got payment 100/round	Yes
	Midstream	43.5			Yes		Yes
	Downstream		25	Mixed	Yes	Paid 100/round	Yes
3	Upstream	32			Yes	Got payment 175/round	Yes
	Midstream	39			Yes		Yes
	Downstream		10.7	All wells without valve	Yes	Paid 150/round	No
4	Upstream	15			Yes	Got payment 500 for 3 rounds	Yes
	Midstream	18			Yes		Yes
	Downstream		25.5	All wells without valve	Yes	Paid 150/round	No

After experiencing the impact of hydrological problems (floods and water shortages), in round 7 a scenario with PES was introduced to the players. All player groups were asked to create a contract of PES, which had to be followed for the next 3 rounds. In the PES program, the downstream groups could ask the upstream and midstream groups to plant and maintain more trees in their landscape by providing payments to compensate for their opportunity lost because of the tree planting program. Based on the agreed contract value (Table 6.5, e), players from game sessions 1 and 2 had a smaller contract value compared to game session 3 and 4. However, when they were asked whether to renew their contract in Round 10, only downstream players from game session 2 were willing to renew the contract (Table 6.5f). As a result, the upstream and midstream groups of game session 1, 3, and 4 returned to their business-as-usual management by replacing their trees with crops (Fig. 6.3).

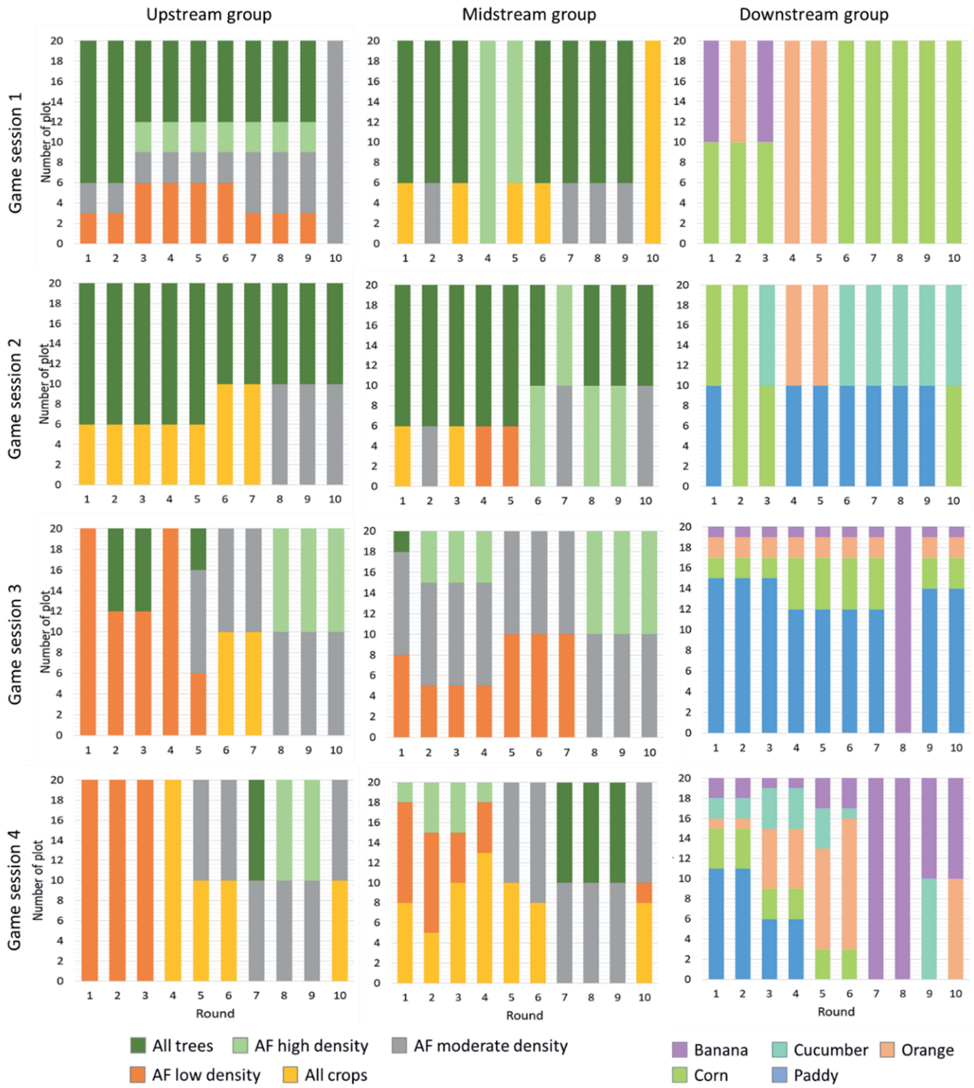


Figure 6.3. Land use combination (indicated by different colours) made by upstream, middle and downstream groups in four game sessions. Game session 1 and 2 included farmers who had experience with PES and water management program, while farmers from game session 3 and 4 had not been part of these programs. Each game session consisted of 10 rounds, where different scenarios were explored. The number of plots owned by each group was 20 plots. AF = Agroforestry.

6.3.2 The discourse of the socio-hydrological concerns in the Rejoso watershed

The Q-methodology analysis produced a different number of factors consisting of one or more statements that represent the socio-hydrological concerns. The number of factors represented the number of the discourse related to the socio-hydrological concerns associated with each topic. The label of the discourses (Table 6.7) refers to the significant positive and distinguished statements that build each factor.

Table 6.6. The reasons behind the land use decisions made by each group of players in each round (PES = Payment for ecosystem services).

		Participants had experience with PES and water management		**Participants did not have experience with PES and water management**	
	Round	Game session 1	Game session 2	Game session 3	Game session 4
Upstream group	1	No answer	Landslide prevention	Staple food and Landslide prevention	No answer
	2	Climate prediction			
	3	Landslide prevention			
	4			To get more income	More profitable
	5			Government regulation	Government regulation
	6	No other options	No answer		
	7	PES agreement	PES agreement		PES agreement
	8			PES agreement	
	9				
	10	No PES contract	To get more income	Environmental sustainability	to get more income
Midstream group	1	Tree for environment and crop for income	Landslide prevention	Tree for environment and crop for income	Tree for environment and crop for income
	2	Just Want more tree	Tree must not be disappeared from our village		Just want more tree
	3	to get more income			to get more income
	4	Tree for environment and crop for income		Tree for environment and crop for income	
	5	to get more income	Government regulation	Government regulation	Government regulation
	6	to produce more water			
	7	PES agreement	Need more money		PES agreement
	8		PES Agreement	PES Agreement	
	9				
	10	To get more income	Need more money to pay debts	Still have money	to get more income
Downstream group	1	Stable price	Balancing water supply and demand	We have a lot of water	We have a lot of water
	2	For soil rotation	The crop does not need a lot of water	As reality	Climate prediction
	3	Mixed crop			For soil rotation
	4	Market price was dropping	Have a good profit	More profitable	
	5	Have a good profit	Still profitable	Adapted to situation	Climate prediction
	6	Changed to another commodities		More profitable	Easy to sell
	7	Have a good profit		Adapted to situation	Not enough water
	8	Usually grow corn for two seasons in a row		Not enough water	
	9	Low risk on crop failure		Adapted to situation	
	10	Stable price and for soil rotation	For soil rotation	We have a lot of water	Less financial capital

For the topic on how to secure water for human needs, the Q-methodology analysis found five discourses of the socio-hydrological concerns, explaining 47.5% of the data (Table 6.7, Topic 1). These five discourse can be labelled into: (F1) effective protection of forest and recharge areas, (F2) controlling water use, (F3) involvement of many parties, (F4) water management based on water budget and (F5) sustainable schemes. Four of the five discourses have the socio-hydrological concerns related to forest and trees as the key factors for securing water (A1; Table 6.3), even the first discourse (F1) explicitly refers to this issue.

For the topic on causes of hydrological problems, the Q-methodology analysis found 7 discourses of the socio-hydrological concerns, explaining 50.3% of the data (Table 6.7, Topic 2). These seven discourses can be labelled into: (F1) natural causes, (F2) lack of grand design and information, (F3) lack of water infrastructures, (F4) human activities, (F5) lack of regulation and spatial planning, (F6) regulatory violation, and (F7) lack of research and supervision. Regarding the causes of problems, the first, second and third discourse respectively refer to natural causes (B1), lack of knowledge (B3) and human activities (B2). The fourth, fifth and seventh discourse are a combination of human activities, lack of knowledge and socio-economic causes (B4), while the sixth concern is mixed between all the causes.

For the topic on factors that determine the success of hydrological restoration to restore the hydrological function, the Q-methodology analysis found 7 discourses of the socio-hydrological concerns, explaining 49.5% of the data (Table 6.7, Topic 3). These seven discourses can be labelled into: (F1) sufficient village budget for restoration, (F2) grant, loan and win-win solution, (F3) multi-stakeholder forum for integrated strategies, (F4) suitable restoration methods, (F5) long-term efforts and involvement of all stakeholders, (F6) sufficient state and regional budget allocation and (F7) cooperation and collaboration from all stakeholders. On this topic, the discourses of the success of hydrological restoration are dominated by the socio-hydrological concerns related to budget and financial capitals (C4) and collaboration and collective actions (C5). The first discourse mentioned directly the allocation of a village budget for restoration, while the sixth discourse focussed on the state and regional (district and provincial) budget for restoration. The third and the seventh discourse referred to the involvement of all stakeholders through collaboration and collective action, including collaboration for the restoration budget. The fourth and fifth discourse are more focused on restoration strategies.

6.3.3 Changes in participants' perceptions between before and after the game session

Regarding the perception on how to secure water for human needs, the largest change (the total percentage of strongly agreement and disagreement is more than 70%) observed was on the involvement of all parties in restoration (F3; Fig. 6.4, Topic 1). Based on changes in factor loadings before and after the game, the upstream, midstream and downstream participants had different changes in perception after the game session. After the game session, the strongly agreement towards the effective protection of forest and recharge area (F1) and sustainable schemes of water management (F5) as the factors needed to secure water, was dominated by the upstream and midstream participants, while the involvement of all parties (F3) was dominated by the downstream and the multi-stakeholder forum participants. The strongly agreement towards controlling water use (F2) and water management based on water budget (F4) was also dominated by the multi-stakeholder forum participants.

Table 6.7. The discourses of the socio-hydrological concerns according to the most positive Z-score and distinguished statements and its classification based on Table 6.3 (A1: Forest and trees as the key factor to secure water, A2: water engineering, A3=understanding of full hydrological cycle, B1=Natural causes, B2=Human activities, B3=Lack of knowledge, B4=Socio-economy conditions, C1=Knowledge system, research and behaviour changes, C2=Regulations and strategies, C3=Stakeholder involvement, C4=Restoration budget and financial capital, C5=Collaboration and collective actions). For loading see Appendix 6A.

Topic		Factors	Most positive Z-score and distinguished statements as the socio-hydrological concerns	The discourse of socio-hydrological concerns
1	Factors needed to secure water for human need	F1	Protecting forest area (A1) Stop illegal logging (A1) Protecting recharge area (A1)	Effective protection of forest and recharge areas
		F2	Limiting use of irrigation water to what is strictly needed (A2)	Controlling water use
		F3	Conducting participatory water monitoring (A3) Increasing skill of forest managers (A1) Encouraging Ministry of Public Work to do a better water infrastructures construction and management (A2)	Involvement of all parties
		F4	Planting trees as much as possible (A1) Connecting all houses to reliable water pipes to increase water use efficiency (A2) Water management based on Flow out = flow in (A3)	Water management based on water budget
		F5	Requiring water user to pay for the amounts used (A2) More incentive for forest protection (A1)	Sustainable schemes
2	The causes of hydrological problems	F1	Changes in rainfall pattern (B1) Differences in topography (B1)	Natural causes
		F2	Lack of information on water management (B3) Unavailable grand design of integrated water management (B3)	Lack of grand design and information
		F3	Lack of water infrastructure to address/prevent hydrological problems (B2)	Lack of water infrastructures
		F4	Deforestation (B2) Land use conversion to mining (B2) Population growth (B4)	Human activities
		F5	Lack of regulation on water management (B4) Over-extraction of water (B2) Improper spatial planning (B2)	Lack of regulation and spatial planning
		F6	Corruption (B4) Illegal logging in forest area (B2) Lack of community's awareness (B3)	Regulatory violation
		F7	Management activities only focus on reducing impact (B3) Lack of data to support hydrological research (B3) Lack of supervision from government to local communities (B4)	Lack of research and supervision

3	Factors needed to determine the success of hydrological restoration	F1	Enough village budget allocation to support environment/restoration (C4)	Sufficient village budget for restoration
		F2	Grant and loan (C4) Win-win solution for all stakeholders (C5)	Grant, loan and win-win solutions
		F3	Existence of multi-stakeholder forum (C5) Integrated restoration strategies from all stakeholders (C5)	Multi-stakeholder forum for integrated strategies
		F4	Restoration methods appropriate to local conditions (C2)	Suitable restoration methods
		F5	Long-term period of restoration activities (C2) Involvement of (local) NGO in restoration (C3) Restoration campaign from all stakeholders (C2)	Long-term efforts and involve all stakeholders
		F6	Enough state budget allocation for restoration (C4) Enough regional budget allocation for restoration (C4)	Sufficient state and regional budget allocation
		F7	Agreed restoration activities (C5) Coordination and collaboration among stakeholders (C5) Sharing budget from all stakeholders (C4)	Cooperation and collaboration from all stakeholders

Regarding the perception on the causes of hydrological problems, the largest change (the total percentage of strongly agreement and disagreement is more than 70%) observed was lack of grand design and information related to water management (F2), regulatory violation (F6), lack of research and spatial planning (F7), lack of regulations and spatial planning (F5) and human activities (F4) (Fig. 6.4, Topic 2). The strongly agreement toward natural causes (F1) was dominated by the midstream participants; lack of grand design and information (F2) and lack of water infrastructures (F3) were dominated by the downstream participants; human activities (F4) was dominated by the downstream and multi-stakeholder forum participants; lack of regulations and spatial planning (F5) and lack of research and supervision (F7) were dominated by the upstream participants; and the regulatory violation (F6) was dominated by multi-stakeholder forum participants.

Regarding the perception on the factors that determine the success of hydrological restoration, the largest change (the total percentage of strongly agreement and disagreement is more than 70%) observed was the existing of the multi-stakeholder forum for integrated strategies (F3), sufficient village budget allocation (F1) and the state and regional budget allocation for restoration (F6) (Fig. 6.4, Topic 3). These changes in perception differ according to the participant's role in society, the village government and place of residence based on topography. After the game session, the strongly disagreement toward village budget for restoration (F1) as the factor that determines the success of hydrological restoration, was dominated by the participants who have roles as farmer group leaders or are part of the village staff. Meanwhile the strongly agreement towards village budget for restoration (F1) and the use of suitable restoration methods to the local condition (F4) were dominated by the participants from the multi-stakeholder forum. Strongly agreement to the existence of a multi-stakeholder forum for integrated strategies (F3) included almost all participants, and collaboration and collective action (F7) was dominated by the downstream participants.

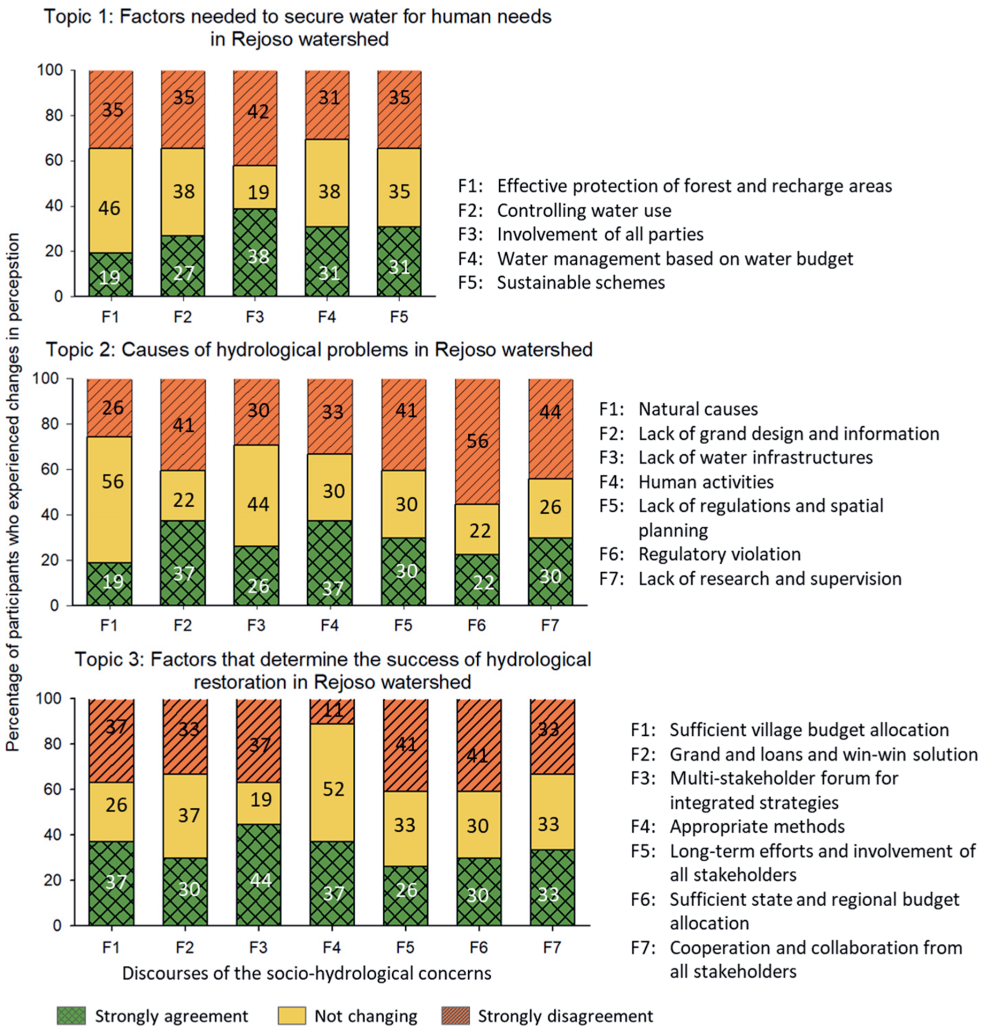


Figure 6 4. Percentage of participants who changed their perception after the game based on individual loading factor (N = 27 people) to the discourse of the socio-hydrological concerns refers to Table 6.7.

