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Advances in global hydrology–crop modelling to support the UN's Sustainable Development Goals in South Asia

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Achieving the United Nation's Sustainable Development Goals (SDG) in the context of a rapidly changing climate and demographics is one of the major challenges for South Asia. Interventions aimed at achieving the SDGs will be varied and are likely to contain basin-wide trade-offs that need to be understood. In this paper, we synthesize recent global hydrology-crop model developments, with a specific focus on human impact parameterisations like the management of human built storage capacity, irrigation withdrawal and supply, and irrigation efficiency. We show that these models can help improve our understanding of the composition and flows of water, and the linkages between water scarcity and food production. To fully exploit the potential of improved models for policy support and the design of pathways towards SDG achievement, we envisage scope to include more local data from test fields and pilot sites, use the models to derive biophysical and financial feasibility of interventions, and improve the interaction with policy-makers and regional stakeholders through the development of better communication and visualisation tools.

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Understanding drivers of water-resources availability and crop-production in South Asia

South Asia is one of several major global climate change hotspots [1]. Sustainable development in this region must overcome both the negative impacts of climate change and persistent social and economic inequality, which traps a large proportion of the South Asian population in poverty. Even if the world manages to meet the ambitious Paris Agreement targets, and global warming is limited to 1.5°C, South Asia, and especially its mountainous regions, is expected to warm more, with temperatures exceeding safe thresholds for crops, livestock and humans[2]. Moreover, shifts in water availability are anticipated due to changing monsoon patterns [3,4] and melting glaciers [5].

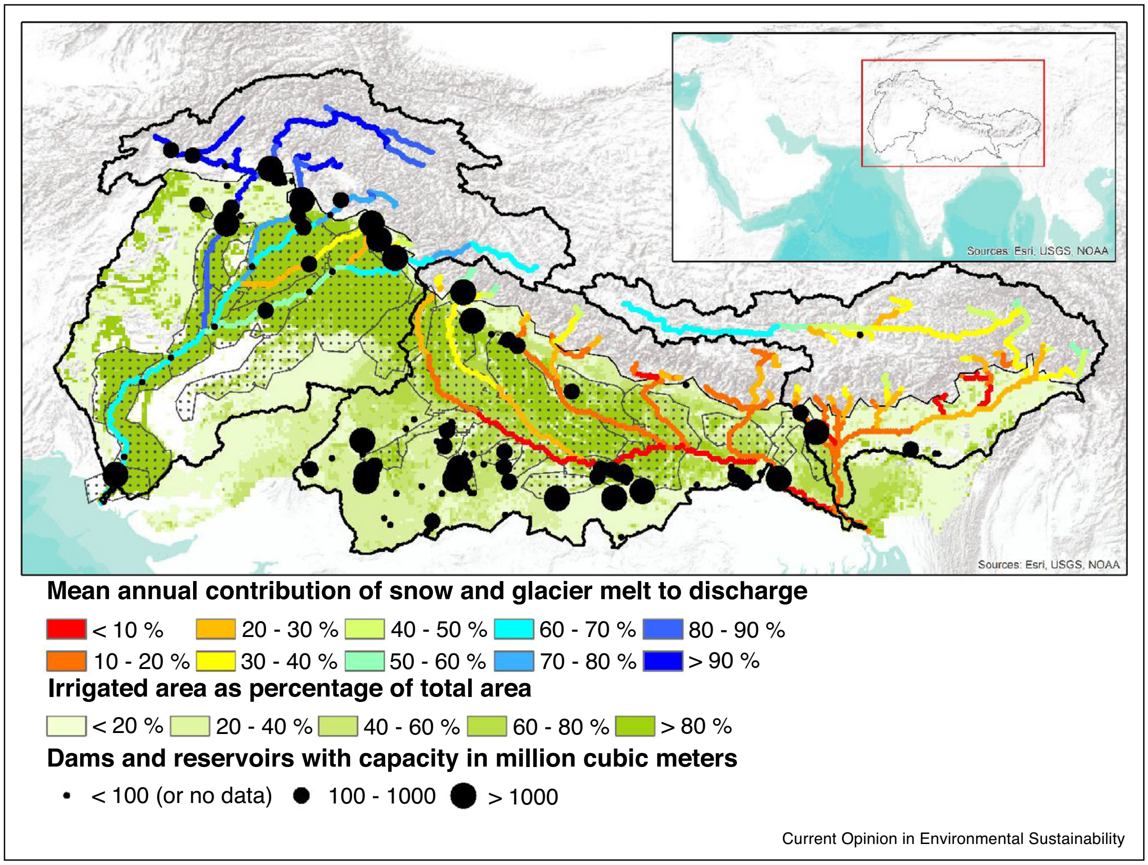
South Asia's glaciers and snow packs are referred to as the 'water towers' or the 'third pole', upon which hundreds of millions of people in Asia rely [6,7]. This reliance varies with location, depending upon the fraction of meltwater to total runoff, and the ways through which meltwater can be transported to the agricultural fields downstream [8], as well as the timing of demand [9]. Meltwater is an important buffer in warm periods and dry periods, when rainfall is scarce [10]. Recent studies suggest that glaciers will have lost at least one-third of their volume by the end of the 21st Century [11]. A diminishing buffering capacity of glaciers, coinciding with rapidly falling groundwater levels due to over withdrawal, raises concerns over water-security, energy-security and food-security [12] and population growth adds increasing pressure on resources [13•]. Achieving the development agenda articulated in the UN's Sustainable Development Goals in the context of these pressures and changes will therefore be a major challenge.

