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Green Water: definitions and data for assessment

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Executive Summary

Green water is that fraction of rainfall that infiltrates into the soil and is available to plants. It includes soil water holding capacity and the continual replenishment of reserves by rainfall. *Green* water is the largest fresh water resource, the basis of rain-fed agriculture and all life on land; and yet it has received remarkably little attention in contrast to *blue* water – the fraction of water that reaches rivers directly as runoff or, indirectly, through deep drainage to groundwater and stream base flow.

This review encompasses:

- **The concept of *green* water:** The distinction between *green* and *blue* water; practical definition, restricting the concept to rain-fed conditions and linking the concept of *green* water with rainwater use efficiency.

- **Physical principles of water storage in the soil:** The climatic, soil physical and ecological factors that determine the amount of *green* water and its distribution across the landscape; and the global availability of fundamental data.

- **Data availability:**
  - The FAO-Unesco *Soil Map of the World*, compiled 20-40 years ago, is the only harmonised geographic source; supporting soil physical and soil water data are restricted for tropical areas generally. The FAO-ISRIC SOTER database at scales from 1:1M to 1:5M is more robust and, now, available for half of the land area.
  - Global and regional climatic data are readily available, though of variable observation density and rarely including rainfall intensity, which is crucial to the partitioning of rainfall between runoff and infiltration. Data for decad or pentad periods and derived data such as length of growing season are most appropriate for determining the green water resource; temporal analysis is necessary to take account of season-to-season variability and long-term climatic trends.
  - For up-to-date land cover data, interpretations of satellite imagery are the only realistic approach.

  - There are various experimental measurements of runoff on well-characterised sites; these provide some basis for extrapolation by soil, terrain and climatic units.
  - Data availability remains a constraint.

- **Ways of optimising green water and its use:** Good husbandry of *green* water means good land husbandry: through soil and water conservation, tillage practices, water harvesting, crop management and management of semi-natural ecosystems. Review of experimental data reveals a rich literature on techniques of soil and water conservation, many studies producing evidence of reduced runoff and increased soil water storage, commonly also with crop yield data; in contrast, there is very little on crop management in relation to soil water and nothing on management of semi-natural ecosystems in relation to soil water. It is striking that there are no reports of failures, little social and economic assessment, and no indication of the extent of areas over which successful management of *green* water is being employed.

- **Models to estimate *green* water and water use efficiency**

- **Applications of remote sensing:** Innovative work will be needed because direct measurements of key attributes are few.

This report was commissioned in September 2002 by FAO Land and Water Division as a foundation for a *Green Water Initiative* to make better use of *green* water resources. The success of this initiative will depend on the cooperation of international, regional and national partners, as well as the active involvement of land users and water managers. The report concludes with an overview of national and international institutes that have mandates encompassing or overlapping with *green* water.

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1 THE GREEN WATER CONCEPT

1.1 Introduction

Concerns about food security and water security have always been with us. We may now add concerns about biodiversity, environmental services and climatic change. Water resources, their use and misuse are central to this debate: scarcity of water is a dominant theme across most of Africa, the Middle East, China, the Indian sub-continent and Australia. Every land use decision is a water decision; most decisions are trade-offs and, yet hardly ever taken with water in mind; and *green* water, the largest component of fresh water resources (Figure 1) has been largely ignored in policy and research.

Rain-fed agriculture and grazing occupy most of the farmland: almost 80 per cent, providing 60 per cent of world food. Although irrigation plays an important role in food production and industrial crops, the possibilities of further extension seem to be limited since water resources of sufficient quality are becoming scarce and expensive. Increasingly, agriculture must compete with domestic, commercial and industrial users and with the need to retain or return water to maintain environmental services.

Increasing human populations and aspirations require increased food and industrial production, so urgent attention to more efficient water use in rain-fed agriculture is required. This is most obviously the case in semi-arid regions where farmers have to cope with capricious rains and recurrent droughts. More than this, soils process much more water than they actually hold: crop-, vegetation- and soil management determine runoff, infiltration, soil water storage, groundwater recharge and stream base flow (Figure 2). All these factors are embraced by the concepts of ***green* water***:* the fraction of rainfall that infiltrates into the soil and is available to plants; and its *doppelganger* - ***blue* water** comprising runoff, groundwater, and stream base flow.

Figure 1

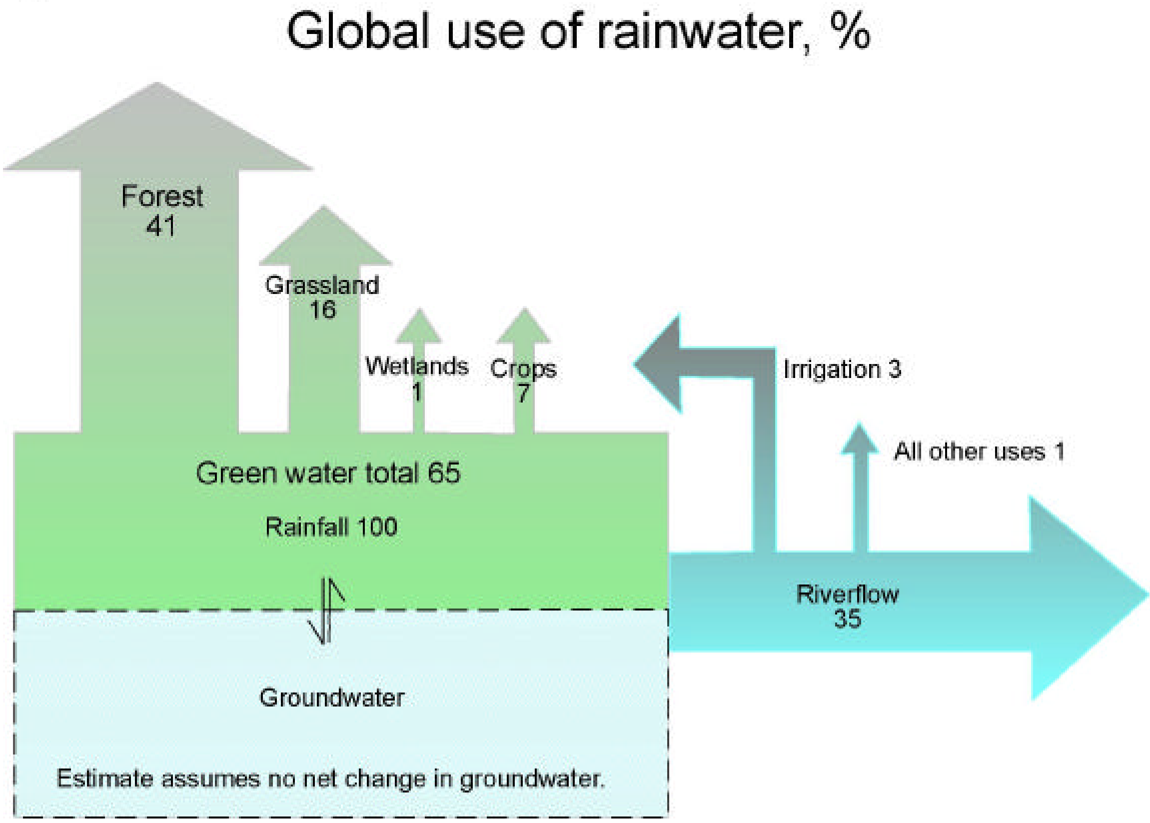
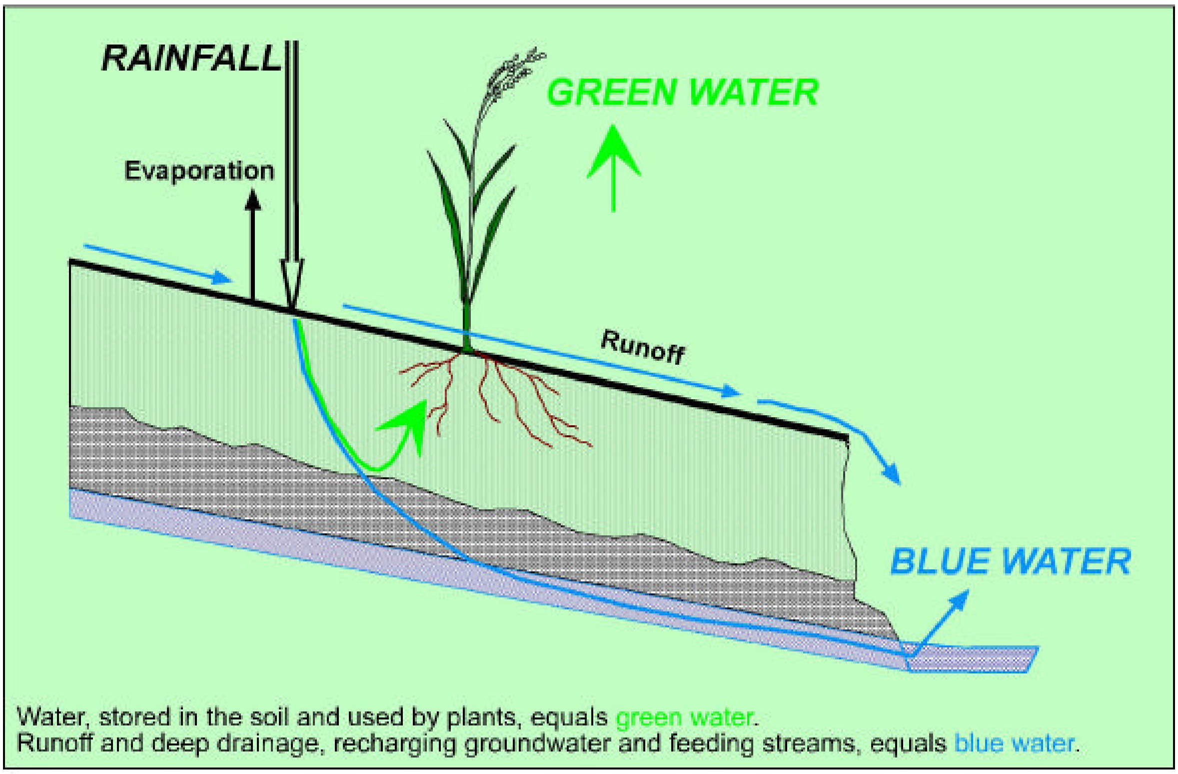


Figure 1 Global use of rainwater

Figure 2



(After Rockström, 1997)

Figure 2 Partitioning of rain water

The goals of the ISRIC – FAO *Green Water Initiative* are: to bring the theme to scientific and public attention; to increase the productivity of rain-fed agriculture, in particular by smallholders, in support of sustainable livelihoods; and to secure improved groundwater recharge and stream base flows for domestic, industrial and environmental needs. Its immediate objectives are:

- Support to policy development, in the shape of *green water maps* showing the availability of *green* water and the efficiency of water use under different land use and management scenarios;

- An accessible *knowledge base* on soil and water conservation technologies, water management technologies and cropping systems management that will promote optimal water use. This knowledge base, in the form of linked biophysical, social, and technological databases with reference maps, could support projects aimed at better water use efficiency in rain-fed agriculture. Ultimately it should be accessible to and used directly by farmers' organisations and professional land and water managers.

This report is a literature review. This first chapter defines the *green* water concept. Subsequent chapters provide information on data availability for preparing reference maps that depict *green water* resources, and distinguish soils and terrain according to their capability for improving *green*- and *blue* water resources.

Contacts have been established with partners in Sub-Saharan Africa to evaluate the possibility of building a database and literature file that covers unpublished sources. Partners were asked to complete a questionnaire on the availability of data (see Annex 1 for the mailing list and questionnaire and Annex 2 for the availability of data at the National Research Institutes).

1.2 The original concept

Green water was introduced together with *water use efficiency* in seeking options and quantifying potentials for increased agricultural production in sub-humid and semi-arid regions (Falkenmark 1995). In the original document, *green* water is defined as the fraction of rainwater that infiltrates into the root zone and is used for biomass production; equating with evapotranspiration.

The concept was introduced as the twin of *blue* water. Soil, terrain and land use influence the partitioning of incoming rainfall between the vertical return flux to the atmosphere (*green* water), and the horizontal flow to aquifers and rivers, dubbed *blue* water. The first partition, at the soil surface, splits the incoming water (rainfall, run-on and/or irrigation) into runoff and infiltration. The second partition, at the bottom of the root zone, separates *green* water from the surplus that drains deeply to groundwater. *Blue* water originates both from the first partition, as run-off, and from deep drainage below the second (Rockström 1997, Rockstrom and Falkenmark 2000) – Figure 2.

The split between runoff and infiltration at the soil surface depends on: (1) rainfall intensity, (2) soil wetness, (3) the infiltration capacity of the topsoil, determined by soil surface conditions (including crusting and vegetation cover), (4) slope length and steepness.

The partitioning of water at the lower boundary depends on (1) water use by the vegetation (in the case of farmland this involves crop, crop management and soil nutrient management); (2) the hydraulic conductivity of the deeper soil layers (Rockström 1997) and (3) climatic factors (Rockström and Gordon 2001).