6.4. Discussion

To meet the objective of this study in evaluating the use of the H_2Oursgame as an explanatory and learning tool, we divide the discussion into three parts. The first part explains how the participants made the decisions during the game session and the factors that influenced it. In Section 6.4.2, we describe participants' perceptions of socio-hydrological discourse and how the design of the H_2Ours game influences their perceptions. In Section 6.4.3, we identify enabling conditions necessary as recommendations for designing restoration strategies and real-life implementation according to according to the decision-making patterns and socio-hydrological concerns of the game participants.

6.4.1 The role of previous experiences on decisions and collaboration to restore hydrological functions

Land use decisions in Round 1-4 was influenced by mental models, norms, or motivation (Table 6.6). Before any external scenarios, the players made land use decisions purely based on economic, ecological or socio-cultural factors. Players in game session 1 and 2 gave more reasons related to the environment, while players in game session 3 and 4 groups gave more reasons related to their economy. In this case, the players who interacted longer with accompanying organizations showed a better result in the game simulation (Meinzen-Dick et al., 2016). Similar results were found in a study carried out with community groups in Andhra Pradesh, India (Meinzen-Dick et al. 2016), using a groundwater management game Player groups with a longer interaction with the local NGO showed a stronger understanding of the groundwater system and its management than players lacking that interaction. Given that people have understanding, perceptions, and assumptions about how a system works through mental models (Moon et al., 2019), people take different decisions regarding the same conditions because of differences in viewpoints and levels of knowledge. In this study, the participants from game session 1 and 2 also linked the causes and effect of their decisions to the conditions of the other groups, e.g., trees for environment, landslide prevention, balancing water supply and demand (Table 6.6).

When the government regulation scenario (Round 5-6) was applied, all player groups complied with the regulations. During the debriefing, participants who were forced to change their land use to comply with government regulations (upstream and midstream groups of game sessions 3 and 4) said that they obeyed because it was a regulation. As a result of these regulations, they maximized their remaining land for seasonal crops that had higher profits to cover the economic losses from the applied regulation. This situation shows that these local stakeholders already have a profitability analysis of their land. If external factors still allow them to have the expected economic outcomes, they can accept and follow these recommendations. Therefore, a program or regulation needs to accommodate stakeholders' needs (e.g., financial, culture) to gain their acceptance (Pascaris et al., 2021). This condition is also in line with studies of stakeholders in Malta regarding water management (D'Agostino et al., 2020a), in which stakeholders stated that improvements to water governance needed to start with developing regulations and policies based on equality and justice for wider acceptance. This is in line with the six principles of successful restoration that require a participatory approach and highlight the need to consider the desire of various stakeholders to develop programs and regulations with high acceptance from the stakeholders (Metzger et al., 2017; Pascaris et al., 2021).

When the PES scheme (Rounds 7-9) were introduced, the upstream and midstream groups were willing to maintain the agreed land use for the next three rounds under the agreed reward, while the downstream group agreed to pay a certain amount of money as part of conservation contribution in the upstream and midstream area (Table 6.5). After having three rounds of experience with the PES agreement, they were asked about renewing the agreement in Round 10. There was only game session 2 where all participants (upstream, midstream and downstream) agreed to renew the contract and there were three game sessions (game session 1, 3 and 4) where downstream participants did not agree to renew the contract. During the debriefing, the downstream groups who disagreed said that the money spent in losses suffered because of flooding or water shortages was equivalent to the money paid for conservation. Therefore, there was no reason to continue the contract. This situation is in line with the five psychological biases towards the environment, which state that humans prioritize self-interest over collective action (Palomo-Vélez and van Vugt, 2021). Apart from that, simulation results also showed that interactions created through a rule or program would at some point weaken if one party considers the contribution to be unequal or not to produce the expected impact (Janssen et al., 2023). Here, the role of government with its authority is needed to balance economic and environmental aspects between providers and beneficiaries of ecosystem services (Aylward et al., 2005). Finally, it may be better to include relational values to show the long-term impact of management decisions (e.g., the impact that will be experienced by their descendants) to change the motivation of stakeholders to embrace a given conservation or restoration practice (Palomo-Vélez et al., 2020; Palomo-Vélez and van Vugt, 2021; Speelman et al., 2023).

6.4.2 The changes in the discourse of the socio-hydrological concerns of each topic covered by the Q-methodology survey

The perception regarding water security changed from relying only on forests protection to broader factors, such as involvement of all parties, controlling water use, sustainable schemes and water management based on water budget (Fig. 6.4, Topic 1). In the Q-methodology survey before the game, people believed that all efforts to secure water depended on forest conditions, but more disagreement on this regard was found after the game session. Their perception before the game was valid because many studies have proven that forests contribute to the provision and regulation of water in ecosystem services (Brockerhoff et al., 2017), and planting more trees leads to more water. This approach focusses on water security requires that the water supply and demand, including water distribution, is considered when taking decisions (Sone et al., 2022). The water security issue, particularly groundwater, was clearly demonstrated in the H_2Ours game in the Rejoso watershed by showing the entire process of water 'production' in the recharge area (upstream and midstream), water distribution from upstream to midstream to downstream, and water utilization in downstream (Fig. 6.2F). During the game sessions, participants could see that the water supply and demand was disrupted when the downstream players exploited groundwater excessively, even if the upstream and midstream players succeeded in maintaining water production. Therefore, the real-life implementation of water conservation measures, the downstream communities of the Rejoso watershed are the beneficiaries of groundwater from the upstream and midstream, and therefore, they should be required to control water use by limiting the number of artesian wells and improving piping and irrigation systems so that water will be distributed more efficiently (Khasanah et al., 2021) than it is currently the case.

The H_2Ours game also expanded participants' perceptions of the causes of hydrological problems in the Rejoso watershed (Fig. 6.4, Topic 2). Based on focus group discussions with local communities in the Rejoso watershed, it seemed that most of people saw the flooding and water shortages, due to long rainy and dry seasons, as the main causes of hydrological problems in the watershed (Amaruzaman et al., 2018). The H_2Ours game allowed participants to see the entire landscape (Fig. 6.2A), so participants could see what other participants were doing and relate these activities to their economic and environmental impacts, and vice versa. The design of the H_2Ours game also showed a landscape hydrological system that allowed participants to see how floods and water shortages occurred during wet and dry years (Fig. 6.2F). As a result, participants identified also other causes of hydrological problems after the game session, such as human induced land use change, lack of socialization of information and regulations related to spatial planning and water management.

Different from the topic of how to secure water and the topic of causes of hydrological problems in the Rejoso watershed, the topic of the factors that determine the success of hydrological restoration (Fig. 6.4, Topic 3) was not explicitly visible through the H_2Ours game. Participants were required to connect some information to reach conclusions about the factors that determine the success of restoration. For example, in exploration during a game session, players could compare the size of the restoration area with the resulting impact so that they understood the need for collective action for having a longer and wider restoration area. The six principles for successful restoration defined by Metzger et al. (2017) corresponded with the socio-hydrological concerns of Topic 3 of the Q-methodology (Fig. 6.4): (a) participatory, transdisciplinary and adaptive approach (associated with F5: involving all stakeholders at every stage of restoration), (b) participatory process to accommodate various stakeholders desire (associated with F7: cooperation and collaboration from all stakeholders), (c) suitable methods for targeted outcome (associated with F4: suitable methods), (d) suitable strategies or scenarios (associated with F3: integrated strategies), (e) evaluation and trade-off analysis (associated with F1, F2 and F6: village, regional and state budget allocation and grants) and (f) implementation incorporate with facilitation (associated with F5: long-term efforts). This match indicated that changes in participants' perceptions spread across the six principles for successful restoration, and that more participants strongly agreed on suitable strategies or integrated scenarios that required multi-stakeholder forum for achieving the restoration goals. Finally, the landscape level design of the H_2Ours game allowed players not only to see the entire landscape but also the stakeholders who are interested in that landscape. The concept of multi-stakeholder forums with various names (e.g., multi-stakeholder platform, multi-stakeholder partnership) has been known since the 2000s and was created for stakeholder collaborations to address issues related to public resources (Sigalla et al., 2021). Therefore, restoration as an effort to restore the landscape conditions to meet the needs of various parties requires the involvement and commitment of stakeholders at various levels (Medema et al., 2019).

The discourse of the socio-hydrological concerns as defined by the Q-methodology (Table 6.7) was dominated by a certain group of stakeholders. The participants of the Q-methodology survey in this study consisted of 22 farmers and 5 public stakeholders (from university, water company, government and journalist backgrounds). Therefore, the socio-hydrological concerns in this research were dominated by the perceptions of local communities. To see the perceptions of other stakeholders, the H_2Ours game session and Q-methodology surveys should be carried out again involving more participants from the public stakeholders.

6.4.3 The identification of enabling conditions for real implementation

There are several factors that can influence participants behaviour in real life as a result of a game session, such as the relevance of the game framework to real conditions, communication during the game session (briefing and game simulation) and after the game (debriefing), and awareness of decision making by participants during the game (Falk et al., 2023). One of the topics raised during the debriefing with the players was their feelings about seeing decisions taken by other groups (Fig. 6.3) that harmed or benefited them. In the game sessions, the downstream groups often experienced flooding because of the land use decisions from upstream and midstream groups, and sometimes upstream and midstream groups got smaller incomes compared to downstream groups who enjoyed higher incomes because of abundant water supplies. In response to this , they respected each other's decisions more because they understood that other groups also needed money, and it was their right to determine how best to manage their land. The direct interaction with other players in the role-playing game encourages mutual respect (Mayer et al., 2021). This condition also strengthens the need for direct interaction between stakeholders.

The H_2Ours game accommodates three of the five cycles of natural resource management (van Noordwijk, 2019), namely awareness raising, share understanding and commitment to goals . Later, the contribution of H_2Our game to the remaining cycles (means of implementation and learning, monitoring and evaluation) can only be seen from the implementation in real life after the game. For the implementation of management practices, the game provided input on what factors influence and are necessary for their decisions (Meinzen-Dick et al., 2016). After the game session, the participants stated that they can implement their decision during the game session to the real life, but implementation would still require enabling conditions (Tanika et al., 2023). For example, the collaboration and negotiation seemed easy to achieve during the H_2Ours game session because the players met and discussed directly, which suggests that face to face meetings and discussions among stakeholders are needed for developing integrated restoration strategies. This is also proven by the Q-methodology analysis that resulted in 44% of participant agreeing more with the existence of multi-stakeholder forum to facilitate integrated restoration strategies (Fig. 6.4, Topic 3, F3). The process of building collaboration begins with face-to-face dialogue to build trust and commitment in following a certain process (Ansell and Gash, 2008). Game simulations that provide space for players to communicate with each other to share knowledge, overcome misunderstandings, and reach consensus perceptions are useful in finding solutions to problems (Moon et al., 2019; Game et al., 2014). In real life, with an area of 1600 km^2, the upstream, midstream and downstream villages of the Rejoso watershed are physically far apart from each other resulting in minimum interaction between farmer groups. Therefore, a mechanism such as a multi-stakeholder forum is needed to facilitate the interaction among stakeholders. Participatory integrated assessment at the catchment scale is more complex in practice than the common portrayal suggests (Villamor et al., 2022), but a locally adapted game, like the one we used, can help in the various stages of the process (Rodela and Speelman, 2023).

6.5. Conclusion

In this study, the H_2Ours game gave insights into the mental models of game participants in making decisions related to land use and water management. Various information related to the environment, livelihoods and other opportunities for farmers (e.g., experience of being involved in a program) can enrich their understanding of the system, giving them more management options. The participants indicated they would follow programs and regulations if these regulations and programs do not interfere with their welfare, and providing other values (e.g., culture, social, environmental) can increase their acceptance of the program or regulation.

H_2Ours contributed to filling the gaps of the knowledge systems and enriching the knowledge of participants. As a simplification of the socio-hydrological system in the Rejoso watershed, the H_2Ours game allowed players to see the entire watershed and hydrological process that led to hydrological benefits and potential problems. The H_2Ours game contributed to changes in player perception by explicitly transforming the information or knowledge systems to be shared with players into the game components. The H_2Ours also helped identifying the enabling conditions required for actual implementation of the hydrological restoration but it is no substitute for further negotiated interventions.

6.6. Supplementary Material

Appendix 6A. Questions and statements of Q-methodology survey

In this study, Q methodology was used to capture changes in participants' perceptions before and after the H_2Ours game. There were three questions with 33 statements as answers to each question (Table 6A.1-6A.3). The statements were collected during formal and informal discussion processes with various stakeholders (Amaruzaman et al., 2018; Leimona et al., 2018).

When implementing the Q method survey, we asked participants to distribute 33 statements on the board provided (Fig. 6A.1) through several stages as follows:

1. Choose 14 statements that were considered most agreeable or relevant as answers to the question
2. From the remaining 19 statements, choose the 14 statements they considered the most disagreeable or irrelevant as answers to the question.
3. Put the remaining 5 statements as a neutral group and place it on the Q-methodology board
4. From the 14 statements that are considered the most agreeable, choose the 2 statements that were considered the most agreeable and put them on the board with value 4, then choose 3 statements with a weight of agreement below them, choose 4 statements with weight 2, until you get 5 statements with a weight of 1
5. Repeat step 4 for 14 statements that are considered disagreeable

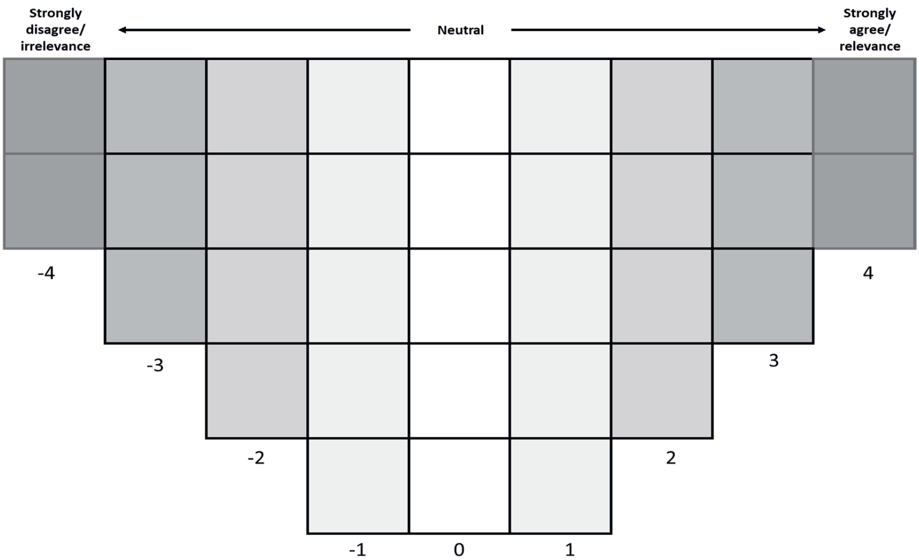
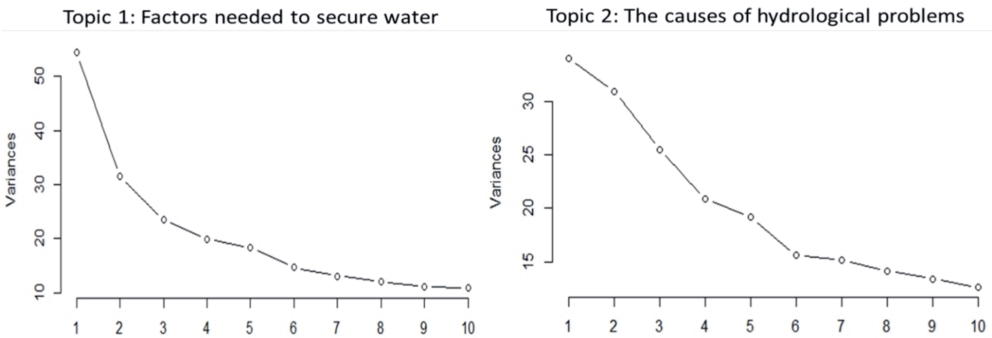
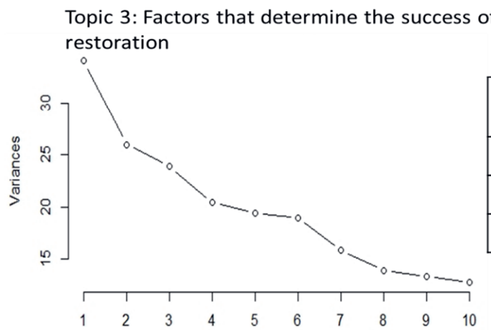


Figure 6A.1. Survey Q-methodology board used by participants. The value -4 to 4 was used as a weight when carrying out q methodology analysis in R.