Regional application of global hydrology-crop models can help to elucidate the effects of climate and socio-economic change on water availability, the links between water-source and water-user, and the downstream impacts of upstream interventions. Understanding hydrology in this region poses specific difficulties. First, at high altitudes, precipitation is often underestimated, because gauges are not corrected for snowfall undercatch and orographic effects. Precipitation datasets that are corrected through the use of glacier mass balance or use of high-altitude precipitation gauges, seem the best choice to force hydrological models in this region [14]. Next, due to the difficulties that many global- and regional climate models have in simulating the typical intra-annual variability in precipitation caused by the summer monsoon [18], models and scenarios for future impact assessment should be carefully selected based on their capability in simulating monsoon precipitation [19]. However, precipitation is not the only important climate parameter. Downstream water-demand for rice is changing due to changes in humidity, increased cloudiness, wind-speed and temperatures [20]. Alongside the climate forcing, good representations of glacier mass, snow mass and melt processes are crucial to understand current- and future timing and composition of river flows [15,16], especially in basins, such as the Indus Basin, where a large part of the river flow originates from these sources [16,17].

While our understanding of atmospheric-process, cryospheric-process and hydrological-process has advanced in recent years, the conceptualisation and parameterisation of how people impact and interact with the hydrological system remains a challenge. South Asian river basins are characterised by vast intensive agriculture, and intersected by the largest connected irrigation canal systems in the world, where water is transported away from the main stem for hundreds of kilometres, where some overirrigate, while many others have too little water, and where more than 20 million groundwater pumps make water flow up, rather than down [21]. It is also a region full of man-made reservoirs and with many more planned [22]. A better understanding of human impacts on the hydrological cycle is therefore needed to support a robust evaluation of sustainable solutions and pathways.

In this paper, we discuss the challenges of applying global hydrology and crop-models (GHMs) in South Asian basins. We pay particular attention to recent developments in the human impact parameterisations (HIP). We focus on developments in GHMs, because they are increasingly used for regional application (for in-depth reviews of bespoke catchment model applications, see R Johnston and V Smakhtin [23], and A Momblanch *et al.* [24]). Subsequently, we reflect on how these state-of-the-art models can support an evaluation of potential interventions, needed to achieve the UN's Sustainable Development Goals. Finally, we provide a future outlook on what more could be done to better use models as planning tools for policy support and in co-creating processes with stakeholders.

