

WaterWorld: a self-parameterising, physically based model for application in data-poor but problem-rich environments globally

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ABSTRACT

This paper describes a spatially explicit, physically based global model for water balance. Its key innovations include the fact that it comes with all data required for application, is very high spatial resolution (1 km or 1-hectare resolution) and yet global in extent and is particularly well suited to heterogeneous environments with little or no available data. The model, WaterWorld, is capable of producing a hydrological baseline representing the mean water balance for 1950–2000 and allows users to apply ensemble scenarios for climate change or examine the impact of policy options for land cover change or land management interventions. WaterWorld is focused on policy support, especially in conservation hydrology and development applications and is delivered through a simple web interface, requiring little local capacity for use. The paper discusses the paucity of hydrological data and the urgency of hydrological problems in much of the less-developed world, which reinforce the need for tools like WaterWorld. We discuss the types of hydrological problems that models might contribute to managing and the requirements of models applied to such problems. By way of example, applications of WaterWorld to understanding large-scale patterns of water resources and uncertainty around adaptation to climate change are described.

Key words | climate change, GIS, hydrological model, policy support, remote sensing

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INTRODUCTION

The ubiquity of data-poor but problem-rich environments

According to the [World Bank \(2004\)](#) some 34,246,000 km² (25.6%) of the Earth's land surface is in national territories that are considered as low income (e.g. Afghanistan, Indonesia, Nepal, Uganda), with a further 67,224,000 km² (50.2%) considered middle income (e.g. Bolivia, Tunisia, Malaysia, Botswana) and the remaining 24.2% of the land surface represent high income national territories (e.g. Brunei, Canada, Germany, Singapore). Thus, some 75.8% of the global land surface can be considered to operate under challenging resource conditions for most hydrological monitoring and modelling efforts.

Low- and middle-income countries tend to lack the hydrological monitoring, climate monitoring and

hydrological modelling capacity and infrastructure that is usually better developed in the high-income countries. This is likely to be particularly the case in rural areas of poorer countries and outside of key water resource infrastructure such as major dams. Moreover, in low-income countries, the already poor hydrological and other monitoring systems have deteriorated over the past decades ([UNESCO–WWAP 2003](#)), as investments have been reduced.

If we consider the number of high quality long-term rain gauges, for example the 45,772 gauges used in WorldClim (WC) database ([Hijmans *et al.* 2005](#)), and calculate the number of gauges per 1,000 km² of land area on a country basis, we find that 142 out of 220 countries have less than 1 gauge per 1,000 km² of area. Only a few countries have >5 gauges per 1,000 km² and all of these are small island nations or very small countries such as

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Costa Rica. Most countries are smaller than 5 Mkm² and have gauge densities varying from close to 0 to close to 1 per 1,000 km² with no apparent relationship to size of territory. A few countries (Australia, Brazil, USA) are between 5 and 10 Mkm² and have gauge densities of 0.38, 0.55 and 0.76 gauges per 1,000 km² respectively. A few more countries vary from 9 to 24 Mkm² and have consistently low gauge densities (0.11 for China, 0.06 for Canada, 0.02 for the Russian Federation and 0.0005 for Antarctica). However, compared on a country basis with mean gross domestic product (GDP), population and population density (World Bank 2004) there is no apparent relationship between the density of the gauge network in place and mean GDP (1992–2010), population or population density (mean 2002–2010) at the national scale. So, economically poorer countries may not necessarily have fewer gauges on a national basis (at least in these databases) than richer countries. There are, however, clear clusters of rainfall stations in the major populated environments and clear gaps in large deserts, tundras and rainforests (see Figure 1). If we compare the location of the WC raingauges with continuous urban fabric as defined by CIESIN *et al.* (2004) we find that 92.3% of the 45,772 stations occur outside of urban areas with only 7.7% in areas classified as urban fabric. This compares with urban and non-urban land proportions of 2.4 and 97.6%, respectively, indicating a slight bias of stations toward urban areas. Most gauges are in thus outside of the continuous urban fabric but away from wilderness areas. Comparison of gauge densities with population densities according to Land-Scan (2007) shows 23.6% of gauges in areas with population

density close to zero, 24.6% in areas with population densities greater than 0 persons/km² but less than 5 persons/km², a further 34% in areas from 5 to 40 persons/km², with the remainder in densely populated areas >40 persons/km². Thus, some 58% of gauges occur in the more populated areas. Comparing with the cropland and pasture maps of Ramankutty *et al.* (2008) indicates that only 15% of gauges fall in areas without cropland or pasture with the remaining 85% of gauges thus largely within the agricultural areas outside of major cities, with low population densities.

For high quality, long-term flow gauges (GRDC 2012), we see a similar distribution to that of rainfall stations with aggregations in populated, agriculturalised environments and gaps in the major wilderness areas (Figure 2). Only 1,283 (0.97%) of the 131,857 basins in the world (defined according to HydroSHEDS, Lehner *et al.* 2008, excluding small coastal basins with areas <5 km²) contain one or more of the 7,240 river gauging stations assembled by the Global Runoff Data Centre (GRDC 2012) within their limits. The remaining 99.3% of basins are thus very likely not gauged. The gauged basins are, however, the largest basins – covering some 71.5 million km² (66.4%) with a further 36.15 million km² of basins with no gauge. Even the gauged basins are rarely gauged in their entirety but rather a few of their sub-basins are gauged (see Figure 3) with between one and 392 gauges per basin and a mean basin-area-per-gauge metric of 10,454 km² (with a maximum of 549,795 km², for the ‘African South Interior’ basin enclosing the Okavango, HydroSHEDS ID# 146411 which has only one GRDC gauge within its boundary).

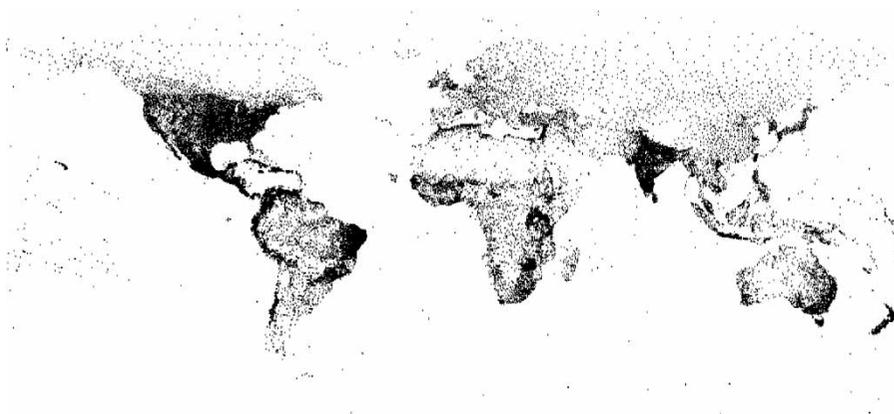


Figure 1 | Precipitation stations used in the WorldClim database (Hijmans *et al.* 2005).



Figure 2 | Flow gauging stations with data in the Global Runoff Data Centre database (GRDC 2012).



Figure 3 | GRDC flow gauging stations from GRDC (GRDC 2012) and the HydroSHEDS basins (Lehner *et al.* 2008) in which they occur.

Clearly the number and distribution of rainfall or runoff gauges made available to global data assimilation efforts such as the WC database or the Global Runoff Data Center may not reflect the exact density and distribution on the ground but there are likely to be similarities that render the broad patterns described above as representative. Moreover, even if other stations exist, if they have not been made available to global hydrological initiatives they may not also be available for local hydrological initiatives and thus may as well not exist.

It is precisely these data-poor environments that also tend to be rich in hydrological and water resources related problems as a result of either climatic water scarcity, high population-related demands, lack of – or poor – land and water management practices, poverty or significant inequalities in sharing water and its benefits. Examples of each are clear in the work of the Challenge Programme on Water and Food, Basin Focal Projects (see Mulligan *et al.* 2011c) which examined the following basins and regions throughout the

less-developed world: Nile, Andes, Niger, Yellow, Ganges, São Francisco, Mekong, Volta, Limpopo. All of these can be considered data-poor at the basin scale and all are also hydrologically problem-rich with respect to climatic water scarcity (Ganges, Karkeh, Niger), high population-related demands (Nile, Ganges, Yellow), poor land and water management practices (Andes, Volta, São Francisco), poverty and inequity (Limpopo, Volta, Niger).

Problem richness

There are a range of hydrological problems whose better understanding and management can be assisted through large-scale hydrological modelling. Many of these are particularly severe in low- and middle-income countries where the rate of recent population, agricultural and infrastructural growth has outstripped the capacity to manage their impacts on water resources. At the national scale these problems range from proactive land-use and water

infrastructure planning through to retrospective management of the hydrological impacts of unplanned land-use change and of climate change. Large-scale hydrological modelling can potentially contribute to understanding: (a) national scale annual and seasonal water balances and the mismatch of supply and demand, facilitating the development of redistribution schemes and more hydrologically and geographically aware land-use planning; (b) the impact of unplanned change such as population growth and agriculturalisation and the associated loss of natural ecosystems, along with the impacts of climate variability and change and the effects of land degradation or urbanisation; (c) the impact on water availability, quality and regulation downstream of soft interventions such as agricultural incentives and land use policies associated with biofuels, afforestation and payments for ecosystem services (PES); (d) the hydrological impacts of hard interventions such as boreholes, flood defences, hydropower and water supply reservoirs (and their associated dams), investments in mining, oil and gas and in water transfer or diversion schemes; and (e) the likely value of planned land- and water-management strategies to improve a sub-optimal hydrological situation including techniques such as rainfall harvesting, afforestation, terracing, contour ploughing, buffer strips and check dams.

