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Modelling multiple threats to water security in the Peruvian Amazon using the WaterWorld Policy Support System

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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Abstract

This paper explores a multitude of threats to water security in the Peruvian Amazon using the WaterWorld policy support system. WaterWorld is a spatially explicit, physically-based globally-applicable model for baseline and scenario water balance that is particularly well suited to heterogeneous environments with little locally available data (e.g. ungauged basins) and which is delivered through a simple web interface, requiring little local capacity for use. The model is capable of producing a hydrological baseline representing the mean water balance for 1950–2000 and allows for examining impacts of population, climate and land use change as well as land and water management interventions on hydrology. This paper describes the application of WaterWorld to the Peruvian Amazon, an area that is increasingly under pressure from deforestation and water pollution as a result of population growth, rural to urban migration and oil and gas extraction, potentially impacting both water quantity and water quality. By applying single and combined scenarios of: climate change, deforestation around existing and planned roads, population growth and rural-urban migration, mining and oil and gas exploitation, we explore the potential *combined* impacts of these multiple changes on water resources in the Peruvian Amazon and discuss the likely pathways for adaptation to and mitigation against their worst effects. See Mulligan et al. (2013) for a similar analysis for the entire Amazon Basin.

1 Introduction

Hydrologic systems are subject to changes that may be natural, such as climatic, ecological and earth surface changes or human-induced (i.e. land use change, infrastructural works, etc.). The interconnectedness of water with biotic, physical and social systems and associated complexity and non-stationarity constitutes a significant challenge to modelling these hydrological systems (Gupta et al., 2000) especially for impacts projection. The feedbacks between water and human society are particularly difficult to understand (Rockström et al., 2009; Gleick and Palaniappan 2010). To understand water management problems in such complicated systems therefore requires the development of models and tools that are able to capture the underlying physical processes of the natural system but also incorporate interactions and feedbacks with human systems (Wagener et al., 2010). The WaterWorld policy support system (Mulligan, 2013b) addresses this challenge by providing users with the possibility of assessing the impacts of a range of either natural or human-induced scenarios on the calculated baseline hydrology. Moreover, it provides scientific information and scenario analysis to users who do not have technical or hydrological capacity, thus allowing for a more open, inclusive and participatory approach to hydrological impacts modelling. In this paper we describe WaterWorld and apply it to the Peruvian Amazon, an area that is increasingly under pressure from deforestation and pollution as a result of population growth, rural to urban migration and oil and gas extraction, potentially impacting water quantity and water quality. We analyse the impacts of these scenarios applied individually and then in combination to understand interactions and implications for water security.

1.1 WaterWorld

WaterWorld is a fully distributed, process-based hydrological model that utilises remotely sensed and globally available datasets for application to supporting hydrological analysis and decision-making, and is especially useful in un-gauged and/or data-poor environments. Where users have local data these can be uploaded and used in WaterWorld analysis but where they do not, simulations are still possible with global datasets delivered with the model. The so-called policy support system is accessible through a web browser (and runs on a server, requiring no local installation) and is available at www.policysupport.org/waterworld. The model (v2.x) currently runs on either 10° square tiles at 1 km^2 resolution or 1° square tiles at 1 ha resolution. It simulates a hydrological baseline as a mean for the period 1950–2000 and can be used to calculate hydrological scenarios of climate change, land use change, land management options, impacts of extractives (oil and gas and mining) and impacts of changes in population and demography as well as a combination of these. As well as modelling water quantity, WaterWorld generates an indicator of the potential level of contamination of water by human activities. This so-called human footprint on water quality index (HF, Mulligan, 2009) is an index of the extent to which water is affected by upstream and local human activities.

The model is "self parameterising" in the sense that all data required for model application anywhere in the world is provided with the model. However, if users have better data than those provided with WaterWorld, it is possible to upload these as GIS files. Results can be viewed visually within the web browser or downloaded as GIS maps. The model's equations and processes are described in more detail in Mulligan and Burke (2005) and Mulligan (2013b). The model is not routinely calibrated to observed flows as it is designed for hydrological scenario analysis and use in ungauged basins. Calibration is inappropriate under these circumstances (Sivapalan et al., 2003). Moreover, it is assumed that if a physically-based model is capable of reproducing current conditions based only on physical relationships, it is likely it would continue to do so under scenario conditions since the physical relationships would remain the same (Mulligan, 2013b).