We analysed the results of the q-methodology in R using Q-method coding package by Zabala (2014). We analysed the survey results before and after the game together to produce the same group of factors so that we could make comparisons before and after the game. We determined the number of factor groups based on factor analysis included in the Q-methodology package in R. By considering the dropped of ‘screen plot unrotated factors’ and the percentage of explained variance (Fig. 6A.2), eigenvalues ≥ 1 and total percentage of variance around 50%, we obtained 5 group factors for question 1, and seven for both question 2 and 3. Next, based on the number of factor groups, we extracted z-scores (values that describe the contribution of each statement to each factor group) and factor loadings (values associated with participants' perceptions of each factor group). Therefore, each participant has two factor loadings that correspond to the group factor: factor loading before the game and factor loading after the game. Changes in participants' perceptions before and after the game are the result of a comparison of the factor loading before and after of each participant.





Topic	Number of factors	% of explained variance
Topic 1	5	47.5
Topic 2	7	50.3
Topic 3	7	49.5

Figure 6A.2. Factor analysis results (screen plot analysis, number of factors and % of explained variance) for each Q-methodology topic obtained using R-package. Detailed analysis results for each topic are given in Table 6A.1-6A.3.

Table 6A.1. Summary of the Q-methodology analysis of Topic 1, that consists of factor analysis and its eigenvalues and percentage of explained variance (F1-F5) and z-scores of each statement. A1, A2 and A3 Is the classification of statement during the statement development and selection.

Topic 1: Factors needed to secure water for human needs in the Rejoso watershed			
Labelling for F1-F5 based on distinguished and positive z-scores:			
Factor label based on positive and distinguished statements		Eigenvalues	Percentage of explained variance
F1	Effective protection of forest and recharge areas	9.68	15.6
F2	Controlling water use	6.32	10.2
F3	Involvement of all parties	4.91	7.92
F4	Climate change mitigation	4.46	7.2
F5	Sustainable schemes	4.10	6.6

NO	Statements	z-scores obtained from Q-method analysis using R (*significant and distinguished statements)				
		F1	F2	F3	F4	F5
A1	Forest and tree protections					
1	Protecting forests area	2.272*	-0.060	1.582	1.408	1.514
2	Planting trees – as much as possible	1.254	0.684	-0.535	1.983*	-0.670
3	Increasing skill level of forest managers in term of forest management and monitoring	0.177	-0.560	1.337*	-0.057	-0.875
4	Law enforcement in forest protection	1.000	-1.219	-0.889	-1.125	0.779
5	Stop illegal logging	1.933*	0.099	-0.502	0.930	-0.953
6	Respecting traditional rules on springs, lakes and streams	0.500	0.316	0.038	-0.626	0.665
7	Not building roads through the protected/conservation forest	-1.281	-1.043	-1.600	-0.914	-0.818
8	Encouraging Ministry of Environment and Forestry to do a better forest management and protection	0.963	-0.799	1.252	0.116	0.084
9	Awareness campaigns: “No forest, No water”	-0.984	-1.189	-0.819	-1.368	-1.221
10	Having at least 30% forest in every District	0.392	-1.317	-0.743	-0.056	0.144
11	More reward or incentive for forest protection	0.306	-0.698	-1.024	-0.475	0.950*
A2	Water engineering					
12	Avoiding fast-growing trees with high water use	-0.895	-0.832	-1.978	-0.038	0.464
13	Engineering pipes and channels for increasing water distribution	-1.259	1.181	1.054	-1.874	1.327
14	Water quality control matching target use	-0.419	1.701	-0.739	1.611	1.981
15	Pollution control along drainage channels	-0.002	1.613	-0.774	-0.746	1.403
16	Limiting use of irrigation water to what is strictly needed	0.451	1.627*	0.821	-0.770	-0.795
17	Stop illegal ground- and river-water abstraction	1.104	1.055	-1.212	-0.533	-2.211
18	Encouraging Ministry of Public Work to do a better water infrastructures construction and management	-1.197	-0.641	1.076*	-0.414	0.120
19	Connecting all houses to reliable water pipes to increase water use efficiency	-0.386	0.608	0.259	1.397*	0.761
20	Wastewater treatment so it can be reused	-0.877	0.477	-1.299	0.327	-1.416

21	Water management focus on water infrastructures development	-0.797	1.429	1.257	0.982	0.406
22	Requiring water users to pay for the amounts used	-0.795	0.971	0.369	0.124	1.583*
A3	Full water cycle					
23	Protecting the recharge area	1.891*	0.992	0.851	0.278	0.161
24	Protecting riparian zone vegetation and wetlands	0.560	-0.864	0.329	-0.289	0.473
25	Controlling climate change	-1.259	-1.392	-0.881	0.205	-1.003
26	Awareness campaigns: “Use water wisely”	-0.160	0.020	-0.828	0.232	0.099
27	Land use planning involving all stakeholders	0.138	-1.439	-0.194	-1.996	0.437
28	Water/watershed management based on carrying capacity	0.368	0.899	0.602	-0.797	-1.071
29	Improving climate and hydrological data management (such as rainfall, water flows, allocations) as the basis of water management plan	-0.128	0.607	0.737	-0.424	0.370
30	Water management based on Flow out = flow in	-1.069	0.042	-0.428	1.596*	-0.360
31	Encouraging watershed forum as the communication forum for water management	0.202	-1.022	1.174	0.970	-0.864
32	Conducting participatory water monitoring and evaluation	-1.043	-0.923	1.480*	0.964	-0.947
33	More reward/incentive for people/institution who apply proper water management	-0.960	-0.326	0.227	-0.623	-0.517

Table 6A.2. Summary of Q-methodology analysis of Topic 2, that consists of factor analysis and its eigenvalues and percentage of explained variance (F1-F7) and z-scores of each statement. B1-B4 are the classification of statement during the statement development and selection.

Topic 2: The causes of hydrological problems in the Rejoso watershed		
Labelling for F1-F7 based on distinguished and positive z-scores:		
Factor label based on significant and distinguished statements	Eigenvalues	Percentage of explained variance
F1 Natural causes	5.5	8.6
F2 Lack of grand design and information	5.3	8.2
F3 Lack of water infrastructures	5.1	7.9
F4 Human activities	4.3	6.7
F5 Lack of regulation and spatial planning	4.2	6.6
F6 Regulatory violations	4.2	6.6
F7 Lack of research and supervision	3.7	5.8

No	Statements	z-scores obtained from Q-method analysis using R (*significant and distinguished statements)						
		F1	F2	F3	F4	F5	F6	F7
B1	Natural causes							
1	Natural disaster	1.241	-1.908	0.774	-0.667	-0.330	0.070	-1.718
2	Changes in rainfall patterns	1.598*	-1.319	0.158	-0.384	0.639	0.298	-0.177
3	Long dry season	1.666	-1.706	1.653	0.820	1.233	1.371	1.297

4	High rainfall intensity	1.716	-0.486	1.361	-1.171	-0.571	-0.301	1.029
5	Differences in the topography	1.126*	-0.647	-0.211	-1.561	-0.557	-0.059	0.251
6	Differences in the soil types	-0.779	-0.497	-1.365	-1.307	-0.685	0.316	0.042
B2	Human activities							
7	Deforestation	-0.139	-0.338	-0.483	2.246*	-0.759	0.329	-0.653
8	Over-extraction of water	0.941	-0.649	-0.900	0.589	1.542*	0.535	-1.051
9	Intensive agricultural practice	-0.010	-0.810	-0.283	-1.446	0.261	0.553	0.884
10	Illegal logging in forest area	2.338	1.009	-1.425	1.455	0.101	2.019*	0.285
11	High industrial growth	0.795	-0.718	0.682	1.234	0.219	-2.278	0.536
12	Land use conversion into mining	-0.661	0.124	-2.304	1.907*	-2.124	1.314	0.605
13	Improper spatial planning	-0.629	-0.147	-1.133	0.289	1.367*	0.040	-0.452
14	improper water infrastructure construction	0.061	0.323	0.426	-0.160	0.075	-1.017	-0.203
15	Lack of infrastructure to address/prevent hydrological problems	-1.066	0.016	1.167*	-0.613	-1.206	-0.525	-0.538
B3	Lack of knowledge							
16	Lack of local community’s knowledge	0.455	1.791	1.991	-0.744	0.375	0.830	-1.175
17	Lack of community’s awareness	-1.520	0.845	1.171	0.863	1.668	1.557*	1.095
18	The absence of culture/behaviour to respect the environment	-0.719	0.825	0.038	0.641	0.547	0.387	-1.215
19	Lack of information/ socialization about water management	-0.730	1.456*	-0.071	0.240	0.169	-1.434	0.568
20	Miss-calculation/ assessment	0.959	1.042	-0.953	-1.364	-1.001	-0.559	-1.722
21	Lack of data to support hydrological research	-0.824	0.684	-1.168	-0.572	0.109	-0.783	1.913*
22	Lack of hydrological research	0.390	1.020	-0.044	-0.371	-0.840	0.208	0.865
23	Unavailability of the grand design of integrated watershed management plan	-0.683	1.386*	0.334	-0.454	0.410	0.157	0.254
24	Management activities are only focused on reducing impact	-0.907	0.021	0.749	1.288	-0.175	-0.042	2.052*
B4	Social economy							
25	High poverty rate	-0.795	-1.650	-0.950	-1.441	-1.256	-0.623	-0.208
26	High population growth	-0.236	-1.860	-0.082	0.775*	-0.671	-1.143	-0.760
27	Lack of regulation on water/watershed management	-0.638	0.312	-1.204	0.933	1.632*	-1.329	-0.044
28	Lack of supervision from government to local communities	-1.104	0.715	-0.650	-0.084	2.008	-0.606	1.578*

29	Lack of budget allocation for conservation	-1.249	0.334	0.759	-0.455	0.065	-0.771	0.046
30	Lack of regulation on water/watershed management	-0.031	0.792	0.839	-0.380	-0.345	-0.150	-0.175
31	Lack of coordination among stakeholders	-0.762	0.356	0.818	0.221	-0.459	0.350	-1.095
32	Corruption of conservation budget	0.453	-0.863	0.337	-0.145	-1.877	2.242*	-1.173
33	Lack of monitoring and evaluation on conservation activities	-0.254	0.549	-0.028	-0.184	0.435	-0.958	-0.941

Table 6A.3. Summary of the Q-methodology analysis of the Topic 3, that consists of factor analysis and its eigenvalues and percentage of explained variance (F1-F7) and z-scores of each statement. C1-C5 are the classification of statement used during the statement development and selection.

Topic 3: Factors that needed to determine the success of hydrological restoration in the Rejoso watershed			
Labelling for F1-F7 based on significant and distinguished z-scores:			
Factor label based on significant and distinguished statements		Eigenvalues	Percentage of explained variance
F1	Sufficient village budget allocation	5.5	8.7
F2	Grand and loans and win-win solution	4.8	7.5
F3	Multi-stakeholder forum for integrated strategies	4.6	7.3
F4	Suitable methods	4.5	7.0
F5	Long-term efforts and involvement of all stakeholders	4.3	6.7
F6	Sufficient state and regional budget allocation	4.3	6.7
F7	Cooperation and collaboration from all stakeholders	3.7	5.8

No	Statements	z-scores obtained from Q-method analysis using R (*significant and distinguished statements)						
		F1	F2	F3	F4	F5	F6	F7
C1	Knowledge, research and behaviour change							
1	Restoration based on scientific study	-0.965	0.320	0.367	0.399	-0.931	-0.808	0.277
2	Strong monitoring and evaluation on restoration activities	-0.419	0.732	0.675	0.882	-0.780	-1.546	-1.172
3	Availability of baseline data to support strategies	0.176	1.007	1.698	1.914	-0.027	0.818	0.099
4	Good government's knowledge on watershed management	-0.574	-0.426	-2.144	-1.452	-1.472	0.081	-0.081
5	Good local community's knowledge on watershed management	2.264	0.934	0.032	-0.110	0.042	-1.197	2.021

6	Good public's knowledge on watershed management	0.268	1.163	-0.980	0.901	0.514	-0.529	-0.045
7	Behaviour changes leading to water/watershed conservation	1.031	-0.539	1.226	0.917	-1.177	-0.198	-1.057
C2	Regulation and strategies							
8	The restoration strategies focus on the prevention effort rather than controlling the problem	0.568	-0.945	-1.137	0.190	-0.880	-0.219	-1.057
9	Conservation/restoration methods suitable for local condition	-0.891	-0.863	-0.736	1.041*	-0.967	-0.776	-0.994
10	Integrated regulation from national, province/district to village about water/ watershed management	-0.170	-1.592	1.038	-1.413	-0.391	-0.032	0.422
11	Law enforcement against environmental offenders	-0.083	-2.024	0.558	-0.553	1.686	1.104	1.271
12	Reward to those who do conservation beyond regulation	-0.407	0.864	0.466	-1.489	1.073	0.159	-0.663
13	Controlling water resources exploitation	1.004	-1.621	0.479	-0.479	-0.703	-0.229	0.649
14	Restoration activities are carried out in a large area	0.213	-0.881	-1.316	-0.158	1.296	-0.289	0.831
15	Restoration activities carried out in a long-term period	-0.495	-0.902	-1.382	-0.266	1.319*	-0.128	-1.457
C3	Actors and stakeholders' involvement							
16	Restoration and conservation campaign from all parties	-1.019	-1.167	-0.342	-1.002	1.126*	-0.237	0.423
17	Participatory monitoring and evaluation on restoration activities	-1.217	0.588	1.094	1.458	-0.415	0.488	0.091
18	Involvement of local communities in restoration	1.415	1.082	0.375	0.581	1.597	0.739	-0.645
19	Involvement of researcher/university in restoration	-1.399	-0.557	0.784	-0.603	-0.839	0.330	0.422
20	Involvement of (local) NGOs in restoration	-0.628	0.251	-0.840	-0.802	1.169*	-1.523	-0.105
21	Involvement of private sector/company in restoration	-2.062	0.221	1.146	-0.383	1.238	-2.002	-0.285
C4	Restoration budgets and financial capitals							
22	Enough village budget allocation for environment/restoration	1.975*	0.532	-0.629	-1.718	-0.303	0.577	-0.917
23	Enough regional government budget allocation for restoration	-0.473	-0.100	-0.604	-0.430	0.294	1.644*	-1.303

24	Enough state budget allocation for restoration	0.726	0.619	-1.201	1.223	0.957	1.233*	-2.007
25	Grant or loan from other parties for restoration	-0.021	2.163*	-0.830	-0.395	-0.453	-0.347	1.445
26	Sharing budget from all stakeholder/beneficiaries for restoration funds	-0.321	1.335	-0.196	-0.881	0.680	0.737	1.330*
C5	Collaborative and collective actions							
27	Existence of multi-stakeholder forum to integrate restoration activities	-0.409	-1.390	1.688*	0.078	-0.378	-0.061	-0.295
28	Commitment from all stakeholders to restore the hydrological condition	1.502	0.027	0.660	1.865	0.050	1.763	-0.500
29	Cooperation and coordination among stakeholders to do the hydrological restoration	1.156	0.143	-0.251	1.479	1.017	1.335	1.534*
30	‘Win-win solution’ for all stakeholders regarding hydrological restoration strategy	-1.293	1.102*	-0.546	0.427	-1.416	0.158	-0.432
31	An agreed restoration activities are stated in an agreement letter or government decree	0.186	-0.482	-1.006	-1.111	-0.238	0.508	1.866*
32	Sharing knowledge/ information among stakeholders related to environment conditions	0.532	0.701	0.312	0.382	-0.742	-2.451	0.009
33	Integrated restoration strategies/actions from all stakeholders	-0.170	-0.295	1.542*	-0.491	-1.946	0.896	0.327

Two farmers from the Galih village, Pasuruan, were taking part in the Q-methodology survey very seriously.

Collecting soil samples in the Pawan-
Kepulu Peatland. One of the enjoyable
moments during the PhD field work.

Chapter 7: General Discussion

7.1. Key Findings

Key findings of the preceding research chapters are summarized in Table 7.1 and linked to the research questions framed in Chapter 1. A more detailed discussion of each research question is provided in the following sections.

Table 7.1. Summary of key findings from this thesis based on each research question.