These are all multifaceted problems and all require at least the following capabilities from large-scale hydrological models.

- (a) *To be physically based.* Ungauged or sparsely gauged basins have little opportunity for the development of empirical methods. Moreover, the multifaceted nature of the hydrological problems defined above means that an understanding of the physical basis of hydrological processes, and a limit to the degree of model calibration, is usually necessary in order to analyse the impacts of scenarios of change.
- (b) *To have both breadth and detail in time and space.* Large-scale hydrological models must provide outputs at policy-relevant spatial and temporal scales (e.g. regions rather than hillslope and decades rather than years). They must do so at a level of temporal detail that is appropriate for the analysis of seasonal and/or extreme events and at a level of spatial detail that is appropriate for the grain of operation for land use or land management interventions and for understanding impacts on and between individual communities of stakeholders.
- (c) *To be able to provide a hydrological baseline on an annual and seasonal basis.* Many conservation and development actions in low- and middle-income countries lack even the spatially explicit hydrological baseline that is necessary to underpin basic water resource policy-making.
- (d) *To be able to analyse the impacts of scenarios for land use and cover change.* Land-use and land-cover has impacts on water resources locally and downstream. Large-scale hydrological models to be used in policy support need to distinguish between the evapotranspiration (ET) and infiltration characteristics of different land use/cover combinations in order to be able to examine the implications of change on water quantity, quality and regulation. Such models need to be spatially explicit and to route flows downstream in order to analyse the impacts of pattern as well as process (see Mulligan *et al.* 2010a, b).
- (e) *To be able to analyse the impacts of scenarios for climate change.* Water resources and other hydrological investments (whether for 'hard' engineering solutions or 'soft' policy solutions) are usually made for the long term. These are often mega-investments, funded sometimes with loans from development banks and sometimes from regional and national public sector or private sector budgets. Such investments need to be made with an understanding of future as well as current climate if they are to contribute to better water management in the long-term. Large-scale models must thus facilitate not only the analysis of climate impacts on the current hydrological baseline, but also their implications for utility of proposed water resources policies or interventions.
- (f) *To be able to analyse the impacts of multiple land and water management interventions.* Water is not always managed through the mega-projects described above. In many cases water management is achieved through small scale interventions at the community or farm scale that may be orchestrated through government policy or development programmes, or even independently responding to external drivers. Such

interventions may have small effects individually but if many individuals participate, the cumulative effects can be significant. Large-scale hydrological models should thus be capable of simulating the impact of successfully upscaled management interventions such as contour tillage, rainwater harvesting, groundwater well perforation.

- (g) *To make the best use of routinely available data and, more importantly, to not require input data that are unlikely to be routinely available.* Small scale modelling is usually supported through intensive field monitoring campaigns, for example in the feasibility study for the development of a dam project. Very large-scale (global) studies (Gosling & Arnell 2010; Sperna Weiland 2010) often benefit from high availability of remote sensing datasets at these scales. However, some remote sensing datasets are marginal in terms of spatial resolution and quality for regional to national scale studies, yet large-scale hydrological models applied at these scales must make use of such routinely available data since intensive field campaigns at regional to national scales will not be routinely available.
- (h) *To provide information on extremes (low flows, high flows) as well as annual and seasonal averages.* Much of water resource hydrology is concerned with ascertaining the annual or seasonal mean or total availability and quality of water but flood hydrology and some water resources problems are concerned with extremes – low flows for droughts and peak flows for flooding. Large-scale models often need to incorporate the processes which lead to these extremes even if the long term observation datasets provide only monthly rainfall and flow data.

Data paucity

These are all challenging areas for large-scale models to contribute, especially given the paucity of data and hydrological capacity available in many low- and middle-income country contexts. There are a number of elements to data paucity and these include where the data: (a) cannot be collected (there is no available means to measure them at the scale required); (b) have not been collected (there

is means but no resources to collect); (c) are not available (they have been collected but are not in the public domain); (d) are available but not located or known of; (e) are available and located but too expensive; (f) are located but require significant technical expertise to use and that expertise is not available; (g) are located but of insufficient spatial extent resolution, or of temporal extent (duration) and resolution (frequency); (h) are located and detailed but highly uncertain in magnitude or georeferencing or are so poorly documented that they are of little use.

All of these can be encountered in the typical application of large-scale modelling to low- and middle-income country contexts. Data on groundwater usually fall into category (a) since there is no means to measure them at the national to continental scale. Though satellite instruments like those employed in the Gravity Recovery and Climate Experiment (GRACE) have helped map changing groundwater levels at the continental scale (Ramillien *et al.* 2005), there is as yet no publicly available global map of aquifers or groundwater resources that is suitable for regional to national scale use. The closest dataset is the Worldwide Hydro-geological Mapping and Assessment Programme (WHYMAP, http://www.whymap.org/whymap/EN/Home/whymap_node.html) effort, but at the time of writing this is neither publicly available nor detailed.

In many low- and medium-income country contexts, most data fall into category (b), that is the property is measurable but there is no operational monitoring scheme at the national to continental scale (or if there is one, it has insufficient spatial extent or temporal duration). Remote sensing can sometimes help where national data collection efforts are insufficient but not all hydrological variables can be remotely sensed.

In situations where significant prior hydrological research and monitoring has been carried out it is often frustrating to find that data that have been collected are not available, (c), either because they are collected by national institutes or private consultants who do not make the data available to others or that the data are ‘lost’ since the contracting organisations or national hydrological institutes have not received a copy and the academics or consultants involved have ‘moved on’ without the data becoming available. This is particularly frustrating where a number of successive projects collect the same baseline data for the

same regions, each without making the data available so that the next project can start with a baseline in place.

In some cases it is simply not known that data have been collected since the details are buried in inaccessible grey literature (consultants reports, etc.) and are not searchable in the professional and academic literature or on the world-wide-web. This is increasingly not the case as the growth in meta-data portals continues and these are increasingly indexed through search engines such as Google. It is still however entirely possible *not* to find, even with sophisticated search methods, datasets that are readily available.

Data cost a lot of time and money to collect and to maintain and this should not be forgotten by those who promote free-of-cost access to data, (e). Where possible, data should be accessible to as wide an audience as possible and this often means that the data supplier should cover the costs of collecting, maintaining and distributing data without passing these costs on to the data user. Research funding organisations, universities and those making significant (especially commercial) use of data must be prepared to share the costs associated with this effort where possible. Some applications of large-scale models in low and middle income countries will have the resources to purchase data but many (especially in the development, community and conservation contexts) will not.

Data for large-scale hydrological modelling are highly heterogeneous (from time series data of runoff at a point to spatial grids of satellite precipitation over a landscape) and require a significant diversity of technical and hydrological expertise to manage (from spreadsheet skills to remote sensing and GIS expertise). Data come in a wide range of highly specialised formats (HDF, NETCDF, Flat Binary, ESRI geodatabase, etc.) and for many in the large-scale hydrological modelling 'user community' these are a significant challenge to model parameterisation. Even where the data are available the capacity to use them may not be.

Large-scale hydrological modelling has specific requirements for data to cover a large spatial and temporal extent at sufficient temporal duration and resolution to represent both the long-term means and the variability of the processes. Many datasets are collected with specific applications in mind which may not have included large-scale hydrological modelling. For example, soils data may have been collected for agricultural applications, terrain

data for national cartography, weather stations for monitoring airport take-off and landing conditions. Sometimes the characteristics of these datasets, even where they are available, are not appropriate or at least not ideal for use in hydrological analyses.

Finally, where data are available, have been located and are sufficiently detailed, it may be that they are so poorly documented that their means of production, key assumptions or even units of measurement are unclear. If well documented, it may be that the data values themselves or the geographic location of the values are highly uncertain. A case in point is rainfall data. Rainfall is the most fundamental of hydrological inputs. According to a comparison of the WC annual total rainfall grid with a 10-year mean actual evapotranspiration (AET) climatology (Mulligan 2011a, b) derived from the MODIS ET product of Mu *et al.* (2011) rainfall is of significantly greater magnitude than the ET flux for some 64% of the global land surface and is more than double the ET flux for some 17% of the global land surface. Yet, rainfall is either (effectively) modelled from remote sensing data with a spatial resolution of 5 km at best (for near-global data) or is measured at highly dispersed meteorological stations covering (for the comprehensive WC database) some 0.02% of the 1 km pixels of the land surface and then interpolated over the remaining 99.98% of pixels. Satellite assessments are made on the basis of visible and infrared satellite data or of ground based or satellite radar and they usually trade-off spatial and temporal resolution such that, for example, the key rainfall products available across much of the developing world are either 5 km spatial resolution and monthly (Tropical Rainfall Monitoring Mission (TRMM) 2b31; see for example Mulligan 2006a) or 25 km spatial resolution and 3 hourly (TRMM 3b42; see for example Mulligan 2006b). Many hydrological problems require *both* 1 km spatial resolution and 3 hourly timesteps (see Tarnavsky *et al.* 2012).

