water2invest

Data-base and report on global analysis of water gap investments

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1 INTRODUCTION

Water scarcity is among the main problems in many parts of the world affecting quality of life, the environment, industry, and the economies of developing nations. Many arid and semi-arid regions worldwide are already confronted with major water scarcity problems. Aquifers are over-pumped, water quality is deteriorating, and water supply and irrigation services are often rationed—with consequences for human health, agricultural productivity, and the environment.

In this 21st century water supply will be compromised in many regions of the world due to climate change and water demand will increase, the urge to bridge the climate induced water gap is larger than ever before. (Figure 1) The world population tripled in the 20th century and is expected to grow from 6 billion in the year 2000 towards nearly 11 billion in 2100. (UN 2013) At the same time economic growth, in developing countries, drives prosperity and corresponding water and food demand. According to the UN World water Development report 2012, water use has been growing at more than twice the rate of population growth over the last century. Each continent is affected by water scarcity, and around 1.2 billion people currently live in areas with physical water scarcity and 500 million people are approaching this situation. Another 1.6 billion people face economic water shortage. The questions arising from these are consequently: How can we prepare for tomorrow, or how can we overcome the climate induced water gap?

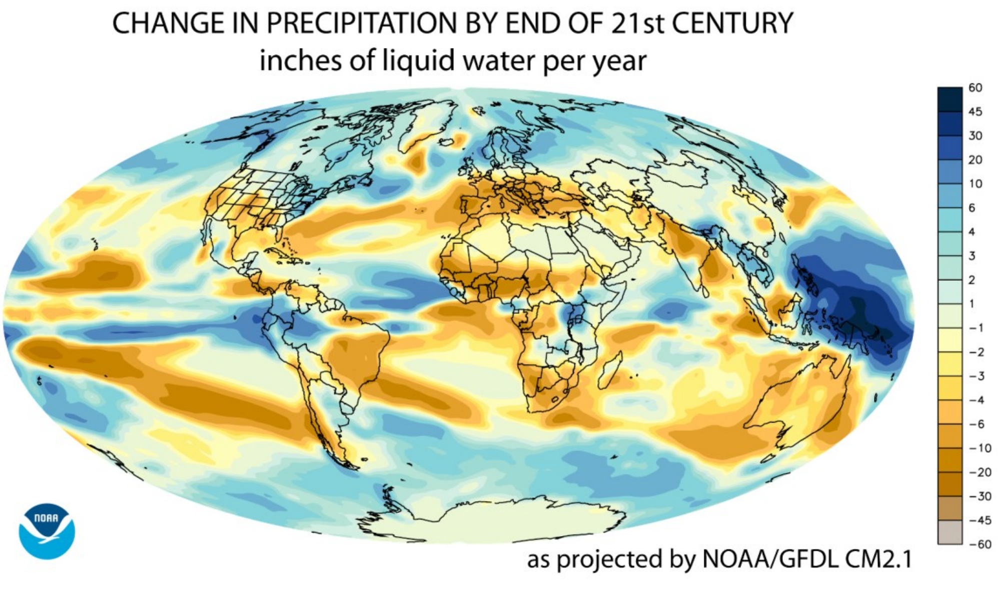


Figure 1: Precipitation change average 2081-2100 compared to average 1951-2000 according to IPCC SRES A1B scenario (Source: NOAA/GFDL 2007)

A World Bank study (MENA) 2007, argues that countries have to adapt to the challenges resulting from water scarcity because if they do not, the social, economic, and budgetary consequences will be enormous. However, decisions makers responsible for climate change adaptation investments are confronted with a huge knowledge gap. On the other hand, scientists have gained much fundamental knowledge about climate impacts, but practical use of this knowledge is very limited as applied tools as well as knowledge transition is sparse. We aim to build a web-based service from which its users can select a country or region on a global map, calculate the current water availability from surface water and groundwater as well as current water demands from the three sectors (agriculture, industry, domestic) and assess from this the current water shortage as well as the looming water shortage under scenarios of climate change and socio-economic development. Based on these assessments, the user can evaluate various technological and infrastructural adaptation measures to assess the investments needed to bridge the water gap. Regional environmental and socio-economic effects of these investments are evaluated. The tool can be used by consultants, water authorities, non-governmental and commercial investors alike to test investment strategies, but could also be used by companies as a vehicle for advertisement water saving or crop water productivity technologies that can be evaluated on their effectiveness on the spot.

The study by the 2030 Water Resources Group "Charting Our Water Future" shows that the challenge in identifying the optimal mix of technical measures to close a given supply-demand gap lies in finding a way to compare different measures. To address this need, the 2030 Water Resources Group developed a "water-marginal cost curve" as a tool to support decision-making (Figure 2). The cost curve's horizontal axis measures the amount of water made available by each measure to close the supply-demand gap. In applying the cost curve in the case study countries, the net impact of each measure on water availability is estimated. The vertical axis of the cost curve measures the cost per unit of water released by each measure in the year of the cost curve. This is the annualized capital cost, plus the net operating cost compared to business as usual. These are costs as measured from an integrated view—in other words the actual financial savings, rather than redistribution effects such as subsidies. In this study we will adopt this concept in assessing the potential to overcome the supply-demand gap in the MENA region.

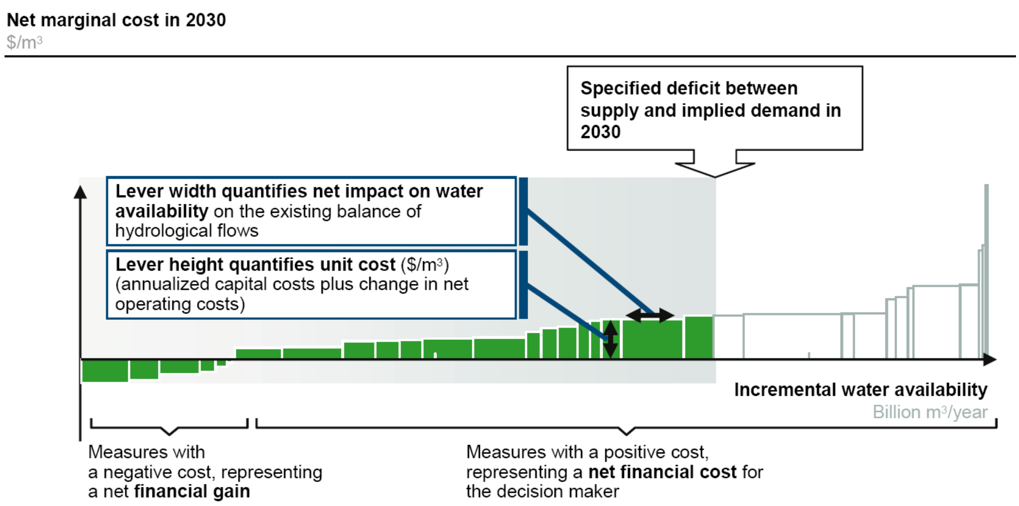


Figure 2. Example of the water availability cost curve (source: Water resources group 2030).