1.2 Water security

Increases in water demand, along with uncertain future climate change and potential changes in frequency and intensity of floods and droughts means many areas around the world may face a decrease in water security into the future (Postel and Wolf, 2001; Gleick and Palaniappan, 2010), with as much as 80 % of the world's population estimated to be affected by high-level water security risk (Vörösmarty, 2010; Bakker, 2012). Low income nations are likely to be more impacted (Hope et al., 2012) but also have the least ability to mitigate these risks as they sometimes lack the capacity and resources to invest in water resources management infrastructure and institutions. There are many definitions of water security currently employed in academic and policy literatures (Cook and Bakker, 2012). In the context of this paper, we define water security as the capacity of a population to ensure sustained access to water in terms of water quantity and quality (Mulligan, 2013a). The analysis therefore focuses on water stress, defined as the ratio of water use (demand) to availability (supply) and water quality, defined as the number of people with access to poor quality water (defined here as water with a human footprint index of $> 50\,\%$).

2 Study area

The study area comprises the northern two thirds of the Peruvian Amazon–Andes Basin (PAB). The region covers an area of 611 653 km^2 and is geographically located within the coordinates of latitude 0° N to 10° S, and 80° W to 70° W of longitude, which is the extent of the relevant WaterWorld 1 km resolution analysis tile (Fig. 1), masked to the PAB Basin. Elevation in the region ranges from more than 6050 m a.m.s.l. (above mean sea level) in the Eastern Andes to less than 46 m a.m.s.l. in the Amazon rainforest. Mean annual rainfall in the study area (based on WorldClim, Hijmans et al., 2005) is approximately 2100 mm with much higher precipitation over the tropical rainforest and much lower precipitation in the Andean mountains. Simulated annual total actual evapo-transpiration averaged over the study area is approximately 780 mm. According to the Modis Vegetation Continuous Field maps produced by Hansen et al. (2006), tree cover makes up 70 % of the region, nearly all of it concentrated in the low lying tropical Amazon. Modis VCF herbaceous cover (which is mostly agriculture) constitutes 28 %, and is mainly found at higher elevations in the Andes and along river valleys. Population in the area is around 10 million with the highest population density found towards the west of the study area in the Andean subbasins, with the exception of the sub-basin containing the city of Iquitos in the heart of the rainforest.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

2.1 Threats to water security in the Peruvian Amazon

2.1.1 Deforestation

Deforestation rates in the study area averaged around 540 square kilometres per year between 2004 and 2011 according to Terra-i data (www.terra-i.org). Most of this change is the result of land conversion to agriculture near settlements and river valleys where there is good access through roads and also accessibility to markets. However, in more recent years there has been a surge in deforestation associated with gold mining (Swenson et al., 2011). Land-use practices affect the annual and seasonal supply of fresh water through changes in the surface water balance and the partitioning of precipitation into evapo-transpiration, surface runoff and subsurface flow (Marengo, 2006), with decreases in forest cover leading to reduced evapo-transpiration and increased water balance. The impact on runoff depends on the land use and management that replaces forest cover. Moreover, conversion of tropical forest to agriculture can lead to increased water pollution as a result of increased soil erosion and inputs of manures, pesticides, herbicides and fertilizers.

2.1.2 Mining and oil and gas exploitation

Mining activities and oil and gas production are economically important for Peru but can also have significant impacts on water security both through their use of water and their contamination of downstream water resources. Small-scale artisanal gold mining is a significant source of mercury pollution to surface waters (Swenson et al., 2011) while oil extraction is responsible for many oil spills and the release of untreated wastes into the environment (Napolitano and Ryan, 2007; Orta-Martinez et al., 2007). These extractive activities can also be a driver of extensive forest degradation through the development of infrastructure such as access roads. The wave of development and deforestation that follows mining and oil can have impacts on water quality and quantity. With nearly fifty percent of the Peruvian Amazon under oil and gas concessions in recent years (Finer and Orta Martinez, 2010) this is potentially a significant threat to the environment and water security.

2.1.3 Climate change

Climate change constitutes a significant compounding factor to water security as it potentially alters hydrological variability and the occurrence and frequency of extremes. Future changes in climate are extremely hard to predict, particularly for precipitation which is fundamental to water security. In the Peruvian Amazon, a slight positive trend in temperature (+0.09 °C) has been shown between 1965–2007 but no discernable trend for precipitation (Casimiro et al., 2012). Projections based on climate models generally predict an increase in temperature by around 2 °C with precipitation projections highly spatially variable with some areas decreasing and others increasing but overall showing a slight increase in precipitation (Casimiro et al., 2011; Guimberteau et al., 2013).

2.1.4 Population growth and urbanisation

Population growth affects water security as it leads to an increase in demand both directly for domestic supply but also indirectly for industrial and agricultural water use. Immigration and settlement into the Peruvian Amazon has been accelerated in recent decades, partly due to the rise in extractive industry with population growth rates of between 5 and 7 % (Cardozo, 2011; Perz, 2010). The growing urban population is a driver for deforestation as a result of more infrastructure development (Weinhold and Reis, 2001) and is also a cause of water pollution due to increased domestic sewage that generally leaves the cities in an untreated state (Braga et al., 2011).