Interpolated ground data and modelled remotely sensed data provide similar broad-scale spatial patterns of rainfall but sometimes fundamentally different values at a point. Figure 4 shows the relationship between 1,000 randomly chosen pixel values taken from the 1 km resolution WC interpolated dataset based on rainguages (Hijmans *et al.* 2005) and a 1 km (native 5 km) resolution 10-year climatology of the TRMM 2b31 product based on rainfall radar

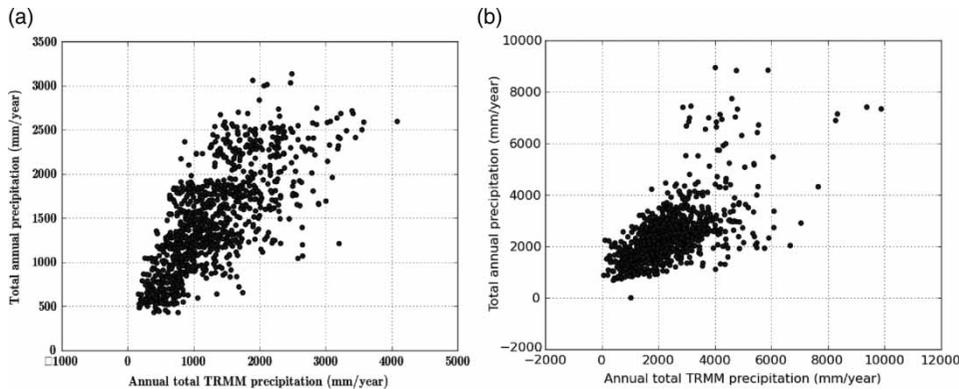


Figure 4 | The relationship between per-pixel rainfall estimated by the TRMM climatology of Mulligan (2006a) and the WorldClim climatology of Hijmans *et al.* (2005) for (a) a lowland area in Brazil (10° tile centred on $-5^\circ, -45^\circ$) and (b) a mountainous area in Colombia (10° tile centred on $5^\circ, -75^\circ$).

(TRMM is an international project jointly sponsored by the Japan National Space Development Agency (NASDA) and the US National Aeronautics and Space Administration (NASA) Office of Earth Sciences; Mulligan (2006a). These data are for (a) a lowland area in Brazil (10° tile centred on $-5^\circ, -45^\circ$) and (b) a mountainous area in Colombia (10° tile centred on $5^\circ, -75^\circ$). The two climatologies differ in period, 1950–2000 for WC compared with 1998–2006 for TRMM, as well as in methodology. Clearly the broad patterns are similar but at-a-point values can vary significantly between the two assessments. The linear regression for the Brazilian tile is $WC = 0.6244TRMM + 668.25$, $R^2 = 0.5187$ and for the Colombian tile is $WC = 0.581TRMM + 1094.9$, $R^2 = 0.3842$. For Brazil, WC rainfall values are on average 180 mm yr^{-1} greater with the standard deviation (SD) of at-a-point differences being 466 mm yr^{-1} . For the mountainous Colombian tile, WC rainfall is on average 112 mm yr^{-1} higher with a SD of at-a-point differences between the climatologies at 999 mm yr^{-1} indicating the particular difficulties of rainfall assessment in the complex mountainous terrain that characterises Colombia. Given the errors associated with gauge measurements, the local scale variability of rainfall and the very few of these 1 km pixels with a rainfall gauge, we cannot know whether the real received rainfall for these areas is closest to the WC interpolated value or the TRMM estimated value. These differences in rainfall in part relate to the difference in what is being measured (rainfall receipt at the ground versus rainfall in the atmosphere) but also how it is measured (ground measured values interpolated between gauges using

elevation as a covariate versus estimated values for each point based on a rainfall radar signal). See also Ward *et al.* (2011) for a more regional example.

Rainfall is particularly uncertain in mountainous environments because of steep elevational gradients as well as impacts of topographic exposure or shelter to wind-driven rain (Bruijnzeel *et al.* 2011) and this uncertainty occurs at all scales from the micro-catchment to the continent. If we cannot even be confident of rainfall inputs then we fall at the first hurdle in hydrological modelling. Uncertainty in rainfall inputs is not specific to large-scale modelling – even small catchments in mountains can have significant within-catchment variability in annual and seasonal rainfall inputs. This is further complicated where catchments are subject to inputs from other forms of precipitation such as snow and fog (Bruijnzeel *et al.* 2011).

Existing hydrological models for data-poor environments

Prediction in ungauged (and data-poor) environments is considered a ‘grand challenge’ for hydrology (Sivapalan 2003) and a ‘catalyst’ for interdisciplinary hydrology (Wagner 2004) yet there are few physically-based, process hydrological models designed specifically for data-poor and ungauged basins. Instead, many that are built for data-rich environments have been subsequently applied to data-poor ones (Jayakrishnan *et al.* 2005; Chaponnière *et al.* 2008; Ndomba *et al.* 2008). In ungauged, data-poor environments, other assessment approaches are usually used, for

example simple GIS approaches (Shrestha *et al.* 2004) or remote sensing water resources assessment (Liebe *et al.* 2009). Where process models built for data-rich environments are used in data-poor ones, the following techniques are used to facilitate model application: use of remote sensing (Lakshmi 2004; Collischonn *et al.* 2008); use of re-analysis products (Choi *et al.* 2009) or weather generator output (Schuol & Abbaspour 2007) for model parameterisation or validation; heavy calibration of models to account for data deficiencies (Ndomba *et al.* 2008); or use of model calibration coefficients derived from nearby and analogous, but gauged, basins.

Approaches involving a high degree of model calibration are usually appropriate for baseline water resources assessment but may be less suitable for analysing the impacts of scenarios for climate, land use or land management change because such analysis requires the physical basis of the model to remain intact. Highly calibrated models may produce accurate baselines (relative to a 'validation' dataset) whether the model is physically realistic or not. Moreover a high degree of calibration to current conditions may render parameter values inappropriate for new conditions of climate or land use to which they are not calibrated. If an uncalibrated model can reproduce current conditions well on the basis of the physical relationships alone, then it is more likely (though not certain) to continue to do so under scenario conditions compared with a model that could only replicate current conditions after significant calibration to an observed dataset. Simple GIS and remote sensing-based national water balances (e.g. Alemaw & Chaoka 2003; Bastiaanssen & Chandrapala 2003; Shrestha *et al.* 2004; Liebe *et al.* 2009) do not usually permit scenario analysis nor facilitate understanding of the process-basis for hydrological state and change. If we are interested in the types of hydrological problems outlined above, this leaves us: (a) having to apply models built for data-rich environments to data-poor ones as best we can; or (b) building models specifically designed for application in ungauged and data-poor environments.

The WaterWorld model (www.policysupport.org) is a fully distributed process-based model designed specifically to make best use of remote sensing and globally available datasets for application to supporting hydrological analysis and decision-making in ungauged and data-poor

environments. It does this at scales from the small basin to the continent. WaterWorld is designed as a policy support system (PSS) which makes scientific information and scenario analysis available for use by a wide range of users without the need for significant technical, hydrological or data handling capacity on their part. There are five stages to using WaterWorld. Stage 1 involves defining the analysis area. Currently users can choose 10 degree tiles at 1 km² resolution or 1 degree tiles at 1 hectare resolution. Stage 2 involves preparing the data. During this stage WaterWorld interrogates the model databases (www.policysupport.org/simterra) (see Table 1), extracts and prepares the data required for the simulation in the chosen tile. Stage 3 is to run the baseline simulation. Stage 4 is to apply any policy options or scenarios (collectively referred to as 'alternatives') and then re-run the simulation with these changes so that their impact can be analysed relative to the baseline. The final stage is to examine the results as maps, charts or a model-generated narrative of outcomes. All of these stages can usually be completed within 30 min.

WATERWORLD

Model heritage

Like most models, WaterWorld is not entirely a new model but rather has a long heritage. Some of the equations are based on the PATTERN model (Mulligan 1998) and later incarnations in the MODULUS (www.ambiotek.com/modulus) (Oxley *et al.* 2004), MedAction (www.ambiotek.com/medaction) (van Delden *et al.* 2007) and DESURVEY (www.ambiotek.com/desurvey) (van Delden *et al.* 2008) PSSs, but the majority of the equations were brought together for the FIESTA model (Mulligan & Burke 2005; Bruijnzeel *et al.* 2011) then modified for the AguaAndes model (Mulligan *et al.* 2010a, b) and finally connected with global databases for WaterWorld. This paper is concerned with version 1.0 of WaterWorld through version 2.0 is currently in open beta and version 3.0 is under development. The model's set of equations describing and linking the respective processes are documented in detail by Mulligan & Burke (2005) and in the model documentation at www.policysupport.org/waterworld. Mulligan & Burke (2005) also outline the