2 CONCEPTUAL FRAMEWORK

2.1 MODELING APPROACH

A two tier modeling approach is used in this study. First we use an advanced distributed hydrological model to determine the renewable water resources including external renewable water resources for the current and future climate. In combination with sectorial water demands the results of the water availability analysis feed into a water allocation model that is used to assess water demand on a monthly basis. The water allocation model includes groundwater, surface water and reservoirs as sources of water, which are used to sustain the sectoral water demands. The allocation model links supply and demand for each country, sector and supply source. The hydrological model provides monthly time series of surface water and natural groundwater recharge to the water allocation model. The water allocation model is subsequently used to assess the effects of different supply and demand options.

The project methodology is organized as follows. First worldwide climate change scenarios are downloaded from the Coupled Model Intercomparison Project (CMIP5), the climate change projections from the IPCC fith Assessment Report (AR5). These data are bias corrected and used to assess the future water availability based on the PCR-GLOBWB global hydrological model (Van Beek et al. 2011). Then the water demand side is analyzed across the irrigation, industrial and domestic sectors. Using a water allocation model (WatCAM) water stress is assessed by confronting water availability with water demands. Finally water availability costs curves are derived using the same modeling framework indicating how much investments are required to close the water gap in each of the water provinces.

It is of paramount importance in these kinds of studies to have a well-defined set of definitions. Many studies are hampered by a loose use of terminology, making interpretation of results difficult. More importantly, policy decisions might be less appropriate due to misconceptions in terminology. A classic example is “efficiency”, where the real question should be “what happens with the non-efficient water?” Following the definitions of FAO (2003) in this study a distinction is made between:

Internal renewable water resources account for the average surface flow of rivers and the recharge of groundwater generated from endogenous precipitation. Internal renewable water resources also account for *green water*, which is captured in the root zone and evaporated by plants without becoming part of the surface water system.

External renewable water resources refer to surface water and to renewable groundwater that come from other countries plus part of shared lakes and border rivers as applicable, taking into account the net consumption of the country in question. Dependency on incoming water from external sources is quantified by the dependency ratio.

Total renewable resources are the total of internal and external surface and groundwater resources. Special care is taken to avoid double counting of surface water and groundwater.

Non-renewable groundwater resources are naturally replenished only over a very long timeframe. Generally, they have a negligible rate of recharge on the human scale (<1 percent) and thus can be considered non-renewable. In practice, non-renewable groundwater refers to aquifers with large stocking capacity in relation to the average annual volume discharged.

2.2 MONTHLY APPROACH

Using a monthly approach in assessing water stress is a crucial component of this assessment. Many studies assess water stress on an annual scale which underestimates actual water stress because water demand and supply are not in phase. This is illustrated in Table 1, which shows the available renewable water resources, the irrigation water requirements and the water stress on a monthly basis for a hypothetical irrigation scheme. On annual basis the water stress would be equal to 20 mm (260-240), while in reality the difference between available and required water should be determined on a monthly basis and then aggregated. This approach would results in an annual water stress of 120 mm. This example assumes that renewable water from the previous month is somehow lost, not accumulated in the ground or a reservoir that could be used for irrigation in the following month. This obviously is a simplification of reality, but the annual approach followed frequently assumes an unlimited storage, which is often not reality. Reservoirs are of course used to attenuate this mismatch in time between demand and supply. However, the use of reservoirs leads to undesirable loss of water due to open water evaporation. The impact of reservoirs is taken into account using the water allocation model. In summary, the often followed annual approach is unrealistic and in our analysis a daily and monthly approach is used where groundwater and reservoir storage is included.

Table 1. Hypothetical example of the importance of using a monthly approach in assessing water stress, assuming no storage in groundwater or reservoirs.

Month	Renewable (mm)	Irrigation requirement (mm)	Water stress (mm)
January	30	10	0
February	20	10	0
March	10	30	20
April	10	30	20
May	10	40	30
June	10	40	30
July	10	20	10
August	10	20	10
September	20	20	0
October	30	20	0
November	40	10	0
December	40	10	0
TOTAL	**240**	**260**	**120**

2.3 WATER AVAILABILITY COST CURVES

Based on the analysis with the water allocation model the amount of water that is required to sustainably close the gap between supply and demand is known. The gaps will most likely increase tremendously as availability is decreasing and demand is projected to increase. A number of supply and demand measures (e.g. desalination, increasing reservoir capacity, improving water productivity) will be analyzed using the water allocation model and water availability cost curves will be derived.

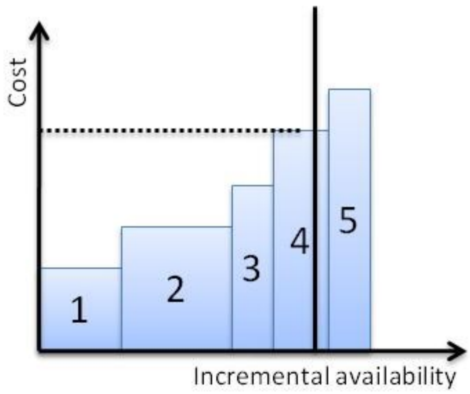


Figure 3. Illustration of prioritization of different options.

The cost-effectiveness of various measures to close the supply-demand gap will be compared in this study by means of the “water-marginal cost curve”, as presented by the 2030 Water Resources Group (2009). This cost curve shows the cost and potential of a range of different measures- spanning both productivity improvements and supply expansion – to close the gap. Such a water-marginal cost curve is estimated for each water province to assess the total costs to close the supply-demand gap projected in the base case (2010) and under various climate change scenarios in 2030 and 2050. A hypothetical graph of such a curve is shown in Figure 3. On the vertical axis the marginal costs in US$/m3 of each measure is shown, while on the x-axis the total amount of water (m3) is shown that can be conserved (or supplied) using the approach. The vertical line crossing box 4 shows the water gap in for example 2030. The first block is the cheapest measure. The surface under the water availability cost curve up to the line showing the water gap equals the investment required to close the water gap.