No	Research questions and key findings	Chapter
1	**What are the impacts of human actions on water resources at various spatial scales?**	
a	The evolution of human knowledge of nature influences how humans perceive and treat nature.	2,
b	Understanding the factors that influence stakeholder decisions regarding land use and water management provides options for overcoming the problems.	3, 4, 5
c	The multifunctional landscape approach allows to optimize the landscape conditions to achieve conservation targets and obtain economic benefits for all stakeholders.	3, 5
d	Implementation of a multifunctional landscape requires a long-term planning and integrated strategies from stakeholders based on shared understanding of the socio-hydrological system.	6
2	**How can complex socio-hydrological systems be simplified into models and games?**	
a	Simplification of the socio-hydrological systems into hydrological models and games requires indentification of the goals of the model and game that correspond to the complexity of the socio-hydrological system.	3, 4, 5 7
b	Socio-hydrological systems can be simplified through fragmentation and integration. Fragmentation into small components that have a theoretical basis (e.g., water balance equation, water budget equation, ecological knowledge), then rearranging them using the components needed according to the goals of the model and game.	3, 4, 5
3	**How can models and serious games be adapted and replicated?**	
a	The flexibility of models and games can be approached through the 'plug and play' feature and open-transparent code or process to make it easier for other users to adapt to system needs and conditions.	4, 5
b	Adaptation of models and games needs to consider the user needs (e.g., new information from the existing area or similar information from other areas).	3, 4, 5
4	**To what extent can games and models contribute to decision making in restoring the hydrological functions?**	
a	The application of hydrological models and serious games complement each other in increasing understanding of socio-hydrological systems and identifying optimal solutions; therefore, they contribute to decision making.	5, 7
b	The credibility, salience and legitimacy of the model and the game increases trust and acceptance of obtained results by stakeholders.	5, 7
c	Objectives, adaptability, resolution level, and communication are factors that need to be considered in selecting, developing and simulating models and games as input for decision making.	3, 4, 5 and 7

7.2. Human Appropriation of Water Resources

According to the human-nature relationship in four concepts of a ‘spiritual forest transition’ (nature is powerful, taming of nature, rational management of nature, and reconnection with nature), the degradation of environmental functions occurs significantly in the second and third concept (Roux et al., 2022). In these concepts, humans see natural capital as a ‘product’ or ‘property’ provided by nature to meet human needs and improve their welfare (Ferreira and Leitão, 2007; Roux et al., 2022). Associated with water resources, the 'product' refers to the definition of 'water footprint' that includes water that is consumed or used directly by humans, and water that is used to produce products and services (e.g., water for plants transpiration, water polluted by industry) (Hoekstra, 2008). Based on this definition, many human activities appropriate water resources in various ways; such as land use changes, groundwater extraction, water irrigation, water regulation (Postel et al., 1996; Weiß et al., 2009). As the property, human treat water resources as their right to nature, which refers to bundle of right (access, withdrawal, management, exclusion, and alienation; Schlager and Ostrom, 1992; Kusters and de Graaf, 2019).

In the Rejoso watershed and Pawan-Kepulu peatland, human appropriation of water resources occurs across various water related components at various stakeholder levels. Farmers, local communities, oil palm companies and water companies work directly at a plot or landscape level and influence the water resources through their activities and water utilization. In the Rejoso watershed, the land use management in the upstream and midstream affect the surface and groundwater through evapotranspiration and infiltration, while intensive agriculture and water companies in the downstream affect the water resource through groundwater harvesting (Chapter 3). In the Pawan-Kepulu peatland, the land use management with massive canal constructions by farmers or oil palm companies has a direct impact on evapotranspiration, groundwater and surface water of the peatland (Chapter 4). At the landscape to national level, the government affects the condition of water resources through spatial planning, policy and regulation at various spatial scales according to their jurisdiction level. District government, in collaboration with the provincial government, has the responsibility for spatial planning that considers landscape boundaries (watershed or peatland) and jurisdiction boundaries (province, district, and sub-district). The spatial planning needs to accommodate the needs of stakeholders who live and work in their area (e.g., local communities, companies), but it also needs to implement policies, regulations and programs from the national government. Researchers and NGOs work across scales by providing recommendations and assistance according to the needs of each stakeholder. Researchers and NGOs working with farmers provide recommendations and assistance related to implementation from the plot to landscape level, and recommendations related to planning and policy to the government. Based on discussions with various stakeholders and finding from a previous study by the World Agroforestry and Tropenbos Indonesia regarding hydrological issues and its causes (Amaruzaman et al., 2018; Leimona et al., 2018; Widayati et al., 2021), stakeholders indicated that there were (socio)-hydrological problems when they felt hydrologically disadvantaged as a result from the decisions made by other parties or natural causes (Q-method, the causes of hydrological problems in Chapter 6). For example, land use changes in the upstream and midstream of the Rejoso watershed has resulted in the reduction of groundwater supply, unproper groundwater management in the downstream of the Rejoso watershed which causes conflict with the water company (Chapter 3). Similarly, the massive canal construction in the Pawan-Kepulu peatland has made the peatland drier so it can easily catch fire which causes health problems, disturbing transportation and contribute to emissions (Chapter 4). Several solution scenarios have been implemented to address these issues (Amaruzaman et al., 2018; Leimona et al., 2018; Widayati et al., 2021). In this thesis, I classified the efforts into three categories based on their knowledge and abilities, namely: (1) influencing the 'source' of water resources, (2) local adaptation to the current situation of water availability (e.g., switching from groundwater to surface water), and (3) restoring harmony with nature. The first and second option are usually short-term efforts and carried out individually or by a group of people with the same interest, while the third option is a long-term effort and need to involve various stakeholders.

When the accessible water resources are insufficient or when the risk of hydrological disasters needs to be reduced, the people who can influence the 'source of water resources' usually choose the first option (Chapter 2), while others choose the second option. The Disaster Management Agency of Ketapang District often carry out cloud seeding to create artificial rain to prevent or control fires on peatlands. The local wisdom of Tengger and Javanese culture of the local communities in the Rejoso watershed still relies on the rain makers and prayers to summon rain when cultivating the land or to delay the rain for the important events. In the beginning, humans influenced precipitation to secure the needs for water resources on land, but later, unfortunately sometimes humans utilize their knowledge in influencing rainfall for various other purposes (e.g., warfare conventions) (Fleming, 2010; Harper, 2017) without considering how the whole system works and it causes various other problems (e.g., human health, floods or droughts in other areas). For the people who do not have the ability to influence rain, they are forced to adapt to the current water conditions. In the Rejoso watershed, the downstream farmers temporarily switched from paddy to other agricultural commodities that require less water (Chapter 6), while in the Pawan-Kepulu peatland during the land fires people wear masks to be able to continue their daily life.

Restoring harmony with nature correlates with the fourth believe of a spiritual forest transition, e.g., to reconnect with nature by providing various values to water resources other than the instrumental values (Roux et al., 2022). This additional value is attractive not only to the prosperous societies, but also to people with strong religion and local wisdom (Torralba et al., 2020; Roux et al., 2022). But the effort to create and maintain these other values is a long-term effort and requires the involvement and commitment of a multitude of stakeholders from local to national, even global levels (Medema et al., 2019). Efforts to restore harmony with nature require suitable methods and strategies down to the local level because it needs to integrate development together with conservation (Dewi et al., 2013; Costanza et al., 2014). The efforts to restore hydrological functions need to be carried out without neglecting human welfare and the needs of other people. A multi-stakeholder forum in the Rejoso watershed and the Pawan-Kepulu peatland were created to communicate various needs of stakeholders. These forums target a multifunctional landscape to restore hydrological function and maintain landscape development. The development process of a multifunctional landscape based on the ten principles of the landscape approach, one of which is the clarification of rights and responsibilities (Sayer et al., 2013; Minang et al., 2015). Both multi-stakeholder forums are a forum for all parties to share information, clarify their rights and responsibilities and integrate their plans for resource management. The Pasuruan Watershed Forum is a multi-stakeholder forum in Pasuruan implementing groundwater restoration in the Rejoso watershed by improving land cover in recharge areas (upstream and midstream) to increase infiltration and promote good agricultural systems with water management downstream. This program has been legalized at regional government spatial plans and supported by economic compensation from water utilization companies to farmers who have lost opportunities because of the program (Leimona et al., 2018, 2020). The Joint Secretariat in the Ketapang district acts as a multi-stakeholder forum that carries out land use management and water management by blocking canals to prevent fire hazards. The district government, accompanied by the provincial, national government and researchers, produced a master plan for land use and water management supported by economic revitalization to replace lost opportunities as a result of implementing the plan (Widayati et al., 2024).

To facilitate the development of restoration strategies that involve many parties, tools are needed to increase stakeholder understanding and facilitate knowledge sharing between stakeholders. Various socio-hydro(geo)logical studies have been carried out to understand the socio-hydrological system in the Rejoso watershed (Amaruzaman et al., 2018; Toulier et al., 2019a; Suprayogo et al., 2020; Khasanah et al., 2021) and the Pawan-Kepulu peatland (Widayati et al., 2021, 2022; Abdurrahim et al., 2023). In this thesis, I used hydrological modelling (Chapter 3 and 4) and serious games (Chapter 5 and 6) as tools to improve stakeholders' understanding to develop mutual understanding and commitment.

7.3. The Simplification of Socio-hydrological System through Models and Serious Games

The complexity of the systems can be classified into four: simple system, complicated system, complex system and wicked system (Andersson et al., 2014). A system is categorized as a simple system if it has a clear way to deal with existing problems and can be translated into a mathematical theory with numerical methods and equations (Glouberman and Zimmerman, 2002; Andersson et al., 2014). Various combinations of these simple systems become complicated system and/or complex system. A system moves from a simple system to a complicated system when dealing with various underlying theories and concepts, while becoming a complex system when built by many interconnected nodes (complexity science). Even though a complex system has many nodes with unclear structures, each node has its own internal processes (van Den Bergh et al., 2011). Lastly, a wicked system is a combination of complex system and complicated system.

The socio-hydrological system is a wicked system as it consists of many interconnected components that carry a high level of uncertainty (Rumeser and Emsley, 2019). However, a wicked system can be understood by fragmenting the system into smaller parts and pulling them to the closest simple, complex or complicated systems, because these systems have a clearer basis for solving them than looking at them as a whole (Andersson et al., 2014). Using the Cascade model of water resources, I categorize the changes of land cover that influence the hydrological functions as a complex systems (Chapter 3 and Chapter 4, Fig. 7.1A), while changes in hydrological functions that influence the benefits received by humans as a complicated system(Chapter 5, Fig. 7.1B).

Breaking socio-hydrological systems into complex systems and complicated systems will make it easier for us to break them down into simpler systems. As part of a complex system, understanding the impact of land cover change on hydrological functions can be understood in a top-down manner (Törnberg, 2017). I used the water balance concept to approach this system, where surface flow, sub-surface flow and base flow are functions of rainfall, which are influenced by landscape conditions consisting of land cover, soil types and water infrastructure (Chapter 3 and 4, Fig 7.1A). Since the 1850s, people have used hydrological models, which continue to be further developed along with the development of computational methods in hydrology (Singh, 2018). Initially, hydrological models tended to be mathematical-physical laws that focused on certain components in water cycle (e.g., evaporation, peak discharge, surface flow) through a series of field and laboratory experiments. The digital era has supported advance computation, so we can involve more data in the calculation. This condition improves the implementation of hydrological models from the basic modelling to the applied modelling to address hydrological problems (e.g., water pollution, soil erosion and sedimentation, reservoir management). The hydrological model in this thesis (Chapters 3 and 4) is a process-based model that was built top-down by breaking down system components into smaller components until they reach the desired level of accuracy and are in accordance with existing data availability. However, Horton et al. (2022) argued that the hydrological model developed should be no more complex than the adapted system and in accordance with the simulation objectives of the model. Computational calculations for each component refer to various pre-existing basic and advanced hydrological models.

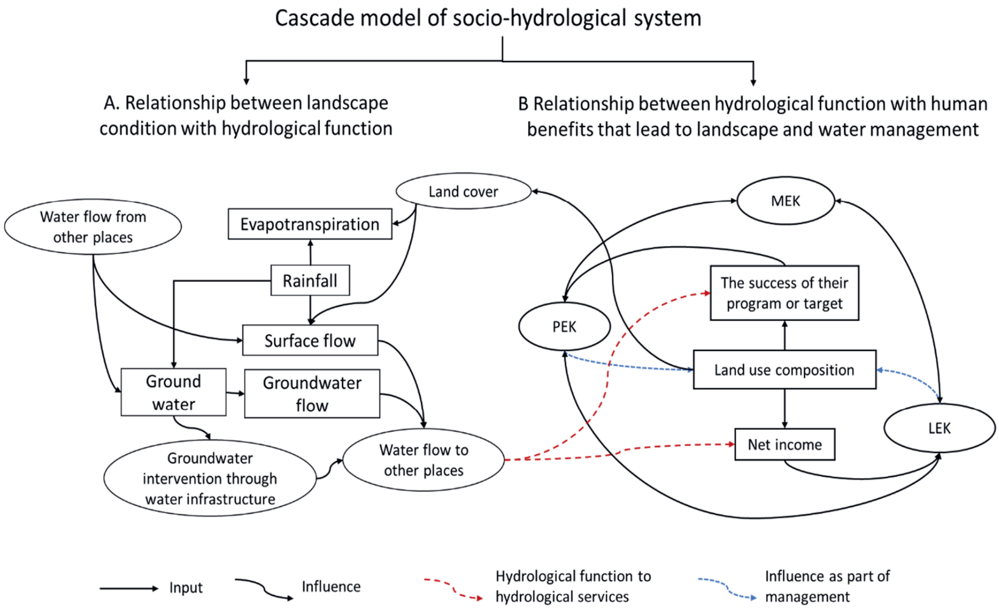


Figure 7.1. The conceptual model of a socio-hydrological system based on the cascade model approach. Hydrological functions (surface flow and groundwater conditions) Hydrological functions (surface water and groundwater conditions) which become water services for people (water flow to other places) influence net income or indicators for evaluating the success of a program. (LEK = Local ecological knowledge from local communities, PEK = Public Ecological Knowledge from public stakeholders, MEK = Modeller Ecological knowledge from modeller/researcher).

The changes in hydrological functions that influence the benefits received by humans are described as a complicated system. Törnberg, (2017) mentioned that the solution of complicated systems requires bottom-up understanding. Each component has its own characteristics that will determine the dynamics of the system. In this thesis, the H_2Ours game used Local Ecological Knowledge (LEK), Public Ecological Knowledge (PEK) and Modeller/Researcher Ecological Knowledge (MEK) as a basis for understanding the response of stakeholders to the hydrological benefits they receive which collected and structured based on Driver, Pressure, State, Impact and Response (DPSIR) and Actor, Resource, Dynamic and Interaction (ARDI) frameworks (Chapter 5). Apart from that, interactions between stakeholders also determine the dynamics that occur in this system. Because the model is built top-down while the serious game is built bottom-up, these two tools complement each other in simplifying the socio-hydrological model system. Therefore, the combination of simulations from the hydrological model and the H_2Ours game simplifies the complexity of the socio-hydrological system without losing local context in the two areas.

7.4. Adaptation of Models and Serious Games in this Thesis

This section discusses how models and games can be adapted for reuse for other issues or at other locations. I answer this question by discussing: (1) adaptation of the hydrological model and serious game, (2) adaptability of the hydrological models used in this thesis, and (3) adaptability of the H_2Ours game.

7.4.1. Adaptation of hydrological models and serious games

The need for flexible and adaptable models and games has encouraged the availability of generic models that can be adapted to the needs of users (Wagener et al., 2001). There are two approaches that can be taken in developing flexible and adaptable models and games: the existence of 'plug and play' component features and an 'open-transparent' framework (Castronova and Goodall, 2010). The 'plug and play' feature is often found in hydrological models, which have many components and databases to maintain model flexibility by accommodating various variations from various systems (Sidle, 2021). Without a database, the model can be built in an open and transparent process-based framework so that users are able to enter the database according to their conditions. On the contrary, the flexibility of role-playing games is based on an open and transparent process using a bottom-up approach, so that users can adapt it according to their needs and system conditions.

Adaptation of models and games needs to consider the goals and targets of the model and game (Mitgutsch and Alvarado, 2012; Silva, 2020; Paul et al., 2021b; Horton et al., 2022). This condition is to prevent the audience of the model and game from being exposed to too much unnecessary information at the same time, so that they can improve their knowledge gradually (Rumeser and Emsley, 2019). If the model and game targets adding other information and increasing the knowledge of the user as part of the learning process, then adaptation is carried out by adding new elements (e.g., adding modules in the model, changing issues in the game, adding challenges for the players). However, if the aim of the model and game is to find out the conditions of different locations with different audiences, then adaptation is carried out by changing the system to suit the new location being targeted (e.g., changing the type of land cover, changing the type of water management, changing the economic and environmental impact variables in-game). This thesis adapted the GenRiver model by adding a more detailed groundwater module in the case of the Rejoso watershed (Chapter 3), and by adapting the GenRiver model to a peatland hydrology model that required an understanding of changes in hydrological conditions because of changes in land cover, peatland water management and distance to canal (Chapter 4). Finally, Sari et al.,(2024) transformed a plot level hydrological model to individual Farmer Options and its Risk in Complex Ecological-Social systems (FORCES) game. To scale up the FORCES game, I transformed the landscape level hydrological model into the H_2Ours game by adding more actors who make changes to land use and water management, and by allowing interactions between actors (Chapter 5, Fig. 7.2).

7.4.2. Adaptability of hydrological models used in this thesis

The hydrological models used in the Rejoso watershed and the Pawan-Kepulu peatland have similar objectives and outputs. Even though it uses the general water balance equation (Eq.1), discharge in the watershed considers the distance to the final outlet based on the river network and the water level in peatlands based on the distance to canal. Below is a more detailed explanation of the adaptation process of the GenRiver model by improving the groundwater module in the Rejoso watershed and the GenRiver model transformation to the Re-Peat model in the Pawan-Kepulu peatland. The differences and similarities in the structure and components of the two hydrological models are given in Table 7.2.