3 Methodology

3.1 WaterWorld water security metrics

WaterWorld produces some 60 mapped output variables, 20 of which are also produced on a monthly basis (see Mulligan, 2013a,c). These outputs include the main hydrological outputs such as modelled wind driven precipitation, actual evapo-transpiration and its cumulation downstream as runoff but also output generated by the wash soil erosion model (based on Thornes, 1990) and snowfall and melt water production produced by the snow and ice energy-balance model component (based on Walter et al., 2005). In order to assess impacts of scenarios for change on water security we will use the WaterWorld water stress index which calculates water supply as the simulated water balance (i.e. after evaporative water use) and demand given as population multiplied by a user-defined per-capita domestic and industrial demand, (set here as 47 $\mathrm{m^3\,yr^{-1}}$ or 130 $\mathrm{L\,day^{-1}}$). Supply and demand are calculated for each month. Agricultural demand is incorporated in the water balance since the water balance includes actual evapo-transpiration from the present land cover and use (thus including the effects of irrigation). The water stress index is the percent of industrial and domestic (blue water) demand not supplied in months at which supply is less than demand averaged for all months of the year. This is thus a cumulative index of water stress for each month and assumes no storage or surpluses in one month that might offset the lack of supply in the next, for example by reservoirs. The metric is thus a measure of climatic and hydrological water stress, seasonally and annually, in the absence of infrastructural water management measures such as storage by dams and groundwater abstraction.

As well as water quantity, water quality is fundamental to water security since it determines the quantity available for a particular purpose (such as irrigation, domestic use etc.). Poor quality water may be unusable for some purposes and bring with it risks of health insecurity. Water quality is very difficult to measure at policy relevant scales since it cannot be remotely sensed per se. Thus, WaterWorld uses an index of the

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

extent to which water is affected by human activities: the so-called human footprint on water quality index (HF, Mulligan, 2009). The HF essentially assumes that if rainfall falls on land that has low human impact then it will generate clean runoff, whereas if it falls on human land uses that may form point (mines, oil wells, roads, urban) or non-point (unprotected cropland and pasture) contaminant sources then the runoff generated is not clean (i.e. has a human footprint). The HF index (%) at a point is thus the proportion of water at that point that fell as rainfall on upstream human-impacted areas and is an indicator of the potential level of contamination of water. All land covers are assumed to have the same unit impact though users can change this if there is reason to believe that particular areas of cropland for example have a higher or lower pollutant release than others. The impacts on water quality are thus the magnitude and distributions of human land uses upstream in relation to where the rainfall falls.

WaterWorld assumes by default that, for withdrawals in all urban areas, 70 % of the HF is routinely removed by water treatment (at a cost) and that 70 % of the 100 % HF of populations living in urban areas is removed (at a cost) through sanitation. A HF index of $> 50\,\%$ is considered to equate to poor quality water. Rural areas are assumed by default to have no effective water treatment and sanitation, such that effluent from rural populations is considered to return to the rivers untreated and domestic water resources are considered to be available at the HF levels provided by the rivers. WaterWorld calculates the number of people affected by post-treatment and post-sanitation, poor quality water by combining its gridded population dataset with the resulting water quality map and the 50 % threshold value. See Mulligan et al. (2013) for further details.

3.2 Scenarios

In order to assess the impacts on water security by the threats described above for the Peruvian Amazon, we used the WaterWorld policy exercises tool to generate scenarios for each individual threat as well as a combination of these. These scenarios were then run in WaterWorld to examine the changes in water stress index and number of people with poor water quality.

3.2.1 Deforestation

To examine the impacts of a scenario for land use change on elements of water security, the WaterWorld land use change model (Mulligan et al., 2013) was applied which works on the basis of projecting recent rates of deforestation based on rates of land use change (for the last 8 yr) from terra-i data (vegetation loss) as a mean per regional administrative boundary continued into the future, deforesting areas with greatest current accessibility to major towns and closest to the existing deforestation fronts first. Land cover in the model is represented as a fractional cover of trees, herbaceous vegetation and bare ground in each 1 km pixel based on MODIS VCF (Hansen et al., 2006) alongside an indication of land use (cropping, grazing, mining, urban, protected areas) based on Ramankutty (2008), IUCN and UNEP (2009) respectively. In the scenario applied, recent rates of deforestation were projected forward by 40 yr to 2050 with protected areas ineffective at halting deforestation in the areas. Current forest cover was converted to a grazing use with a tree, herb and bare cover of 5, 90 and 5 % respectively and an intensity of use of 1.0 (the standard, indicating low input, eco-efficient methods not used). Figure 2a and b shows the baseline and scenario tree cover in percentage by pixel for the study area and Fig. 3a shows the change in tree cover by major subbasin.