Figure 1



South Asia's major river basins downstream of the Hindu Kush Himalayas (from left to right: Indus, Ganges and Brahmaputra). The Indus River is largely dependent on snow and glacier melt (coloured lines; source: H Biemans *et al.* [8]). The rivers are characterised by human interactions in the hydrological cycle: human build storage capacity (black dots represent large reservoirs) and large scale irrigation (green shades). The dotted polygons represent the command areas of the large-scale irrigation canal systems, through which water from the main river is diverted and distributed.

Advances in simulating human-impact parameterisations

In recognition of the fact that almost all global rivers are by now to some extent modified by humans [25], parameterising human—water resource impacts in GHMs is receiving increased attention [26,27••,28]. In parallel, improvements in remote-sensing, community-based observations and datamining, and increased computational power and parallel computing, have increased the spatial resolution of GHMs to a level that they now compete with bespoke regional models [29,30]. Increasingly, they are used regionally and context-specific for impact assessment or the evaluation of measures. This leads to higher demands on the parameterisation and process description of these human-water resource impacts, especially in complex basins, such as the Indus- and Ganges Basins, with high degrees of management (Figure 1). Recent relevant HIP developments in GHMs can be clustered around four components that will be discussed in the remainder of this section:

- Water storage: parameterisation of reservoirs, *and* their operation;
- Irrigation demand: improved timing of irrigation demand
- Irrigation supply: parameterisation of lateral conveyance and groundwater withdrawal and depletion;
- Application: crop-specific and source-specific water-use efficiency estimates;

Table 1 provides an overview of general features of a selection of GHMs, and their parameterisation of the human impacts discussed in this paper.

Water storage

Ever since the first algorithm to simulate reservoir operations in global scale models was published [37], the importance of reservoirs for water availability has been widely acknowledged. General, strongly simplified reservoir operation rules are implemented, based upon the purpose of the dam (irrigation, hydropower or flood control), and the storage capacity of the reservoir determines to what extent the flow is modified [38] (see Table 1 on reservoir features in selected GHMs). The increased resolution of models now allows for more spatially explicit schematisation of reservoirs but also requires new approaches to deal with reservoirs covering multiple grid cells [39]. To better represent the release decisions of dam operators the use of fuzzy rules and artificial neural networks, based on historical inflows, storage levels and releases, is suggested [40]. Especially in regions of strong water-stress or strong environmental flow-alteration by dams, like in South Asia, a regionalisation of the parameterisation of operating rules could improve model simulations and the relevance of their output. With the region rapidly losing its natural 'reservoirs' — glaciers, snow cover and, in places, access to groundwater — a good understanding of the impact of man-made reservoirs, and the extent to which these can offset this loss or can buffer strong seasonal shifts in runoff, becomes ever more important.

Irrigation demand in multi-crop systems

With the largest irrigation systems in the world, simulating irrigation water-demand, withdrawal and supply is an essential process to include when trying to understand water-resources and link sources to supply in this region. Irrigated agriculture in South Asia is very intensive with multiple crops being harvested sequentially from the same field. Irrigation demand has been incorporated into global hydrological-models and crop-models for years, but with demand generally represented by a single crop, per year, per location [41–44]. Incorporating the temporal water-demand pattern that results from the sequential cropping in two or more growing seasons is important to understand water-stress resulting from mismatches between supply and demand. This is increasingly recognised and implemented in global models [45,46], as well as regional applications for South Asia [9].

Irrigation supply from multiple sources

Applying GHMs at higher spatial and temporal resolution means human-resource interactions that were hidden within grid parameterisation and process description now need a more explicit representation. Addressing the potential mismatch in supply and demand between locations becomes more important. Explicit simulation of lateral water transfers has not been a standard feature of

Table 1

Overview of global hydrology-crop models

Model	South Asia application	Spatial resolution (in South Asia)	Double cropping irrigation demand	Endogenous crop growth model	Reservoir storage and operation	Local ponds for rainwater harvesting	Groundwater withdrawal	Groundwater depletion
VIC [31]	n	0.5°	n	n	y	n	n	n
WATERGAP [32]	n	0.5°	n	n	y	n	y	y
PCR-GLOBWB [33]	n	5 min	y	n	y	n	y	y
LPJmL [34]	y [8]	5 min	y	y	y	y	y	y
H08 [35]	y [36]	10 km	y	y	y	n	y	y