3 MODELS

3.1 INTRODUCTION

Water related problems are diverse and location and timing specific and ranges from issues as water shortage, water flooding, to contamination. The problems the water sector faces can be attributed to a wide variety of factors such as climate change, population growth, socio-economic development, mismanagement, changing priorities by societies, amongst others. Decision makers and water managers are confronted with insufficient knowledge about the current state of water resources, and have even more problems in assessing future changes and impact of potential decisions to be taken.

Data are essential to assess the current condition of water resources and to understand past trends. However, to explore options for the future tools are required that are able to explore the impact of future trends and how we can adapt to these in the most sustainable way. Simulation models are the appropriate tools to do these analyses.

In summary one can say that the two main objectives of models are to: (i) understanding processes and how they interact, and (ii) scenarios analyses. Understanding processes is something that starts at during model development. In order to build our models we must have a clear picture on how processes in the real world function and how we can mimic these in our models. The main challenge is not in trying to build in all processes, which is in fact impossible, but lies in our capability to simplify things and concentrate on the most relevant processes of the model under construction.

The main reason for the success of models in understanding processes is that models can provide output over an unlimited time-scale, at an unlimited spatial resolution, and for difficult to observe sub-processes (e.g. Droogers and Bastiaanssen, 2002). These three items are the weak point in experiments, but are at the same time exactly the components in the concept of sustainable water resources management.

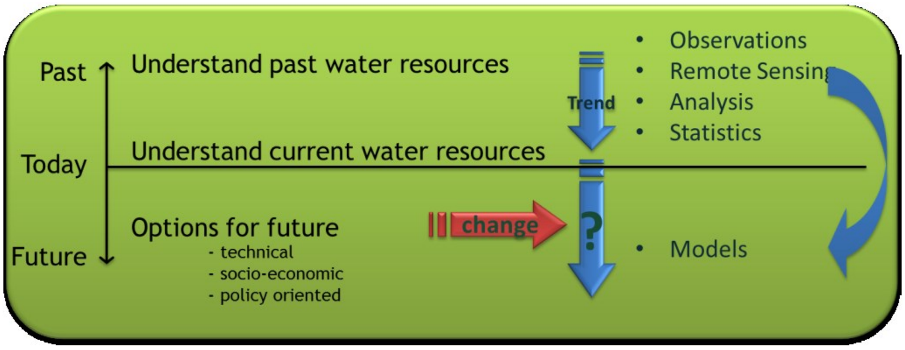


Figure 4: The concept of using simulation models in scenario analysis.

The most important aspect of applying models, however, is in their use to explore different scenarios. These scenarios can capture aspects that cannot directly be influenced, such as population growth and climate change (Droogers and Aerts, 2005). These are often referred to as *projections*. Contrary to this are the *management scenarios* or interventions where water managers and policy makers can make decisions that will have a direct impact. Examples are changes in reservoir operation rules, water allocation between sectors, investment in infrastructure such as water treatment or desalinization plants, and agricultural/irrigation practices. In other words: models enable to change focus from a re-active towards a pro-active approach. (Figure 4).

3.2 WATER SUPPLY MODELLING: PCR-GLOBWB

The water balance was computed using the PCR-GLOBWB model (Van Beek and Bierkens, 2009;Van Beek et al., 2011). PCR-GLOBWB (PCRaster Global Water Balance) is a grid-based global hydrological model developed at the Department of Physical Geography, Utrecht University. For each grid cell, PCR-GLOBWB simulates moisture storage in two vertically stacked upper soil layers, as well as the water exchange between the soil, the atmosphere and the underlying groundwater reservoir. Exchange with the atmosphere comprises of precipitation, evaporation and transpiration, as well as snow accumulation and melt, which are all simulated by considering vegetation phenology and sub-grid variations in elevation, land cover and soil saturation distribution. The model includes improved schemes for runoff-infiltration partitioning, interflow, groundwater recharge and baseflow, as well as river routing of discharge (Figure 5).

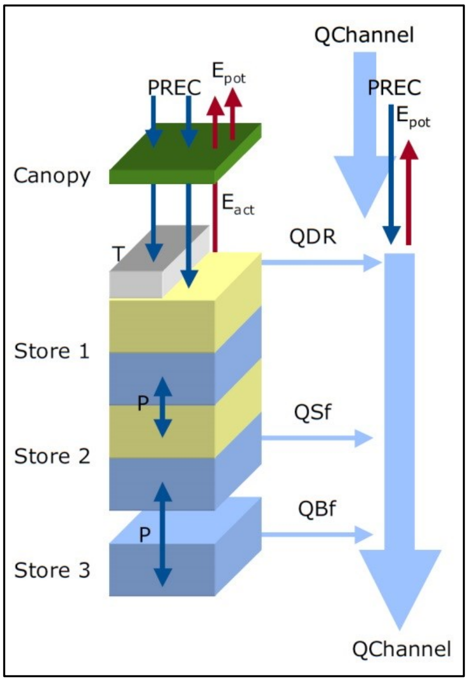


Figure 5 Conceptual scheme of the PCR-GLOBWB hydrological model.

We have established a new model parameterization at 5 arcminutes spatial resolution with a global coverage. This represents a cell of 9.26 by 9.26 km at the equator, and 9.26 by 5.95 km at 50 degrees south, or north, which gives a 36-fold increase in model resolution and much more detail in the spatial representation of the hydrological processes. The methods for parameterizing the soil, vegetation, and reservoirs equalled the methods used in the 30 arcminute version of PCR-GLOBWB, but the hydrologic network has changed. Creation of the flow direction map is explained in section 3.2.1

PCR-GLOBWB was forced with daily temperature and precipitation fields from the Hadgem2-ES global circulation model that participated in the latest coupled model intercomparison project (CMIP5). Data were bias corrected using the observation-based WATCH dataset within the ISI-MIP project (Hempel et al. 2013) Two runs were carried out. One for the historic period between January 1960 and December 2005, and one between January 2006 and December 2099. The representative concentration pathway (RCP) scenario that was chosen was RCP 6.0. Model output consisted the available blue water (direct runoff, interflow, and baseflow), the reference potential evapotranspiration, groundwater recharge and the groundwater storage. Each of these variables were stored in a netcdf file. PCR-GLOBWB output was aggregated to timeseries with a monthly timestep for each water province (Water2Invest deliverable 1.1).