Falkenmark and Rockström (1995) argue that *blue* water (the main focus of global assessments of present and future water resources, is of limited interest when it comes to food security in Sub-Saharan Africa, where farmers depend essentially on the rain for survival. But *green* water has to be used *in situ; blue* water can be withdrawn for domestic and stock-water, irrigation, and industrial use (Döll 2002).

1.3 Evolution of the Green Water concept

As soon as the concept was introduced, there was ambiguity about the division between *green* and *blue* water. Although the focus of *green* water was on rain-fed agriculture and ecosystems, it did not exclude irrigation; rather, it was a new term for evapotranspiration. Rockström (1997) espoused *green* water originating mainly from rainfall but, also, both run-on and overland flow infiltrating the root zone, and irrigation water.

The question arises whether to include runoff diverted by water harvesting, and irrigation water – both of which might be considered to be *blue* water. Rockström (1999) acknowledged the crucial role of scale when analysing the availability of *green* and *blue* water resources: a catchment with different ecosystems (e.g. crop land, forests, wetlands, and grasslands) will be a series of *blue-green* flow flips, before final *blue* water resource is determined from measurements of surface and groundwater discharge at the outlet of the catchment. Thus the *blue* water resource is defined by a measurement of water flow, which is a matter of convenience, i.e. scale. The distinction is clear when *blue* water is abstracted from rivers, surface storage or groundwater for large-scale irrigation, household and industrial use.

In the same article, Rockström also stoked confusion, stating that open water evaporation and evaporation of intercepted water can be included in the non-productive fraction of *green* water.

When first introduced, *green* water was part of a package; the total package being an instrument to analyse and quantify potentials for increased agricultural production in sub-humid and semi-arid regions (Falkenmark 1995). In later publications, it became more and more a stand-alone concept.

1.4 Removing confusion

Savenije (1999) sharpened the *green* water concept to transpiration by plants of water derived directly from rainfall stored in the soil. The total resource available over a given period of time equals the accumulated amount of transpiration over that period. Irrigation is not taken into account in this definition: by completely restricting the concept to rain-fed agriculture, Savenije removes the first point of confusion between the original and evolved concepts. He tackles the second point of confusion by introducing the class *white* water: that part of rainfall that returns directly to the atmosphere through evaporation of water intercepted by the ground cover and from bare soil; therefore excluding Rockstrom's "non-productive'' *green* water.

1.5 Rainwater use efficiency

Water use efficiency (WUE) is the biomass produced, divided by the mass of water used by the plant in producing it. It is mostly applied to irrigated agriculture, although it might equally well be applied to rain-fed production. The amount of water used to produce a given yield is mainly influenced by the atmospheric demand and the crop characteristics. WUE can be improved by converting soil evaporation to plant transpiration or by diminishing any of the non-productive water flows above in order to increase the available water (Rockström 1997).

Rainwater use efficiency (RUE) was introduced by Gregory (1987) and has been used recently by Stroosnijder and Hoogmoed (2002) to distinguish between water use efficiency in rain-fed and irrigated agriculture. The farmer's goal is to maximize the productive flux of water (transpiration) and minimize the non-productive (interception, soil evaporation, run-off and percolation beyond the root zone). RUE can be increased by: decreasing the non-productive vertical flux (*white* water) and by reducing the water loss at the water partitioning boundaries (Figure 2), thus creating more *green* water and less *blue* water.

Rockström (1997) has adapted the following mathematical expression for WUE from Gregory (1987):

$$WUE_r = \frac{Y/E_c}{1 + (E_s + D + R_{off})/E_c}$$

where: Y is yield, E_c is the crop transpiration, Y/E_c is the transpirational water use efficiency (WUE_T), E_s is soil evaporation, D is percolation, R_{off} is run-off. Increasing the crop yield with the same amount of rainfall means increasing the productive component of vertical water flow (*green* water) at the expense of the non-productive vertical component E_s and the horizontal flow (*blue* water).

1.6 Re-definition of green water

For the purposes of the *Green Water Initiative*, the term *green* water is used solely in the context of rain-fed land use, whether under arable, grazing or natural ecosystems. It comes in the original package of *blue* and *green* water together with water use efficiency. A *white* water fraction is, also, adopted - so that evaporation of intercepted water, and from bare soil and open water, is excluded from *green* water.

We also propose to define *green* water, not as transpired water, but as *the water resource held in the soil that is available to plants*. This enables focus on the practical goals of better use of *green* water in rain-fed farming systems, and improving groundwater recharge and stream base flow: there isn't a lot we can do about transpiration. A key distinction is between *green* water, that has to be used *in situ* by plants, and *blue* water that can be tapped for various uses elsewhere. The revised concept is in line with the *World Water Vision* document prepared for the World Water Council (Cosgrove and Rijsberman 2000).

The revised concept is restricted to rain-fed conditions, so it seems appropriate to use it along with the term Rainwater Use Efficiency (RUE), while retaining the mathematical definition given by Rockström (1997).

Considering the possible confusion between *blue* and *green* water, arising from scales of operation, four levels may be distinguished:

1. Field level - techniques to increase infiltration on the spot;
2. Farm level - water harvesting techniques and on-farm water redistribution;
3. Catchment level, small dams - water redistribution within the catchment;
4. Large dams - water storage for irrigation and electricity generation.

Levels 1 and 2 fall easily within *green* water. Whether level 3 should be included or excluded remains fuzzy; small dams on the farm might well be included and small dams to supply water to multi-farmer small-scale irrigation schemes might not, although the question is pedantic. Level 4 clearly concerns large *blue* water reservoirs and irrigated agriculture.

1.7 Quantification of blue and green water resources

Global quantification

Shiklomanov (1998) estimated the global precipitation over land to be 119 000 km^3y^{-1}; stream flow (*blue* water flow) is estimated to be 47 000 km^3y^{-1} and evapotranspiration (*green* water) 72 000 km^3y^{-1}; with mankind using 3500-4000 km^3y^{-1} of the *blue* water - 69 per cent in agriculture, 23 per cent for industry, and 8 per cent for domestic use.

Cosgrove and Rijsberman (2002) estimated the annual resources to be:

- 40 000 km^2 of *blue* water, the portion of rainfall that enters streams and recharges groundwater and the traditional focus of water resources management;
- 60 000 km^2 of *green* water, or soil water, the portion of rainfall that is stored in the soil.

See also Falkenmark's estimate depicted in Figure 1.

Conceptual quantification

The split into *green, white* and *blue* water occurs at two yield-determining partitions (Figure 2). To quantify the fractions, the parameters influencing the apportioning ratios need to be described: Table 1.

Table 1 Parameters influencing the partitioning ratios of *green, white* and *blue* water

Soil	Water	Atmosphere	Soil Management	Plant Management
				Crop factors
Surface conditions				Transpiration coefficient
Crust status	Runoff	Rainfall		
Infiltration	Run-on	Intensity	Mulching	Plant density
		Quantity	Tilling practices	
		Duration	Early soil prep.	
Topography			Slope length	
Slope			Stone rows	Early planting
Landform			Hedgerows	Weeding
			Bunds	
Soil thickness			Water Harvesting	
Soil wetness	Soil evaporation	Atmospheric demand (PET)		
Rootable thickness				
Storage capacity				
			Manuring*	
Nutrients*			Fertilization*	
Infiltration rate	Percolation			
Hydraulic conductivity				

* Nutrients, manuring and fertilization as far as they influence the water balance

Plant management parameters are more-or-less fixed. Besides crop modifications and manipulations that could improve the transpiration coefficient of the crop, variations in the plant density and planting period are the only two factors that can be modified by farmer. Plant management practice was included when found in the literature search.

Climatic data are fundamental: rainfall intensity, especially, affects runoff and run-on. Atmospheric demand and ground cover determine *white* water. Potential evapotranspiration is determined by radiation, temperature, relative humidity, and wind speed acting on the vegetation cover. Climatic data are becoming more readily available through the Internet. Climatic data atlases and other possible data sources have been included in the data and literature search. However, data on rainfall intensities are rare in the climatic archives mentioned. References to articles and reports mentioning rainfall intensity data have been included in the Endnote file.

Soil data are of fundamental: the data and literature review concentrate on soil physical parameters derived from the ISRIC global datasets. References to articles and reports mentioning these parameters are included in the Endnote file.

Soil management practices influencing the partitioning of water include mulching and tillage that influence infiltration and, thus, run-off. Modifications to reduce slope length and, thus, soil erosion - stone rows, hedgerows and bunds - also influence infiltration and represent some of the more successful cases of management. References to articles and reports are in the Endnote file. Where applicable, a summary of these cases is given.

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2 SOILS

2.1 Global and regional datasets

Global and regional assessments depend upon modelling (Cramer and Fischer 1997, Scholes *et al.* 1995) and, hence, on the compilation and processing of large data sets for land and water resources, using well-documented procedures and standards. In the case of soil and terrain data, the requirements include: up-to-date geographical coverage, secondary information obtained via transfer functions or models from the primary (measured) soil data, and monitoring of changes in soil characteristics as associated, for example, with changes in land use systems and processes of global change (Baumgardner 1999, Bullock 1999).

A wide range of national and regional digital databases on soil resources is becoming available (see: http://lime.isric.nl/index.cfm?contentid=287 and http://www.itc.nl/personal.rossiter). They include both soil geographic and attribute data - for example, the data sets for the USA (Lytle 1999), Canada (Lacelle 1998) and the European Union (Le Bas *et al*. 1998).

2.2 Soil Map of the World and derived databases

The *Soil Map of the World* (SMW) at scale 1:5 million (FAO-Unesco 1974-1981) remains, more than 40 years after its commencement and more than 20 years after its completion, the most comprehensive overview of world soil resources. It is a compilation of numerous national and regional maps, using a common legend. At the time of compilation, in the 1960s to early 80s, soil maps for many countries were available for limited areas only and at various scales. In addition, relatively few regionally representative profiles were available. Hence, interpretations were often qualitative and based on expert judgement.

The digital SMW (FAO 1995) includes both a vector version and a rasterized version (5′ x 5 ‘). The latter was used to prepare a 30 by 30 minutes raster map for the World Inventory of Soil Emission Potentials (WISE, Batjes *et al.* 1995). The spatial component of the WISE database is linked to an extensive collection of soil profile data, presented in a uniform and harmonized format (Batjes and Bridges 1994). Several WISE-derived data sets can be downloaded from the ISRIC website (www.isric.org).

In 1997, the International Institute for Applied Systems Analysis (IIASA), FAO and ISRIC identified the need to refine the agro-edaphic element of the FAO Agro-Ecological Zones (AEZ) methodology and the IIASA's Land Use Change and Land Cover project for Europe and Northern Eurasia. The resulting study was based on the analysis of the 4353 soil profiles held in version 1.0 of the WISE database. It led to the development of a set of files holding ‘derived soil data for use in global and regional AEZ studies’ (Batjes *et al.* 1997). Soil unit, topsoil textural class, and depth zone (0-30 cm and 30-100 cm) were used to cluster the horizon data in accordance with conventions developed by FAO for use with the *Soil Map of the World*. Soil parameter estimates are presented for the two FAO soil legends: 1974 and 1988. The 1988 Revised Legend has been used to linkage with SOTER databases that use the same legend (see below).

The above study identified many gaps in the extant datasets - geographic, taxonomic and soil physico-chemical; it showed the persisting need for expanding the set of soil profile data available for this type of analyses, and for the development of pedo-transfer functions. Batjes (2002 b and c) plugged important gaps in the soil profile data and refined the methodology to generate a revised list of soil parameter estimates for the world: 28 parameter estimates including organic carbon; cation exchange capacity; bulk density; total porosity; weight percent of sand, silt and clay; and available water held between –5 kPa and -1500 kPa, –10 kPa and -1500 kPa, and –33kPa and -1500 kPa, respectively. All these soil attributes are very relevant to the *Green Water* Initiative.

The above set of soil parameters should be seen as best-estimates, based on the worldwide selection of soil profiles and the adopted data clustering procedure; it is appropriate for use in studies at a regional to global scale (smaller than 1:250 000). Correlation of soil analytical data, however, must be done more accurately when more precise scientific research is considered (Batjes 2002b). Similarly, national sets of representative profiles should be used in more detailed studies whenever available. A comprehensive update of soil parameter estimates for the soil types of the world will first become feasible upon the completion of the World Soil and Terrain (SOTER) program.

Examples of applications of the soil parameter and spatial data sets derived from WISE include: modelling of global environmental change (Alcamo *et al.* 1998, Bouwman and van Vuuren 1999, Cindery *et al.* 1998, Ganzenveld *et al.* 1998, Hootsmans *et al.* 2001): up-scaling and down-scaling of greenhouse gas emissions (Bouwman *et al*, 2002a, Bouwman *et al.* 2002c, Knox *et al.* 2000); global emissions of NH_3 (Bouwman *et al.*, 2002b); and agro-ecological zoning (Fischer *et al.* 2001, 2002). A subset from WISE version 1.0 provided the soil profile attribute basis for the activities of the Global Soil Data Task Force of IGBP-DIS (2000).