GHMs [28] as this was not necessary at lower resolution, and not facilitated by the standardised datasets with global coverage (e.g. the Hydrosheds river routing database), which do not include river diversions such as irrigation canals. While bespoke basin models can be attuned to the local situation, part of the strength of GHMs is their reliance on these published, uniform datasets, which add consistency and ease comparison. However, a certain degree of regionalisation might be necessary. In a recent regionalisation of a GHM for the Indus, Ganges and Brahmaputra basin, at five minute resolution [8], the implicit nearest neighbour cell irrigation link was replaced by the explicit delineation of irrigation command areas linked to defined inlets along the river sections. A regional policy of SDG-size importance, that could be evaluated better with such an explicit delineation, is the massive the Indian River Linkages Scheme, which is currently being revived [47], and plans to redirect flows from one tributary to the next thereby strongly affecting the region's hydrology.

Next to the supply from irrigation canals, groundwater is an important source of water supply in regions in which water-demand is high and surface water is scarce or highly variable, such as in South Asia. Most large scale hydrological models include some representation of groundwater withdrawals, but with different levels of complexity. It is often either parameterised as an unlimited supply to complement when surface water is not available, or as a simple linear reservoir model that releases water to base flow that can be used to withdraw from, but without lateral interaction. The most advanced method to simulate groundwater availability and depletion rates is by full coupling to a groundwater flow model [e.g. Ref. 48•], which also allows for a quantification of limits to extraction. A good review is given by MF Bierkens and Y Wada [49]. As South Asia is one of the regions with high levels of groundwater depletion [50], including a good representation of groundwater withdrawals is critical to estimating regional water scarcity. These estimates have global relevance, as their contribution to total unsustainable use embedded in the global food trade show [51••].

Efficiency of irrigation

The way in which water is diverted to and applied on the field determines the efficiency of its use. Deterministic models have several inherent difficulties in simulating the field-scale and canal-scale inefficiency in water-use that characterises many of South Asia's irrigation systems. Most models simulate optimal irrigation timing, with water-demand based on soil moisture deficit thresholds, and fixed application volumes and/or ponding depths. Sources are surface water and groundwater, the latter assumed unlimited (in most model applications). Field-scale efficiency is then calculated as beneficial consumption (transpiration) over water applied, which is determined as crop demand divided by a predefined application factor per country, crop [e.g. Ref. 52], irrigation method [52,53] and/or source [53], with losses a resultant of simulated soil moisture flows. An additional canal (in)efficiency is often imposed as a pre-determined share, comprises fixed conveyance losses, part of which returns to the river system, while the other part is assumed lost through evaporation [as in Ref. 52]. In reality, farmers face further constraints as most cannot track soil moisture effectively, those in canal supply systems are subject to irrigation scheduling, much of it supply- rather than demand driven, and some might (or might not) anticipate rainfall using local knowledge or official weather forecasts to delay or bring forward irrigation moments. Avoidance of risk and other factors apart from water-stress, such as pests and weed control, further affect farmers' irrigation preferences. These decision processes are obviously hard to capture within a single model, but incorporating (some) specific behaviour that links to the strengths of hydrology–crop models, like adjusting water supply or seasonal land-use decisions to meteorological forecasts, could be considered.

Another way of looking at efficiency of (irrigation) water use is crop water productivity, that is, the amount of crop produced per unit of water used [54]. This is an indicator in which both the use of water and the crop yields are reflected, but can only be assessed properly with GHMs that include an endogenous crop model [as in Ref. 52].