Table 1 | Data sources for WaterWorld

Variable	Units	Source
Boundary layer wind direction (monthly)	degrees from N	Derived from BADC (2004)
Mean sea level pressure (monthly)	mb	Derived from BADC (2004)
Elevation (SRTM1 k)	metres (a.s.l)	Farr & Kobrick (2000)
Elevation	metres (a.s.l)	Jarvis <i>et al.</i> (2008)
Air temperature (monthly)	°C	New <i>et al.</i> (2003)
Wind speed (monthly)	m s ⁻¹ × 10	New <i>et al.</i> (2003)
Relative humidity (monthly)	%	New <i>et al.</i> (2003)
Mean annual temperature	°C	Hijmans <i>et al.</i> (2005)
Mean monthly precipitation (monthly)	mm month ⁻¹	Hijmans <i>et al.</i> (2005)
Total annual precipitation	mm year ⁻¹	Hijmans <i>et al.</i> (2005)
Mean daily maximum temperature (monthly)	°C × 10	Hijmans <i>et al.</i> (2005)
Mean monthly temperature (monthly)	°C × 10	Hijmans <i>et al.</i> (2005)
Mean daily minimum temperature (monthly)	°C × 10	Hijmans <i>et al.</i> (2005)
Cloud frequency (DJF)	Fraction	Mulligan (2006c)
Cloud frequency (JJA)	Fraction	Mulligan (2006c)
Cloud frequency (MAM)	Fraction	Mulligan (2006c)
Cloud frequency (SON)	Fraction	Mulligan (2006c)
Mean annual cloud frequency	Fraction	Mulligan (2006c)
Cloud frequency (monthly)	Fraction	Mulligan (2006c)
Cloud frequency 00:00–06:00 hrs	Fraction	Mulligan (2006c)
Cloud frequency 12:00–18:00 hrs	Fraction	Mulligan (2006c)
Cloud frequency 18:00–24:00 hrs	Fraction	Mulligan (2006c)
Cloud frequency 06:00–12:00 hrs	Fraction	Mulligan (2006c)
Local drainage direction	Direction	Mulligan (2011b)
Local drainage direction	Direction	Mulligan (2011b)
Cover of bare ground	Percentage	Hansen <i>et al.</i> (2006)
Cover of herb-covered ground	Percentage	Hansen <i>et al.</i> (2006)
Cover of tree-covered ground	Percentage	Hansen <i>et al.</i> (2006)
Daily temperature range (monthly)	°C × 10	Hansen <i>et al.</i> (2006)

SRTM: Shuttle Radar Topography Mission; DJF: December–February; JJA: June–August; MAM: March–May; SON: September–November.

model's application to predict water balance – as well as its changes after prescribed changes in regional land cover and climate – across Costa Rica (at 90 m spatial resolution) and Central America as a whole (at 1 km spatial resolution).

Key innovations

WaterWorld is built for rapid and easy application by non-specialists and runs on a load-balanced cluster of web servers (not on the user's local computer), through a web

browser in which the model interface is accessible to anyone. It is 'self-parameterising', meaning that the developers provide all of the data required for model application anywhere in the world. If users have access to better data than those provided with the system, they can upload these data as GIS files for use by the model. WaterWorld simulates a hydrological baseline representing mean monthly and annual values for the period 1950–2000. Simulations are possible at 1 hectare resolution for tiles with dimensions of 1 degree of latitude and longitude or at

1 km² resolution for 10 degree tiles. Results are provided visually and as GIS files for download and further analysis. In addition to calculation of a hydrological baseline, WaterWorld can be used to calculate hydrological scenarios following climate change or land use change or analyse the impacts of applied land management options.

Conceptual basis

WaterWorld v. 1.0 simulates surface hydrology only, ignoring subsurface stores and fluxes on the basis that: (a) it is essentially a water balance model focusing on the spatial detail of rainfall minus actual evapotranspiration at a monthly timescale and is not used in crop growth or in low flows applications where soil and groundwater become important; (b) there are no global datasets to parameterise the subsurface properties necessary to model subsurface flow on a physical basis; and (c) given the model focuses on the hydrological outcomes of long-term climatological means for large catchments and with a monthly timestep, the short-term stores represented by soil moisture and subsurface flow have little impact on water balance since they are short-term stores rather than additional fluxes in the system.

If WaterWorld were to be used to analyse streamflow, streamflow seasonality, etc. then a sub-surface component would be necessary and this is indeed a component of the development version 3.0 of the model, making use of some new data sources. Similarly, in areas downstream of snow and ice fields, a snow and ice component would be needed and is available in version 2.0 but is not part of version 1.0 used here. The fact that WaterWorld calculates AET from the present satellite-observed vegetation cover means that where vegetation is supported by sub-surface or fluvial inputs from upstream that are unaccounted for in the modelled local water balance then a negative water balance (excess of local AET over local rainfall) results.

WaterWorld is a raster-based model that calculates inputs of wind-driven rainfall (after [Arabi *et al.* 1996](#)) and fog (see Appendix 1, available online at <http://www.iwaponline.com/nh/044/017.pdf>), combines these with an energy driven assessment of potential evapotranspiration (PET), then modifies PET by the available leaf area to calculate AET (see Appendix 1). Wind-driven rainfall plus fog (Cloud water interception – CWI) inputs minus AET determines

the water balance. This can be cumulated downstream using a drainage direction network calculated by the system globally from the hole-filled 1 km SRTM ([Jarvis *et al.* 2008](#)) or the 90 m SRTM ([Farr & Kobrick 2000](#)) data using the D8 algorithm. Where flow lines cross the 1 degree or 10 degree tile boundaries used by WaterWorld then ‘no data’ are recorded for all points downstream. Runoff (cumulative water balance) outputs are thus available only for watersheds enclosed entirely within a tile. Version 3 will include background datasets that are cut on a watershed rather than a tile basis to avoid this issue, but since WaterWorld is primarily a water balance model, not a runoff model, it is not a significant issue for most applications of the system.

Key inputs

WaterWorld V. 1.0 requires some 126 input maps representing 29 variables over a monthly or diurnal cycle and they are provided globally with the system at 250 m to 1 km spatial resolution. These variables characterise the climate, terrain and vegetation and are summarised in [Table 1](#). When the model is run at 1 hectare resolution, all maps except those derived from the digital elevation model (DEM) are resampled using bilinear interpolation to 1 hectare resolution since all inputs for the model need to have the same cs. If users have better data than are available in the system then they can upload these (as simple ESRI ARCASCII grids) instead of using those provided with the system.

Model structure

The WaterWorld V. 1.0 model equations are outlined in detail in [Mulligan & Burke \(2005\)](#) and in the model documentation with the model at www.policysupport.org/waterworld, and are discussed briefly here and in Appendix 1 (available online at <http://www.iwaponline.com/nh/044/017.pdf>). WaterWorld includes modules for distribution of rainfall through interaction with wind, occult precipitation through CWI inputs, solar radiation receipt, PET and AET on the basis of climate and vegetation cover, water balance and its cumulation downstream as runoff. There is also a simple model for soil erosion by wash. The model calculates monthly and annual hydrological variables for a baseline representing land cover for the year 2000 and mean 1950–2000 climate.

During simulation, the model iterates between four diurnal timesteps (at 00:00–06:00 hrs, 06:00–12:00 hrs, 12:00–18:00 hrs, 1800–00:00 hrs) representing the mean diurnal cycle for each of 12 monthly timesteps making a total of 48 timesteps for a complete simulation. Representation of the diurnal cycle is important for processes such as CWI and ET which are highly diurnal. The model incorporates modules for atmospheric processes, precipitation, ET and water balance and its structure is summarised in Figure 5 and detailed in Appendix 1, further to Mulligan & Burke (2005).

Model testing

WaterWorld places particular emphasis on a physically-based representation of inclined rainfall, CWI and ET since these are fundamental to the impacts of climate and land-management upon water balance. WaterWorld has been applied and tested widely throughout Latin America and parts of tropical Africa and Asia. Testing of the ET estimates against measured field data for montane forest and pasture sites was carried out in Mulligan & Burke (2005) indicating agreement within 1.4% of AET for the pasture site and 10.4% for the more spatially variable forest site. The wind driven rain and CWI components were tested relative to field data at 15 sites throughout the tropics (Bruijnzeel *et al.* 2011) with good agreement, particular at low wind speeds. At high wind speeds it is impossible to

separate the fog and wind-driven rainfall components in measured canopy water balances since canopies capture wind driven rain in very different ways to raingauges (Bruijnzeel *et al.* 2011) and thus validation of CWI becomes difficult. Moreover, scale averaging effects become important and begin to separate at-a-point field measured wind-driven rainfall from mean modelled wind-driven rainfall over 1 hectare or 1 km² areas.

Mulligan & Burke (2005) also tested catchment-scale modelled accumulated water balances (runoff) against flows recorded in the GRDC database (GRDC 2012) for 17 catchments covering more than half of Costa Rica, with climates varying from hyper-humid in the Atlantic to semi-arid in the Pacific north-west areas of the country. For catchments with high quality rainfall data the model performed well but for some others, although the model results and the flow data were in general agreement, the model would underestimate measured flows, especially in highly exposed areas with few raingauges and would overestimate flows in dry, cloud-free lowlands. The model mean runoff was 194 mm yr⁻¹ greater than the observed mean across all catchments (i.e. the bias is 8% of the observed mean). Much of the error results from six anomalous catchments which have much higher modelled runoff than measured. If we examine the predictive error on a catchment basis in relation to the mean physical characteristics of the catchments, no obvious patterns emerge except that the model over-predicts runoff (positive errors) for half of the Pacific

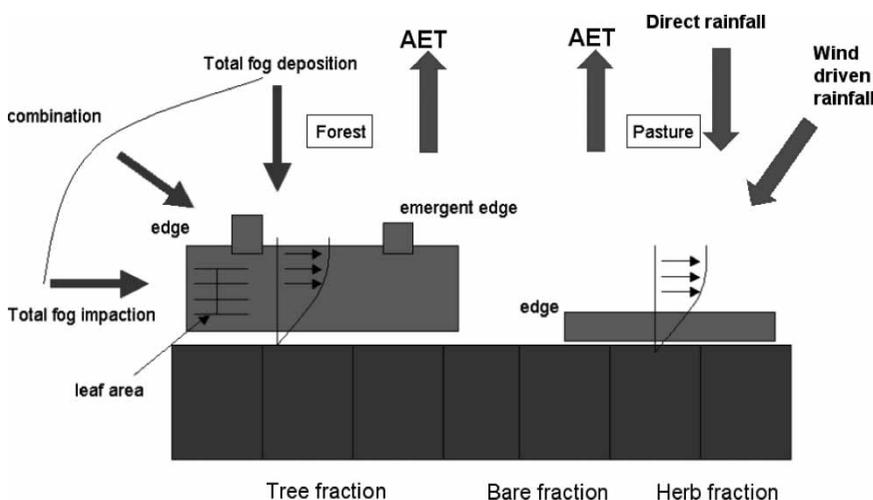


Figure 5 | Key components of the WaterWorld model.

catchments but under-predicts (negative errors) for a number of Atlantic catchments. There is no obvious relationship between relative prediction error and catchment altitude, exposure to wind driven rain, fog inputs or catchment average rainfall inputs suggesting no systematic error for particular landscape settings (see Mulligan & Burke (2005) for the full analysis). Given the uncertainties in the input datasets, particularly rainfall and also in the validation runoff dataset, it is difficult to say to what extent the uncertainty in these (un-calibrated) model results arises from uncertainties in input data, or uncertainties in model structure, or uncertainty in the runoff estimates of the validation dataset. This is a common challenge with large scale modelling.