2.3 World Soil and Terrain Database

The advantages and disadvantages of the *Soil Map of the World* and its grid-based derivatives have been reviewed by Bouwman (1990), Nachtergaele (1999) and Batjes (2000): the spatial data are known to be outdated; the associated area data have been derived from composition rules (FAO 1995); the density and quality of the available soil profiles varies greatly (Batjes 2002b). Hence, the need for the current program to update the information on the world's soil resources at scale 1:5 million in SOTER, *the World Soils and Terrain Database* program (Oldeman and van Engelen 1993, van Engelen 1999).

SOTER was initially developed for use at scale 1:1 million (Baumgardner and Oldeman 1986) but the procedures can be applied, with minor modifications, at scales ranging from 1:100 000 up to 1: 5 million. Each SOTER unit represents a unique combination of terrain and soil characteristics, and is characterized by at least one representative soil profile (van Engelen and Wen, 1995). SOTER units (areas with distinctive, often repetitive patterns of landform, slope, parent material and soils) and their component soils are linked to a map using GIS. The geographic and point attributes of each SOTER unit are held in a relational database.

Nachtergaele (1999) compiled a comprehensive overview of national-scale databases available for use in the SOTER program. Completed regional SOTER databases include those for Latin America and the Caribbean (FAO *et al.* 1998) and Central and Eastern Europe (FAO and ISRIC 2000). SOTER Southern Africa at scale 1: 2 million, which covers Angola, Botswana, Mozambique, Namibia, South Africa, Swaziland, Tanzania, and Zimbabwe, is completed (January 2004). Examples of national SOTER databases include those for Hungary (Varallyay *et al.* 1998), Benin (Igue 2000, Welle, 2002), and Kenya (Mantel and van Engelen 1999). Mantel et al. (1999) demonstrated the usefulness of the SOTER approach at scale 1:250 000 in Berau, East Kalimantan (Indonesia). Figure 3 shows the current status of SOTER worldwide.

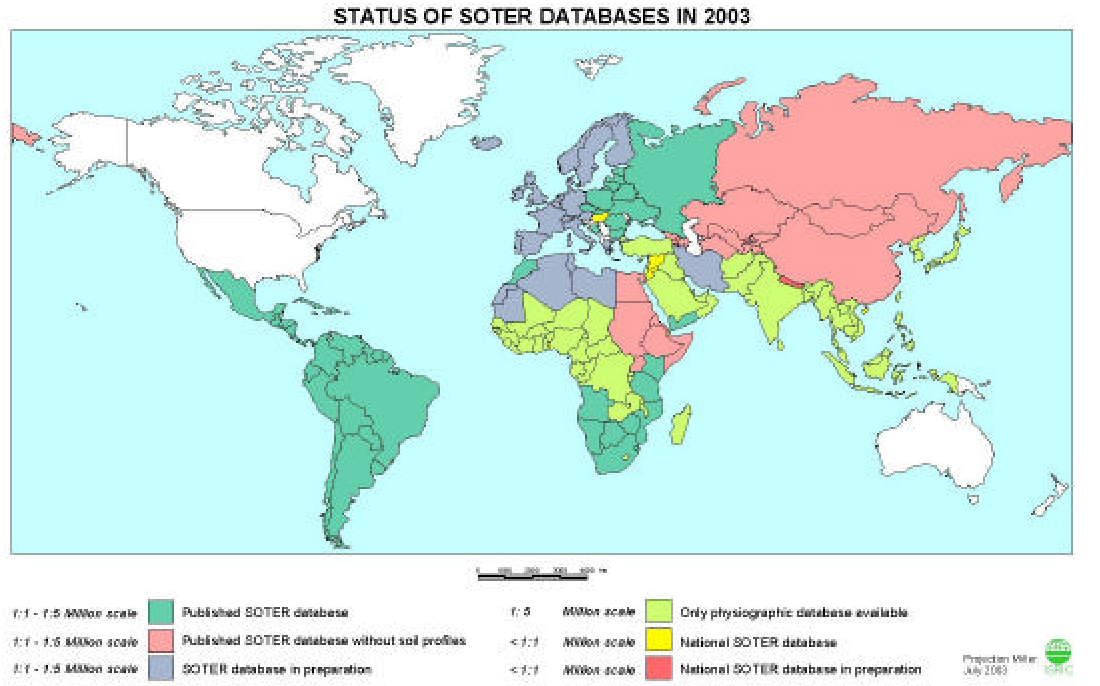

Figure 3 Status of worldwide SOTER, July 2003

SOTER mapping at 1:5 M scale, using digital elevation models and remote sensing, is ongoing in Europe (King *et al.* 2002) and the USA (Dobos *et al.* 2002). So far, few SOTER-related activities have been undertaken in Asia, Australia and Canada but work is beginning in India and Australia.

Examples of applications of SOTER data include land evaluation (Weller 2002), modelling of yield decline upon water erosion (Mantel *et al.* 1996), assessments of soil organic carbon stocks and change at national scale (Batjes 2002a, Falloon *et al*. 1998), and studies of soil environmental protection (Batjes 2001, Varallyay *et al.* 1998) and similar techniques may be applied to generate *green water* interpretations.

2.4 Database of soil water and hydraulic properties

Complex computer models have been developed to simulate water and solute movement in the unsaturated zone. A bottleneck for applying these models remains the lack of accessible and representative soil hydraulic data: soil texture, hydraulic conductivity, water retention characteristics and infiltration rate. Commonly, these data are under-represented in SOTER and WISE because these databases have been compiled using profiles derived from standard, systematic soil surveys.

The *UNsaturated SOil hydraulic DAtabase* (UNSODA) was developed at the U.S. Salinity Laboratory to provide unsaturated hydraulic data and several other soil properties. It includes water retention, hydraulic conductivity and soil water diffusivity, as well as standard soil properties such as particle-size distribution, bulk density, and organic matter content (Nemes *et al.* 2003). For Western Europe, a similar database has been developed in the framework of HYPRES (*Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning*) (Wösten *et al.* 1998).

Both UNSODA and HYPRES focus on soils of the temperate regions. Strongly weathered soils of tropical regions often show markedly different soil hydraulic properties (Tomasella and Hodnett 1997, 1998; Van den Berg *et al.* 1997) but there are few data sets to develop pedotransfer functions. The *IGBP-DIS data set for pedotransfer function development* (Tempel *et al.* 1996), for example, contains only 771 horizons from tropical soils with sufficient data to develop a PTF (Hodnett and Tomassella 2002). This lack of measured data for tropical soils, and for low-density soils like Andosols, constrains the modelling of water movement and uptake in tropical areas.

Wosten *et al.* (1998) have published a comprehensive list of references on pedotransfer functions.

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3 WATER

3.1 Scales of study

To determine actual and potential *green water*, it is necessary to measure the partitioning of rainfall. Figure 2 illustrates the water flows in rain-fed cropping systems as well as the dynamic components of the water balance: rainfall, runoff, run-on, evaporation, drainage and transpiration. Quantification of the dynamic components depends very much on spatial and time scales.

The point scale is mostly used to measure infiltration but is not appropriate to measure runoff (which is prevented in most techniques measuring infiltration under a constant head of water). Hydraulic conductivity, used for the determination of drainage, can however be measured at the point scale. Likewise, the point scale is the most appropriate to quantify direct evaporation from the soil surface (Ritchie 1972). The time scale is usually per minute or per hour.

The plot scale (<100 m^2) is the Wischmeier scale at which soil erodibility is commonly determined. On this scale, also, runoff can be measured e.g. to determine rainfall-runoff relations for different soil types or to study the influence of slope length or slope angle; and water balance studies can be performed at the plot scale when soil water measurements are conducted and when soil evaporation is determined. The most appropriate time scale for these determinations is hours or days.

The field is the management unit. The field scale (1-8 ha) is most used for on-farm water balance. Amongst others, Rockström *et al.* (1997, 1999, 1998) have determined runoff, run-on, evaporation and drainage at the field scale. Since fields are not homogeneous in terms soil and terrain, it is difficult to apportion the quantified parameters to a particular soil type or landform. The time scale usually used for these determinations is hours or days.

At the catchment scale, measurements of runoff are performed in the river channels, usually at a weir. Zimbabwe is an example of a country in Africa with an extensive network of river gauging stations, originally set up to estimate the storage potential for small earth dams (Interconsult and NORAD 1985). Catchment runoff is mostly determined on a monthly or annual basis.

Runoff and evaporation data are available from most of the respondents to the questionnaire (2,4,6,7,8) but the scale of determination scale was not given.

3.2 Information at point and plot scale: examples

Early measurements by Stroosnijder and Kone (1982) showed that cumulative actual soil evaporation between showers in the growing season can be described by:

$$\Sigma E = f(LAI) * PEVAP + 3.5 * (t^{0.5} - 1)$$

Where f(LAI) is a correction term depending on the leaf area index, PEVAP is the potential evaporation (in Mali, approx. 70% of pan evaporation), t is the number of days since the previous rain.
The cover only affects evaporation on the day after the rainfall. Thereafter the cumulative evaporation is proportional to the square root of time (Stroosnijder 2003).

Within the HAPEX-Sahel experiment, measuring the hydrological functioning of different soil types under various covers, Peugeot *et al.* (1997) report on two catchments studied at the plot scale and the catchment scale. Runoff plots were set-up in sandy soils with erosion crusts, particular plots were assumed to be representative of the hydrological behaviour of a particular surface cover (bare, fallow grassland and millet).

Zougmoré *et al*. (2000) provide runoff data at plot level for bare soils and soils under sorghum-cowpea intercropping for Saria, Burkina Faso over a three year period.

Valentin and d'Herbes (1999) and Rockström (1999) provide runoff data at plot level for Niger.

Rockström *et al.* (1998) modelled water balances for runoff-producing surfaces, surfaces receiving run-on water, and a reference surface with zero runoff and run-on. Besides data on runoff, they include data on evaporation and drainage.

Examples from the literature are listed in Table 2.

Table 2 Examples of runoff, run-on, evaporation and drainage data at point or plot scale in selected countries of Africa

Country	Soil type	Cover	Data	Reference
Burkina Faso		Bare Sorghum-cowpea	Runoff	(Zougmoré *et al.* 2000)
Kenya	Rhodic Ferralsols	Maize	Runoff	(Wakindiki and Ben-Hur 2002)
Niger	Sandy soil crusts	Bare Grassland Millet	Runoff	(Peugeot *et al.* 1997)
Niger	Sandy soil crusts	Natural vegetation	Runoff	(Valentin and d'Herbes 1999)
Niger	Ustic isohyperthermic Typic Haplustult	Fallow Millet Sorghum	Runoff, Evaporation, drainage	(Rockström et al. 1998)
Niger	Typic Haplustult	millet	Runoff, Evaporation, drainage	(Rockström 1999)

3.3 Information at field and hill slope scale: examples

Rockström (1999) studied the water balance in millet fields with a 2%-3% slope, from a part of a typical Sahelian toposequence draining from a laterite plateau.

Bennie and Hensley (2001) overview techniques to maximize infiltration in dryland agriculture in South Africa, giving runoff data for various soil types under various cultivation practices.

Stroosnijder (1982) provides runoff values for different Sahelian soil types, measured at the hill slope scale.

Schwab *et al.* (1981) list runoff values for a large range of soil types, with various vegetation covers and for different rainfall intensities.

Some of the publications referred to in Chapter 5 also provide data on runoff (or other water balance factors) at the field scale, see Tables 10, 11, and 12.

Information at catchment and country scales

Data on runoff and evaporation at catchment and country scale are available on the Internet but their usefulness for the Green Water Project is limited: in most cases, the long time period considered (monthly or annual) is not appropriate for rainwater use efficiency calculations, and does not distinguish the high variability of rainfall. Likewise, the spatial resolution is too coarse to differentiate different soil types and vegetation covers. However, some indication of the potentially available water can be of interest as a starting point in studies of hydrological dynamics.

The state of freshwater systems and resources in South Africa is given on http://www.ngo.grida.no/soesa/nsoer/issues/water/state.htm
South Africa has one of the lowest annual precipitation:runoff ratios in the world (Figure 4). The website also shows the distribution of the mean annual runoff over the country, with low runoff in the western regions and high runoff in the east. Also, http://amanzi.beeh.unp.ac.za/agency/users/lynch/atlas_266.htm provides median annual runoff data for the different provinces of South Africa.