Global hydrological models are often uncalibrated. The same holds for PCR-GLOBWB. To use the runoff fields from the model output, a correction based on measured discharges was therefore required. Based on available river discharge measurements from the RivDis (Vörösmarty et al. 1998) and the Global Runoff Data Centre (GRDC, 2011) datasets. All stations were positioned on the LDD by checking the upstream area reported in the station file with the upstream area based on the LDD. For each river basin the most downstream station was selected to compute the correction factor (CF) by:

$$CF_{stat} = Qsim_{avg,\ ann} / (Qobs_{avg,ann} + DemTot_{avg,ann}) \quad (1)$$

where $Qsim_{avg,\ ann}$ is the simulated annual average discharge from PCR-GLOBWB under pristine conditions, $Qobs_{avg,ann}$ is the observed annual average discharge from RivDis, or GRDC, and $DemTot_{avg,ann}$ is the total net water demand over the catchment upstream of the station based on the water demand study of Wada et al. (2011). All units were converted to m^3/s. The correction factor per station was converted to a map by assigning the correction factor to the whole basin in which the station is situated. Basins without observation data were assigned a correction value based in inverse distance interpolation, which was subsequently averaged over the ungauged basin. Baseflow, interflow, and direct runoff were corrected by dividing the time series of the model output by the correction factor map.

3.2.1 Raster-based flow direction network

Global scale hydrography maps include the Hydro1K, and HydroSHEDS projects. The HYDRO1K provided global coverage of topographically derived datasets including terrain height, flow direction, flow accumulation, and river basin delineation (USGS 1996) based on the GTOPO30 dataset. The data were provided with a 1 km spatial resolution and an equal area projection per continent. NASA's Shuttle Radar Topography Mission (SRTM) led to a higher quality Digital Terrain Model (DTM) between 60^0 North and 56^0 South with a 90m spatial resolution. The hydroSHEDS dataset (Lehner et al. 2008) that built upon the SRTM DTM was released in 2008. Void regions in the SRTM dataset were filled with additional data from the GTOPO30 dataset. Data were provided in a geographic coordinate system (WGS 84). Derived data included basins, sub-basins, flow accumulation and upstream area.

Deriving river location and extent from terrain height data comprises a large amount of work that includes sink filling, stream burning, flow direction mapping, and has included more than 50 000 manual edits for the HydroSHEDS dataset (Lehner et al. 2008). For the 5 minute resolution flow direction map, or local drain direction (LDD) map, we therefore used the flow accumulation maps of HydroSHEDS and Hydro1k rather than the underlying Digital Terrain Model (DTM). We created a PCRaster-Python script that generated a LDD based on the following steps:

1. Create a upstream area map based on the HydroSHEDS data between 60^o North and 56^o South by resampling the original upstream area map at 30 arcseconds. Resampling was carried out by assigning the largest upstream area of the fine resolution map to the output coarse resolution map. This led to a one-pixel widening of the river area when meanders at the fine resolution would cover multiple cells at the coarse resolution.

2. Reproject the Hydro1k flow accumulation data from the continent specific equal area map to the WGS 84 at 30 arcseconds resolution. We used to the nearest neighbour method in reprojecting the file to avoid interpolation between high values on the river low values adjacent to the river. The drawback of interrupted connectivity along the river was overcome by the subsequent resampling with the maximum value. This leads to good results as long as the resulting resolution is twice as high as original resolution of 30 arcseconds as the interruption was one pixel at most.
3. Integrate the HydroSHEDS and Hydro1k data to generate a seamless global LDD. To avoid artefacts at the edge of the area covered by HydroSHEDS, all the river basins were delineated that were not fully covered by HydroSHEDS. The two options included (1) the basins whose head waters were in the HydroSHEDS area, but debouched in the area solely covered by Hydro1k, and (2) the basins whose head waters were in the Hydro1k area, but debouched in the area solely covered by HydroSHEDS. The upstream area map of these northern basins were supplemented with the upstream area map from the HydroSHEDS to create global coverage. Two regions were left out: Antarctica and Greenland. In these regions the terrain height is not linked to drainage direction due to the ice coverage.
4. Create a LDD basin by basin. In river deltas different rivers may be close together, but stil be part of separate river basins. However, in the global upstream area map these rivers may get merged when they are adjacent to each other at the 5 minute resolution. Therefore, we used the map of the major river basins developed by HydroSHEDS to determine the LDD for each of the basins iteratively to come to a global LDD at 5 minutes. No flow of water was allowed across river basins.

Figure 6 shows the upstream area of the MENA region. Note the the endorheic basins in the Sahara.

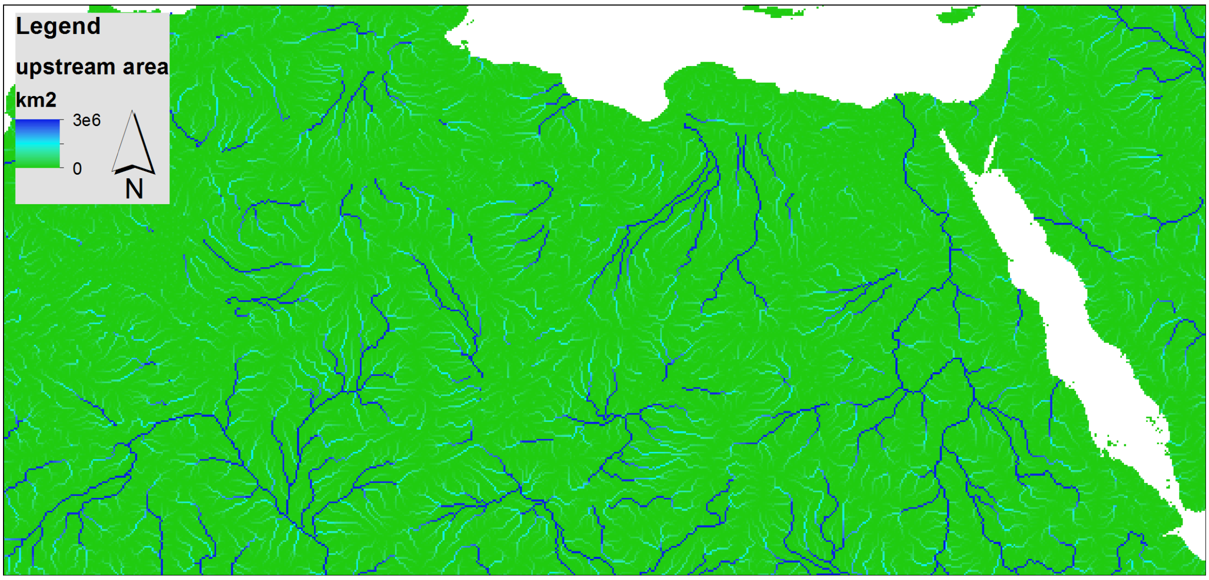


Figure 6 Upstream area based on the 5 arcminute LDD for the MENA region

3.2.2 Deriving water province topology

Water allocation software requires a network of supply nodes to route the water through the catchment, instead of a raster-based representation of the catchment. Based on the water provinces (WPs) that were delineated (ref D1.1) and the 5 arcminute LDD, we have created a WP topology that provided that hydrologic links between the WPs (Figure 7). Attributes of these links were subsequently added by including information from the annual total runoff, and the locally generated baseflow, interflow, and runoff.