3.2.2 Mining in 10 % of concession

Within the study area, some 18 000 km^2 or 2.5 % currently has a concession for open pit mining (Mulligan, 2011), nearly all of these are located along the western border of the basin in the Andes. It is difficult to predict how many of these concession areas will actually be developed into mining activities. We chose to simulate a scenario whereby a conservative 10 % of these concessions is turned into active mines, which means any vegetation cover is replaced by bare ground and the mining area expands to create an increase in point contaminant sources for the human footprint index. Figure 3b shows the increase in number of mines by sub-basin.

3.2.3 O & G in 1 % of the concession

According to the WaterWorld Oil and Gas concessions dataset (Mulligan, 2011), currently, around 500 000 km^2 or 70 % of the study area is under oil and gas concessions. Similar to the scenario for mining a scenario whereby 1 % of these concessions gets converted to oil production sites was implemented in the model (Fig. 3c). The actual conversion will depend upon the quantity and quality of oil reserves found and the price of oil and costs of production and transport but 1 % is not unreasonable and is broadly similar to the occupancy of concessions in nearby Ecuador that has a much longer history of exploration and production.

3.2.4 Climate change

To examine the likely impacts of projected climate change, which can exacerbate or cancel out water security risks, WaterWorld was run with a climate change projection. We chose the SRES A2A scenario (Nakicenovic et al., 2000) representing high growth and a global 3.5 °C warming (relative to 1900) by 2100, although other IPCC climate change scenarios are also available from WaterWorld (Mulligan, 2013b). Rather than running the model with the projections of a single GCM we ran with an ensemble mean scenario for the 2050s of all 17 available GCMs which is considered as a good representation for use in spatial studies (Tebaldi, 2010). For the study area, a mean annual increase of 61 $\mathrm{mm\,yr^{-1}}$ (+12 %) in precipitation is projected under this scenario with highest values towards the north-west (up to 180 $\mathrm{mm\,yr^{-1}}$ increase, Fig. 3d). An area average mean warming of 2.7 °C is also projected. WaterWorld uses the monthly temperature and precipitation grids from the IPCC SRES GCM data, downscaled to 1 km spatial resolution by CCFS (Ramirez and Jarvis, 2008) to drive the scenario hydrology. Processes of snowfall and snowmelt, fog and fog water interception, rainfall and evapo-transpiration respond to these climatic forcings.

3.2.5 Population growth

Population growth was simulated in the model by applying the WaterWorld population scenario generator (Mulligan et al., 2013). The population scenario generator calculates a rate of change based on the IPCC SRES scenarios for years 1990 to 2100 and applies these deltas to the population dataset used for the Baseline (Landscan, 2007). Here we apply the SRES rates of change up to 2050. This results in an increase in population of nearly 45 % throughout the region, mostly around current population centres with greatest increase in the Andean sub-basins (Fig. 3e) The nearly doubling of the population under this scenario agrees with the current population growth rates in the region of between 5–7 % (Perz, 2010; Cardozo, 2011).

4 Results and discussion

4.1 Baseline water security

The baseline assesses the current situation based on long term climatic data (1950–2000) and current land cover (2010). Figure 4a shows the WaterWorld simulated baseline water stress index by major sub-basin (HydroSHEDS), defined as the % of industrial and domestic (blue water) demand not supplied in months at which supply $<$ demand averaged across the year.

The water stress index shows that towards the south-west of the study region and particularly in the Andean Basin up to 20 % of the demand cannot be met climatically which means these areas depend on water storage or transfer during parts or all of the year. Further north and thus further into the Amazon rainforest, demand is met climatically for nearly every month. Figure 4b shows the areas in which populations are currently likely to be subject to poor water quality. Although urban areas will also be subject to this low water quality, investments in water treatment and sanitation are assumed to offset them but do so at a considerable economic cost.

4.2 Changes to water security

Figure 5 shows the WaterWorld simulated changes in water stress by major sub-basin and Fig. 6 shows the changes in number of people with poor quality water for all 5 individual scenarios as well as a combined scenario.

4.2.1 Deforestation

Under a scenario of deforestation where forest is converted to pasture, there are increases in available water since short herbaceous cover has lower evapo-transpiration than the trees it replaces. This results in minor decreases in water stress (max $-1\,\%$) with the greatest change in those sub-basins where most of the deforestation has taken place (Figs. 2b and 3a). The changes in water quantity are minor because there is relatively little difference in AET between the cover types and the changes in resulting runoff tend not to affect the stress index significantly since AET is often much lower than precipitation for the region. The change in the number of people with poor quality ($\mathrm{HF} > 50\,\%$) water under this scenario (as shown in Fig. 6) is more significant since the differences between non-agricultural and agricultural land in terms of their potential contaminant inputs to downstream are considered to be significant where ecoefficient techniques are not in operation. Overall, land use change projections that might be expected in the next 50 yr lead to only very small effects on water quantity. The resulting impacts on people's exposure to water stress are minor though the impacts on water quality are more significant.