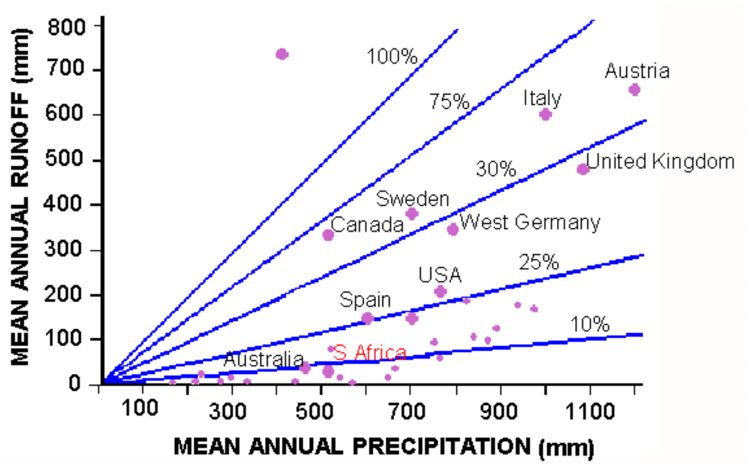

Figure 4 Mean Annual Runoff vs. mean annual precipitation

A Global Water Database is a meta-data system managed by the University of New Hampshire, containing annual and monthly country river discharges at a 30-minute spatial resolution (http://www.grdc.sr.unh.edu/index.html).

The Water Systems Analysis Group is involved in broad-scale aspects of the terrestrial water cycle. The website provides links to global water databases, global runoff datasets and water cycle data (http://www.watsys.unh.edu).

The Center for Research in Water Resources (University of Texas at Austin) has developed a digital atlas of the *World Water Balance* - an integrated set of data files and models in GIS format that can be used to characterise the water balance (http://www.ce.utexas.edu/prof/maidment/atlas/atlas.htm). Details are provided for Morocco and Niger.

FAO and UNESCO maintain an educational and informational website on the *Soil Water Balance of Africa* which demonstrates how simple, monthly potential evaporation and soil-water budget calculations can be made within ArcView GIS. Input requirements are precipitation, potential evapotranspiration and soil water holding capacity. Links to obtain the input data are provided (http://www.ce.utexas.edu/prof/maidment/gishydro/Africa/ex3af/ex3af.htm).

Table 3 Sites providing data on (global) runoff and/or evaporation data

Country	Website
South Africa	http://www.ngo.grida.no/soesa/nsoer/issues/water/state.htm
South Africa	http://amanzi.beeh.unp.ac.za/ageng/users/lynch/atlas_266t.htm
Global	http://www.grdc.sr.unh.edu/index.html
Global	http://www.watsys.unh.edu
Global/Morocco/Niger	http://www.ce.utexas.edu/prof/maidment/atlas/atlas.htm
Africa	http://www.ce.utexas.edu/prof/maidment/gishydro/Africa/ex3af/ex3af.htm

Savenije (1997) presents a method to determine total evaporation at catchment and decadal/monthly scale, based on the water balance of the Bani catchment in Mali under savannah.

Roberts and Harding (1996) use simple soil moisture deficit and canopy interception models to calculate actual evaporation losses from three different land covers in an upland area of Kenya. They provide catchment characteristics and annual runoff and evaporation data for 1958-1974.

Everson (2001) measured daily evaporation, stream flow and soil water storage over a two-year period in a 97 ha grassland in the Drakensberg, in Natal. He provides catchment parameters and annual water balance data (evaporation and runoff) for a 10-year period. The data were used to develop single expressions to calculate annual stream flow and evaporation. Actual data were compared to modelled data using the ACRU model (see Chapter 7).

Table 4 Availability of runoff, run-on, evaporation and drainage data at catchment scale

Country	Cover	Area	Data	Reference
Kenya	Pine Bamboo forest Pine- Bamboo-grass	36.4 ha 64.9 ha 36.8 ha	Runoff, evaporation	Roberts and Harding 1996
Mali	Savannah		Evaporation, runoff	Savenije 1997
Niger	Various	0.04 km^2 0.09 km^2	Runoff	Peugeot *et al.* 1997
South Africa	Natural grasslands	97 ha	Runoff, evaporation	Everson 2001

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4 CLIMATIC AND METEOROLOGICAL DATA

4.1 The need for climatic data

Climate data are fundamental to the quantification of *green, blue* and *white* water fluxes. Precipitation (P) is the ultimate source; its intensity strongly influences the partitioning of runoff (*blue* water) and infiltration (potentially *green* water). The atmospheric demand, or potential evapotranspiration (PET), drives direct evaporative losses (*white* water) and transpiration by crops and, thus, any surplus for deep drainage to groundwater and stream base flow (*blue* water).

4.2 Global availability

Rainfall data from the annual to the daily time scale are relatively easy to obtain. PET data are not so widely available; annual and monthly data are available from FAO or Internet sources but decadal and daily data, sometimes, have to be derived from other climatic data. Allen *et al.* (1998) show how to calculate PET from limited data sets containing temperature and relative humidity data. Most respondents to the enquiry indicated that they have climatic data available (Annex 3).

The WMO website provides detailed information on where to obtain specific climatic data worldwide. Mostly, the links are to the national meteorological services. The INFOCLIMA DATA Centre can be found on
http://www.wmo.ch/web/wcp/wcdmp/infoclim/cenreg1.html#cen102A

Table 5 Climatic data format availability

	Annual	Monthly	Decad	Daily	Intensity
Average (long-term)	P PET	P PET	P PET	P	P
Temporal	P PET	P	P	P	
Spatial	P PET	Rainfall-derived factors	Rainfall-derived factors		

4.3 Annual data

Rainfall

Annual rainfall may be used for coarse global assessments. Means are used for general classifications of the type: "rainfall (1960-2000) is 650 mm y^{-1}". In conjunction with PET, mean annual rainfall is often used to define sub-humid and semi-arid regions.

Temporal analysis of annual data can show variations between so-called normal, dry and wet years – using, for example, the median and probabilities of occurrence (50per cent, 25 per cent and so forth). Trends over different periods may be observed: for example periods of warming; long, dry periods; and El Niño effects. However, the annual time scale is too coarse for assessment of *green* water resources.

Potential evapotranspiration (PET)

Annual PET data may be used for global assessments; means are used for general classifications. In comparing mean annual rainfall with mean annual PET, it has to be remembered that the difference between the two does not indicate water surplus or shortage (see remarks under Monthly Data).

Temporal analysis of annual PET can show variations between normal, dry and wet years; PET will be lower in wet years, because of cloud and humidity, and higher in dry years, because of greater sunshine and lower humidity. As in the case of rainfall, annual PET data are too coarse for *green* water assessments.

Table 6 Availability of annual P and PET data

Data	Source	Available from	Format
Climatic maps	FAO AGROMET	http://metart.fao.org	JPEG Maps
Mean Annual R and PET	FAO AQUA-STAT	http://www.fao.org/ag.agl/aglw/aquastat/gis/index2	JPEG Maps
	JISAO data	http://toa.atmos.washington.edu/data/willmott/africa	JPEG ASCII

The data sources mentioned in Table 6 all give references to the source files that may be used to obtain the JPEG maps as well as information on the spatial availability of these data (grid).

4.4 Monthly data

Rainfall

Monthly rainfall data are used for global and regional assessments, for instance Agro-ecological Zone (AEZ) studies. Monthly values may be used for the analysis of length of growing period and temporal distribution of growing periods, which vary from year to year, and rainfall amount and distribution in normal, wet, and dry years. Spatial analysis can show variations comparable with those revealed by annual data; factors derived from the rainfall (e.g. length of growing season) often yield more insight than the raw, monthly rainfall figures.

PET

Monthly PET data may be used for coarse, global assessment of *green* water resources.

Table 7 Availability of monthly P and PET data

Data	Source	Available from	Format
Worldwide mean monthly P, PET, temperature and humidity	FAOCLIM	FAOCLIM-CDROM	ASCII
South Africa KwaZulu-Natal mean monthly P	Umgeni	http://www.umgeni.co.za	Excel
Southern Africa Mean monthly P and temperature	JISAO data	http://toa.atmos.washington.edu/data/willmott/africa	JPEG ASCII
Worldwide mean monthly P and temperature	NCDC	download from ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/v2/	ASCII
Monthly PET Kenya (4 stations)	Karongo and Sharma (1997)	Article	paper

Decad and pentad data

Rainfall data for decades (10-day periods) and pentads (5-day periods) are used for water balance and plant growth modelling. This is the level of analysis that is of most interest for *green* water. Decadal averages can be used to determine the start and end of the growing period(s) – that is the period during which *green* water is available and the period over which efforts should be made to increase the RUE. In determining the start of the growing season, attention should be paid to the fact the runoff can occur before the beginning of the growing season.

Temporal analysis can be used for risk analysis, for wet-normal-dry year occurrence, or to indicate drought within growing seasons. Using these derived factors (length of growing season, drought periods), which will vary from year to year, spatial variations can be analysed.

Table 8 Availability of decadal P and PET data

Data	Source	Available from	Format
Decadal P Burkina Faso (135 stations)	IRA	Diskette	Excel
Decadal PET Burkina Faso (9 stations)	IRA	Diskette	Excel
Decadal P Eritrea (7 stations)	WMO stations	www.punchdown.org/rvb/rain/raindata.html	*.DAT
Estimated decadal P	FAO-AGROMET	http://metart.fao.org/~~/gbr/Eprodmen.htm	ASCII
Worldwide decadal P, PET, temperature and humidity	FAO	CLIMWAT for CROPWAT – diskette & CD-ROM	*.cli (for import in CROPWAT)
Decadal P estimates* Africa	CPC	http://www.cpc.ncep.noaa.gov/products/fews/data.html	*.bil *.dat
Decadal P (13 countries)	Africa Data Dissemination Service	http://edcw2ks21.cr.usgs.gov/adds/readme.php?symbol=rf	NDVI data Maps

Herman *et al.* (1997) describe a technique to estimate decadal precipitation in Africa, developed to fill gaps in the sparse observational network.

4.5 Daily data

Rainfall

Daily rainfall data are used to study rainfall-runoff relationships - for instance Vigiak (2002) divided 24-hour rainfall in three classes: less than 10mm, 10-20mm, and more than 20mm. These classes reflected the probability of overland flow, which was considered unlikely for rains of less than 10mm in 24hours. The grouping in classes simplifies runoff analysis and calculation of the likelihood of the occurrence of a given amount of rainfall in certain periods of the year. Zougmoré *et al*. (in press) also use rainfall classes to predict runoff.

Temporal analysis reveals the variation in rainfall-dependent parameters such as yield. Scenarios for extreme events (e.g. the probability of occurrence of consecutive wet days or a long dry spell within the growing season) can be established by analysis of daily rainfall data.

Daily rainfall is available from several of the National Research Institutes (Annex 3).

Rainfall intensity

In combination with antecedent rainfall, vegetation cover and surface soil conditions, rainfall intensity determines runoff. In many runoff-simulating models, intensity is either a required parameter or it is derived from daily rainfall. Rainfall-intensity data are available from several National Research Institutes (Annex 3).

Table 9 Availability of daily P and PET data

Data	Source	Available from	Format
Daily P estimates Africa, 1998-2000	Climate Prediction Center	http://www.cpc.ncep.noaa.gov/products/fews/data.html	*.bil
Daily P, Francophone Africa, 1930-1965	CIEH (1965)	ISRIC library	Paper
Daily P, temp. and humidity, South Africa - KwaZulu Natal	Umgeni	http://www.umgeni.co.za	Excel
Intensity (I_{30})	Zougmoré *et al.* (2003)	Article	Paper
Daily P	Annex 3	Respondents: 1,2,3,4,5,6,7	
Intensity	Annex 3	Respondents: 1,2,4,5,6	
Daily PET	Annex 3	Respondents: 1,2,4,6	

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5 SOIL AND WATER MANAGEMENT

5.1 Links between *green* water, nutrient status and soil fertility

Making the most of *green* water means adopting effective soil and water conservation practices: practices that are matched with local soil, climatic and social conditions. Effective soil and water conservation and crop management increase infiltration of rainfall and soil water storage, reduce evaporation from the soil surface, control the flow of water over the soil surface or store the excess rainfall (runoff) for later use (FAO 1993). Runoff management, also, maintains soil nutrients - so the benefits to rainwater use efficiency cannot be attributed solely to increased *green* water.

This section reviews experimental work on mulching (reducing runoff and soil evaporation), tillage systems (reducing or increasing runoff), and water conservation and water harvesting techniques.

Soil and water management: sources

WOCAT (WOCAT 2002) is a database that documents all relevant aspects of soil and water conservation technologies, and where they have been adopted worldwide. It describes the technical and social aspects of the application of different management techniques, enabling evaluation of success, or otherwise, of different cases.

A wide-ranging review of grey literature of available technologies for semi-arid Zimbabwe may be found on http://www.sri.bbsrc.ac.uk/science/idg/zimbabwerecent.htm.

Hatibu and Mahoo (1999) discuss rainwater harvesting technologies for agricultural production used in Dodoma, Tanzania. Although not quantitative, they evaluate the viability of the various practices.

Stroosnijder (2003) discusses the effect of different soil and water management techniques on rainwater use efficiency with success stories from Burkina Faso, Mali, Kenya and South America.