Model parameterisation

WaterWorld is driven by the best-available global data-sets for terrain (SRTM; Farr & Kobrick 2000), climate (WC; Hijmans *et al.* 2005) and land cover (MODIS Vegetation Continuous Fields VCF2000; Hansen *et al.* 2006). These maps are used to spatially model inputs of inclined rainfall (along the lines of Arazi *et al.* (1996)) and CWI, with particular emphasis on the influence of wind speed, topographic exposure and vegetation structure (distinguishing between tree and herb functional types) on the capture of both rainfall and CWI (Appendix 1, available online at <http://www.iwaponline.com/nh/044/017.pdf>). To model CWI, information is required on (i) the spatial extent of ground-level cloud (i.e. fog), (ii) the type of vegetation present (trees *vs.* shorter herbaceous vegetation), (iii) the magnitude and variability of vertical and lateral fog fluxes (i.e. deposition and impaction), and (iv) the CWI efficiency of the vegetation present (Mulligan & Burke 2005). The pan-tropical monthly and diurnal cloud climatology derived by Mulligan (2006c) from the MODIS MOD35 product is used to obtain atmospheric cloud frequency at each timestep. This is then combined with a lifting condensation level (i.e. the cloud base) as computed from temperature lapse rate calculations over the climate grid to estimate the frequency of *ground-level* cloud. Cloud liquid water content (LWC) is assumed to scale linearly with relative humidity and fog inputs are calculated as the fog flux carried by the wind and impacted or deposited on the vegetative leaf area (Mulligan & Burke 2005).

Cloud/fog inputs are calculated to occur predominantly through deposition (sedimentation) in locations of minimal wind (e.g. topographic lees and hollows), and predominantly through impaction where vegetation is exposed (e.g. on windward slopes, ridges and around summits). For a given pixel, its topographic exposure, fog and wind speed conditions, as well as its vegetation structure (both height and fractional cover of tree and herb functional types, with characteristic leaf area index, LAI, values assigned to each type) determine the balance between the two processes of fog delivery (see Appendix 1). Uniquely, WaterWorld accounts for the impact of atmospheric and ground-level cloud frequency on solar radiation inputs using the cloud climatology of Mulligan (2006c) and therefore on PET and AET losses.

Each raster cell of the model is split into tree, herbaceous and bare covers according to the Hansen *et al.* (2006) vegetation continuous fields maps. For each month wind speeds are corrected for topographic exposure according to Ruel *et al.* (2002) and the wind speed in each cell determines the proportion of rainfall that falls as direct vertical precipitation and the proportion that is wind-driven, falling at an angle with respect to the terrain and thus having greater inputs to windward slopes than leeward ones (Appendix 1). Fog is present if the lifting condensation level occurs at ground level (according to atmospheric vapour pressure and temperature lapse rates, Appendix 1) and at a frequency each month determined by the MODIS observed cloud frequency for the month and time of day. Where fog is present, the wind speed also determines the proportion of fog that falls under gravitational processes as fog *deposition* (which occurs to all leaf areas) versus the proportion that is driven onto vegetation by wind as fog *impaction* which tends to occur on wind-exposed surfaces only (see Appendix 1).

Exposure of vegetation is a function of the height of the vegetation and the number of tree-herb and tree-bare edges in the direction of the fog bearing winds (derived from an empirical relationship with tree cover based on a comparison of MODIS and LANDSAT imagery for Costa Rica which produces the maximum number of edges at around 50–60% tree cover; Mulligan & Burke 2005). This relationship may differ slightly for different forms of forest fragmentation but the tendency for a greater number of

edges at medium forest covers should be generally robust. Fog impaction tends to be greatest therefore in very windy, highly exposed areas of the terrain with patchy tree cover. In any one pixel, fog and rainfall inputs will be a mixture of gravitational and wind driven inputs to the different plant covers. AET occurs according to the solar energy available and atmospheric conditions using a Penman approach (Penman 1948) constrained by LAI as a proxy for water availability for the tree and herb fractions separately (see Appendix 1). LAI (area of leaf per unit area of covered ground) for the two fractions are set at typical values (LAI = 3 for tree cover, LAI = 2 for herb cover so that aggregate LAI will vary according to the fractional cover of tree and herb types in each pixel). The water balance in a pixel is thus rainfall plus fog inputs minus AET every diurnal time-step, every month. Water balance is thus affected by changes in climate, terrain and vegetation cover at the pixel level and downstream.

At the regional to continental scales at which WaterWorld is typically applied, there are significant uncertainties in some of the model inputs, particularly for rainfall, wind speed and direction, land cover and even topography. However, WaterWorld has been used predominantly to indicate the likely effect of scenarios for land-cover change on the water balance in comparison with a baseline simulation, rather than to predict the magnitude of the water balance. In this way, the understanding gained from the model is less sensitive to errors of magnitude in input data but probably more sensitive to the representation of the physical processes underlying the computations of CWI, inclined and wind-driven rain and ET and their spatial distribution and dependence on the scenarios of change (Mulligan & Burke 2005). In addition, when the model is used to compare relative spatial patterns over large-scales (as in the applications below), it is less sensitive to absolute errors in the input data-sets since we focus on comparing relative magnitudes geographically rather than the absolute magnitudes. Since the model is web-based, successive and seamless improvement of the input datasets is possible as new data comes in.

WaterWorld is not usually calibrated to observed flows since its focus is on understanding sensitivity of hydrological fluxes and stores to land use or climate change in complex geographies rather than predicting the absolute magnitudes

of the baseline or alternative states. It is therefore critical that the model's physical basis remains intact and that the model is improved through improvements to its physical basis rather than through empirical calibration. Given that most basins it is applied to are ungauged, calibration is often not possible anyway.

Key outputs

The model writes outputs including wind-driven rainfall, fog impaction and deposition, ET and water balance. These are written as downloadable maps for each timestep, monthly maps summarising the four timesteps per month and annual integrals. The maps can also be visualised online using a number of in-built web mapping tools (so-called geo-browsers). Time-series for individual points or for the entire map tile are also written and can be visualised or downloaded. WaterWorld is predominantly used in conservation hydrology research for development applications and has some 340 registered users as of December 2011, some 60 of which have used the system more than 10 times. Users are from all over the world but particularly Latin America, North America and Europe. The system is sometimes used simply to assess the current baseline (water balance) where no data are available but is also often used in scenario analysis for understanding the implications of climate change, land use change or land management practices. Three case-study applications are examined below as a means of introducing the capabilities of the PSS. These are presented to give the reader an idea of the capability of the system rather than to present results of interest *per se*. The reader is encouraged to read the model documentation and try it out for their own areas and topics of interest.

Continental scale application: Latin America

As an example continental scale application of WaterWorld, we will ask the question: *Where in Latin America might fog water harvesting contribute to water resources development?* as proposed for example by Cereceda *et al.* (1992) In order to provide an answer we must run 1 km resolution simulations of WaterWorld for each of the 10 degree tiles covering Latin America and examine the output variables *Total annual fog*

inputs and Fog inputs as a percentage of total precipitation (where total precipitation = wind driven rainfall + fog).