4.2.2 Mining in 10 % of concession

Development of 10 % of the mining concessions in the region, leads to a clearing of forest cover and thus a decrease in AET which results in a localised decrease in water stress. From Fig. 5 it can be seen that the extent of the impact on water stress for this scenario surpasses that of the deforestation scenario with more major sub-basins affected as a result of the random implementation of this scenario within the mining concessions that are spatially distributed throughout the region. A more sophisticated rule that clusters around existing mines or roads is possible but the simplest case was used here. This scenario has a large impact on water quality with the number of people with poor quality water increasing significantly, particularly in the Andean sub-basins. It is these regions where current mining activities are taking place, where most concessions are, and it can be assumed that future developments will most likely focus on these areas first.

4.2.3 O & G in 1 % of the concession

Similar to the results on the development of mines, a scenario whereby oil and gas extraction is developed on 1 % of all land with oil and gas concessions in the study area leads to an increase in the water budget as a result of decreases in AET. This leads to a decrease in water stress. The impacts are minimal though with most basins only showing a very minor decrease. In terms of water quality, changes are minimal as well with no single basin showing a significant increase in the number of people affected by poor quality water because of the low footprint of the affected pixels. Clearly if mining or O & G were responsible for highly toxic emissions then the impacts of these on water quality would transcend very far downstream. Local scale impacts at or downstream of the new developments can be significant but since these are relatively small developments within large sub basins, the impacts are less apparent at the basin scale.

4.2.4 Climate change

The multi-model climate change scenario shows a much greater impact on water stress because it projects significant increases in precipitation. However, increased temperature also leads to higher evapo-transpiration rates, which means the mean overall water stress shows increases in some sub-basins (mainly in the Amazon) and decreases in others (mainly in the Andes). This is the result of the spatial variability of the temperature changes in the region resulting in much lower AET in these basins and the variablity in precipitation projection. Water quality changes as a result of climate change are minimal as there is no change in pollution sources. More water however, tends to dilute pollution inputs and therefore overall there is a slight decrease in number of people with poor quality water in the region. Changes in the distribution of precipitation could drive changes in human land use to decrease water quality, though these effects are not incorporated in this analysis. Water quality issues could also result from changes to the frequency and magnitude of extreme events projected for the future (IPCC, 2012). Such events are extremely difficult to model though and since WaterWorld, as a water resource model uses a monthly time-step, such impacts cannot be quantified. It also should be noted that there is significant uncertainty in GCM climate projections, particularly for rainfall and especially in heterogeneous environments such as the Andes (e.g. Buytaert et al., 2009) where often, there is not even agreement on the sign of change between GCMs. While we attempt to limit this uncertainty by applying a scenario using the mean of all GCMs as a measure of the central tendency of the projections, using single GCMs or different combinations of GCMs could lead to very different results.

4.2.5 Population growth

A scenario of population growth based on the SRES growth projection rates extended to 2050 leads to no change in water stress even though water demand will clearly increase under this scenario. This is because domestic and industrial use are not consumptive uses and thus all domestic water use is returned to the system as grey or brown water and thus the quantity based water stress metric does not change in this scenario: although demand increases, supply is not affected. The water quality metric is affected though, and as is clear from Fig. 6, a number of sub-basins see a significant increase in the number of people with poor quality water as a result of increased inputs of brown and grey water.

4.2.6 The combined scenario

When all the above scenarios are combined into one single scenario, water stress decreases for most sub-basins that are affected by the deforestation and extractives scenarios although this is partly offset by the climate change scenario that increases water stress for those regions. It is important to note here that we do not examine the impact of changed climate on vegetation growth and cover and thus the potential of a drying climate to reduce vegetation cover and thus evapo-transpiration, offsetting some of the effects on water balance. The effects of climate change are also clearly visible in the north-eastern basins where increases in water stress can be seen. Climate change has a significant impact upon water stress but the uncertainty in climate change projections makes it difficult to develop hazard preparedness strategies to mitigate these impacts. In terms of water quality, the mining and population growth scenarios and to a lesser extent the deforestation scenario have the greatest impact on the number of people with poor quality water. Since most of these changes take place in the most densely populated western Andean sub-basins, it is these basins, that are also most impacted in their water security. With such a large area of the region under mining and oil and gas concessions, strict management and regulation of development and its cascading impacts will be essential to protect the region from serious environmental and water resource degradation.

While this analysis has captured the most pertinent threats to water security in the region, some major infrastructural threats such as dams and roads have not been included. Currently there are 6 large dams in the study area (Mulligan et al., 2011b) but there are plans for the development of a further 39 large dams (Finer and Jenkins, 2012). The development of these dams may drive deforestation as a result of road building, transmission lines and displacement associated with inundation. New dams have the potential to increase water security through their storage potential but are also themselves at risk from sedimentation – which could be accelerated by upstream developments such as urbanisation and extractives development – and climate change.