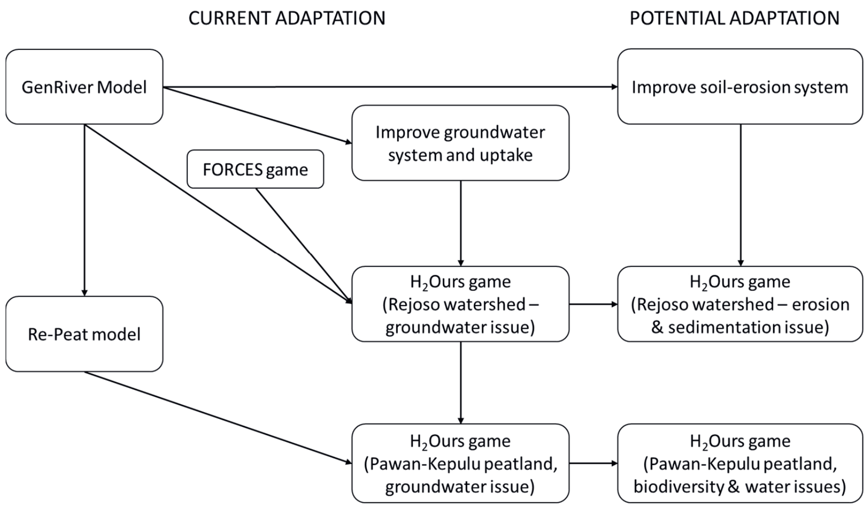


Figure 7.2. Two adaptations from the GenRiver model are: improving the groundwater module to meet the Rejoso watershed context and transforming into the Re-PEAT model to adjust with peatland hydrology system for the Pawan-Kepulu peatland case. Both hydrological models were adapted into two versions of the H_2Ours game (watershed and peatland) with FORCES game as the intermediate game to simulate individual farmer decision making at the plot level.

The GenRiver model has been applied on various watershed conditions, both inside and outside Indonesia, for areas ranging largely in size: 6.3 – 9861 km^2 (Lusiana et al., 2008a, b; Khasanah et al., 2010; Tanika et al., 2018). Although it has been applied in many places to study the historical water balance and predict its future, the GenRiver model is categorized as a Land Surface Model (LSM). The LSM cannot capture the groundwater dynamic in the aquifer, resulting in unrealistic water table values (Niu et al., 2007). In the current version of the GenRiver model, the amount of groundwater is derived only from the infiltration rate, percolation rate and soil water holding capacity per soil type, modified by land cover. Its outflow is directly added to the river at the spatial unit, and subject to the routing information for river-flow. Therefore, the GenRiver model could not fully simulate the overall groundwater problem in the Rejoso watershed. To overcome these limitations, we focused on the issue of groundwater utilization in downstream areas in Chapter 3. We added to the model a component to describe groundwater uptake by farmers based on the number of drilled wells and the average amount of discharge from drilled wells. Using a simple water budget equation where the groundwater that has the potential to enter the Umbulan spring is the difference between the groundwater that flows from upstream and midstream to downstream (groundwater supply), and the groundwater up take taken by farmers (groundwater demand by farmers) (Eq. 1). Because it used a simple water balance and water budget mathematical equations, the modelling in the Rejoso watershed can be categorized as a simple 'problem' which is easy to adapt to other places if the required inputs are met.

Adapting the GenRiver model which connects Hydrologic Response Unit (HRU) to watershed landscape based on a river network (van Noordwijk et al., 2011), while in Re-Peat model, I connected HRU to peatland landscape based on a canal network (Chapter 4). The GenRiver model and the Re-Peat model divide the HRU according to land cover types, soil factors and water network. Land cover in the GenRiver and Re-peat models contributes to the calculation of evapotranspiration and the amount of infiltration and runoff. The soil component in the GenRiver model is based on the variation and distribution of soil types in the watershed, which influences the level of infiltration and the capacity of the soil to store water. In the case of the Re-Peat model, because it only uses peat soil types, we included peat-depth into the calculations, as peat-depth is an important factor influencing the capacity of peat soil to store water. The water network in the GenRiver model is in the form of a river network that divides the landscape into several sub-watersheds, which are then related to the river flow travel time from each watershed to a particular outlet. In the Re-Peat model, the water network represents the canal distribution that influences the distance between canals, which influences the number of peatland water entering the canal.

In general, the input and the modelling process of the Re-peat model are the same as other hydrological models. The Re-Peat model requires at least daily rainfall data, daily groundwater level data associated with the nearest daily canal water level, land cover map, peat depth map and river network map (Chapter 4). For model adaptation to other places, I encourage to obtain groundwater level data that represents several types of land cover and distance between canals that can be used to validate model performance but can also be used to calibrate peat soil characteristics related to hydraulic conductivity (the ability of groundwater to move horizontally and vertically), which may be difficult to obtain. If measurement data are not available, then it is possible to use references to the bulk density and hydraulic conductivity of the variations in peat soil types in the area to be modelled. The modelling process of the Re-Peat model consists of input preparation, model calibration and validation and model simulation. The challenge in the Re-peat modelling process is in the first two stages, where we need to obtain data that can represent variations at the landscape level with quality that can be used for the model calibration and validation process. I collected groundwater level variations based on several dominant land covers combined with the presence of canal blocking (with and without) and variations in distance to the canal. For model validation, I compared the average groundwater measurements with the simulation results of the Re-Peat model at the measurement plot. However, a better validation approach is needed; one that considers the landscape elevation (Chapter 4).

7.4.3. Adaptability of the H_2Ours game

The adaptation target of serious games is carried out to accommodate adaptivity and adaptability of the games (Streicher and Smeddinck, 2016). Adaptivity is needed to meet the needs of players playing the game. It and is related to the player's learning path by maintaining the level of challenge and skills acquired by the player so that the game remains enjoyable by maintaining a balance between frustration and boredom (Streincher 2016). Meanwhile, the adaptability of the game aims to meet general user needs (e.g., user or player from other areas).

The open design of the H_2Ours game with its generic design aims to accommodate adaptivity and adaptability (Chapter 4). The adaptability of the H_2Ours game was demonstrated by changing the game setting from the Rejoso watershed to the Pawan-Kepulu peatland. This describes a change in game context to adapt to a new location, but still maintains the structure and objectives of the game. The adaptivity of the H_2Ours game can be seen from increasing challenges during the game session through scenarios provided by facilitators or other groups of players (e.g., tree planting regulations from the government, canal blocking programs by multi-stakeholder forums, etc.). The open design of the H_2Ours game also allows game modification for other issues, so that the same player can gain understanding regarding other issues. For example, this thesis building the H_2Ours game focuses on groundwater problems only, which does not include other problems such as landslides and sedimentation. Modifying the H_2Ours game with new problem issues but played by the same players, will provides a different level of challenge and knowledge.

Table 7.2. Similarities and differences of the hydrological models used in the Rejoso watershed and the Pawan-Kepulu peatland.

No	Parameters	Rejoso watershed	Pawan-Kepulu peatland
1	Objective of hydrological modelling	Phase 1: To simulate the impact of land cover and water management to the infiltration in the upstream and midstream of the Rejoso watershed. Phase 2: To simulate the impact of land cover and water management to the discharge of the Umbulan spring in the downstream.	To simulate the impact of land cover and water management to the groundwater level.
2	Number of Hydrologic Response Unit (HRU)	Phase 1: 1,104 as the combination of the number of sub-catchments, land cover types and soil types. Phase 2: 3 units(Upstream, midstream and downstream.	92,076 polygons as the combination of the number of land cover types, peat depth and distance to canal.
3	Basic calculation in each HRU	Simple water balance model: $P = E + Q + \Delta S$ Eq. 1	
4	Connection from HRU to landscape level	Phase 1: River network Phase 2: Elevation	Canal distribution.
5	Input	Phase 1: Daily rainfall, land cover, soil type, DEM. Phase 2: Annual rainfall, elevation, land cover, and average of water extraction from artesian wells.	Daily rainfall, peat depth, land cover, distance and density of canal.
6	Type of water management	Phase 1: - Phase 2: Deep groundwater extraction through artesian wells.	Shallow groundwater outflow through artificial drainage.
7	Output	Phase 1: Daily water balance Phase 2: Average of the Umbulan spring discharge	Daily groundwater distribution.
8	Modelling time-step	Phase 1: Daily Phase 2: Annual	Daily

7.5. The Functionality of a Model and a Serious Game to Support Human Appropriation of Water Resources

To tackle the question of how serious games and models can support the decision making in restoring the hydrological condition, I discuss it through three sections: (1) The roles of models and games in conservation and restoration strategies, (2) Attributes of models and games to support conservation and restoration strategies and (3) Factors to consider in selecting or developing a model and game. First, I discuss why models and games are needed in restoration planning, then how we can trust our models and games, and provide insights on the factors that influence the performance of models and games.

7.5.1. The roles of models and games in conservation and restoration strategies

Formulating policies on water-related issues often uses socio-hydrological models as a tool to improve the understanding of the system, to carry out forecasting and predictions to better informed decision-making (Blair and Buytaert, 2016). Models are also used to provide an explanation of the behaviour of the hydrological system and the causes of its changes (Jakeman et al., 2006; Pianosi et al., 2016; Mozafari et al., 2023). Similarly, serious games are used to increase understanding (e.g., factors that influence decision making), gather information and trigger changes in decisions (e.g., changes in land and water management) (Rodela et al., 2019; Meinzen-Dick et al., 2016; Janssen et al., 2023; van Vugt et al., 2014).

Hydrological models and serious games complement each other in supporting the implementation of water resource restoration or conservation methods (Figure 7.3). Hydrological models, through their role in prediction, help simulate various hydrological conditions based on data and information related to technical aspects (e.g., land cover, existence of water-related infrastructure) (Singh and Kumar, 2017). The gap between the results of the hydrological simulation and the implementation of a given strategy is the result of the many combinations of strategies that are possible as a consequence of the fact that socio-hydrological system is a wicked problem (Blair and Buytaert, 2016). If we develop serious games based on forecasting and prediction results from hydrological models, the simulation results of serious games can increase the credibility in formulating policies and making decisions related to water resource management when exploring various scenarios (Villamor et al., 2023; Fleming et al., 2016, 2014). The results of policy formulation and decision making from serious games are then simulated again using a hydrological model to obtain optimal solutions that can be used as a basis for implementation (Villamor et al., 2023). As part of the understanding to action chain, monitoring and evaluation will connect implementation back to understanding the system. I developed the environmental impacts of the H_2Ours game of the Rejoso watershed based on the results of the GenRiver model simulation (Chapter 3 and 5). For the H_2Ours game of the Pawan-Kepulu peatland, I developed the environmental and economic impacts based on the plot measurement results combined with the tree-crop preference survey for local stakeholders (Chapter 4 and 5). As part of future recommendations, I suggest additional model simulation based on the results of decision making related to land use and water management from the H_2Ours game simulation as the consideration for real life implementation.

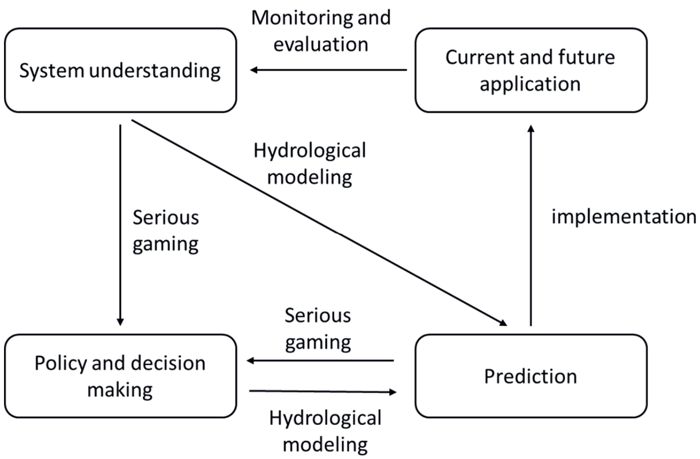


Figure 7.3. The looping and complementary roles of hydrological models and serious games in supporting conservation and restoration plans.

When designing a multifunctional landscape, stakeholders need to identify contributions from and to the landscape (Fagerholm et al., 2020), and need to see the entire landscape to develop a shared understanding of the entire space (Medema et al., 2019). The hydrological model and the H_2Ours game in this thesis simplified the spatial dimension,which make it easier for stakeholders to see the entire landscape (Chapter 2, 4 and 5). Stakeholders needed to try various management combinations throughout the landscape to identify the risks and benefits experienced by each stakeholder. In this case, the hydrological model and the H_2Ours game had simplified the time, allowing them to carry out safe exploration of various management scenarios. It is expected that the results of these simulations will provide an overview for each stakeholder of how they are involved, the risks and benefits that may occur, what factors influence decisions (motivation) and the necessary enabling conditions (van Noordwijk et al., 2013). Based on the results of the H_2Ours game simulation in the Rejoso watershed (Chapter 6), the game participants realized that land use and water management decisions by a certain stakeholder had environmental and economic impacts on other stakeholders. Negotiation for collaborative actions between stakeholders occurred more effectively when stakeholders meet face to face. Therefore, a multi-stakeholder forum for integrated management strategies from all stakeholders is a factor that determines the success of restoration.

7.5.2. Attributes of models and games to support conservation and restoration strategies

Modelers and game designers build hydrological models and serious games using many assumptions, which make it difficult for public stakeholders and local stakeholders to accept the simulation results from models and games because of different points of view (van Voorn et al., 2016). Therefore, we need approaches that can facilitate different points of view from various stakeholders and increase stakeholders' trust and acceptance of the results. This thesis used credibility, salience and legitimacy to assess the quality of the H_2Ours game, but it only used credibility to assess the hydrological model. By applying input-output assessment, I applied credibility, salience and legitimacy since the development of the H_2Ours game (Chapter 4). Various options for land cover, water management and program scenarios used in the H_2Ours game in the Rejoso watershed and the Ketapang peatland result from LEK, PEK and MEK identification. We validated these results during the game testing stage with farmers (from the non-targeted participants) to see the suitability and acceptability of the game rules (Chapter 5). The evaluation results after the H_2Ours game session in the Rejoso watershed and the Pawan-Kepulu peatland showed that the participants understood the purpose of the game and recognized their real-life system in the game (Chapter 4). Based on before and after surveys with q-method, there was a shift in perception towards the factors that secure water availability, the causes of hydrological problems and the factors that determine the success of restoration efforts (Chapter 5). This change is the first step towards changing behavior and management for real implementation. In the case of the hydrological model, the credibility of the model was assessed by the model's ability to estimate one or more water balance components in approaching the measurement data. The simulation results of this model become the MEK component in the H_2Ours game at the Rejoso watershed, so this research did not carry out an assessment of the salience and legitimacy, specifically of the hydrological model.

7.5.3. Factors to consider in selecting or developing a model and game

Several factors need to be taken into consideration in developing hydrological models and serious games that are expected to support hydrological conservation and restoration strategies. Based on this thesis, I identified the following factors:

a. The objective of the model and game should be in accordance with the needs of the implementation (Wagener et al., 2001; Mitgutsch and Alvarado, 2012; Silva, 2020; Paul et al., 2021b). In this thesis, the model supported in forecasting and predicting changes in hydrological function conditions because of landscape changes, while the H_2Ours game facilitated exploration of solutions by stakeholders. Apart from that, the models and games in this thesis were used to complement each other to overcome/narrow the gap between LEK, PEK and MEK.

b. Adaptability of models and games. Generic models and games allow users to adapt them to the conditions of the area to be simulated (Paul et al., 2021b). Because of using the generic version, the model or game requires input preparation before being used for simulation. Section 6.4 provides an overview of the adaptation of the hydrological model and the H_2Ours game used in this thesis.

c. Medium to high resolution. Simulation models and games require a level of assessment precision from medium-to-high to influence regional land use planning and policy analysis (Costanza et al., 2014). In this thesis, I simulated the hydrological model and H_2Ours game in the Rejoso watershed and the Pawan-kepulu peatland at the landscape level. However, I included information at the local level consisting of types of land use and water management during the model and game development process, either based on secondary data or field measurements.

d. Communications. The communication process (e.g., word choice, two-way communication) during the information gathering process, simulation and evaluation after the simulation can influence changes in the perceptions and behaviour of the stakeholders involved (Falk et al., 2023). In the H_2Ours game session, communication occurred during briefing, game simulation and debriefing influenced the changes in participants' perceptions.

Several limitations need to be considered supporting conservation and restoration planning:

a. The explored scenarios of model and game simulations cannot be implemented directly. Even though models and games are built as close as possible to real conditions with medium to high resolution, the results of the model and game simulations do not guarantee that these scenarios can be implemented directly. Models help to identify factors that influence changes in technical hydrological conditions, while serious games help to identify factors that influence decision making. Therefore, re-simulating land use and water management decisions resulted from game simulations as input to the hydrological model provides a clearer picture of forecasting hydrological conditions to stakeholders (Fig. 7.3), including presenting factors that influence hydrological conditions and enabling conditions needed for implementation.

b. There are no definitive benchmarks regarding models and games that can support a restoration strategy. Even though the model and game development process followed the framework of credibility, salience and legitimacy to increase trust and acceptance of wider parties, it still requires mutual agreement regarding indicators of credibility, salience and legitimacy. Each stakeholder has a different perspective regarding credibility, salience and legitimacy (Cash and Belloy, 2020). For example, for researchers, the credibility of the data lies in scientific credibility, while the government refers more to the legal entity of the data used. Therefore, agreement on indicators within the framework of credibility, salience and legitimacy needs to be part of the discussion by the parties.