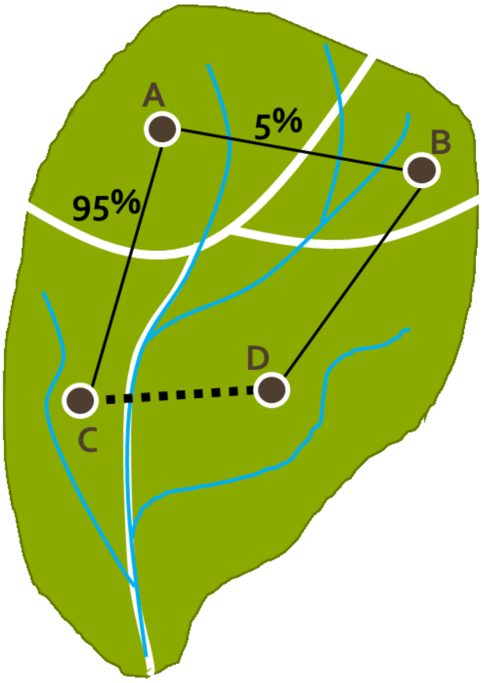


Figure 7 Example of the water province topology. For each water province the distribution of the water over downstream water provinces is required, depicted as black lines. In case of a border river the the fraction of water through the border river is required.

The following method has been fully automated in an PCRaster-Python script to generate the topology:

1. *Definition of the water province outlets*. Multiple outlets are possible for water provinces as they do not represent purely hydrological units. The downstream cells of the outlets provided the IDs of the downstream water provinces, which gave a directional link with the flow direction to for example WP A to WP B in Figure 7. These links contained many redundant links as water may flow from X to Y and vice versa, because the water provinces do not represent purely hydrological units.

2. *Net flow for each of the links*. Depending on the flow direction map, water may cross the water province border several times before the final outlet of the water province is reached. Therefore, we selected the final outlets for each link and computed the annual sum of water that is generated locally in the catchments of the final outlets. In Figure 7 this is exemplified by a flow fraction of 95% from A to C, and 5 % from A to B.

3. *Flow through border rivers.* We defined a border river as a river with Strahler order larger than 4 that contained 2 or more different water provinces in a 3 by 3 cell window. A minimum length of the border river was set to 8 cells to prevent labeling clean border crossings as a border river. Decreasing the minimum length would increase the number of border rivers, and we found that at a 5 minute resolution, a minimum of 8 cells prevented misclassification of border rivers. Similar to the net outflow of the water province, the net border flow was computed by searching for the most downstream point on the border rivers and computing the annual sum of the locally generated water in the catchment, or catchments.

4. *Removal of double links and computation of flow fractions*. The double links in the topology (X to Y and Y to X) were removed from the flow network. The link with lowest flow was removed. For each of the water provinces the total net annual outflow was computed. Flow fractions for each link were derived by dividing the outflow per link by total outflow. Flow fraction through the border river was determined similarly by dividing the border flow by total outflow.

5. *Creation of network attributes*. In addition to the pairwise assessment of the flow between two adjacent water provinces also the ID of the final pit of the water province network was determined by following the main flow path downstream from each water province. The main flow path was selected because the water provinces may have bifurcating flow, contrary to the LDD. The network length, defined as the number of water provinces until the water province that contains the basin mouth, was added as an additional attribute. The most downstream water province would get network length 1. The ModSim computational order, the order in which ModSim determined water allocation, was defined as the maximum network length of the basin minus the network length of the water province.

6. *File output.* The network topology was exported to a point shapefile with the ID of the water province, a line shapefile with the ID of the link between two adjacent water provinces, and an ASCII file with the attributes listed in Table 2.

The resulting network topology shows a bifurcating pattern (Figure 8) and many links between the water provinces.

Table 2 Attributes of the water province topology

attribute	description
fromID:	WP ID of the WP where water flows out of
toID:	WP ID of the WP where the water flows to
flowFromTo:	Total annual discharge of link between “fromID” and “toID”
flowThroughBorderRiver	Total annual discharge through border river if present, else 0
netOutflowFromID:	Sum of all the outflow from WP “fromID”
flowFractionToID:	Fraction of the total outflow per WP to WP “toID”
flowFractionThroughBorderRiver	Discharge through a border river as a fraction of the sum of all outflow
mainDownstreamWatprov	Downstream water province that recieves the largest discharge volume
pitID:	ID of the WP with the pit of the river basin
lengthToPit:	Number of water provinces until the basin mouth
computationOrder:	ModSim order of handling water provinces
fromX:	Longitude of WP “fromID”
fromY:	Latitude of WP “fromID”
toX:	Longitude of WP “toID”
toY:	Latitude of WP “toID”
linkID:	ID to the link between the WPs