This could have serious implications for water quantity and water quality downstream due to managed flow regulation and changes in sediment loads.

WaterWorld has been used to identify those areas that are under greatest water security threat from multiple factors. This has been done by modelling individual scenarios and a then a combined scenario of change. WaterWorld's built-in scenario generator allows for a rapid assessment of the impacts of many different scenarios relative to baseline conditions. Since the model includes all necessary data, non-technical users can model their areas of interest and apply local knowledge in generating these scenarios exploring a multitude of feedbacks between the hydrological system and human interventions within this system – and do so quickly and interactively.

5 Conclusions

This paper has discussed a new approach to hydrological scenario modelling with the WaterWorld policy support system that combines the best globally available data with a broad and deep understanding of hydrological processes. It allows users without specific technical or hydrological capacity to explore the hydrological baseline and potential impacts of scenarios of change for anywhere in the world. Here we carried out an assessment of multiple threats to water security in the Peruvian Amazon showing that people living in the more populated Andean Basins within the study area are under threat from a decrease in water quality as current deforestation and population growth continues and if 10 % of all mining and 1 % of all oil and gas concessions in the region were to be developed. Whilst individual drivers of change have geographically variable effects, the combined effect is both more relevant to real futures and shows evidence of different drivers exacerbating or reducing the impact of others. Climate change has the potential to exacerbate or cancel out some of the land based threats but impacts of climate change are also hugely uncertain because of uncertainty in the magnitude and even direction of rainfall change at these scales.

It is critical for analyses of the water resource impact of land use change or climate change to take account of this climate uncertainty but also to understand climate change within the context of multiple other threats to water quantity and quality in the region. If these multiple threats will occur at the same time scale as climate change then their interaction with climate change cannot be ignored.

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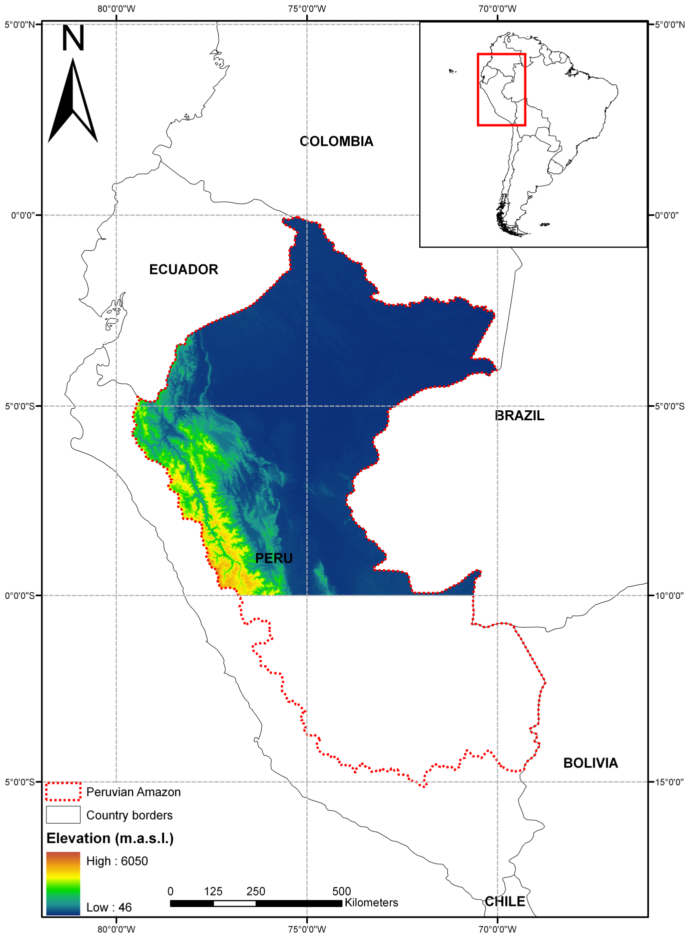

Fig. 1. Study area, extent of coverage of the Peruvian Amazon Basin and elevation in the region.