7.6. Limitation and Lesson Learned

In this section, I present limitations and lessons learned of this thesis during data collection, hydrological modelling, and serious gaming.

a. Lack of groundwater data in the Rejoso watershed to validate the groundwater model. I only had some information about the discharge of the Umbulan spring from previous studies. Therefore, the hydrological model validation in the Rejoso watershed only used one point validation based on the average discharge of the Umbulan spring(Chapter 3).

b. To be able to pursue peatland groundwater data in the dry season (June – September), the selection of measurement plots in the Pawan-Kepulu peatland was carried out at the dominant land cover obtained based on field observations before obtaining the land cover map of the Pawan-Kepulu peatland. Therefore, there were several adjustments to the classification of the land cover map to the observation data (Chapter 4).

c. Need more sophisticated validation in the Pawan Kepulu Peatland. Even though we have groundwater level measurement data for the Pawan Kepulu, we only got one measurement location which is close to 1-1 line. We suspect that elevation has an influence on groundwater measurement values. For example, 50 cm in plot A is not necessarily the same as 50 cm in plot B with a different height. Therefore, we suggest that modelling be carried out by considering elevation as an additional layer (Chapter 4).

d. Because the H_2Ours game involved many participants, inviting participants to attend and take part in the game session was a challenge. Serious games for adults in Indonesia are not yet a familiar thing. Therefore, I used 'simulation' rather than 'game', and explained what they would do during the simulation session.

e. The format of the game session is an important factor, especially when game simulation is part of the research. Combining game sessions with other activities carries the risk of reducing the focus of the game participants. Therefore, the game session format needs to consider the location and overall agenda of the event to prevent participants from being distracted by external factors and boredom.

7.7. Potential Future Work

In this section, I have three recommendations for potential future work related to some of the finding of this thesis. Firstly, the groundwater module in Chapter 3 is still being developed in MS Excel with yearly time steps. Therefore, integrating the groundwater module with the original version of the GenRiver model will provide daily time steps. This module can also potentially be added with potential groundwater outflow from wells and springs in the upstream, midstream and downstream to increase the accuracy of the water budget from the overall groundwater system. This model has the potential to be used to simulate other watersheds around the Rejoso watershed with similar characteristics, namely volcanic areas with many springs and groundwater utilization. Secondly, the H_2Ours game is designed to be a generic and open game, making it easy to adapt to other problems. The modification of H_2Ours with the issue of erosion and sedimentation, which has an impact on flooding and river silting in the downstream area and landslides in the upstream area, become a learning path for stakeholders in the Rejoso watershed. After the participants gain an understanding of the problems of groundwater, flooding, landslides and sedimentation, we can try to combine all the problems in one game to see the overall economic and environmental trade-offs in the entire Rejoso watershed. Finaly, to continue analysis of the application of the Re-Peat model in the Pawan-Kepulu peatland to identify parameters that significantly influence fire occurrence in this landscape. I propose a further analysis of the results of groundwater simulations by overlapping the groundwater map at the landscape level (Chapter 4) along with distance to roads, land management (or ownership), relative to canal distance, and other parameters that have the potential to cause land fires with hot-spots and fire incidents.

7.8. Conclusion

Understanding human actions to influence water resources refers to the relationship between humans and water resources, and the factors that influence their perceptions and actions. Stakeholders need to optimize their landscape conditions to meet their various needs through a multifunctional landscape. To achieve this, a shared understanding is needed to create an integrated and long-term strategies. Hydrological models and serious games are widely used to be an explanatory and learning tool to facilitate coordination and negotiation between stakeholders in creating a multifunctional landscape. Presenting the complexity of socio-hydrological systems in a simpler form through hydrological models and games allows stakeholders to understand the interactions and dynamics between nature and humans, and the impact of these relationships. The simplification process can be carried out through fragmentation and integration of the components of the socio-hydrological system using a clear framework. This process also accommodate the adaptability and reusability of the hydrological models and games for other problems or for replication in other locations. To contribute to stakeholders' decisions in land and water management, the hydrological models and serious games need to gain acceptance from stakeholders. To meet these conditions, models and games need to accommodate various spatial scale variations. This acceptance acts as a basis for forming shared commitments and responsibilities among stakeholders to develop a multifunctional landscape which provide more values to water resources. This condition changes human appropriation of water resources to no longer be concentrated on the exploitation of water resources only as a product as the instrumental value, but also on recreation for other functions as a relational value.

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Taking a break during soil data collection in the Pawan-Kepulu peatland. Pineapples were always the best thirst quencher in the middle of the day.

Summary

The reciprocal relationship between humans and nature is constantly changing and is perceived in many ways by society. This relationship varies with changes in perspective that are influenced by relational and instrumental values associated with natural resources, such as water resources. Human appropriation of water resources in socio-hydrological systems can be understood as part of the four phases of the 'spiritual forest transition': (1) nature is powerful and humans adapt to current water resource conditions; (2) taming of nature when human began to manage nature to get the hydrological services they want; (3) rational management of nature when science-based water management tries to stay within planetary boundaries and use nature-based solutions in land, water and climate management where feasible; and (4) reconnection with nature by exploring other services associated with water, e.g., spirituality, aesthetics, pleasure, recreation. The disruption of natural water supply and demand can trigger different hydrological problems. To address them, people attempt to restore desired hydrological functions to fulfil human needs.

Multifunctional landscapes with diverse land uses for a variety of purposes are expected to provide a range of ecosystem services. However, the development of multifunctional landscapes requires the integration of various human needs and knowledge systems, which is often very challenging. Hydrological models and serious games (with conceptual and formal models in the background) can be used to simplify the representation of socio-hydrological systems and to facilitate the development of a shared understanding from stakeholders. These models and games should be adaptable and re-useable to local context and issues, and replicated so that they can be implemented in locations that face similar problems. Such models and games are expected to contribute to the articulation of responsibilities and to stakeholder decision making in the process of developing real-life multifunctional landscapes.

The objective of this thesis is to develop a fuller understanding of socio-hydrological systems for sustainable water resource management in multifunctional landscapes by integrating information from different knowledge systems and perspectives of different stakeholder. This thesis addresses the objective through four research questions: (RQ1) What are the impacts of human actions on water resources at various spatial scales?, (RQ2) How can the socio-hydrological system be simplified into hydrological models and serious games?, (RQ3) How can hydrological models and games be adapted and replicated?, and (RQ4) To what extent are games and models contributing to decision making in restoring the hydrological functions?. To answer the research questions, I used a transdisciplinary approach that combines social and biophysical research. I identified the Local Ecological Knowledge (LEK), Public Ecological Knowledge (PEK) and Modeller/researcher Ecological Knowledge (MEK) based on literature reviews, interviews and discussions with stakeholders, and conducted field measurement and hydrological modelling. I structured the LEK, PEK and MEK information using Driver, Pressure, State, Impact and Response (DPSIR) and Actor, Resource, Dynamic and Interaction (ARDI) frameworks to develop serious games to assess and predict the hydrological functions. I evaluated the use of serious game to the changes of stakeholders' perception using the Likert and Q-methodology survey. Two study sites were used to demonstrate the adaptability of the hydrological models and the serious games.

This thesis uses the experience of ongoing development and research projects in two contrasting study areas: the Rejoso watershed and the Pawan Kepulu peatland, both in Indonesia. These areas have different biophysical characteristics and allow to demonstrate the adaptability and replicability of hydrological models and serious games. Both areas have a national priority status in landscape management for their important roles in human welfare with diverse and multi-level stakeholders. The Rejoso Watershed (62,733 ha) supplies water for downstream irrigation and it is a source of

drinking water for 1.3 million people. This landscape is experiencing hydrological problems due to intensive agriculture, which reduces groundwater supply in the recharge area (upstream and midstream) and increases groundwater demand from the abundant unregulated artesian wells in the downstream area. The Pawan-Kepulu peatland (64,263 ha) has a high frequency of fires, which cause various problems at local, provincial and national scales such as health issues, and social, economic and environmental disruptions. To make this landscape more economically productive, people dug many canals to drain the peatlands for plantations and agriculture. As a result, this area becomes drier and prone to fires during the dry season. In both landscapes, a transition from unbounded water resource extraction to water resources management within environmental limits is needed.

Chapter 2 provides a literature review of ten paradigms that describe the relationship between humans and nature, in freshwater availability through rainfall (or otherwise):rain god, rain makers, forests, topography, cloud seeding, warfare convention, global climate change, precipitation-shed teleconnections, biotic ice-nucleating particles, and desalinizing sea water. This review addresses the question of human impact on water resources (RQ1) and shows the evolution of human efforts to influence rainfall from meeting water needs to water for other purposes as part of the instrumental and relational values on the relationship between humans and nature. The ten paradigms are spread across three of the four transition phase of human–nature relationships listed above. This chapter shows that the relationship between humans and rain has been established for a long time, and humans also recognize that rain has become an important part of water resources. This is proven by various human efforts to influence rain.

Chapter 3 addresses for the Rejoso watershed the impact of land use and water management on recent hydrological degradation and current efforts to restore the discharge of the Umbulan spring (RQ1). Through adjusting a simple hydrological simulation model (RQ2), I represented groundwater uptake to parameterize the conditions of the Rejoso watershed with artesian wells and the Umbulan spring for urban/industrial groundwater utilization. The hydrological model simulated four land and water management scenarios: i) business as usual, ii) land use enrichment in upstream and midstream zones, iii) water management in the downstream areas, and iv) a combination of interventions in upstream, midstream and downstream water management. This chapter also provides a typology of rice farmers who use groundwater to understand their decisions in cultivating their land and utilizing the artesian wells. According to the result of the hydrological simulation and the typology of rice farmers, effective and efficient interventions need to be implemented based on field and farmer characteristics.

Chapter 4 presents the development of a process-based and semi-distributed peatland hydrological model (RE-PEAT model) for the Pawan-Kepulu peatland. The model was built based on field measurement of groundwater levels to provide a multi-scale hydrological understanding of the impact of land and water management (RQ1), given the temporal fluctuations due to rainfall patterns, the spatial patterns linked with depth of the peat profile, position in the peat dome and distance to the nearest drainage canal, the influence of vegetation (land cover) and the way the water levels in the canals are regulated. The model combined two approaches (RQ2): a simple water budget equation (flow in = flow out) for temporal buffering, and peat-depth dependent hydrostatic gradients perpendicular to drainage canals. The resulting peatland hydrological model can be applied at plot and landscape level. Groundwater level and canal water level data from periodic monitoring were scaled up to the whole Pawan-Kepulu peatland to quantify the temporal and spatial risks of groundwater levels deeper than 40 cm, which have been linked to increased fire risk. A combination of climate scenarios (wet, dry and normal year based on precipitation), land use scenarios (forest, oil palm plantations and seasonal agricultural crops) and water management scenarios (with and without canal blocking) were used to assess the various impacts of land and water management on groundwater levels. The simulation results support a choice of tree-based land use to keep the peatland moist and the construction of canal thresholds (‘blocking’) to reduce groundwater outflow during the dry season and therefore, reduce the risk of fire hazards.

Chapter 5 focusses on the development process of the H_2Ours game in the Rejoso watershed as the simplification of the system (RQ2) and the adaptation process in the Pawan-Kepulu peatland (RQ3). The Driver, Pressure, State, Impact and Response (DPSIR) and Actor, Resource, Dynamic and Interaction (ARDI) frameworks were used to identify the connectivity of social and biophysical components that influence hydrological functioning conditions in both landscapes. I used credibility, salience and legitimacy criteria to develop and evaluate the quality of the H_2Ours game in facilitating knowledge sharing to gain a shared understanding among stakeholders to support restoration strategies. Based on the Likert survey after the game sessions, most of the participants indicated that they enjoyed the game session and gained new knowledge from the simulation. Even though they stated that the collaborative and collective actions could be implemented in real conditions, it is necessary to create enabling conditions that support implementation.

Chapter 6 reports the use of the H_2Ours serious game in the Rejoso watershed to explore the land use and water management decisions made by game participants and the changes in their perceptions after the game session (RQ4). The patterns and the reasons of the participant’s decisions, as well as their responses to governmental regulation and Payment for Ecosystem Services (PES) scenarios, provided information on the factors that influence their decision making. The results shows that during the game session, participants made decisions based on their ecological knowledge. Information, training and mentoring broaden their insight, thereby providing more options for land and water management. The Q-methodology surveys before and after the game show that the game changed the participants’ knowledge by improving their water supply-demand concept, expanding their knowledge on the causes of the hydrological problems and identifying the factors that determine the success of restoration.

Chapter 7 is the General Discussion of this thesis. In this chapter I started by emphasizing forms of human appropriation of water resources in various components of the water balance at various scales. In the Rejoso watershed and the Pawan-Kepulu peatland, many forms of human appropriation of water resources lead to various socio-hydrological problems. Because land and water management at the landscape level involve many stakeholders, efforts to restore hydrological functions require a shared understanding of the socio-hydrological system to create shared commitment and responsibility. Hydrological models and serious games developed by simplifying the socio-hydrological system without losing its essence allowed to create shared understanding through sharing knowledge among stakeholders. The tools developed in this thesis are adaptable through plug and play features or an open and transparent approach, which will facilitate their use in other areas facing similar socio-hydrological problems. Finally, the hydrological models and serious games developed seem to be effective and efficient tools for forecasting and prediction in developing multifunctional landscapes to accommodate various human needs. However, these models and games need recognition from stakeholders so that new knowledge and insights gained from the model simulations and game sessions can lead to shared commitment among stakeholders to change landscape management. The steps from shared understanding to recognized responsibilities and actions on the ground are primarily dependent on the social side of socio-hydrological systems; from our experience so far, games adjusted to local context can help in the process of moving actors in that direction.

Samenvatting

De wederkerige relatie tussen mens en natuur verandert voortdurend en wordt op veel manieren gezien door de maatschappij. Deze relatie varieert met veranderingen in perspectief die worden beïnvloed door relationele en instrumentele waarden die verband houden met natuurlijke hulpbronnen, zoals water. Menselijke toe-eigening van water in sociaal-hydrologische systemen kan worden begrepen als onderdeel van de vier fasen van de 'spirituele bostransitie': (1) de natuur is krachtig en mensen passen zich aan de huidige hydrologische omstandigheden aan; (2) temmen van de natuur wanneer de mens de natuur beginnen te beheren om de hydrologische diensten te krijgen die ze willen; (3) rationeel beheer van de natuur wanneer op wetenschap gebaseerd waterbeheer probeert binnen planetaire grenzen te blijven en op de natuur gebaseerde oplossingen gebruikt in land-, water- en klimaatbeheer waar haalbaar; en (4) herverbinding met de natuur door andere diensten te (v/h)erkennen die verband houden met water, bijvoorbeeld spiritualiteit, esthetiek, plezier, recreatie. De verstoring van de natuurlijke watervoorziening en -vraag kan verschillende hydrologische problemen veroorzaken. Om deze aan te pakken, proberen mensen gewenste hydrologische functies te herstellen om te voldoen aan menselijke en maatschappelijke behoeften.

Multifunctionele landschappen met divers landgebruik voor verschillende doeleinden zullen naar verwachting een scala aan ecosysteemdiensten leveren. De ontwikkeling van multifunctionele landschappen vereist echter de integratie van verschillende menselijke behoeften en kennissystemen, wat vaak een grote uitdaging is. Hydrologische modellen en serieuze spellen (met conceptuele en formele modellen op de achtergrond) kunnen worden gebruikt om de weergave van sociaal-hydrologische systemen te vereenvoudigen en de ontwikkeling van een gedeeld begrip van belanghebbenden te vergemakkelijken. Deze modellen en spellen moeten aanpasbaar en herbruikbaar zijn voor de lokale context en problemen, en gerepliceerd kunnen worden zodat ze kunnen worden gebruikt op locaties die met vergelijkbare problemen te maken hebben. Van dergelijke modellen en spellen wordt verwacht dat ze bijdragen aan de formulering van verantwoordelijkheden en aan de besluitvorming van belanghebbenden in het proces van de ontwikkeling van echt bestaande multifunctionele landschappen.

Het doel van dit proefschrift is om een vollediger begrip te ontwikkelen van sociaal-hydrologische systemen voor duurzaam waterbeheer in multifunctionele landschappen door informatie uit verschillende kennissystemen en perspectieven van verschillende belanghebbenden te integreren. Dit proefschrift benadert het doel via vier onderzoeksvragen: (OV1) Wat zijn de effecten van menselijke acties op waterbronnen op verschillende ruimtelijke schalen?, (OV2) Hoe kan het sociaal-hydrologische systeem worden vereenvoudigd tot hydrologische modellen en serieuze spellen?, (OV3) Hoe kunnen hydrologische modellen en spellen worden aangepast en gerepliceerd?, en (OV4) In welke mate dragen spellen en modellen bij aan besluitvorming bij het herstellen van de hydrologische functies?. Om de onderzoeksvragen te beantwoorden, heb ik een transdisciplinaire aanpak gebruikt die sociaal en biofysisch onderzoek combineert. Ik heb de lokale ecologische kennis (LEK), publieke ecologische kennis (PEK) en modelleur/onderzoeker ecologische kennis (MEK) geïdentificeerd op basis van literatuuronderzoek, interviews en discussies met belanghebbenden, en veldmetingen en heb hydrologische modellen ontwikkeld. Ik heb de LEK-, PEK- en MEK-informatie gestructureerd met behulp van Driver, Pressure, State, Impact and Response (DPSIR) en Actor, Resource, Dynamic and Interaction (ARDI)-frameworks om serieuze games te ontwikkelen om de hydrologische functies te beoordelen en te voorspellen. Ik heb het gebruik van serieuze spellen geëvalueerd voor wat betreft veranderingen in de perceptie van belanghebbenden met behulp van de Likert- en Q-methodologie.