Figure 6(a) shows that fog inputs occur throughout much of Latin America but for the lowlands these likely contribute little on an annual basis (<50 mm), however on the

eastern flanks of the Andes, the Guyana shield and the mountainous areas of the state of Para, Brazil as well as the Central American mountain zones inputs are much greater, often hundreds of mm per year. The highest values (above 300 mm per year and up to 1,000 mm per year)

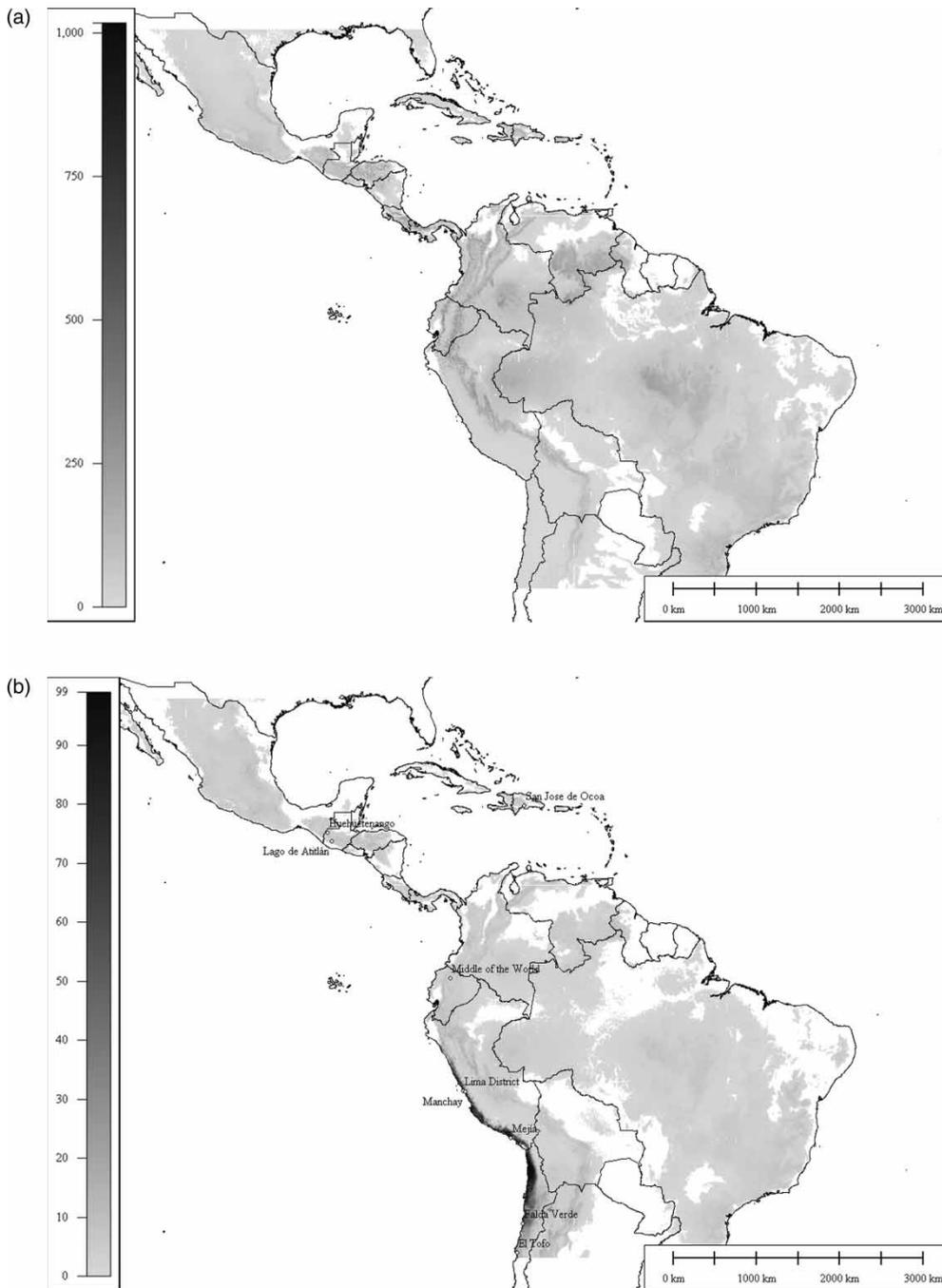


Figure 6 | Total fog (cloud water interception) inputs for Latin America (a) in mm yr⁻¹ and (b) as a percentage of total precipitation (rainfall + fog).

occur on highly restricted wind-facing exposed mountain ridges throughout the region, where impaction fluxes dominate. The water resource value of these fog inputs depend, however, on their magnitude in relation to the rainfall inputs since in high rainfall areas, water resources may be plentiful and these fluxes contribute little whereas, in low rainfall areas, fog fluxes may be the dominant water supply (Bruijnzeel *et al.* 2011).

Figure 6(b) shows fog inputs as a percentage of total precipitation. For most of the continent, fog contributions are small (a few percent) either because fog inputs are small or because rainfall inputs are high. On exposed windward mountain ridges, especially in the drier southern Andes of Ecuador, Peru and Bolivia, fog inputs can be 10–15% of annual precipitation. However, for the dry coastal zone of central and southern Peru, and northern Chile, fog contributions are close to 100% of total precipitation for the coastal lowlands and greater than 50% for the coastal valleys and foothills of the Andes. Figure 6(b) also shows the location of a series of water resources-based fog collection projects by the FogQuest organisation (www.fogquest.org) in which large nets are constructed to collect fog. The WaterWorld map thus indicates the areas in which such projects could be expanded to provide community-scale enhancement of water resources because fog is a major component of precipitation in those areas.

National scale application: southern India

Here we use WaterWorld to examine the potential impacts of climate change in southern India at 1 km spatial resolution. First we run the hydrological baseline for the tile producing the results depicted in Figure 7. Figure 7(a) shows rainfall to be low (600–800 mm yr⁻¹) for most of the lowlands of the subcontinent but reaching values in excess of 3,000 mm yr⁻¹ over much of the Western Ghats and >7,000 mm yr⁻¹ in isolated wind-exposed ridges. AET (b) is high (>1,000 mm yr⁻¹) throughout the Western Ghats (as might be expected given the water availability and forest cover) but also high for some of the irrigated areas around Kolbal in Karnatakur state and some forested areas to the south and east. For much of the rest of the lowlands values are constrained to 700 mm yr⁻¹ or less by water availability. Fog inputs (c) are zero for much of the east but

significant (>100 mm yr⁻¹) in exposed parts of the south west and Western Ghats. As a result of precipitation (including fog) minus evaporation, the water balance is negative for much of the agricultural lowlands. This indicates that local precipitation is supplemented by irrigation from groundwater and from water storage and transfer from the 3,675 dams that are present in this 10° tile according to the assessment of Mulligan *et al.* (2009) and that these additional inputs maintain the observed vegetation cover and thus ET. Water balance is, however, in excess of 3,000 mm yr⁻¹ for much of the Western Ghats and above 7,000 mm yr⁻¹ for isolated, exposed ridges, in line with the observed rainfall.

Since the major basins of the Krishna and the Cauvery run west to east, these positive water balances in the Western Ghats supply much of the water required to sustain agricultural production in the central and eastern lowlands. Figure 7(e) indicates that mean water balance aggregated at the HydroSHEDS major sub-basin level is positive throughout the region with sub-basins draining the Western Ghats being significantly wetter than sub-basins enclosing lowlands only.

Impacts of climate change on water balance: southern India

According to IWMI (2011), the Krishna basin is India's fourth largest river basin, with a population close to 74.2 million and a predominantly semi-arid climate. Some 77% of the basin is cultivated (IWMI 2011). The total capacity of the 1,493 dam reservoirs censused by Mulligan *et al.* (2009) is estimated by IWMI (2011) to approximate the total water yield of the basin, leading to almost total budget closure with discharges substantially reduced at the basin and sub-basin level. Nevertheless water requirements for irrigation, industrial and urban use continue to increase, leading to serious conflicts.

Here we use WaterWorld to apply a multi-model spatial ensemble scenario using the IPCC fourth assessment A2a scenario for the 2050s. WaterWorld calculates the mean of the results for all 17 available general circulation models (GCMs) for temperature and precipitation change on a monthly basis. The ensemble mean is used as representative of the most likely climate projection for the region under