Biophysical conditions are just one determinant of (in) efficiency. A vast body of literature describes the inequality in water allocations, with location along the canal network [55,56], socio-economic status or distortive policies and incentives [57–60] influencing who has access to how much water, and when. This highlights the importance of understanding the political ecology of water-use. What could prove a way forward is an irrigation system-specific parameterisation of efficiency, based upon more than just soil types, source or application method, and also including management factors and other socio-political indicators using, for example, insights from concepts like hydro social territories [61]. With the increasing resolution in models and observations, further developments in remote sensing and, in the near future, app-supported place-based observations, distinguishing and simulating such characteristics of tail and head end users in canal systems becomes feasible.

Modelling interventions to support the SDGs

The ability to evaluate the impact of (sets of) measures or interventions is an important precondition for using models for more than the standard impact assessment, for example, as tools for policy support and the evaluation of policy strategies with concrete and measurable objectives such as the UN's SDG's. For interventions to have strong regional impacts, they need to be scaled out over larger geographical domains. However, these impacts are not always the positive ones intended. Here we show how two of the most discussed interventions (increasing storage and increasing efficiency) can be parameterised in GHMs.

Moving beyond large reservoirs

Apart from large dams, which are now implemented in most GHMs, farm ponds, tanks and village reservoirs form important tools to temporarily store water to overcome dry periods, along with subsurface storage through managed aquifer recharge [62,63]. Filling with rain during the monsoon and used in the same cropping season or the season after, these distributed reservoirs blur the line between purely rainfed- and irrigated agriculture. While a small contribution on the overall water balance, it might relieve the pressure on groundwater resources [64,65], while at the same time increase crop yields substantially [66]. Policy interest in these measures is reflected in an increase in watershed development programmes, in which rainwater harvesting and recharge is an important structural component [65]. Quantitative evidence for the performance of enhanced groundwater recharge is, however, still scarce [64], with many past modelling studies either having limited focus or being based on insufficient data [65]. Downstream impacts are often ignored, though some studies show that local retention in small scale reservoirs can have negative effects on downstream water availability [67], evaporation amounts and overall hydrology of catchments [68]. An assessment of local benefits (e.g. by field pilots) versus basin scale impacts of increased storage by using models therefore clearly has added value. Because of their small size and ubiquitous presence small ponds and reservoirs are difficult to model explicitly in GHMs; including them as an additional storage reservoir implicitly covering a certain percentage of cell or hydrological response unit area, fed by local rainfall, seems a first step forward. C Siderius *et al.* [69] showed, in post-processing of GHM output that the inter-annual variability of production in the Ganges basin was better simulated including these as 'virtual reservoirs' limited by a certain size and depth and fed by local runoff. J Jägermeyr *et al.* [70] introduced a somewhat similar approach in the LPJmL model, through water-harvesting parameters, effective on a predefined fraction of land. We are not aware of any other GHMs that parameterise this small-scale and spatially distributed reservoir component (Table 1).

Improving irrigation efficiency?

A recent discussion on the paradox of irrigation efficiency [59,71] highlights that there is still much confusion and need for proper quantification of the effect of efficiency measures at field-scale, canal-scale *and* basin-scale. GHMs are well-suited for such a task, as they can trace the various flow components, and changes therein, through the soil and river system. Sprinkler and drip irrigation are measures typically parameterised, through a reduction in evaporation and return flows, both at field scale and canal level [52]. More refinements are possible. Recently, in the LPJmL model, the most basic parameterisation of a single canal conveyance loss parameter was made dependent on soil characteristics [70]. Parameterising canal lining separately — a major activity of departments dealing with irrigation system maintenance and rehabilitation — and assessing its basin scale impact, seems a simple subsequent step.

One aspect that is largely ignored still though, is the way in which water quality concerns affect return flows. Especially in irrigated areas in arid and semi-arid areas, for example in the downstream Indus basin, management of salinity levels plays a large role in water management decisions with water in drainage canals often considered to be too saline to return into the river system [55]. Models might be too positive when it comes to reuse of return flows in such systems (and, thus, too negative about the effect of efficiency improvements at field scale). We are not aware of GHM applications in which any form of water quality constraint on return flows, be it endogenously- or exogenously parameterised, is currently implemented.