Dit proefschrift maakt gebruik van de ervaring van lopende ontwikkelings- en onderzoeksprojecten in twee contrasterende studiegebieden: het Rejoso-stroomgebied en het Pawan Kepulu-veengebied, beide in Indonesië. Deze gebieden hebben verschillende biofysische kenmerken en laten toe om de aanpasbaarheid en repliceerbaarheid van hydrologische modellen en serieuze spellen te toetsen. Beide gebieden hebben een nationale prioriteitsstatus in landschapsbeheer vanwege hun belangrijke rol in het menselijk welzijn met diverse en multi-level stakeholders. Het Rejoso-stroomgebied (62 733 ha) levert water voor stroomafwaartse irrigatie en is een bron van drinkwater voor 1,3 miljoen mensen. Dit landschap ondervindt hydrologische problemen als gevolg van intensieve landbouw, wat de grondwatervoorziening in het inlaatgebied (stroomopwaarts en stroomafwaarts) vermindert en de vraag naar grondwater uit de overvloedige ongereguleerde artesische putten in het stroomafwaartse gebied vergroot. Het Pawan-Kepulu-veengebied (64.263 ha) brandt vaak, leidend tot verschillende problemen op lokale, provinciale en nationale schaal, zoals gezondheidsproblemen en sociale, economische en ecologische verstoringen. Om dit landschap economisch productiever te maken, groeven mensen veel kanalen om de veengebieden te draineren voor plantages en landbouw. Als gevolg hiervan wordt dit gebied droger en vatbaarder voor branden tijdens het droge seizoen. In beide landschappen is een transitie nodig van onbeperkte waterwinning naar waterbeheer binnen milieugrenzen.

Hoofdstuk 2 biedt een literatuuroverzicht van tien paradigma's die de relatie tussen mens en natuur beschrijven, in de beschikbaarheid van zoet water door regenval (of anderszins): regengod, regenmakers, bossen, topografie, wolken zaaien, oorlogsconventie, wereldwijde klimaatverandering, neerslagbrongebied, teleconnecties, biotische ijs-nucleërende deeltjes, en ontzilting van zeewater. Dit overzicht behandelt de vraag over de menselijke impact op waterbronnen (OV1) en toont de evolutie van menselijke inspanningen om regenval te beïnvloeden van het voldoen aan waterbehoeften naar water voor andere doeleinden als onderdeel van de instrumentele en relationele waarden in de relatie tussen mens en natuur. De tien paradigma's bestrijken drie van de vier hierboven genoemde overgangsfasen van mens-natuurrelaties. Dit hoofdstuk laat zien dat de relatie tussen mens en regen al langere tijd bestaat en dat mensen ook erkennen dat regenval een belangrijk onderdeel van waterbronnen is geworden. Dit wordt bewezen door verschillende menselijke inspanningen om regenval te beïnvloeden.

Hoofdstuk 3 behandelt voor het Rejoso-waterscheidingsgebied de impact van landgebruik en waterbeheer op recente hydrologische degradatie en de huidige inspanningen om de afvoer van de Umbulan-bron te herstellen (OV1). Door een eenvoudig hydrologisch simulatiemodel (OV2) aan te passen, heb ik de grondwateropname weergegeven om de omstandigheden van het Rejoso-waterscheidingsgebied te parametriseren met artesische bronnen en de Umbulan-bron voor stedelijk/industrieel grondwatergebruik. Het hydrologische model simuleerde vier land- en waterbeheerscenario's: i) huidige situaatie, ii) verbetering van landgebruik in stroomopwaartse en midstream-zones, iii) waterbeheer in de stroomafwaartse gebieden en iv) een combinatie van interventies in stroomopwaarts, midstream en stroomafwaarts waterbeheer. Dit hoofdstuk biedt ook een typologie van rijstboeren die grondwater gebruiken, om hun beslissingen te begrijpen bij het bewerken van hun land en het gebruiken van de artesische bronnen. Op grond van het resultaat van de hydrologische simulatie en de typologie van rijstboeren kunnen effectieve en efficiënte interventies worden uitgevoerd op basis van kenmerken van het veld en de boer.

Hoofdstuk 4 presenteert de ontwikkeling van een procesgebaseerd en semi-gedistribueerd veenland hydrologisch model (RE-PEAT model) voor het Pawan-Kepulu veengebied. Het model werd opgebouwd op basis van veldmetingen van grondwaterstanden om een multi-schaal hydrologisch inzicht te bieden in de impact van land- en waterbeheer (OV1), gegeven de fluctuaties in de tijd, als gevolg van regenvalpatronen, de ruimtelijke patronen gekoppeld aan de diepte van het veenprofiel, positie in de veenkoepel en afstand tot het dichtstbijzijnde afwateringskanaal, de invloed van vegetatie (landbedekking) en de manier waarop de waterstanden in de kanalen worden gereguleerd. Het model combineerde twee benaderingen (OV2): een eenvoudige waterboekhouding (instroom = uitstroom) voor tijdelijke buffering en veendiepte-afhankelijke hydrostatische gradiënten loodrecht op afwateringskanalen. Het resulterende veenland hydrologische model kan worden toegepast op perceel- en landschapsniveau. Grondwaterpeil- en kanaalwaterpeilgegevens van periodieke monitoring werden opgeschaald naar het hele Pawan-Kepulu-veengebied om de temporele en ruimtelijke risico's van grondwaterpeilen dieper dan 40 cm te kwantificeren, die in verband zijn gebracht met een verhoogd brandrisico. Een combinatie van klimaatscenario's (nat, droog en normaal jaar op basis van neerslag), landgebruikscenario's (bos, oliepalmplantages en seizoensgebonden landbouwgewassen) en waterbeheerscenario's (met en zonder kanaalblokkering) werden gebruikt om de verschillende effecten van land- en waterbeheer op grondwaterpeilen te beoordelen. De simulatieresultaten ondersteunen een keuze voor op bomen gebaseerd landgebruik om het veengebied vochtig te houden en de constructie van kanaaldrempels ('blokkering') om de grondwaterafvoer tijdens het droge seizoen te verminderen en daarmee het brandgevaar te verkleinen.

Hoofdstuk 5 richt zich op het process van de ontwikkeling van het H2Ours spel in het Rejoso-stroomgebied als de vereenvoudiging van het systeem (OV2) en de aanpassingen in het Pawan-Kepulu-veengebied (OV3). De Driver, Pressure, State, Impact and Response (DPSIR) en Actor, Resource, Dynamic and Interaction (ARDI) schematisering werden gebruikt om verbanden tussen sociale en biofysische componenten te herkennen die het hydrologische functionern in beide landschappen beïnvloeden. Ik gebruikte geloofwaardigheids-, saillantie- en legitimiteitscriteria om de kwaliteit van het H2Ours spel te ontwikkelen en te evalueren bij het faciliteren van een gedeeld ecohydrologisch begrip onder belanghebbenden ter ondersteuning van herstelstrategieën. Op basis van de Likert-enquête na de spelsessies gaven de meeste deelnemers aan dat ze spel sessies prettig vonden en nieuwe kennis hadden opgedaan door de simulatie. Hoewel ze aangaven dat de samenwerking en gezamenlijk acties in echte omstandigheden konden worden geïmplementeerd, is het noodzakelijk om omstandigheden te creëren die implementatie ondersteunen.

Hoofdstuk 6 rapporteert het gebruik van het H2Ours spel in het Rejoso stroomgebied om de beslissingen over landgebruik en waterbeheer van deelnemers aan het spel en de veranderingen in hun percepties na de spelsessie te onderzoeken (OV4). De patronen en de achtergronden van de beslissingen van de deelnemers, evenals hun reacties op overheidsregulering en Betaling voor milieudiensten (PES)-scenario's, gaven informatie over de factoren die hun besluitvorming beïnvloeden. De resultaten laten zien dat deelnemers tijdens de spelsessie beslissingen namen op basis van hun ecologische kennis. Informatie, training en mentoring verbreden hun inzicht, waardoor er meer opties voor land- en waterbeheer worden geboden. De Q-methodologie-enquêtes voor en na het spel laten zien dat het spel de kennis van de deelnemers veranderde door hun concept van de aanbod-vraag waterbalans te verbeteren, hun kennis over de oorzaken van de hydrologische problemen uit te breiden en de factoren te identificeren die het succes van herstel bepalen.

Hoofdstuk 7 is de algemene discussie van dit proefschrift. In dit hoofdstuk begon ik met het benadrukken van vormen van menselijke toe-eigening van waterbronnen in verschillende componenten van de waterbalans op verschillende landschapsniveaus. In het Rejoso-stroomgebied en het Pawan-Kepulu-veengebied leiden veel vormen van menselijke toe-eigening van waterbronnen tot verschillende sociaal-hydrologische problemen. Omdat land- en waterbeheer op landschapsniveau veel belanghebbenden omvat, vereisen inspanningen om hydrologische functies te herstellen een gedeeld begrip van het sociaal-hydrologische systeem om gedeelde betrokkenheid en verantwoordelijkheid te creëren. Hydrologische modellen en serieuze spellen die zijn ontwikkeld door het sociaal-hydrologische systeem te vereenvoudigen zonder de essentie ervan te verliezen, hebben het mogelijk gemaakt om gedeeld begrip te creëren door kennis te delen tussen belanghebbenden. De in dit proefschrift ontwikkelde instrumenten zijn aanpasbaar via plug-and-play-functies of een open en transparante benadering, wat hun gebruik in andere gebieden met vergelijkbare sociaal-hydrologische problemen zal vergemakkelijken. Tot slot lijken de ontwikkelde hydrologische modellen en serieuze spellen effectieve en efficiënte hulpmiddelen te zijn voor prognoses en voorspellingen bij het ontwikkelen van multifunctionele landschappen om tegemoet te komen aan verschillende menselijke behoeften. Deze modellen enspellen hebben echter erkenning van belanghebbenden nodig, zodat nieuwe kennis en inzichten die zijn verkregen uit de modelsimulaties en spelsessies kunnen leiden tot een gedeelde toewijding onder belanghebbenden om landschapsbeheer te veranderen. De stappen van gedeeld begrip naar erkende verantwoordelijkheden en acties op de grond zijn voornamelijk afhankelijk van de sociale kant van sociohydrologische systemen; op basis van onze ervaring tot nu toe kunnen spellen die zijn aangepast aan de lokale contekst helpen bij het proces om actoren in die richting te bewegen.

Ringkasan

Hubungan timbal balik antara manusia dan alam terus berubah dan dirasakan dalam banyak hal oleh masyarakat. Hubungan ini bervariasi seiring dengan perubahan cara pandang yang dipengaruhi oleh nilai-nilai relasional dan instrumental yang terkait dengan sumber daya alam, misalnya sumber daya air. Pemanfaatan sumber daya air oleh manusia dalam sistem sosio-hidrologi dapat dipahami sebagai bagian dari empat fase 'transisi hutan spiritual': (1) alam mempunyai kekuatan dan manusia beradaptasi dengan kondisi sumber daya air saat ini; (2) penaklukan alam ketika manusia mulai mengelola alam untuk mendapatkan jasa hidrologi yang diinginkannya; (3) pengelolaan alam secara rasional ketika pengelolaan air berbasis ilmu pengetahuan mencoba untuk bertahan dalam batas-batas planet dan menggunakan solusi berbasis alam dalam pengelolaan lahan, air dan iklim saat memungkinkan; dan (4) berhubungan kembali dengan alam dengan mengeksplorasi manfaat lain yang terkait dengan air, misalnya spiritualitas, estetika, kesenangan, rekreasi. Terganggunya pasokan dan kebutuhan air secara alami dapat memicu berbagai permasalahan hidrologi. Untuk mengatasinya, masyarakat berupaya memulihkan fungsi hidrologi yang diinginkan untuk memenuhi kebutuhan manusia.

Bentang alam yang multifungsi dengan penggunaan lahan yang beragam untuk berbagai tujuan diharapkan dapat menyediakan berbagai jasa ekosistem. Namun, pengembangan lanskap multifungsi memerlukan integrasi berbagai kebutuhan manusia dan sistem pengetahuan, yang seringkali menjadi tantangan tersendiri. Model hidrologi dan permainan serius (dengan latar belakang model konseptual dan formal) dapat digunakan untuk menyederhanakan representasi sistem sosio-hidrologi dan untuk memfasilitasi pengembangan pemahaman bersama dari para pemangku kepentingan. Model-model dan permainan-permainan ini harus dapat diadaptasi dan digunakan kembali dalam konteks dan isu-isu lokal, dan direplikasi sehingga dapat diterapkan di lokasi-lokasi yang menghadapi permasalahan serupa. Model dan permainan seperti ini diharapkan dapat berkontribusi pada artikulasi tanggung jawab dan pengambilan keputusan para pemangku kepentingan dalam proses pengembangan lanskap multifungsi di kehidupan nyata.

Tujuan dari tesis ini adalah untuk mengembangkan pemahaman yang lebih lengkap tentang sistem sosio-hidrologi untuk pengelolaan sumber daya air berkelanjutan di lanskap multifungsi dengan mengintegrasikan informasi dari sistem pengetahuan yang berbeda dan perspektif pemangku kepentingan yang berbeda. Tesis ini membahas tujuan tersebut melalui empat pertanyaan penelitian: (RQ1) Apa dampak tindakan manusia terhadap sumber daya air pada berbagai skala spasial?, (RQ2) Bagaimana sistem sosio-hidrologi dapat disederhanakan menjadi model hidrologi dan permainan serius?, (RQ3) Bagaimana model dan permainan hidrologi dapat diadaptasi dan direplikasi?, dan (RQ4) Sejauh mana permainan dan model berkontribusi terhadap pengambilan keputusan dalam memulihkan fungsi hidrologi?. Untuk menjawab pertanyaan penelitian, saya menggunakan pendekatan transdisipliner yang menggabungkan penelitian sosial dan biofisik. Saya mengidentifikasi Pengetahuan Ekologi Lokal/*Local Ecological Knowledge* (LEK), Pengetahuan Ekologi Masyarakat/*Public Ecological Knowledge* (PEK) dan Pengetahuan Ekologis Pemodel/*Modeller Ecological Knowledge* (MEK) berdasarkan tinjauan pustaka, wawancara dan diskusi dengan pemangku kepentingan, serta melakukan pengukuran lapangan dan pemodelan hidrologi. Saya menstrukturkan informasi LEK, PEK dan MEK menggunakan kerangka *Driver, Pressure, State, Impact and Response* (DPSIR) dan *Actor, Resource, Dynamic and Interaction* (ARDI) untuk mengembangkan permainan serius serta untuk menilai dan memprediksi fungsi hidrologi. Saya mengevaluasi penggunaan permainan serius terhadap perubahan persepsi pemangku kepentingan menggunakan survei Likert dan Q-Methologogy.

Tesis ini menggunakan pengalaman dari proyek pengembangan dan penelitian yang sedang berlangsung di dua wilayah studi yang berbeda: DAS Rejoso dan lahan gambut Pawan-Kepulu yang keduanya berada di Indonesia. Area-area ini memiliki karakteristik biofisik yang berbeda dan memungkinkan untuk menunjukkan kemampuan beradaptasi dan replikasi model hidrologi dan permainan serius. Kedua area ini mempunyai status prioritas nasional dalam pengelolaan lanskap karena peran pentingnya dalam kesejahteraan manusia yang melibatkan pemangku kepentingan yang beragam dan multi-level. DAS Rejoso (62.733 ha) menyuplai air untuk irigasi hilir dan merupakan sumber air minum bagi 1,3 juta jiwa. Lanskap ini mengalami masalah hidrologi sebagai akibat dari pertanian intensif yang mengurangi pasokan air tanah di wilayah resapan air tanah (wilayah hulu dan tengah) dan meningkatnya ekstraksi air tanah melalui banyaknya sumur artesis yang tidak diatur di wilayah hilir. Lahan gambut Pawan-Kepulu (64.263 ha) memiliki frekuensi kebakaran yang tinggi sehingga menimbulkan berbagai permasalahan pada skala lokal, provinsi, dan nasional seperti permasalahan kesehatan, serta gangguan sosial, ekonomi, dan lingkungan. Untuk menjadikan lanskap ini lebih produktif secara ekonomi, masyarakat menggali banyak kanal untuk mengeringkan lahan gambut untuk perkebunan dan pertanian. Dampaknya, kawasan ini menjadi lebih kering dan rawan kebakaran saat musim kemarau. Kedua lanskap ini memerlukan transisi dari ekstraksi sumber daya air tanpa batas ke pengelolaan sumber daya air sesuai dengan daya dukungnya.