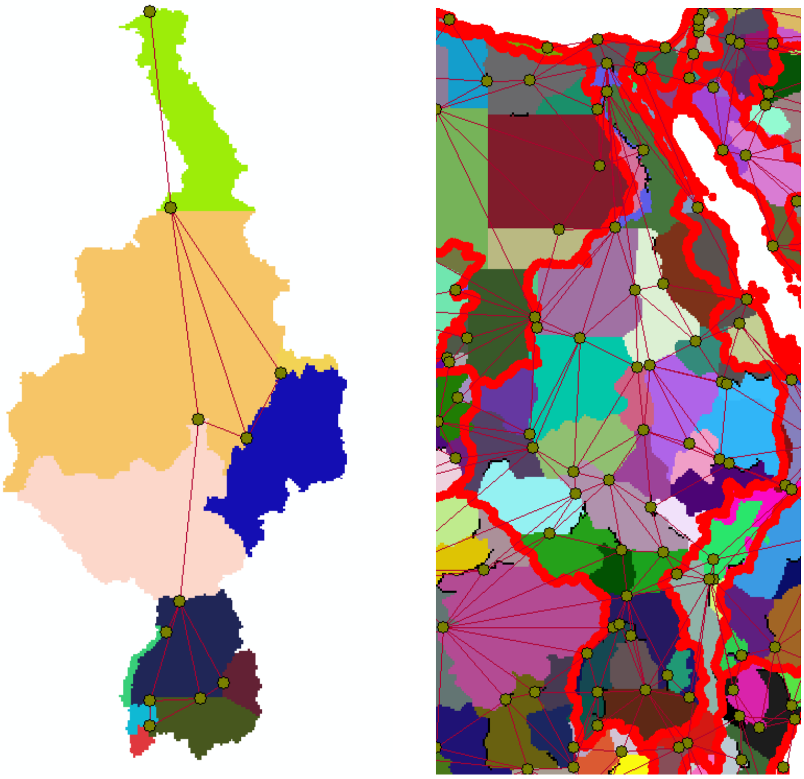


Figure 8 Examples of water province topology for the Nile basin. The left panel depicts the relations between countries. The right panel provides all the links between the water provinces. Note that the points are located at the outlet point of the main river for each country, or water province.

3.3 WATER ALLOCATION MODELLING: WATCAM

3.3.1 Overview

Multiple papers have given an overview of Water and Climate Adaptation Models (WatCAM), among which Evgenii et al (2011), and Labadie et al (2004). In the next paragraph a short abstract is given from the paper from Evgenii et al. (2011) which explains the two types of models and their capabilities.

Water resource simulation models help water managers plan, design and operate water systems (Loucks et al., 1981; Loucks and van Beek, 2005). Such models use user-defined operating and allocation rules to predict flow and storage of water throughout the water resource node-link network (Letcher et al., 2007; Maass et al., 1962) over time. They help predict how different management rules and infrastructure configurations react to adverse conditions such as droughts, flooding or long-term change. Simulation models are frequently used in integrated assessments (Jakeman and Letcher, 2003) and can be embedded in decision support systems (e.g. Lautenbach et al., 2009) or linked to optimization models (e.g.Ahrends et al., 2008).

Two main computational approaches exist for simulating water resource management: 'rule-based' and 'optimization-driven' simulation. Rule-based models use procedural or object-oriented computer code where programming instructions sequentially define how water is managed using for example "if then else" statements and iterative instructions ('loops'). Iterative solution procedures are used to represent the interconnections between water requirements and management rules at different locations, often moving from upstream to downstream to route flows and track storage throughout the system. Optimization-driven simulation models solve a distinct optimization model at each simulated time-step to route flows, track storages and allocate water through the network. This method is popular because of its relative ease of use and flexibility; optimization-driven allocation takes some of the burden off the programmer whose code no longer has to consider every conceivable system state or outcome. However, some complex rules may be difficult to represent using optimization and model results may not be easy to replicate in practice. Examples of such models with user-interfaces include WATHNET (Kuczera, 1992), AQUATOOL (Andreu et al., 1996), OASIS (Randall et al., 1997), MISER (Fowler et al., 1999), MODSIM (Labadie and Baldo, 2000), RIVERWARE (Zagona et al., 2001), MIKE BASIN (Jha and Das Gupta, 2003), CALSIM (Draper et al., 2004), REALM (Perera et al., 2005) and WEAP (Yates et al., 2005). Further information on the optimization-driven simulation approach is given by Labadie (2004) and descriptions of modeling systems that use it can be found in Wurbs (2005a). Since each approach has advantages and limitations, the institutional and water management context often determines which modeling type is most suitable for a particular application. For example a model seeking to predict water trading will benefit from an optimization engine, whereas rule-based models are well-suited for modeling actual system operating procedures (e.g. reservoir release tables) and predicting their performance under certain conditions.

For Water2Invest the PCR-GLOBWB (PCRaster Global Water Balance) model will be used to model the water balance factors, such as water availability, groundwater recharge, evaporation, runoff, etc. per water province. The data produced by PCRGLOBWB will be used as input in a water allocation model. For a more extensive description of the PCR_GLOBWB model can be found in FutureWater report 98: http://www.futurewater.nl/wp-content/uploads/2011/04/Final_Report_v11.pdf.

To optimize the water allocation a water allocation model will be used. Two water allocation models stand out from the others by their capabilities, user friendliness, and proven applications. See Table 3. These two models, WEAP and MODSIM will be discussed in more detail.

Table 3: Water allocation models

	Applications world wide	Support	Options	Costs	Up to date	Water allocation optimazation	Strategic (vs operational)	Source code available
WEAP	++	++	++	o	++	++	++	o
MIKEBASIN	++	++	+	o	++	+	+	o
RIBASIM	+	+	+	o	+	+	+	?
AQUATOOL	+	o	o	++	o	+	+	?
AQUATOR	++	++	+	+	++	+	+	o
MODSIM	++	+/O	++	++	++	++	++	+

3.3.2 WEAP

3.3.2.1 Approach

The WEAP model includes a semi-physical, irregular grid, lumped–parameter hydrologic simulation model that can account for hydrologic processes within a water distribution system. WEAP works with nodes and arrows as indicators of water flow and distribution.

While the model can be run on any time-step where routing is not a consideration, the model description assumes a monthly time-step. The time horizon can be set from the user, from as short as a single year to more than 100 years. Scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

WEAP contains built-in models for: rainfall runoff and infiltration, evapotranspiration, crop requirements and yields, surfacewater and groundwater interaction, and in stream water quality. It has a GIS-based, graphical "drag and drop" interface. WEAP allows user-defined variables and equations and has a model building facility. It has dynamic links to spreadsheets and other models. Data structures are flexible and expandable.

3.3.2.2 INPUT / OUTPUT

Since WEAP primarily goal is to evaluate water allocation options is the major input related to so-called demand and supply sites (nodes) that are connected by links. Examples of required input: urban areas, agricultural areas, groundwater, reservoirs, catchment nodes, rivers, canals. The catchment nodes can be specified to be more hydrological oriented including rainfall-runoff processes.

WEAP operates always in an optimization water allocation mode, based on priorities set for each demand site. This makes WEAP unique in comparison to other water allocation tools such as RIBASIM or MIKE-BASIN.

Output of WEAP includes flows for all connection lines (rivers, canals) and met and unmet demands for all the demand sites. Outputs are generated in a very attractive form and has similarity with the EXCLAIM (EXploratory Climate Land Assessment and Impact Management) modeling environment as developed by University of Newcastle.