Bennie and Hensley (2001) overview techniques to maximize infiltration in dryland agriculture in South Africa. They provide figures for runoff reduction under various soil management techniques.

Several respondents to the questionnaire indicated that they have data on the application of soil and water management techniques.

Mulching

Mulching maintains a protective cover on the soil surface. Materials used include crop residues such as straw, paper, plastic sheet, even gravel. The beneficial effects include: protection against raindrop impact; decrease in surface water flow velocity; lessening of runoff through increased infiltration; lessening of evaporation from the soil surface; and, in the case of crop residues, addition of nutrients and organic matter.

Mulching can increase the water use efficiency. In a lysimeter experiment, Tolk *et al.* (1999) found that mulching provides a more favourable soil water regime compared with a bare soil surface; the effect of the mulching depends on the amount of mulch applied. Stroosnijder and van Rheenen (2001) found that mulch cut runoff by some 65 per cent and that mulch applied at 6000 kg ha^{-1} cut evaporation from the soil surface by 25 per cent. FAO (1993) reviews the effect of mulch on runoff and erosion. All sources give positive figures for runoff reduction.

On the loess plateau of China, gravel mulching is an ancient practice. In some areas, plough ridges are covered by plastic sheet and furrows lined by gravel – protecting against both evaporation from the soil surface and runoff in the furrows. Li *et al.* (2000) found that he combination increases RUE by 260 per cent compared with bare ridge and furrow. Volcanic gravel is used as mulch on Lanzarote, Canary Islands (Tejedor *et al.* 2002).

Mando (1997) found that application of mulch to a crusted, bare soil triggers termite of worm activity within a few weeks. New macropores are created so water infiltration is greatly improved: in the first year of application, mulch lessened runoff by some 15 per cent; in the following years, this improves to 50 per cent.

Table 10 Literature and the availability of data on the effect of mulching on runoff

Country	Soil type	Runoff reduction	Reference
Burkina Faso	Chromic Luvisol	65% (plus evaporation reduction 25%)	(Stroosnijder and Hoogmoed 2002) (Stroosnijder and Rheenen 2001)
Burkina Faso		60%	(Zougmoré *et al*. 2000)
Burkina Faso	Lixisols and Cambisols	15 – 50%	(Mando 1997)
China	Sandy loam (loess origin)	100%	(Li *et al*. 2000)
Ghana		90 %	(FAO 1993)
Nigeria		90 %	(FAO 1993)
Mauritius		85 %	(Facknath and Lalljee 1999)
Morocco	Calcic Chromoxerert	*RUE: 5.7 → 6.5	(Mrabet 2002)
Mozambique		*WUE: 6.8 → 8.4	(Rothert and Macy 2002)
Niger	Ustifluvent sandy loam	*RUE: 2.48 → 3.14	(Zaongo *et al*. 1997)
Canary Islands	Various	90%	(Tejedor *et al*. 2002)
USA - lysimeter	Clay loam & sandy loam	*RUE (biomass): 2.6 → 2.93	(Tolk *et al*. 1999)
Respondents 1,2,3,4,6,7,8	Various	For details see hardcopies of filled questionnaires	

* Results are given in terms of rainwater use efficiency (in kg ha^{-1} mm^{-1}) and not in terms of runoff reduction

Tillage

Farming practices that incorporate conservation (minimal) tillage or zero tillage usually bring about increased rainwater use efficiency by increasing infiltration and deeper penetration of water into the root zone. Zero tillage involves no seedbed preparation other than opening the soil (a small slit or hole) in order to place seed at the desired depth (Stroosnijder and Hoogmoed 2002).

Conservation tillage is usually practised in combination with residue management:

Ghuman and Sur (2001) describe the effects of tillage and residue management on rain fed maize and wheat yields in India: RUE was raised by 80 per cent with the combined management, compared with conservation tillage alone;

Mrabet (2002) studied the combined effect of tillage and residue management on a shrink-swell soil in Morocco: the effect of deep disking on the rainwater use efficiency was comparable to the effect of residue management;

In Ontario, Tan *et al.* (2002) compared the effect of conventional tillage with the effect of reduced tillage, without further management practices. Reduced tillage increased the total annual surface runoff relative to the conventional tillage, although the increase was not significant for two out of the three years' experiment.

Hoogmoed (1999) reviews water conservation under various tillage systems in the semi-arid tropics, based on the soil characteristics and on different levels of mechanization. He also discusses the difficulty of modelling tillage effects.

Kaumbutho *et al.* (1999) review tillage practices and their effectiveness in East and Southern Africa.

Table 11 Summary of literature and the availability of data on the effect of tillage on runoff and rainwater use efficiency

Country	Soil type	Result	Reference
Ghana		Runoff reduction up to 90 %	FAO 1993
India	Fluventic Ustochrept	Minimum tillage plus residues most effective	Ghuman and Sur 2001
Mauritius		Runoff reduction 30 – 40 %	Facknath and Laljee 1999
Morocco	Calcic Chromoxerert	RUE* 5.7→6.6	Mrabet 2000, 2002
Ontario	Clay loam	Increased runoff	Tan *et al*. 2002
Sudan	Vertisol	Subsoil tillage most effective	Salih *et al*. 1998
Zimbabwe	Fersiallitic	RUE* 12 → 24	Riches *et al*. 1997

* Rainwater use efficiency, kg ha^{-1} mm^{-1}

Rainwater harvesting and water conservation

Rainwater harvesting means inducing, collecting and applying local surface runoff for agriculture (Boers and Ben-Asher 1982). Either the runoff is collected and stored in tanks or cisterns, or in-field water harvesting is practised – for instance the half moon technique whereby small catchments are created in the field and water is held in small basins, blocked by the half-moon ridge, to increase infiltration; the crop is planted on the ridge.

Spate irrigation harvests flash floods by diverting runoff into fields where it is stored in the soil profile. It is widely used in the Mahgreb, Yemen, Sudan, Somalia and Eritrea. Hedera (2001) reports on the gain in soil fertility and water quantity of spate irrigation systems in Eritrea.

Water conservation increases the amount of water in the soil by trapping the water where it falls, or where there is local runoff:
Line measures (mostly along the contour) trap runoff from the land upslope and, so, increase infiltration time. They may be impermeable - made of earth or stones; or semi-permeable – hedgerows, vegetation or trash lines; or a combination of ditch and bank (*fanja juu*). In other cases, line measures are constructed perpendicular to the contour line, for example the *jessours* system in Tunisia (Ouessar *et al*. 2002, Schiettecatte *et al*. (2002)) which consists of three components: the *impluvium*, the terrace and the bund. Water and soil from the *impluvium* is collected and runs off to the terrace. There, the bund blocks the flow so that the water is stored in the terrace.
Areal measures such as tied ridging, manuring and mulching, trap runoff water and promote infiltration on the spot.

FAO (1993) reviews water conservation techniques in various countries; Pacey and Cullis (1986) describe techniques and successful cases of water harvesting world-wide, including Botswana, Zimbabwe and Zambia; the proceedings of a workshop held in Niamey (FAO 1999) deal with water harvesting systems in West and Central Africa.

Line measures

Kiepe (1995), in Kenya, measured runoff over six cropping seasons and on four different treatments of mulch and hedgerows. Hedgerows cut runoff by 60 per cent. Combining hedgerow and mulch management cut runoff by 75 per cent.

Spaan *et al.* (in press) claim that vegetation barriers, which are semi-permeable, reduce the risk of waterlogging during wet years and are most effective when closely spaced. In trials in Burkina Faso, slope lengths in the trial varied form 1.25 m to 12.5 m. Runoff was cut by 90 per cent for the shortest slope length and by 70 per cent in the longer slope length. Also in Burkina Faso, Stroosnijder and van Rheenen (2001) found that the stone rows placed every 50 m cut runoff by 50 per cent, and by 80 per cent when combined with mulching. Grass strips placed every 50 m were as effective as the stone row-mulch combination.

Wakindiki and Ben-Hur (2002), in Kenya, found that stone lines spaced about 15 m across the slope cut runoff by about 50 per cent; trash lines were almost equally effective.

Valentin and d' Herbes (1999), in Niger, found that natural vegetation retained in dense bands aligned across the slope lessened the runoff. Banded landscape systems have the advantage of a wood biomass production three times higher than for landscapes without natural vegetation bands.

Areal measures

Tied ridging involves blocking plough furrows with earth ties spaced at a fixed distance apart. The resulting basins retain the runoff within the field and increase soil water storage. However, storms may lead to ridge overtopping, ridge failure or waterlogging. In Mali, Stroosnijder and Hoogmoed (1984) found that tied ridges giving a surface storage of 20-30 mm, could completely prevent runoff (which was 50 per cent of rainfall under conventional systems); this might increase the average millet production by some 40 per cent.

Wiyo *et al.* (2000), in Malawi, evaluated the effect of tied ridging on soil water status by simulating seasonal changes in retained rainwater, surface runoff, drainage, soil moisture storage, waterlogging and actual transpiration. They found that tied ridging reduced the surface runoff; the positive effect of increased soil water storage was almost completely lost by increased drainage on coarse-textured soil; but was effective for fine-textured soils.

Table 12 Summary of literature on water harvesting and water conservation

Region	Soil type	Result	Reference
Burkina Faso	Luvisol	Runoff reduction 70 – 90 %	Spaan *et al*. in press
Burkina Faso	Chromic Luvisols	Runoff reduction 50 – 80 %	Stroosnijder and van Rheenen 2001
Burkina Faso	Sandy	No runoff	Hoogmoed 1999
Burkina Faso	Sandy, crusted	Runoff reduction (Not quantified)	Serpantié and Lamachère 1992
Burkina Faso, Sierra Leone, Nigeria (Ibadan)			FAO 1993
Eritrea	Fluvisols		Hedera 2001
Kenya	Rhodic Ferrasols	Runoff reduction 50 %	Wakindiki and Ben-Hur 2002
Kenya	Chromic Luvisols	Runoff reduction 60%	Kiepe 1995
Malawi	5 types	100 %	Wiyo *et al*. 2000
Mali	Sandy	100%	Stroosnijder and Hoogmoed 1984
Niger	Various	Production increase: 300 %	Valentin and d' Herbes 1999
Tunisia	Various		Schiettecatte *et al*. 2002
Respondents 1,2,3,4,6,7,8	Various	For details see hardcopies of filled questionnaires	

Black holes in the literature

It is striking that there is no report of failure in the literature, although we judge that the areas where soil and water conservation technologies have been abandoned is greater than the area over which they are now being applied. There is no information about the areas involved.

Also, there is not a lot of social and economic analysis - although Blaikie highlighted the significance of the social dimension as long ago as 1985. The WOCAT database could be drawn upon to establish the circumstances in which various techniques work, or do not work.

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6 CROP MANAGEMENT

6.1 Crop-dependent parameters

Increased crop production as a result of increased RUE is a goal of the *Green Water Initiative*. One component of the RUE is transpirational water use efficiency: the ratio of crop yield to transpiration. Information on crop- and transpiration coefficients can be found on the FAO website and in Doorenbos and Pruitt (1975), Doorenbos and Kassam (1986), Smith (1992) and Allen *et al.* (1998) – the last also gives global data on length of growing season, yield reduction due to water shortage, a method to separate the crop evaporation from total evapotranspiration, and ways to estimate parameters for natural vegetation or for crops for which data are not available in the literature. Van Heemst (1988) and Van Keulen and Wolf (1986) provide plant data values for crop growth simulation.

Plant management practices

Crop management practices can affect RUE, see for example Day *et al*. (1992) and Karrou (1998), but few publications deal with the direct effect of plant management on the water use efficiency. Several mention the effect of the management practices on crop growth without relating these to the water use – for instance Gormus and Yucel (2002), Lafarge and Hammer (2002) and Nagashima *et al.* (1995) or, discuss plant management factors like early planting and intercropping in relation to pest management (Nabirye *et al.* 2003).

Day *et al.* (1992) and Wiyo *et al.* (1999) emphasise the importance of socio-economic factors on the success of adopted management practices.

A few of the respondents of the questionnaire indicated available data (Table 13).

Plant density and intercropping

Karrou (1998), in Morocco, studied the effect of seeding pattern (plant density) on RUE of wheat over two growing seasons. He found that both biomass and grain yield increases with greater plant density, with evapotranspiration unchanged. RUE increased by 18 per cent when planting density was doubled.

In Brazil, Medeiros (2001), experimenting with beans, showed that the basal crop coefficient based on measurements of leaf area index (LAI), enabled good estimates of water use for different plant densities. Crops were sown with densities of 14 and 28 plants per m^2. Ground cover and LAI were related to crop evapotranspiration. The LAI of the 28 plants m^{-2} density was 25% higher than 14 plants m^{-2}; the ground cover was also higher; and crop transpiration was 20 per cent higher for the higher plant density. Although the study was not designed to evaluate WUE, it indicates an increase of 20 per cent under the higher plant densities.