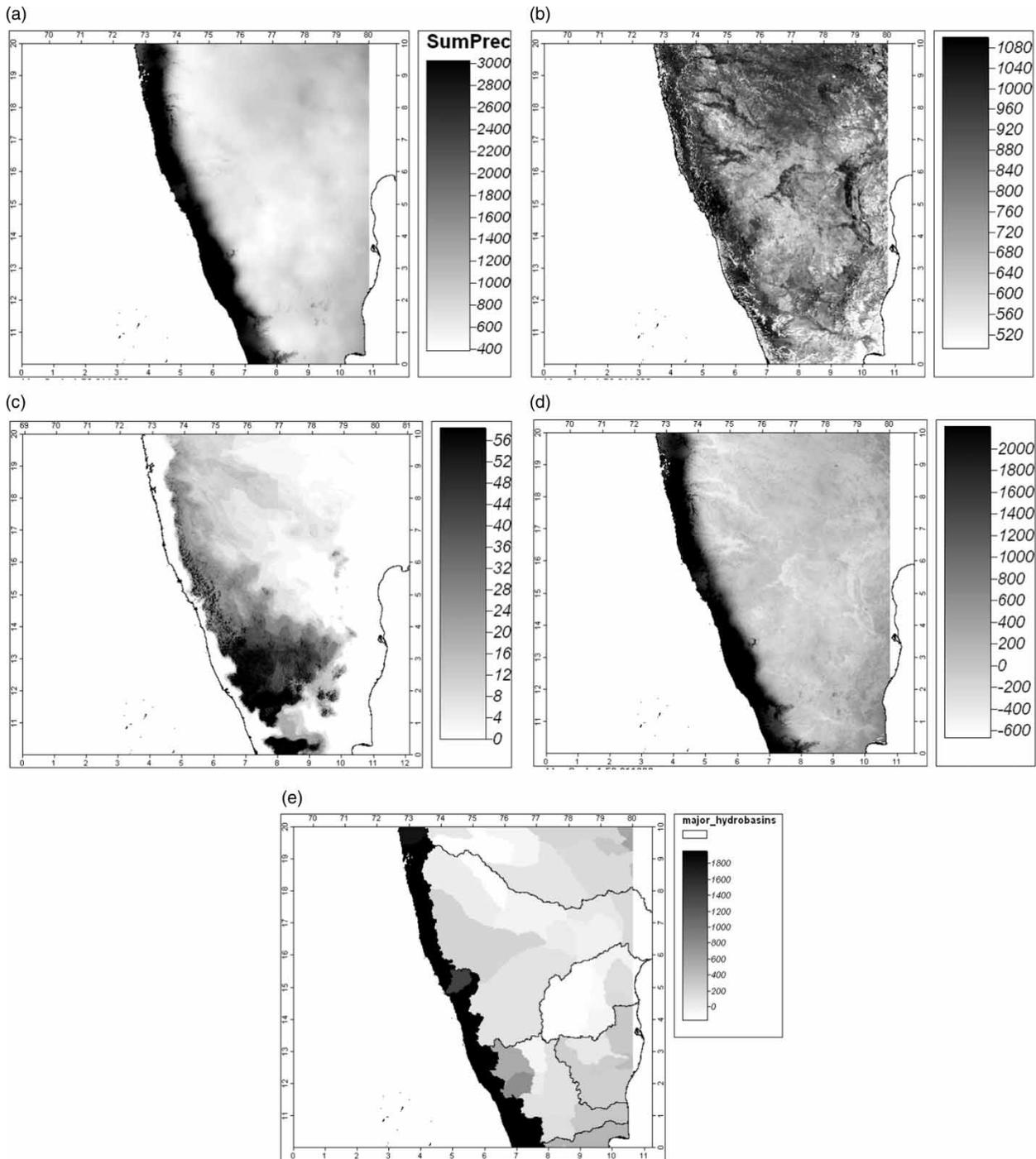


Figure 7 | Baseline results for the South India tile including (a) wind-driven rainfall, (b) actual evapotranspiration, (c) fog inputs, (d) water balance per pixel, (e) mean water balance per major sub-basin.

this A2a ('business as usual') scenario. Running a WaterWorld simulation for these inputs and calculating the change in hydrological variables between the baseline and the scenario gives the outputs shown in Figure 8. Figure 8(a)

shows the change in modelled (wind-driven) rainfall as a result of the ensemble scenario with significant decreases in a few restricted highly exposed ridges of the Western Ghats. Throughout the rest of the region increases in rainfall

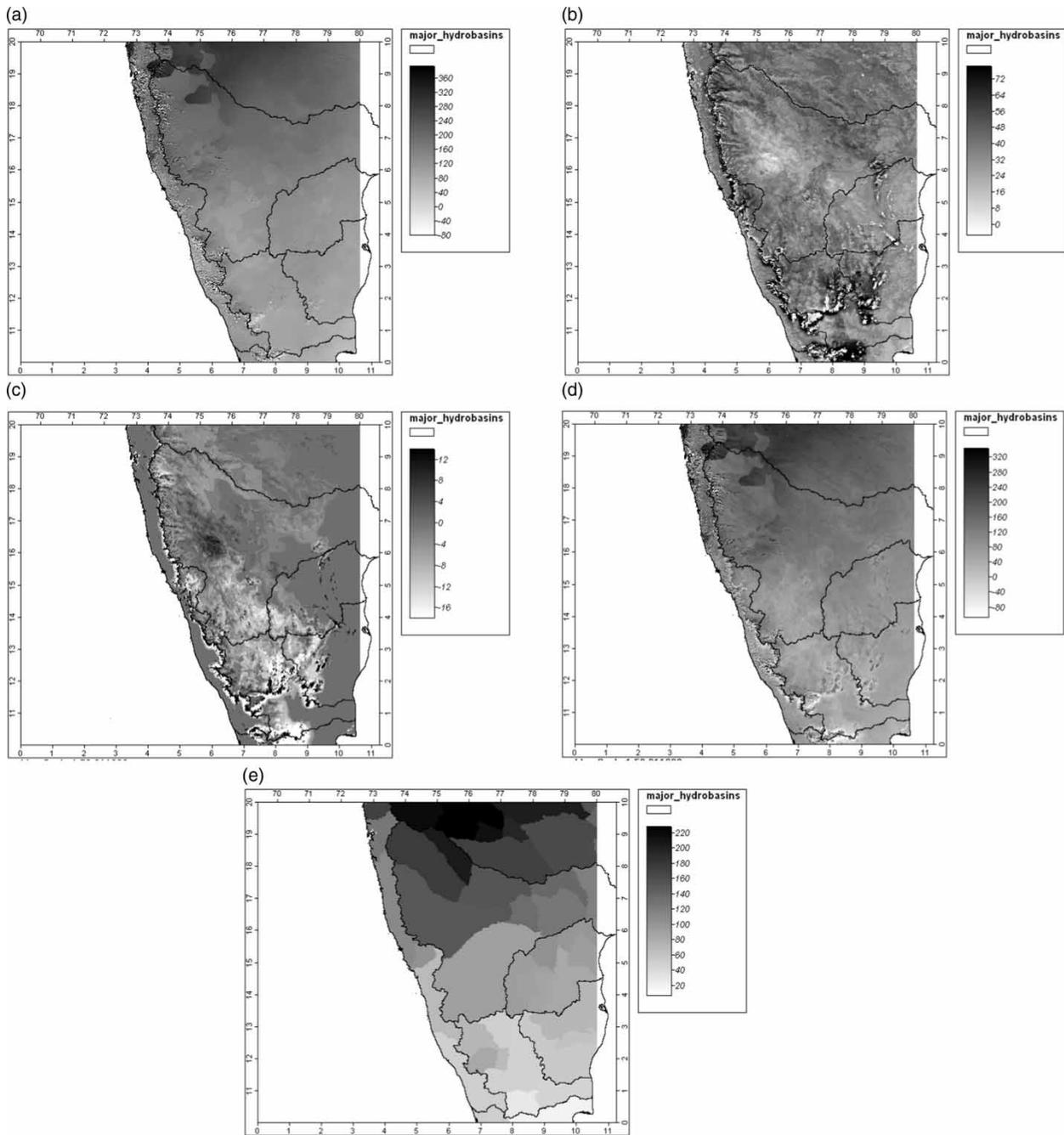


Figure 8 | Difference in outputs between baseline and AR4 A2a mean of 17 GCM climate scenarios (scenario-baseline) for (a) wind-driven rainfall, (b) actual evapotranspiration, (c) fog inputs, (d) water balance per pixel, (e) mean water balance per major sub-basin.

of 100 mm or less in the west and south and 200 mm or more in the north are observed. AET (Figure 8(b)) is affected by atmospheric warming. Note that no change is made to the vegetation cover to reflect the impact of climate change but since water balances generally increase in this

region no major change in vegetation cover is expected given that vegetation is already sustained through irrigation at levels greater than possible under current climate conditions. As a result of warming, fog inputs (Figure 8(c)) decrease in some high elevation mountainous areas but

increase elsewhere: these effects are mostly of a few tens of mm yr^{-1} . Fog inputs are affected by the changing temperature but since no GCM data for potential changes in pressure, diurnal temperature range and humidity were available, these results should be treated with caution since those variables had to remain at their baseline values. Current work with the UEA/Tyndall Centre links WaterWorld to more comprehensive GCM scenarios, providing a much wider array of variables. Overall, water balance (Figure 8(d)) increases especially in the north-west. This leads to significant increases of $150\text{--}250 \text{ mm yr}^{-1}$ in water balance for the sub-basins of the Godavari watershed in the north and the north-western sub-basins of the Krishna (Figure 8(e)).

There is, however, huge uncertainty in the projection of – even annual total – rainfall by GCMs, especially at the

regional scale (see Buytaert *et al.* 2009). Since changes in rainfall have such a significant influence on water balance, these uncertainties are critical. By using the mean of 17 GCMs we hope to represent the central tendency of the rainfall projections. However, the central tendency may not represent the best model, the best model may be one at the lower or upper end of rainfall projections. Thus, we also use WaterWorld to run the mean of all GCMs plus and minus one SD of the inter-GCM variability in order to place lower and upper bounds on this mean scenario, spatially, variable by variable. Figure 9 shows the change in water balance by sub-basin for (a) the mean of the 17 GCMs minus 1 SD, (b) the mean of 17 GCMs and (c) the mean of 17 GCMs plus 1 SD, all to the same scale. Figure 9(a) shows decreases in water balance throughout the region but especially for the Western Ghats (-300 mm yr^{-1}) and