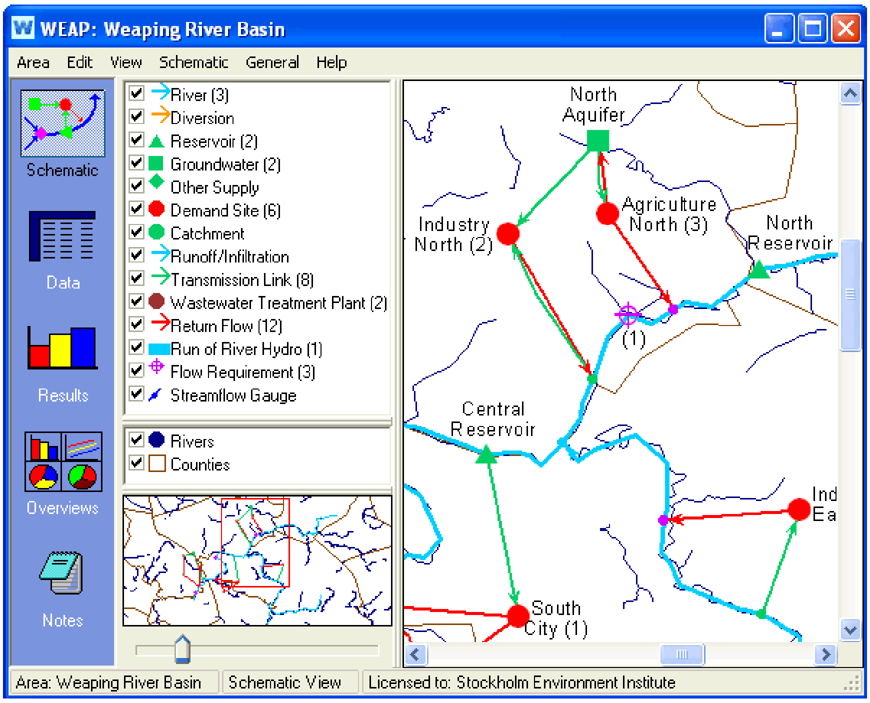


Figure 9: Example of the WEAP interface.

3.3.3 MODSIM[1]

"MODSIM (Labadie and Baldo 2000) and MODSIM-DSS were designed for highly complex and constantly evolving river basins. MODSIM-DSS has been linked with stream-aquifer models for analysis of the conjunctive use of groundwater and surface water resources. MODSIM-DSS has also been used with water quality simulation models for assessing the effectiveness of pollution control strategies. MODSIM-DSS can also be used with geographic information systems (GIS) for managing spatial data base requirements of river basin management.

MODSIM-DSS is structured as a Decision Support System, with a graphical user interface (GUI) allowing users to create any river basin system topology. Data structures embodied in each model object are controlled by a data base management system. Formatted data files are prepared interactively and a network flow optimization model can be executed from the interface. Results of the network optimization are presented in graphical plots (see example in Figure 10). More: http://modsim.engr.colostate.edu/"

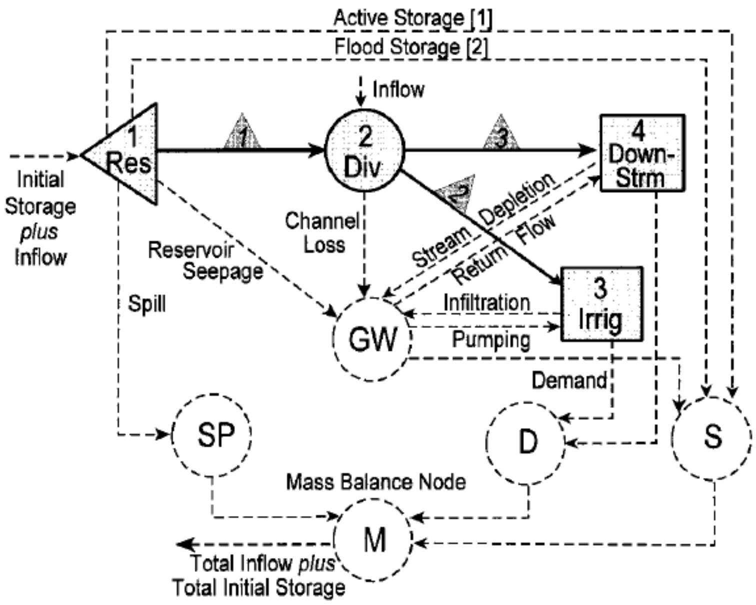


Figure 10: Illustration of the MODSIM network structure. Source: Labadie and Baldo, 2000

3.3.3.3 BACKGROUND

MODSIM is a generic river basin management decision support system originally conceived in 1978 at Colorado State University (Shafer and Labadie, 1978), making it the longest continuously maintained river basin management software package currently available.

MODSIM is designed as a generalized river basin management decision support system (DSS) designed as a computer-aided tool for developing improved basin wide and regional strategies for short-term water management, long-term operational planning, drought contingency planning, water rights analysis and resolving conflicts between urban, agricultural, and environmental concerns. Sprague and Carlson (1982) defined a DSS as "an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems." MODSIM is designed to aid stakeholders in developing a shared vision of planning and management goals, while gaining a better

[1] Part of this section is copied from Labadie and Baldo, 2000

understanding of the need for coordinated operations in complex river basin systems that may impact multiple jurisdictional entities. MODSIM provides for integrated evaluation of hydrologic, economic, environmental, and institutional/legal impacts as related to alternative development and management scenarios, including the conjunctive use of surface water and groundwater resources. As a robust river basin management DSS, MODSIM provides both a planning framework for integrated river basin development and management, as well as aid in real-time river basin operations and control. (Labadie, 2010).

3.3.3.4 APPROACH

The basic principle underlying MODSIM is that most physical water resource systems can be simulated as *capacitated* flow networks. The term capacitated refers to imposition of strict upper and lower bounds on all flows in the network. Components of the system are represented as a network of *nodes*, both storage (i.e., reservoirs, groundwater basins, and storage right accounts) and non-storage (i.e., river confluences, diversion points, and demand locations), and *links* or *arcs* (i.e., canals, pipelines, natural river reaches, and decreed water rights) connecting the nodes. Although MODSIM is primarily a simulation model, the network flow optimization provides an efficient means of assuring allocation of flows in a river basin in accordance with specified water rights and other priority rankings.