Wiyo *et al.* (1999), in Malawi, found that maize densities on subsistence smallholdings were 6-40 per cent higher than the government-recommended plant density (of 3.7 plants m^{-2}). There is no analysis of the effect on yield or RUE or the farmers' motivations but the study does show that farmers do not follow government recommendations.

Rodriguez-Montero *et al.* (2001) studied the effect of plant populations of yam on yield in Costa Rica: plant populations varied from 20 to 95 x 10^3 plants ha^{-1}, apparently unrelated to yield.

Fedorenko *et al.* (2002) studied the effects of plant density of lucerne, phase-cropped with wheat in Australia. Wheat yield was lower on fields with high lucerne density. Latta *et al.* (2002) also found that higher lucerne plant densities, and thus higher lucerne production, depressed the wheat yield but that wheat yield following lucerne increased.

Zougmoré *et al*. (2000) studied the effects of intercropping on runoff in Burkina Faso over three years: sorghum-cowpea intercropping reduced runoff by 20-30 per cent compared with sorghum monoculture, and by 45-55 per cent compared with cowpea monoculture.

Early planting

Gormus and Yucel (2002) studied the effect of early planting and potassium fertilization on cotton yields in Turkey. Potassium application in combination with early planting resulted in the highest boll weight. Yields were 11 per cent higher for the early planting data compared with the late planting date. Hulugalle *et al.* (2002), in sub-tropical Australia, also report that early planting reduces runoff and erosion and increases cotton yields.

Early planting was also shown to raise yields by Nabirye *et al.* (2003) on cowpea/sorghum intercropping systems in Uganda and by Day *et al.* (1992) on divers food grain crops in Mali.

Perhaps it goes without saying that early planting jeopardises the crop if adequate rains fail to materialise.

Table 13 Summary of literature and available data on the effect of plant management practices on RUE

Publication	Area	Crop	Practice	Result
Latta *et al*. 2002	Australia	Wheat/lucerne	Phase cropping with variable densities	Lower wheat yield with higher lucerne density
Hulugalle *et al*. 2002	Australia	Cotton	Early planting	Less runoff
Medeiros *et al*. 2001	Brazil	Beans	Double planting density	RUE increase 20%
Zougmoré *et al*. 2000)	Burkina Faso	Sorghum-cowpea	Intercropping	Runoff reduction 20-55%
Rodriguez-Montero *et al*. 2001	Costa Rica	Yam	Variable planting density	No relation with yield
Wiyo *et al*. 1999	Malawi	Maize	Variable plant density	No data for RUE or yield
Day *et al*. (1992)	Mali	Various crops	Early planting	Yield increase
Karrou (1998)	Morocco	Maize	Double planting density	RUE increase 18%
Fedorenko *et al*. (2002)	Australia	Wheat/lucerne	Phase cropping, variable densities	Yield decrease with higher lucerne densities
Gormus and Yucel (2002)	Turkey	Cotton	Early planting	Yield increase 11%
Nabirye *et al*. (2003)	Uganda	Cowpea/Sorghum	Early planting	Yield increase
Respondents 1,2	Various	For details see hardcopies of completed questionnaires		
Riches et al. 1997	Zimbabwe	Maize	Weeding	WUE increase

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7 MODELS

7.1 Scope and availability

Maps to depict *green* water resources or the potential to increase of *green* water resources and water use efficiency in rain-fed agriculture cannot be made with existing data: these are limited in scope and areal coverage. Models will be needed to estimate the required parameters from standard soil, climatic and land cover data. This chapter reviews pedotransfer functions that predict specific soil parameters from standard data, and models that predict field water balances based on climate, plant and soil data.

Internet pages http://eco.wiz.uni-kassel.de/ecobas.html and http://www.bib.wau.nl/camase/ give available models in the agro-ecological field. The selection of the models hereunder is based on one or more of the following criteria: availability of information (updated websites, verifiable references), regional scope (Southern Africa), proven usefulness and inclusion of subroutines that could be useful for assessment of green water. Models that are specifically meant for the estimation of crop production in irrigated agriculture (*e.g.* CROPWAT from FAO) are not included although they may be useful for their evapotranspiration subroutines.

Before choosing one of the models, attention has to be paid to the required output and the available data (required input), and to the issue of parameter estimation. The March 2002 issue of *Agronomie* deals with the problems related to parameter estimation in soil-crop models: the need for it, or otherwise (Gabrielle *et al*. 2002); the impossibility of estimating all parameters in a model (Ruget *et al*. 2002); solutions for over- parameterization (Wallach *et al*. 2002).

Recently, neural network (NN) modeling has been applied to soil-water-plant relations. Alterra (Nemes *et al*. 2002) is currently developing and testing NN models used for pedotransfer functions for water retention curves and soil moisture time curves.

ACRU

The *ACRU* (Agricultural Catchments Research Unit) model has its hydrological origins in a distributed catchment evapotranspiration study carried out in the Drakensberg, Natal, in the early 1970s. The model can be downloaded and a user group exists. User documentation was first published in 1984, updated in 1989, and is available from the link (http://www.beeh.unp.ac.za/acru/). The model requires a JAVA runtime environment. Although many publications are mentioned on the website, references are vague and could not be verified.

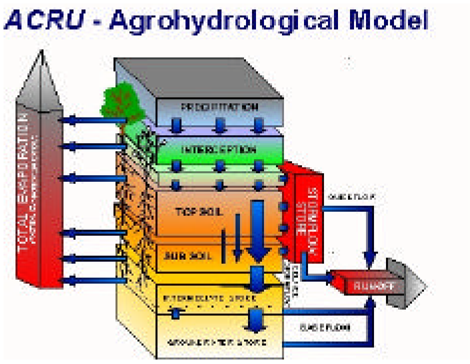


Figure 5 ACRU – Agrohydrological model

Applications: The website reports that regional runoff in the Qwa-Qwa area was simulated on a one minute lat/long grid (Schulze *et al.* 1990). The simulated stream flow at each grid point was summed to assess regional runoff in average, wet and droughty years. Schulze (1988) used a semi-distributed sub-catchment approach in a regional assessment of water resources in the Winterton area of KwaZulu-Natal for multiple irrigation abstractions.

Input: Daily rainfall, daily or monthly evaporation, soils and land use parameters

Output: simulated stream flow, sediment and crop yield, reservoir yield analysis

EPIC

The Erosion-Productivity Impact Calculator (EPIC) is a mechanistic simulation model used to examine long-term effects of various components of soil erosion on crop production (Williams *et al.* 1983). It is a public-domain model that has been used in over 60 different countries in Asia, South America and Europe.

The model has several components: soil erosion, economic, hydrologic, weather, nutrient, plant growth dynamics, and crop management. The model requires input from GRASS GIS layers. These include soil series and weather data, although the model can generate the necessary weather parameters. The model also requires management information that can be input from a text file. Currently, there are many management files and an effort is underway to catalogue these files and provide them to users.

The model is downloadable from: http://www.brc.tamus.edu/epic/index.html. There is a users' group that and can be reached through the website. EPIC is written in Fortran v 5.1.

Applications: Crop productivity, soil degradation, input levels and management practices, effects of climatic change, water quality

Input: Depending on the application
Output: Depending on the application

ETPOT1_0
ETPOT1_0 calculates Penman reference evapotranspiration for a reference crop and open water, and for field crops with a soil or surface water background (van Laar *et al.* 1992). The model is written in FORTRAN (utility library TTUTIL is also required). Information from: http://www.plant.wageningen-ur.nl/ e-mail to: cajo.terbraak@wur.nl. See also: PET (University of Florida), PNET (University of New Hampshire) and WEATHER (University of Hawaii at Manao) http://eco.wiz.uni-kassel.de/model_db/mdb/pnet.html

Applications: Calculation of open water evaporation and crop potential evapo-transpiration

Input: Relative soil water content in first layer, volumetric water content at saturation in first soil layer, total area index (leaves and stems), daily average temperature, solar radiation, extra-terrestrial radiation, actual vapour pressure, average wind speed

Output: Potential evapo-transpiration of a crop with a water layer, with a soil background, open water evaporation, potential evaporation of water layer below a crop; evaporation from a soil below the crop; radiation and atmospheric components. Time interval of simulation: 1 day. Basic spatial unit: 1 m2.

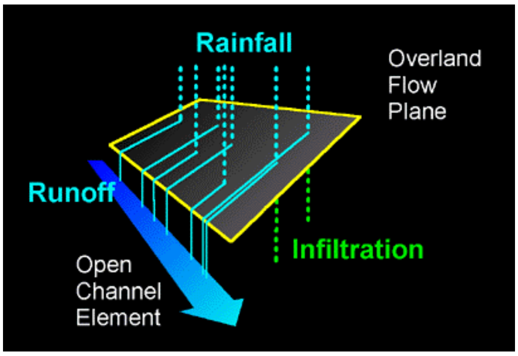
KINEROS2

KINEROS2 is an event-based hydrological model; so that long periods of soil water redistribution, plant growth, and other inter-storm changes are not considered.

A rainfall record describing the rainfall rate pattern is used to simulate the runoff over a catchment of arbitrary complexity. The catchment is described by an abstraction into a dendritic network of surfaces and channels. A model that includes small-scale spatial variability, a crust layer, and treatment of redistribution during rain hiatus simulates infiltration. Runoff is routed with an implicit finite difference solution of the kinematic wave equation. Erosion is simulated as a transport process operating with erosive detachment from splash and hydraulic sources, in equilibrium with settling based on particle fall velocity (Smith *et al*. 1995).

The model allows pipe flow and pond elements as well as infiltrating surfaces, and includes a partially paved element to use in urban area simulation.

The model is written in FORTRAN 77 and can be operated on a DOS-based first generation Pentium processor. Informatio n available at: http://wmuinfo.usda.gov/



Applications: Simulation of runoff over a catchment. Infiltration can be derived form a sub-routine.

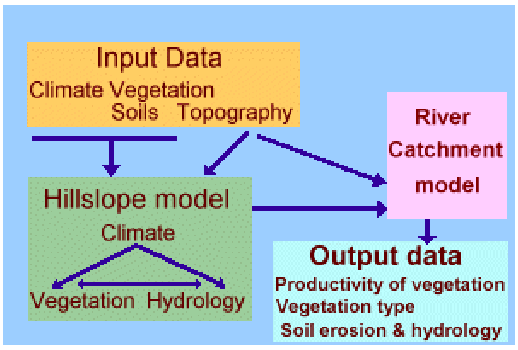
Input: Parameters must describe the network, the characteristics of each element, and the rainfall. Two ASCII files, in open format [@parameter1 = nn, etc.@], describe the parameters and weather for the simulated storm. There are global data, such as temperature, and element-specific parameters for each kind of network element.

Output: The model produces a variety of output depending on options chosen, *e.g.* sediment transport. For any element (surface or channel or pond), a water balance summary only may be chosen, or a table of the hydrograph, or a file written in spreadsheet format. The user may interactively request graphical output of either the flow profiles or hydrographs for any element during running.

MEDRUSH

MEDRUSH is a combined geographical information system and broad-scale distributed process model, applicable to areas of up to 5000 km^2 and for periods of up to 100 years. It provides scenarios of vegetation growth and the distribution of functional types, forecasts of runoff, sediment yield, and the various ways in which these factors evolve in response to short term sequences of storms, seasonal/annual variations in climate, and long term trends in climate and land use.

The model in C++ is under development (Kirkby *et al.* 2002), and the users guide is available. Detailed information can be found on the website: http://www.nmw.ac.uk/GCTEFocus3/Publications/reports/Report6/erosmod/MEDRUSHmod.htm



Applications: Vegetation growth, runoff forecast. Subroutines provide infiltration, evapotranspiration, subsurface flow

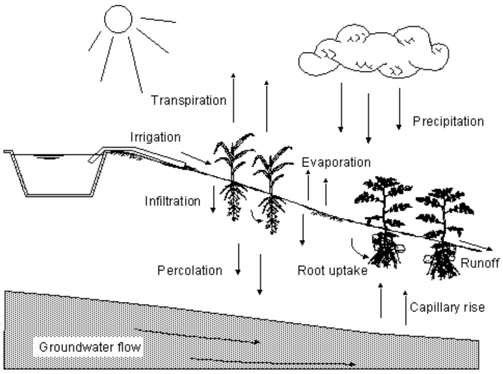
Input: Weather data, soil data (texture, stoniness), infiltration curves (or from subroutine), plant cover, soil surface cover, management practices, topography

Output: Runoff, soil moisture profiles, sediment transport and net erosion/deposition for sub catchments (1-20 km^2), integrated over selected time intervals; vegetation and organic soil biomass, surface roughness and armour characteristics over time - generalised within sub-catchments

SWAP

SWAP (Soil, Water, Atmosphere and Plant) simulates transport of water, solutes and heat in unsaturated/saturated soils. SWAP is the successor of the SWATRE model of 1978, developed within Alterra – Wageningen UR. The program simulates the transport processes at field scale level and during entire growing seasons, useful in both research and practical questions in agriculture, water management and environmental protection. http://www.alterra.dlo.nl/models/swap/index.htm

SWAP operates under DOS and is written in FORTRAN-77. References include Dam (2000), Dam *et al*. (1997), Droogers and Kite (2001).