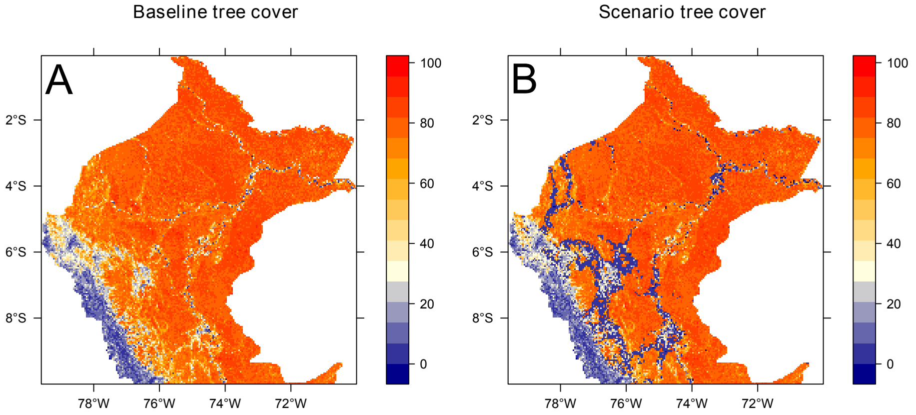

Fig. 2. (a) Baseline tree cover for study region based on MODIS VCF (Hansen et al., 2006). **(b)** Scenario tree cover generated by WaterWorld land use change scenario generator.

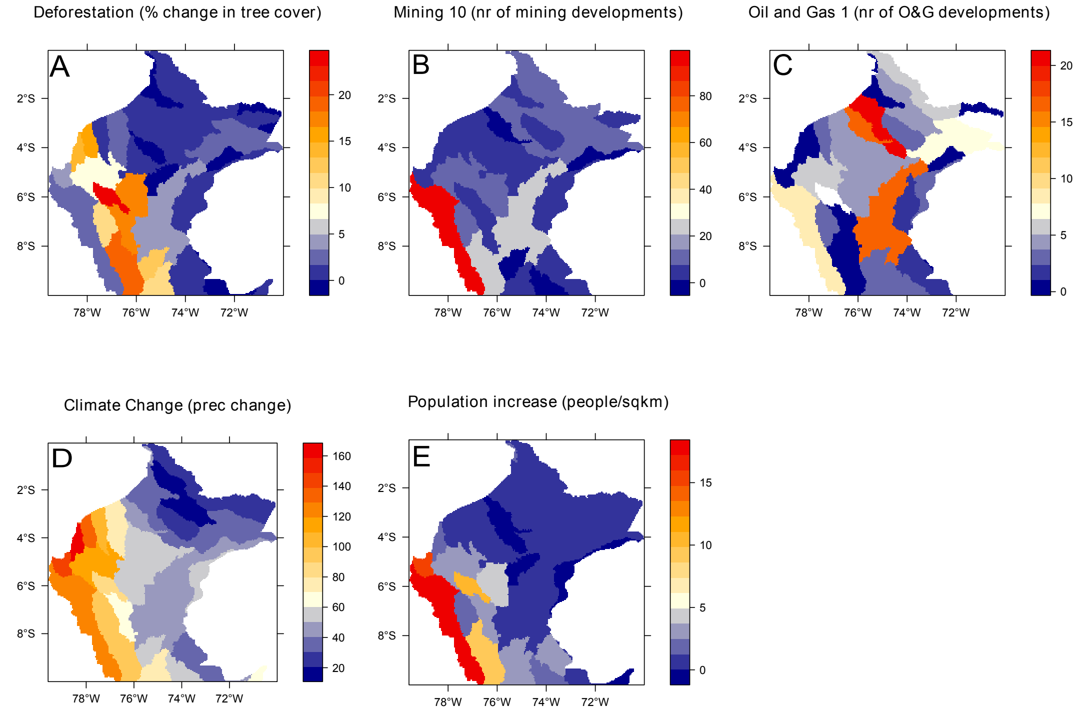

Fig. 3. (A–E) Key changes for 5 individual scenarios by major subbasin. **(A)** % change in tree cover based on WaterWorld land use model for 2050s. **(B)** Number of mining developments if 10 % of current concessions get converted. **(C)** Number of oil and gas developments if 1 % of current concessions get converted. **(D)** Precipitation change for mean of 17 GCM under A2A scenario for 2050s. **(E)** Population increase based on SRES projections for 2050s.

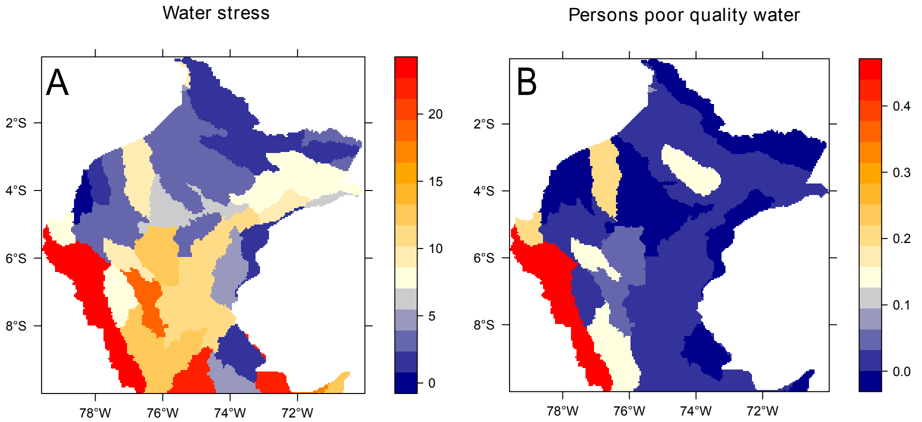

Fig. 4. **(A)** Baseline annual average water stress (%) and **(B)** average population with poor quality water (> 50.0 HF) averaged over major sub-basins (Hydrosheds) classes (persons per km^2).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