Efficiency improvements extend beyond agriculture, and are relevant for domestic- and industry applications. Currently around 5% of the overall water balance in most basins, these water-uses are expected to rise strongly in South Asia the coming decades [13•], which means the efficiency with which they are used is becoming relevant for the overall water-balance.

Small-scale measures distinct from irrigation application techniques, like mulching, intercropping or land-levelling, might seem irrelevant in isolation, but have a high potential when applied at scale. They enhance infiltration and/or reduce evaporation, making a larger proportion of rainfall or applied irrigation water available for crop growth, and improving the overall efficiency of the system. A discussion on the scope to reduce water-use by several of these measures and a description of their parameterisation in LPJmL can be found in J Jägermeyr *et al.* [70].

The way forward: simulating pathways towards SDG achievements

The capacity to simulate measures is one of the prerequisites for policy support, but more is needed on the design of pathways to realise the SDGs.

Firstly, further integration of socio-economic and bio-physical drivers in one framework is required to fully understand the future dynamics between water-resources and crop production in the major river basins of South Asia. Melting glaciers are only one of the symptoms, and drivers, of change [72]. Whereas regional climate models provide scenarios for the biophysical drivers, regional socio-economic scenarios are mostly still simply cut out from global scenarios, such as the shared socio-economic pathways (SSPs) [73]. Deriving consistent, comparable regional socio-economic scenarios is still a challenge. Merging these scenarios with conceptualisations of human behaviour at shorter timescales, by incorporating not only how humans impact water resources, but also feedbacks, for example, how they respond to fluctuations in its availability [69,74–76], can help assess the feasibility of interventions in these strongly modified river basins. In this light, HIP would stand for Human-resource '*Interactions*' or '*Interface*' Parameterisations rather than '*Impacts*' [28], embedding it into the socio-hydrology paradigm [28,77].

Secondly, the few model applications in which water-management measures are explicitly evaluated, mainly show the aggregated, generic impacts and upstream-downstream linkages at basin-scales and global-scales [e.g. Ref. 70]. However, most actual innovation is local. Its success is often determined by site-specific factors that are not always captured in the global datasets used as input. Integrating data and knowledge from the local- and regional scales with insight from models will improve the evaluation of the upscaling potential of promising measures [78••]. Although acquiring the hydrological data to validate the regionalised GHM is often an issue, particularly in South Asia, the local data monitored at test fields and pilot sites is often available from regional water-resources and agricultural research institutes. Similarly, upscaling of measures is often strongly influenced by socio-economic considerations that are not included in GHMs. Combining knowledge of the most important regional development programmes with extrapolation analysis could identify both suitable and feasible areas to implement the tested methodology and evaluate its impact when applied at scale [79,80•,81].

Thirdly, limitations to the feasibility of measures are not just biophysical, but also financial. There have been few studies that have combined GHM output at aggregated, national level with price and cost data to derive estimates for the (shadow) value of water and the costs and feasibility of measures [82,83], but as far as we are aware, none are making full use of the increasing spatial detail of GHMs. To inform decision-making and for the design of realistic pathways, a spatially explicit representation of the benefits of using water-resources and the costs of measures could be helpful.

Finally, for model results to be used for decision support in consultation with stakeholders, we believe it is essential to create credibility and relevance, to not only simulate impacts and individual measures, but also explore different spatially explicit pathways that lead to SDG achievement. Disclosing model results in a visually attractive way to stakeholders can help tailor it to their needs. Vice versa, models should be able to reflect the plans and ideas co-designed with stakeholders. The development of communication and visualisation tools to facilitate dialogue between scientists and stakeholders is an important step still required, with climate and climate adaptation applications providing good examples [84–86].

Improved modelling of hydrology, crop production and HIP in South Asia has relevance beyond the regional scale. Performance here — in this complex system — means a model has potential to perform anywhere. But the opposite is also true; South Asia is often one of the main hotspots regions in global assessments. For the outcomes of any global assessment to have merit, the human — resource interactions that define this region cannot be ignored.

Conflict of interest statement

Nothing declared.

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