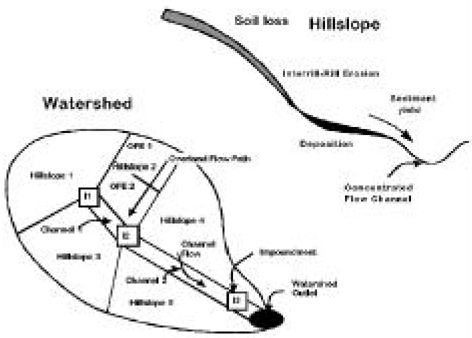
Applications: Field scale water balance, evapotranspiration, plant growth as affected by water and/or salinity stress, improvement of surface water management, soil moisture indicators for natural vegetation

Input: Input parameters are described by Kroes *et al.* (1999)

Output: Output parameters are described by Kroes *et al.* (1999)

WEPP

The Water Erosion Prediction Project (WEPP) model is a process-based, distributed-parameter, continuous-simulation, erosion-prediction model for use on personal computers. The current version (v99.5) available through the Internet is applicable to hill-slope erosion processes (sheet and rill erosion), as well as simulation of the hydrologic and erosion processes in small watersheds http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html.
See also CREAMS (http://dino.wiz.uni-kassel.de/model_db/mdb/creams.html)
References on WEPP, available from the Internet website, include Retta *et al.* (2001) and Flanagan *et al.* (2001).



Applications: Hydrological processes simulation, plant growth modelling, hydraulics of overland flow simulation and erosion prediction; pedotransfer subroutines

Input: WEPP requires a minimum of four input data files to run: 1) a climate file, 2) a slope file, 3) a soil file, 4) a plant/management file. An additional input file (called a run file) can be created that contains the answers to all of the model interactive questions, and which greatly speeds the running of the model.

Output: WEPP produces many different kinds of output, depending upon user requirements. The most basic output contains the runoff and erosion summary information; this may be produced on a storm-by-storm, monthly, annual, or average annual basis. The time-integrated estimates of runoff, erosion, sediment delivery, and sediment enrichment are contained in this output, as well as the spatial distribution of erosion on the hill slope. Abbreviated summary information for each runoff event (rainfall, runoff, soil loss, *etc*.) can also be generated. Other outputs include detailed soil, plant, water balance, crop, yield, winter and rangeland files. These files can be useful to study the response of the model under specific conditions. These output files can also be useful to users who have access to basic soil, plant and climate data, but require more specific soil physical, crop production or other detailed data.

WOFOST

The WOrld FOod STudies model developed at Wageningen (van Diepen *et al*. 1989, van Keulen and Wolf 1986) simulates annual crop production for selected combinations of crop species, soil type and climate. Crop files for wheat, maize, barley, rice, sugar beet, potato, beans, soybean, oilseed rape and sunflower are in the standard data files. Theoretical yields are calculated, and the relative importance of the major constraints on crop production (water, nutrients, light,

temperature) can be assessed, and used to plan optimum input strategies. Interactions between water and nutrient supply are not taken into account.
(kees.vandiepen@wur.nl) An Updated System Description of the WOFOST Crop Simulation Model as implemented in the E.U. Crop Growth Monitoring System can be found at: http://www.iwan-supit.cistron.nl/~iwan-supit/contents/

Applications: The model can be applied at three levels of increasing complexity: (a) potential crop production under optimum water and nutrient regime, limited only by light and temperature (b) water-limited production under optimum nutrient regime (c) nutrient-limited production. The time unit of 1 day is used for the crop growth and soil water balance calculations, nutrient uptake is modelled for the whole growing season.

Input: 60 crop parameters (initial values and coefficients), and daily weather (radiation, minimum and maximum temperature, vapour pressure, wind, rainfall). Initial dry weight, life span of leaves, rate of phenological development, death rates, partitioning coefficients, properties determining assimilation and respiration rates and minimum and maximum nutrient concentrations per plant organ.

Output: Theoretical yields are calculated, and the relative importance of the major constraints on crop production (water, nutrients, light, temperature) can be assessed, and used to plan optimum management strategies. Interactions between water and nutrient supply are not taken into account.

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8 REMOTE SENSING

8.1 Applications

Remote sensing infers surface and sub-surface attributes from measurements of the reflected electromagnetic radiation from the land surface, or from gamma radiation, radar, magnetic or electromagnetic signals. It can provide information on hydrological parameters, like precipitation, soil moisture, evapotranspiration, runoff, water resources and water quality. Most importantly, it contributes to our knowledge of their spatial variation and, if observations are made repeatedly, the temporal variability.

Smugge *et al.* (2002) describe the methods used to quantify the components of the water balance and energy balance equation, starting from the water and energy balance. They elaborate on: land surface temperature, surface moisture content, snow cover, landscape roughness and vegetation cover, water quality and evapotranspiration. Engman (1995) gives examples of current uses of remote sensing information in hydrology: precipitation, snow hydrology, soil moisture, evapotranspiration, and runoff. Kustas and Normann (1996) give details of the use of remote sensing for evapotranspiration monitoring. Schultz and Engman (2000) review developments in the different areas of hydrology; they discuss the application of remote sensing to precipitation, evaporation, water quality and rainfall-runoff modelling. Koster *et al.* (1999) evaluate remote sensing for modelling large-scale hydrological and atmospheric processes.

Precipitation

Remote sensing is used to estimate rainfall for those areas for which surface observations are sparse. Improved analysis of rainfall can be achieved by combining satellite and conventional gauge data.

Techniques have been developed for inferring precipitation from the visible and/or infrared imagery of clouds, *e.g.* the GOES precipitation index and the cloud indexing approach (Engman 1995, Schultz and Engman 2000).

Microwave radiation provides a more direct determination of precipitation, however this approach only yields monthly rain data.

Evapotranspiration

There is no remote sensing technique to measure evapotranspitation (ET) directly. However, remote sensing offers ways of extending point measurements to much larger areas, including those areas where meteorological data may be sparse

One of the more common ways of estimating ET is to consider both the water (1) and the energy (2) balance equations:

$$\frac{\Delta S}{\Delta t} = P - ET - Q \qquad (1)$$

$$In - G = H + LE \qquad (2)$$

Where ?S/?t is the change in water storage in the soil, P is the precipitation, ET is the evapotranspiration and Q is the runoff and In is the net radiation, G is the soil heat flux, H is the sensible heat flux and LE is the latent heat flux. ET and LE represent the same water vapour exchange rate across the surface, except that ET is usually expressed in mm d^{-1} and LE is usually expressed in W m^{-2} (Smugge *et al*. 2002). See Figure 6.

Figure 6 Water and energy balance (from: http://www.ears.nl)

Using remote sensing In, G and H can be obtained. Incoming radiation can be estimated from satellite observations of cloud cover, primarily from geosynchronous satellites (GMS or MeteoSAT). Surface temperature can be estimated from measurements in thermal infrared wavelengths and can be used to estimate the outgoing, long-wave radiation term in the net radiation equation.

The soil heat flux term can be estimated with remote sensing: a simplified approach defines the ratio of soil heat flux to net radiation in terms of vegetation cover that, in turn, is determined from visible and near infrared.

The sensible heat flux can be estimated using the aerodynamic surface temperature and near surface air temperature using different methods described by Engman (1995), Kustats and Norman (1996) and Smugge *et al.* (2002).

The Energy and Water Balance monitoring project of EARS Remote Sensing Consultants in Delft operates a METEOSAT primary data users station that provides synoptic information on rainfall, net radiation and actual evapotranspiration. It has been used for monitoring desertification in the Mediterranean region. (http://www.ears.nl).

Maas and Doraiswamy use NOAA-AVHRR data for the estimation of regional evaporation and biomass production. They use a model that uses both vegetation growth and soil water balance processes. The NOAA data are used to calibrate the model. Also, amongst others, Kumar *et al.* (2002) use NOAA –AVHRR data to obtain the normalized difference vegetation index, which they further use to estimate primary vegetation growth, showing the relationship between vegetation growth rates at different soil types in the Sahel of Burkina Faso.

Runoff

There are two general areas where remote sensing can be used in hydrologic and runoff modelling: (1) determining watershed geometry, drainage network, and other map-type information for distributed hydrologic models and for empirical flood peak, annual runoff or low flow equations; (2) providing input data such as soil moisture or delineated land use classes that are used to define runoff coefficients.

Remote sensing data can be used to obtain almost any information that is typically obtained from maps or aerial photography. In many regions of the world, remotely sensed data and, particularly, Landsat or Système Probatoire d'Observation de la Terre (SPOT) data are the only source of good cartographic information. Drainage basin areas and the stream network are easily obtained from good imagery.

Land cover is an important characteristic of the runoff process that affects infiltration, erosion, and evapotranspiration. Distributed models, in particular, need specific data on land use and its location within the basin. Most of the work on adapting remote sensing to hydrologic modelling has involved the Soil Conservation Service (SCS) runoff curve number model (USDA, 1972). The SCS Curve Number model is as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \qquad (3)$$

Where, Q is runoff, P is precipitation, I_a is initial abstraction and S is potential maximum retention given as:

$$S = \frac{(254000 - 254)}{CN} \qquad (4)$$

Where CN is a function of land use, treatment and condition: infiltration characteristics of the soils and antecedent moisture conditions.

CN values are discussed in McCuen (1982). I_a is calculated depending on the moisture condition of the soil before a rainstorm occurs (the antecedent moisture condition).

Melesse and Shih (2002) use Landsat images and GIS to estimate the runoff form watersheds and agricultural fields. A temporal series of Landsat images was analysed to determine land cover. Spatial resolution of the images used was 30 m to 60 m. Also, Gineste and Puech (1997) combined Landsat and SPOT imagery with ground observations to derive local runoff maps for Sahelian catchments. They acknowledge that the scale of the surface features relevant to determine the runoff maps is generally smaller than the image pixel size of 30 m. The Landsat channels found to be the most suitable were: PVI – Perpendicular Vegetation Index and SBI – Soil Brightness Index. Sharma *et al.* (2001) used remote sensing images from the IRS 1B LISS-II sensor (spatial resolution 36m)in hydrological response calculations using the SCS Curve Number method.

Soil moisture

Currently, only microwave technology has demonstrated a quantitative ability to measure soil water under a variety of topographic and vegetation cover conditions so that it could be extended to routine measurements from a satellite system (Engman 1990). For the most part, scientists have been restricted to data from short-duration aircraft campaigns: see e.g. Grayson and Western (1998).

Pauwels *et al.* (2001) used data from the European Space Agency in a study that shows the importance of spatial variability of soil moisture in runoff prediction. Measured backscattered data for bare soils are inverted into soil moisture data by assuming that the soil roughness parameters do not change between two overpasses of the satellite and by an assumption on the surface function. They use two backscatter models to solve for the soil roughness parameter and the dielectric constant. The latter is inverted into soil moisture values.

Data availability

Data are available from meteorological satellites, including polar orbiters such as The National Oceanographic and Atmospheric Administration (NOAA) series and the Defense Meteorological Satellite Program (DMSP), and from geo-stationary satellites such as Global Operational Environmental Satellite (GOES), and MeteoSAT.
NOAA: http://www.noaa.gov/
DMSP: http://dmsp.ngdc.noaa.gov/dmsp.html
GOES: http://rsd.gsfc.nasa.gov/goes/
MeteoSAT: http://www.eumetsat.de/en/
LandSAT: http://geo.arc.nasa.gov/sge/landsat/landsat.html
SPOT: http://www.spot.com/

Selected subject- or area-organized links to the different websites can be found on:

1. Remote sensing data directories and inventories: http://www.itc.nl/~bakker/invdir.html
2. Satellite images and Data Sets: http://www.itc.nl/~bakker/satellite.html
3. Africa Remote Sensing Data Bank: http://informatics.icipe.org/databank
4. Remote sensing data and information: http://rsd.gsfc.nasa.gov/rsd/RemoteSensing.html
5. Reduced Resolution Radiance Data Documentation http://isccp.giss.nasa.gov/docs/B3-toc.html

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9 INSTITUTES

The *Green Water* Initiative depends upon cooperation between many organisations. The following list includes international, regional and local organisations that could be sponsors, or partners.

9.1 International institutes

The Consultative Group for International Agricultural Research (CGIAR) (www.cgiar.org) focuses on crop productivity, forestry and agroforestry, water management, aquaculture, and livestock. There are 16 CGIAR institutes, each with a special field of interest. The following may be able to contribute to the *Green* Water Initiative, particularly under the Challenge Programs and the Future Harvest Initiative:

ICARDA is involved in research and training in dry areas of the developing world; increasing the production, productivity and nutritional quality of food, while preserving and enhancing the natural resource base. In the Central and West Asia and North Africa (CWANA) region, ICARDA is responsible for the improvement of durum and bread wheat, chickpea, pasture and forage legumes and farming systems; and for the protection and enhancement of the natural resource base of water, land, and biodiversity (http://www.icarda.cgiar.org).