Bab 2 memberikan tinjauan literatur sepuluh paradigma yang menggambarkan hubungan antara manusia dan alam, dalam ketersediaan air melalui curah hujan (atau sebaliknya): dewa hujan, pembuat hujan, hutan, topografi, penyemaian awan, konvensi peperangan, perubahan iklim global, curah hujan- melepaskan telekoneksi, partikel inti es biotik, dan desalinisasi air laut. Tinjauan ini menjawab pertanyaan tentang dampak manusia terhadap sumber daya air (RQ1) dan menunjukkan evolusi upaya manusia untuk mempengaruhi curah hujan dari memenuhi kebutuhan air menjadi air untuk keperluan lain sebagai bagian dari nilai instrumental dan relasional dalam hubungan antara manusia dan alam. Sepuluh paradigma tersebut tersebar di tiga dari empat fase transisi hubungan manusia-alam yang disebutkan di atas. Bab ini menunjukkan bahwa hubungan antara manusia dan hujan telah terjalin sejak lama, dan manusia juga menyadari bahwa hujan telah menjadi bagian penting dari sumber daya air. Hal ini dibuktikan dengan berbagai upaya manusia dalam mempengaruhi hujan.

Bab 3 membahas dampak penggunaan lahan dan pengelolaan air terhadap degradasi hidrologi di DAS Rejoso dan upaya yang sedang dilakukan saat ini untuk memulihkan debit mata air Umbulan (RQ1). Melalui modifikasi model simulasi hidrologi sederhana (RQ2), Saya memodelkan pengambilan air tanah melalui sumur artesis dan mata air Umbulan untuk pemanfaatan air tanah untuk area perkotaan untuk memparameterisasi kondisi DAS Rejoso. Model hidrologi ini menyimulasikan empat skenario pengelolaan lahan dan air: i) bisnis seperti biasa, ii) pengayaan lahan di zona hulu dan tengah, iii) pengelolaan air di wilayah hilir, dan iv) kombinasi intervensi di hulu, tengah, dan hilir. Bab ini juga memberikan tipologi petani padi yang memanfaatkan air tanah untuk memahami keputusan mereka dalam mengolah lahan dan memanfaatkan sumur artesis. Berdasarkan hasil simulasi hidrologi dan tipologi petani padi, maka perlu dilakukan intervensi yang efektif dan efisien berdasarkan kondisi lapangan dan karakteristik petani.

Bab 4 menyajikan pengembangan model hidrologi lahan gambut berbasis proses dan semi-terdistribusi (model RE-PEAT) untuk lahan gambut Pawan-Kepulu. Model ini dibangun berdasarkan pengukuran tinggi muka air tanah di lapangan untuk memberikan pemahaman hidrologi multi-skala mengenai dampak pengelolaan lahan dan air (RQ1), memberikan fluktuasi temporal akibat pola curah hujan, pola spasial terkait dengan kedalaman profil gambut, posisi terhadap kubah gambut dan jarak ke kanal terdekat, pengaruh vegetasi (tutupan lahan) dan cara pengaturan tinggi air kanal. Model ini menggabungkan dua pendekatan (RQ2): persamaan neraca air sederhana (aliran masuk = aliran keluar) sebagai penyangga sementara, dan gradien hidrostatik yang bergantung pada kedalaman gambut yang tegak lurus terhadap saluran drainase. Model hidrologi lahan gambut yang dihasilkan dapat diterapkan pada tingkat plot dan lanskap. Data tinggi muka air tanah dan tinggi muka air kanal yang diperoleh dari pemantauan berkala diperluas ke seluruh lahan gambut Pawan-Kepulu untuk menghitung risiko temporal dan spasial dari tinggi air tanah yang lebih dalam dari 40 cm, yang dikaitkan dengan peningkatan risiko kebakaran. Kombinasi skenario iklim (tahun basah, kering dan normal berdasarkan curah hujan), skenario penggunaan lahan (hutan, perkebunan kelapa sawit dan tanaman pertanian musiman) dan skenario pengelolaan air (dengan dan tanpa sekat kanal) digunakan untuk menilai berbagai dampak dari pengelolaan lahan dan air pada tingkat air tanah. Hasil simulasi mendukung pilihan penggunaan lahan berbasis pohon untuk menjaga lahan gambut tetap lembab dan pembangunan ambang batas kanal (‘blocking’) untuk mengurangi aliran air tanah selama musim kemarau sehingga mengurangi risiko bahaya kebakaran.

Bab 5 berfokus pada proses pengembangan permainan H_2Ours di DAS Rejoso sebagai penyederhanaan sistem (RQ2) dan proses adaptasinya untuk lahan gambut Pawan-Kepulu (RQ3). Kerangka pemikiran *Driver, Pressure, State, Impact and Response* (DPSIR) dan *Actor, Resource, Dynamic and Interaction* (ARDI) digunakan untuk mengidentifikasi konektivitas komponen sosial dan biofisik yang mempengaruhi kondisi fungsi hidrologi di kedua lanskap. Saya menggunakan kriteria kredibilitas, arti-penting, dan legitimasi (*creadibility, salience and legitimacy*) untuk mengembangkan dan mengevaluasi kualitas permainan H_2Ours dalam memfasilitasi pertukaran pengetahuan untuk mendapatkan pemahaman bersama di antara para pemangku kepentingan guna mendukung strategi restorasi. Berdasarkan survei Likert setelah sesi permainan, sebagian besar peserta menyatakan bahwa mereka menikmati sesi permainan dan memperoleh pengetahuan baru dari simulasi. Meskipun mereka menyatakan bahwa aksi kolaboratif dan kolektif tersebut dapat dilaksanakan dalam kondisi nyata, namun masih perlu menciptakan kondisi pemungkin yang mendukung implementasi.

Bab 6 melaporkan penggunaan permainan serius H_2Ours di DAS Rejoso untuk mengeksplorasi keputusan penggunaan lahan dan pengelolaan air yang dibuat oleh peserta permainan dan perubahan persepsi mereka setelah sesi permainan (RQ4). Pola dan alasan pengambilan keputusan para partisipan, serta tanggapan mereka terhadap peraturan pemerintah dan skenario Pembayaran Jasa Ekosistem/*Payment for Ecosystem Services* (PES), memberikan informasi mengenai faktor-faktor yang mempengaruhi pengambilan keputusan mereka. Hasil kajian menunjukkan bahwa selama sesi permainan, peserta mengambil keputusan berdasarkan pengetahuan ekologi mereka. Informasi, pelatihan dan pendampingan memperluas wawasan mereka sehingga memberikan lebih banyak pilihan dalam pengelolaan lahan dan air. Survei Q-methodology sebelum dan sesudah permainan menunjukkan bahwa permainan ini mengubah pengetahuan peserta dengan meningkatkan konsep pasokan-kebutuhan air, memperluas pengetahuan mereka tentang penyebab masalah hidrologi dan mengidentifikasi faktor-faktor yang menentukan keberhasilan restorasi.

Bab 7 merupakan Pembahasan Umum skripsi ini. Dalam bab ini saya memulai dengan menekankan bentuk-bentuk pemanfaatan sumber daya air oleh manusia dalam berbagai komponen neraca air pada berbagai tingkat skala lanskap. Di DAS Rejoso dan lahan gambut Pawan-Kepulu, berbagai bentuk pemanfaatan sumber daya air oleh manusia menimbulkan berbagai permasalahan sosio-hidrologi. Karena pengelolaan lahan dan air pada tingkat lanskap melibatkan banyak pemangku kepentingan, maka upaya pemulihan fungsi hidrologi memerlukan pemahaman bersama mengenai sistem sosio-hidrologi untuk menciptakan komitmen dan tanggung jawab bersama. Model hidrologi dan permainan serius yang dikembangkan dengan menyederhanakan sistem sosio-hidrologi tanpa kehilangan esensinya memungkinkan terciptanya pemahaman bersama melalui pertukaran pengetahuan antar pemangku kepentingan. Alat yang dikembangkan dalam tesis ini dapat diadaptasi melalui fitur plug and play atau pendekatan terbuka dan transparan, yang akan memudahkan penggunaannya di wilayah lain yang menghadapi permasalahan sosio-hidrologi serupa. Terakhir, model hidrologi dan permainan serius yang dikembangkan nampaknya merupakan alat yang efektif dan efisien untuk peramalan dan prediksi dalam mengembangkan lanskap multifungsi untuk mengakomodasi berbagai kebutuhan manusia. Namun model dan permainan ini memerlukan pengakuan dari para pemangku kepentingan sehingga pengetahuan dan wawasan baru yang diperoleh dari simulasi model dan sesi permainan dapat menghasilkan komitmen bersama di antara para pemangku kepentingan untuk mengubah pengelolaan lanskap. Langkah-langkah dari pemahaman bersama hingga pengakuan tanggung jawab dan tindakan di lapangan terutama bergantung pada sisi sosial dari sistem sosio-hidrologi; Berdasarkan pengalaman kami selama ini, permainan yang disesuaikan dengan konteks lokal dapat membantu proses menggerakkan aktor ke arah tersebut.

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About the Author

Lisa Tanika (lisa.tanika@gmail.com) was born in Semarang, Central Java, Indonesia, on December 24th, 1983. In 2002, after graduating from high school, she decided to move out from her hometown to pursue a BSc degree at the Bogor Agricultural University. She studied Mathematics, specifically studying mathematical modelling which became the basis for her future career as a researcher.

Lisa started her career in research as a research assistant at the World Agroforestry (ICRAF) to examine the mathematical equations used in the Generic River Flow (GenRiver) Model. Through this work she indirectly learned the basic science of hydrology related to the water cycle in a watershed. In 2011, Lisa decided to pursue the Master's in Applied Climatology at the Bogor Agricultural University to strengthen her hydrological understanding; she finished it in 2013 with a *cum laude* evaluation. After that, she conducted more extensive hydrological research in various locations in Indonesia for various ICRAF projects. Her research focused on identifying the hydrological issues and their causes, as well as providing the technical recommendations to address hydrological issues. During this period, she enriched the GenRiver Model to accommodate variations in watershed characteristics in Indonesia. She synthesized all the watershed evaluation results from various watersheds in Indonesia and built the Flow Persistence (FlowPer) model, which can be used to quantitatively assess the watershed conditions. In 2018, Lisa moved her career from World Agroforestry to the Peatland Restoration Agency to carry out peatland hydrological assessments in Indonesia. In this organization, she had the opportunity to learn about the peatland hydrological system and to enrich her hydrological knowledge with peatland ecosystems.

From the research on various watersheds and peatlands, Lisa came to the conclusion that unsustainable human activities with inadequate coordination due to lack of understanding of the hydrological system have led to several hydrological problems in Indonesia. The solution to all these problems involves various stakeholders with diverse backgrounds and levels of knowledge. Therefore, she thought that a mechanism is needed to facilitate stakeholder collaboration and to align economic and environmental benefits to resolve socio-hydrological problems in watersheds and peatlands. This realization motived her to enrol in a doctoral program in Wageningen University on the topic of Human Appropriation of Water Resources in A Multifunctional Landscape, as part of the SESAM program. By developing models and games, she expected to help people with non-technical backgrounds to understand the hydrological systems so that they can make better management strategies in watersheds and peatlands. She hopes to take the positive conclusions of this research forward in future work.

Publications

Peer-review journal articles:

Sari, R. R., **Tanika, L.**, Speelman, E. N., Saputra, D. D., Hakim, A. L., Rozendaal, D. M. A., Hairiah, K., and van Noordwijk, M.: Farmer Options and Risks in Complex Ecological-Social systems: The FORCES game designed for agroforestry management of upper watersheds, Agric. Syst., 213, https://doi.org/10.1016/j.agsy.2023.103782, 2024.

Tanika, L., Sari, R. R., Hakim, A. L., van Noordwijk, M., Peña-Claros, M., Leimona, B., Purwanto, P., and Speelman, E. N., The H2Ours game to explore water use, resources and sustainability: connecting issues in two landscapes in Indonesia. *Hydrology and Earth System Sciences*, *28*(16), 3807-3835, 2024.

Hakim, A.L., Saputra, D.D., **Tanika, L.**, Kusumawati, I.A., Sari, R.R., Andreotti, F., Abdurrahim, A.Y., Wamucii, C., Lagneaux, E.G., Githinji, M., Suprayogo, D.,Speelman, E., and van Noordwijk, M., Protected spring and sacred forest institutions at the instrumental—relational value interface. Current Opinion in Environmental Sustainability, *62*, 101292, 2023.

Tanika, L., Wamucii, C., Best, L., Lagneaux, E. G., Githinji, M., and van Noordwijk, M., Who or what makes rainfall? Relational and instrumental paradigms for human impacts on atmospheric water cycling. *Current Opinion in Environmental Sustainability*, *63*, 101300, 2023.

van Noordwijk, M., van Oel, P., Muthuri, C., Satnarain, U., Sari, R. R., Rosero, P., Githinji, M., **Tanika, L.**, Best, L., Comlan Assogba, G. G., Kimbowa, G., Andreotti, F., Lagneaux, E., Wamucii, C. N., Hakim, A. L., Miccolis, A., Abdurrahim, A. Y., Farida, A., Speelman, E., and Hofstede, G. J.: Mimicking nature to reduce agricultural impact on water cycles: A set of mimetrics, Outlook Agric., 51, 114–128, https://doi.org/10.1177/00307270211073813, 2022.

Khasanah, N., **Tanika, L.**, Pratama, L. D. Y., Leimona, B., Prasetiyo, E., Marulani, F., Hendriatna, A., Zulkarnain, M. T., Toulier, A., and Noordwijk, M. van: Groundwater-Extracting Rice Production in the Rejoso, Land, 10, 586, 2021.

van Noordwijk, M., Speelman, E., Hofstede, G. J., Farida, A., Kimbowa, G., Geraud, G., Assogba, C., Best, L., and **Tanika, L**.: Sustainable Agroforestry Landscape Management: Changing the game, Land, 9, 1–38, 2020.

In preparation/will be submitted:

Tanika, L., van Noordwijk, M., Speelman, E.N., Leimona, B., and Peña-Claros , M., Managing trees and restoring groundwater: enhancing shared understanding through the H_2Ours game in the Rejoso Watershed, Indonesia

Tanika, L., van Noordwijk, M., Wijaya, K., Mariati, H., Speelman, E.N., Dohong, A., and Peña-Claros, M., Rewetting a tropical peatland by canal blocking? Linking groundwater dynamics at plot and landscape scale in the Pawan-Kepulu Peatland of Indonesia.

Other publications:

Widayati, A., **Tanika, L.**, Wijaya, K., Abdurrahim, A. Y., Purwanto, E., and Zagt, R.: Integrated landscape approaches for reducing peatland fires in Ketapang District, Indonesia, Trop. For. Issues, 101–108, https://doi.org/10.55515/pqbh9761, 2022.

Dohong, A. and **Tanika, L**. Hydrological management practices. *Tropical Peatland Eco-Management*, pp.567-593. 2021

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 30 ECTS (= 20 weeks of activities)

Review/project proposal (6 ECTS)

- Agroforestry as part of climate change response
- Hydrological restoration: from collaborative understanding to action using models and simulation games

Post-graduate courses (6 ECTS)

- Companion modelling (2020)
- Water quality modelling using QUAL2Kw and WASP (2020)
- Resilience of Living System (2021)
- Q-Methodology (2020)
- Fuzzy Cognitive Mapping (2020)
- Introduction to R for Statistical Analysis (2020)

Deficiency, refresh, brush-up courses (1.5 ECTS)

- Forest Ecology and Forest Management (2021)

Invited review of journal manuscripts (3 ECTS)

- Land Use Paper: Exploring Decision-making in campaign-based watershed management by using a role-playing game in Boset District, Ethiopia (2020)
- Ecosystem Services: Measuring the Incremental Impact of Payments for Watershed Services on Water Quality in a Transboundary River Basin in China (2020)
- Ecosystem Services: Understanding Smallholder Farmers' Dependence and perceptions on Ecosystem Services in Batang Toru Forest: From Economic Value to Traditional Ecological Knowledge' (2023)

Competence, skills and career-oriented activities (3.5 ECTS)

- Organizing Culture (2020)
- Reviewing Scientific Manuscript (2020)
- Competences assessment (2021)
- Intensive writing week (2020)
- Writing grant proposal (2023)

Scientific Integrity/Ethics in science activities (0.3 ECTS)

- Ethics in Plant and environmental Sciences (2022)

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (0.9 ECTS)

- PE&RC last year's weekend (2023)
- PhD carousel

International symposia, workshops and conferences (9.2 ECTS)

- International SESAM workshops (2021)
- 5th World Congress of Agroforestry (2022)
- iSAGA 2023 conference (2023)
- International Conference on Tropical Agroforestry in Indonesia (2023)
- 9th International Wild land fires conference (2023)

National scientific meetings, local seminars, and discussion groups (1.2 ECTS)

- Irrigation and groundwater management (2021)
- Old Wells and New Wells: management of artesian wells in Rejoso Watershed (2021)
- SESAM game outreach: open games demonstration to WUR community (2022, 2023)

Lecturing/supervision of practicals/tutorials (3.3 ECTS)

- Policy brief development using Detective Game (2020)
- H2Ours Game simulation (2021, 2022)
- H2Ours Game development (2023)

Colophon

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