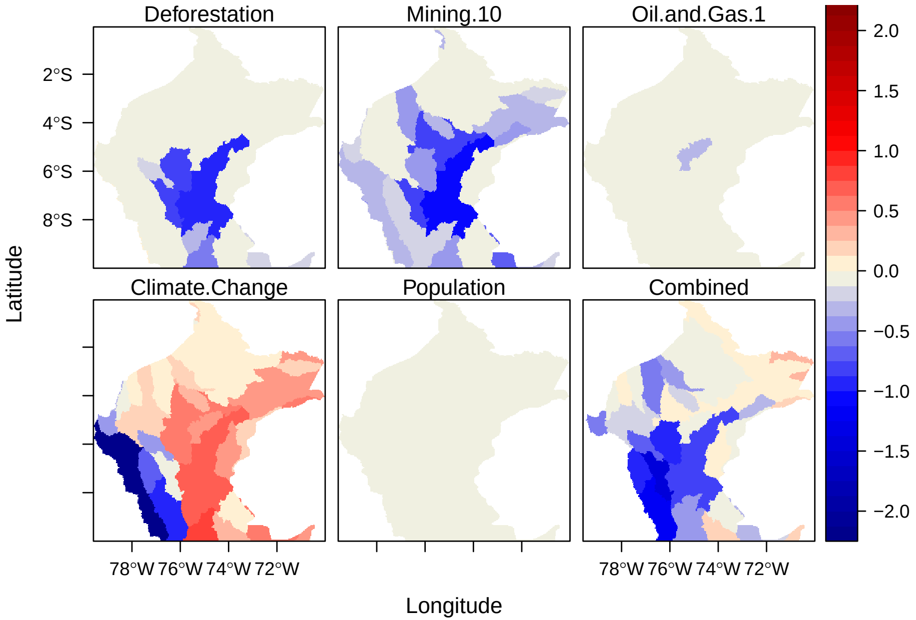

Fig. 5. Change in water stress index by major sub-basin for scenarios of change, % of industrial and domestic (blue water) demand not supplied in months at which supply < demand across the year.

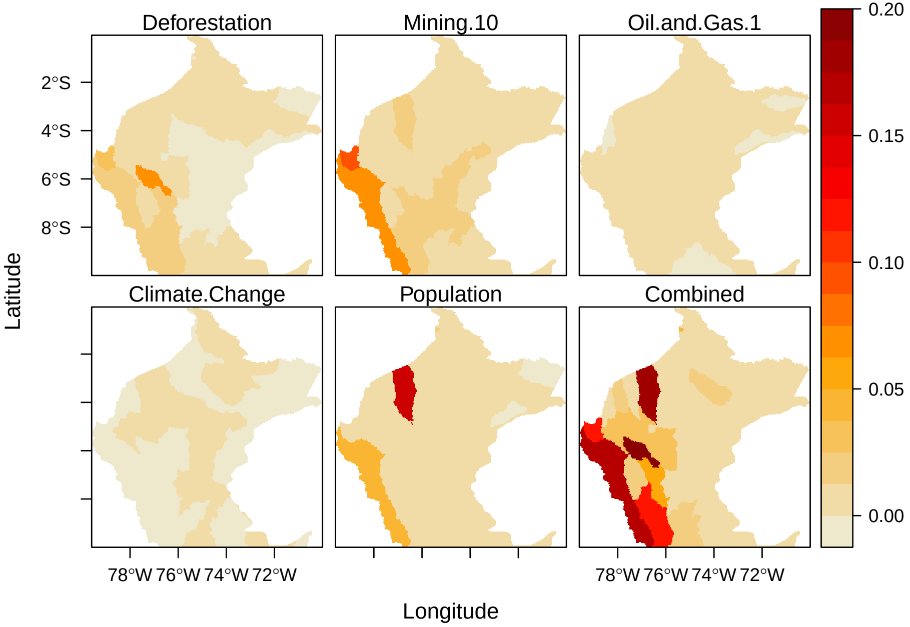

Fig. 6. Change in average population with poor quality water (> 50.0 HF) averaged over Major sub-basins (Hydrosheds) classes (persons per km^2) for scenarios of change. Negatives in light yellow.