World Agroforestry Centre (formerly ICRAF), Nairobi, is involved in agroforestry research and development. The Southern Africa regional program operates in Malawi, Mozambique, Tanzania, Zambia, and Zimbabwe (http://www.worldagroforestrycentre.org/home.asp).

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, works in semi-arid farming systems through integrated genetic and natural resource management strategies. One of ICRISAT's research themes is Water, soil and agrobiodiversity management for ecosystem health. In Sub-Saharan Africa, the main entry point for raising the productivity of SAT systems remains improving soil fertility but, within this program, 'efficient use of water' is one of the themes.
Deliverables: low cost, risk-reducing, income-generating water and soil management options (www.icrisat.org).

International Water Management Institute (IWMI) focuses on the sustainable use of water and land resources in agriculture and on the water needs of developing countries. IWMI's research is organized in five themes, mainly focussing on irrigation, but one of interest for the *Green* Water Initiative is Sustainable Smallholder Land and Water Management (www.cgiar.org/iwmi).

The ***CGIAR Challenge Programs*** are a new concept to bring together the best minds at the international, regional and local levels – to make a real impact on pressing poverty and development problems:

- The Challenge Program on Water and Food (CP Water and Food): Theme 1 of the program has been defined as "Crop water Productivity improvement" (http://www.cgiar.org/iwmi/challenge-program/index.htm).

- The Challenge Program on Desertification, drought, poverty and agriculture is in the pre-proposal phase. Theme 1 is Understanding and Coping with Land Degradation and Drought Risk. Wageningen UR has been identified as a partner (http://www.cgiar.org/research/res_preproposals.html).

Future Harvest is a global initiative, incorporated in June 1998 as a charitable and educational organization to advance debate and catalyse action for a world with less poverty, a healthier human family, and a better environment. Future Harvest was created by 16 food and environmental research centres, known as the Future Harvest Centres, located around the world. 58 Governments, private foundations, and CGIAR support these centres.

Food and Agriculture Organization of the United Nations (FAO) was founded in 1945 to raise levels of nutrition and standards of living, to improve agricultural productivity, and to better the condition of rural populations. FAO is the lead agency for agriculture, forestry, fisheries and rural development (www.fao.org). The Agricultural Land and Water Development Division is a partner in the *Green* Water Initiative. Many relevant publications, databases, e-mail discussions and background papers can be found through http://www.fao.org/ag/agl/default.stm

ISRIC – World Soil Information, Wageningen, founded at the initiative of UNESCO in 1968 is involved in education, through the World Soil Museum; documentation and dissemination of soil information, through the ICSU World Data Centre for Soils; and applied research in land and water resources, including the global Soil and Terrain Database, global assessment of land degradation and improvement, and the *Green* Water Initiative (http://www.isric.org/).

Global Water Partnership/World Water Forum is a partnership in water management between government agencies, public institutions, private companies, professional organizations, multilateral development agencies and other committed to the Dublin-Rio principles. It identifies critical knowledge needs at global, regional and national levels, helps design programs for meeting these needs, and serves as a mechanism for alliance building and information exchange on integrated water resources management. The partnership seeks to support countries in the sustainable management of their water resources by pulling together financial, technical, policy and human resources. (http://www.gwpforum.org/servlet/PSP). Global Water Partnership as a Southern Africa network (http://www.gwpsatac.org.zw/).

World Water Council (WWC) is an international think-tank for water issues, established through the initiative of water specialists, the academic community and international organizations (http://www.worldwatercouncil.org/).
At the 1st World Water Forum in Marrakesh (1997) WWC was given the mandate to develop a vision for Water, Life and the Environment in the 21st Century.
During the 2nd WWF in The Hague (2000) the *World Water Vision* (http://www.watervision.org) was created and a Framework for Action that delineates a strategy for the realization of the World Water Vision by 2025. At the 3rd World Water Forum in Kyoto (2003) (http://www.worldwaterforum.org/eng/index.html) one of the agenda items was *Agriculture, Food, and Water. Africa*. It became evident that there is a great gap in knowledge of *green water* and its links with *blue* water, in particular the need to carry this knowledge to where it is needed and can be applied (http://www.water-forum3.com/ta/agenda/ml9.htm#agri).

9.2 National institutes with world focus

Institut de Recherche pour le Développement (IRD) is a French public science and technology research institute under the joint authority of the French Ministries in charge of research and overseas development. IRD has three main missions: research, consultancy and training. It conducts scientific programs contributing to the sustainable development of the countries of the South, with an emphasis on the relationship between man and the environment. IRD has local offices in several African countries, mostly in West Africa, but including South Africa and Kenya. In West Africa, the institute works closely together with the National Agrarian Research Institutes of francophone countries (www.ird.fr).

Wageningen University and Research Centre: Wageningen University, founded in 1918, is one of the world's leading education and research centres in the plant, animal, environmental, agrotechnological, food and social sciences. In 2002, the Wageningen Water Vision was specified as "Wageningen UR contributes to ecological and socio-economic sustainable management of water in a changing world". Relevant Wageningen UR institutes and groups are: Alterra (Water and Environment, ILRI), Aquatic Ecology and Water Quality Management Group, Hydrology and Quantitative Water Management Group, Erosion and Soil & Water Conservation Group (http://www.wageningen-ur.nl/).

Centre for International Rural Development of the University of Kassel, Witzenhausen, is involved in research and teaching, including international activities and an information and documentation centre for rural development in the tropics and subtropics. The Centre for International Rural Development publishes the journal *Der Tropenlandwirt* and the series *Beihefte zu Der Tropenlandwirt.* (http://www.wiz.uni-kassel.de/). It provides (on the Internet) detailed information on agro-ecological models (http://www.wiz.uni-kassel.de/model_db/models.html).

9.3 Regional institutes – Southern Africa

FAO provides an easy-to-use database on national and regional institutions dealing with agricultural water management. The database and search engine can be found on http://www.fao.org/ag/agl/aglw/aquastat/institutions/index.asp.

It provides access to over 300 national and regional institutions dealing with water resources management and irrigation in the AQUASTAT program. The coverage for Sub-Sahara Africa is: Benin, Malawi, Senegal, Swaziland, South Africa, and Zambia. Typically they are the institutions having a mandate in either of the following fields:

- Water resources assessment
- Water resources management (including water supply)
- Irrigation and drainage
- Water quality management, environment and sanitation

Research and academic institutes

The *waterpage* on http://www.thewaterpage.com/edulist.htm provides links with universities with 'water' departments in Africa, focussing on South Africa and Zimbabwe.

WaterNet http://www.waternet.ihe.nl/members/ or http://www.waternet.org
WaterNet member institutions have expertise in water supply, sanitation, groundwater, wetlands, irrigation, water law, water economics, community-based resource management, flood forecasting, drought mitigation, water conservation and information technology. These institutions are based in Botswana, Kenya, Lesotho, Mozambique, Namibia, South Africa, Tanzania, Uganda, Zambia, and Zimbabwe. Links to the institutions, but also to international institutions involved in the same field, can be found on the site.

Agricultural Research Council (ARC) is involved in many diverse activities in the production of food, feed, fibre, fruit and flowers. ARC has an Institute for Soil, Climate and Water (http://www.arc.agric.za/).
This ISCW is part of the Optimising Soil and Water Use Consortium of CGIAR. The ISCW organized (jointly with: IWMI and the Water Research Commission of South Africa) a symposium and workshop on "Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa" from 8-11 April in Bloemfontein, South Africa.

Southern African Development Community-SADC has a Program of Action covering several broad economic and social sectors: Energy, Tourism, Environment and Land Management, Water, Mining, Employment and Labour, Culture, Information and Sport and Transport and Communications. On the SADC Water Resources page (http://www.fao.org/fi/alcom/aml.htm) links can be found to institutions in Angola, Botswana, Lesotho, Malawi, Mozambique, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe concerned with agricultural water use; most of them concentrate on irrigation.

Annex 1 Correspondence to NARs, simple questionnaire and mailing list

Dear …….

"Optimizing Green Water use, improved crop water productivity under rainfed agriculture", is a new initiative launched by ISRIC and FAO. Falkenmark introduced the "Green Water" concept in 1995 (see http://www.fao.org/docrep/V5400E/v5400e06.htm). It is part of a package that also contains "Blue Water" and water use efficiency. The package is meant to serve as a tool to realize a more efficient water use. "Green Water" stands for crop transpiration in rainfed agriculture. For more information on "Green Water" see attached draft document, on which your comments are welcome.

The main goal identified for the initiative is to establish a knowledge base on various water saving land and water management technologies that result in more efficient rainfed crop production. Maps that show the potential for increase of water use efficiency in rainfed agriculture will be part of this knowledge base. Research and development projects aiming at the improvement of the water use efficiency in rainfed agriculture may benefit from this initiative.

The region of southern Africa has been chosen as pilot region for this "Green Water" initiative. The outcome of the feasibility phase will lead to a full-scale project formulation wherein the participating national institutions will form the backbone. With this letter and attached questionnaire we would like to know whether your institution is supportive to the "Green Water" initiative. In this case, we would also like to know whether you could contribute with relevant data and information and/or specific services or expertise.

We hope that you and your organization will be willing to assist us in completing the attached, concise, questionnaire on information/data. (The questionnaire has been developed so that it will require a minimum of your time to fill it). Relevant information/data for the Green Water initiative are in the fields of soil, surface water, rainfall and soil&plant management practices, which will be further specified in the attached questionnaire. Our preference is to have the information soon, preferably before December 2002 send to Mrs. Jacquelijn Ringersma (ringersma@isric.nl), responsible for this preparatory phase. Please inform Mrs. Ringersma also if you would like to respond, but cannot complete the questionnaire soon. In case you would advice us to contact another person for this initiative, please send us name and e-mail address.

Mr…. we hope to hear from you and thank you for your kind cooperation.

Yours sincerely,

Roel Oldeman
(Director ISRIC)

	Institute is dataholder Yes/No	Quantity of information 10 L/M/H	Access of data Print/Digital	Availability of data Free/Price
1. Soil				
1.1 Soil surface conditions				
Infiltration				
Topography				
1.2 Topsoil conditions Soil type				
Texture				
Rootable depth				
Storage capacity				
1.3 Subsoil conditions				
Saturated conductivity				
2. Water				
2.1 Run-off				
2.2 Run-on				
2.3 Soil evaporation				
2.4 Percolation				
3. Climate				
3.1 Daily rainfall				
3.2 Intensity of rainfall				
3.3 Evapotranspiration				
4. Soil/water management practices to improve water use efficiency				
(specify e.g mulching, stonerow, waterharvesting etc)				
5. Crop management practices to improve water use efficiency				
(specify e.g. early planting, weeding etc.)				

Annex 2 Availability of data at National Research Institutes

Number / Respondent	1	2	3	4	5	6	7	8	9	10
1. Soil										
1.1 Soil surface conditions										
Infiltration	X	X		X	X		X	X		
Topography	X	X		X	X		X	X		
1.2 Topsoil conditions										
Soil type	X	X	X	X	X	X	X	X		
Texture	X	X	X	X	X	X	X	X		
Rootable depth	X	X	X	X	X		X	X		
Storage capacity	X	X		X	X		X	X		
1.3 Subsoil conditions										
Saturated conductivity		X		X	X					
2. Water										
2.1 Run-off		X		X		X	X	X		
2.2 Run-on										
2.3 Soil evaporation		X		X				X		
2.4 Percolation				X						
3. Climate										
3.1 Daily rainfall	X	X	X	X		X	X	X		
3.2 Intensity of rainfall	X	X		X		X	X	X		
3.3 Evapotranspiration	X	X		X		X	X	X		
4. Soil/water management practices to improve water use efficiency (specify e.g mulching, stonerow, waterharvesting etc)[1]	X	X	X	X		X	X	X		
5. Crop management practices to improve water use efficiency (specify e.g. early planting, weeding etc.)[1]	X	X					X	X		

If required use additional sheets

[1] For specifications see hard copies

Annex 3 Searching the Endnote Reference File

a. All entries have been labeled by one of the following:

Level 1	Level 2
Concept Green Water	RUE
Soil	Global data Physical properties
Water	Evaporation (Rain)water use efficiency Runoff Water Balance
Management	Cases Mulch Tillage Water conservation
Plant	Crop factor Early planting Intercropping Plant density
Climate	PET Rainfall
Remote Sensing	Applications
Models	-
Institutes	-

b. Using the ‘Search’ option under the ‘References’ menu can create a thematic sub-file. Search on the ‘Label’ field and fill in the required label following the table above. A first level search will yield a file containing all references for the first level parameter. Deeper searches on this newly created file can be performed in the same manner.

c. Searches can also be performed on other Endnote entry field. Most common are author and title.

EN.REFLIST