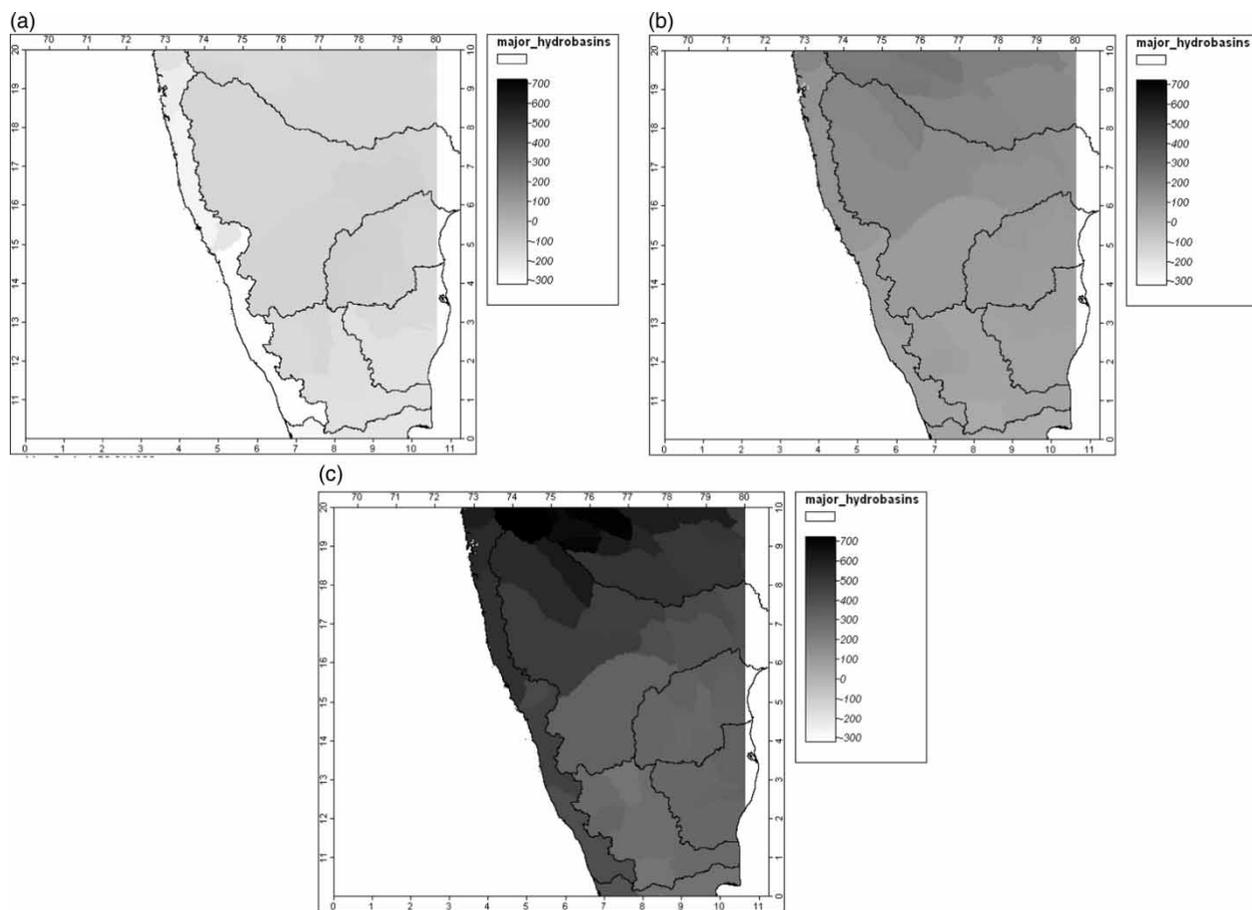


Figure 9 | Mean water balance per major sub-basin for (a) AR4 A2a mean of 17 GCMs minus 1 SD, (b) AR4 A2a mean of 17 GCMs and (c) AR4 A2a mean of 17 GCMs plus 1 SD, all at the same scale.

sub-basins of the Cauvery (-200 mm yr^{-1}) with sub-basins of the Krishna showing changes of -100 to -150 mm yr^{-1} . In Figure 9(b) we see increases in water balance throughout but especially ($150\text{--}200 \text{ mm yr}^{-1}$) in the north-western sub-basins of the Krishna. In Figure 9(c) we again see increases throughout of up to 700 mm yr^{-1} in the north and 300 mm yr^{-1} in the central south.

If we believe the projections of the ensemble mean of the GCMs then we can expect some of the water resource pressure of the Krishna basin to be alleviated by climate change. If however, the ensemble mean overestimates the likely increase in rainfall and temperature as a result of climate change such that the lower end of model projections is more appropriate then this already water stressed region may see even greater pressure as a result of climate

change. The seasonal patterns of change may further complicate the water resource situation and can also be examined with WaterWorld. The uncertainty of rainfall projections are currently so great that the best adaptation possible is to ensure land and water management policies and strategies are flexible, adaptable and hydrologically sustainable, since we cannot say, with any degree of certainty, what hydroclimate we will need to adapt to.

CONCLUSIONS

WaterWorld is a sophisticated but easy to use spatially explicit and physically based model for examining hydrological baselines globally. It can also be used as a PSS for

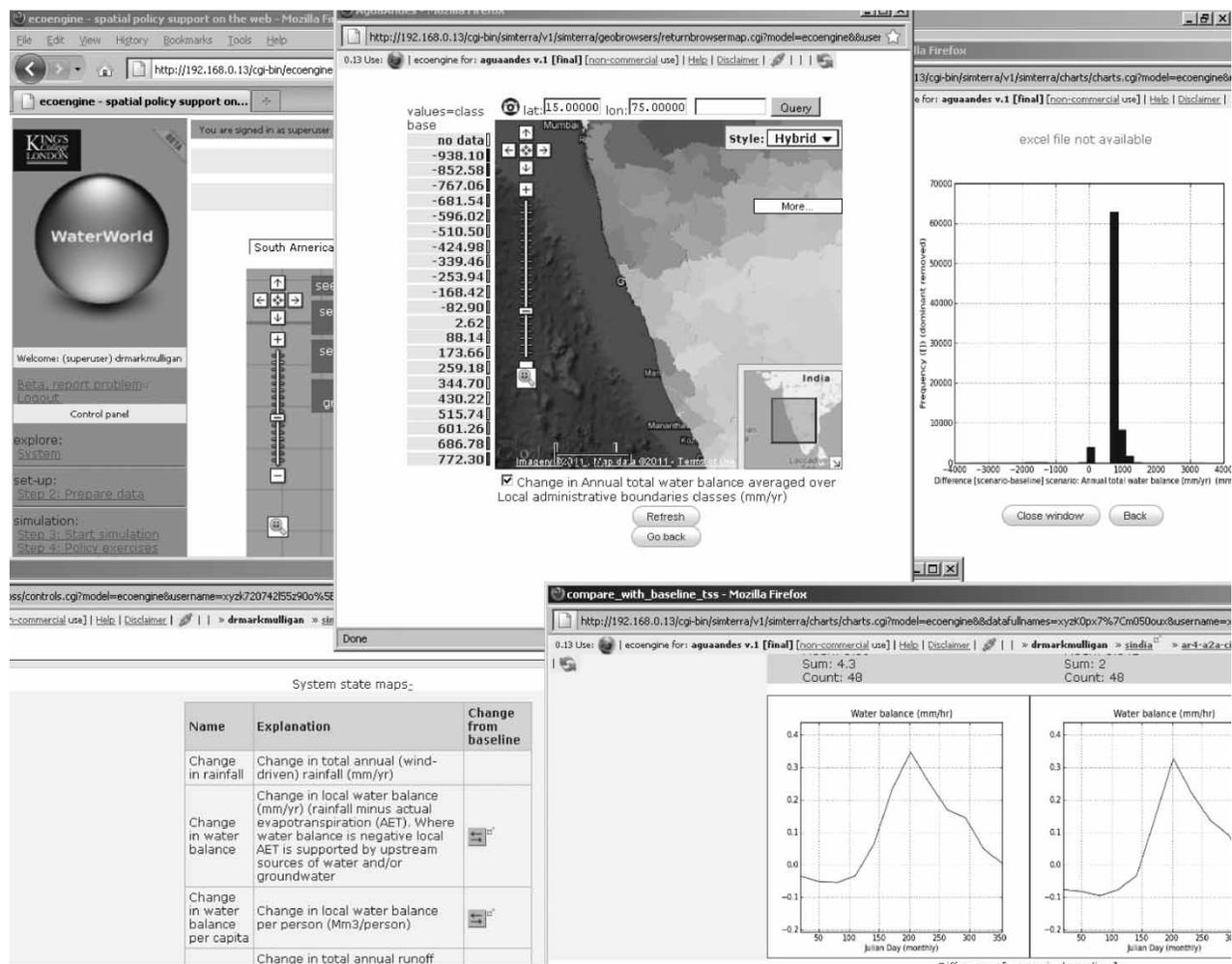


Figure 10 | The web based interface to WaterWorld (see www.policysupport.org/waterworld).

understanding the impacts of scenarios for change such as climate change and policy options or interventions for land and water management. The system requires very little local capacity, comes with all data required, and runs on servers accessed by the user through a simple web-browser interface as shown in Figure 10. We have focused here on WaterWorld version 1.0 and have outlined a number of applications for which it is a contribution to the available suite of tools.

Version 2.0 is currently in open beta testing and includes additional modules for soil erosion, deposition and transportation and snow and ice (after Walter *et al.* 2005). This is thus applicable in cold mountains where snowmelt dynamics may be an important component of response to climate change. Version 3.0 which is currently under development, brings in a dynamic vegetation growth and development model and modules for subsurface hydrological processes (infiltration, throughflow, returnflow and groundwater). These developments will widen the number of applications to which the tool can be put but make significantly greater data and processing demands on the system.

WaterWorld is a PSS not a policy-making system. It brings together the best available data and an understanding of hydrological processes so that users can explore the hydrological status quo and examine the potential impacts and uncertainties around policies they may be considering. It is a tool to contextualise and rationalise decision making around our still limited hydrological knowledge, especially in developing country situations where decisions sometimes have to be made in the more or less complete absence of hydrological data and capacity.

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made for the CGIAR Challenge Programme on Water and Food (CPWF) Basin Focal Project for the Andes (BFP-ANDES) and the current CPWF COMPANDES project (AN3) on benefit sharing (www.benefitsharing.net) and later expanded for global application. We are grateful to all of those providing data used in WaterWorld.

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