A network formulation of a river basin system provides a physical picture revealing the morphology of the system that is readily recognizable. In effect, the graphical network links are the model decision variables. Network optimization techniques are specialized algorithms that perform integer-based calculations on linear networks that are considerably more efficient than real number computations and matrix operations employed in standard linear programming codes based on extensions of the revised simplex method. Integer-based calculations are not a disadvantage since appropriate scaling of link flows can produce solutions for any desired order of accuracy. The high efficiency of network flow optimization algorithms allows rapid solution of large-scale networks comprising thousands of nodes and links on desktop computers. This also makes it feasible to perform several iterative solutions so as to consider certain nonlinear or dynamic system features. (Labadie, 2010)

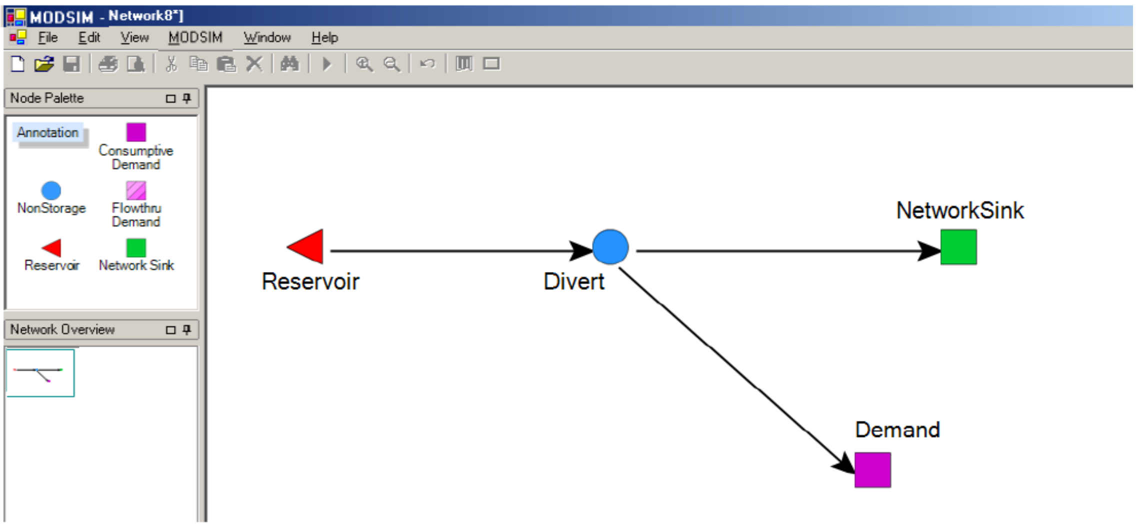


Figure 11: Node and link objects in the MODSIM GUI.

Important *assumptions* associated with MODSIM are listed as follows (Labadie, 2010):

- All storage nodes and linkages are bounded from below and above (i.e., minimum and maximum storage and flows are given, with the latter allowed to vary over time.

- Each linkage must be unidirectional with respect to positive flow; flow reversals can be modeled by assigning an additional reverse direction link between two nodes.
- All inflows, demands, system gains and losses must accumulate at nodes; increasing the density of nodes in the network thereby increases simulation accuracy, but also increases computer time and data requirements.
- Each reservoir is designated as a spill node for losses from the system proper. Spills from the system are the most expensive type of water transfer, such that the model always seeks to minimize unnecessary spills. Spills may be retained in the network by specification of an additional release link from a reservoir which can be labeled as a high cost link.

3.3.4 Model selection WatCAM

Within the Water2Invest project the allocation model should be able to optimize the water allocation among all demands, which are schematized as i) Urban ii) Industry iii) Irrigation iv) Environment and v) Downstream demand nodes. The basic model schematization can be seen in Figure 12. The model should be able to run without the interface on a web-based platform, and allow users to interact with the system, and see the result which certain measures will have on their chosen area.

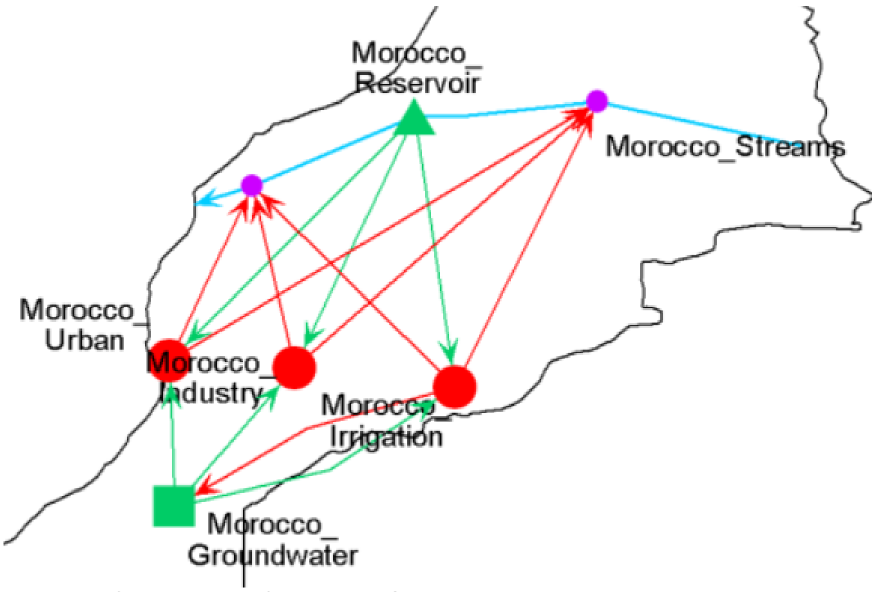


Figure 12: Conceptual framework of MENA-WOF model as implemented in WEAP with Morocco as example.

3.3.4.5 Evaluation

WEAP and MODSIM have been compared and a model like in Figure 12. The scheme of Figure 12 has been built in both models. The results from this comparison show that both models have the capability to optimize the water availability. After a first analysis, which is described in the earlier deliverable D1.2, the decision is made that for the use within the Water2Invest project the use of MODSIM will be preferred as MODSIM is in the public domain which makes it possible to integrate MODSIM in the online interface. Besides, MODSIM allows for creating custom scenarios, can be run in batch mode, and without the GUI. For this reason MODSIM has been wrapped into WATCAM so that it could run automatically for the selected water provinces with the correct values. This MODSIM based version of WatCAM has been tested extensively, for the Nile, Africa and the World. Results of these tests have been described in deliverable 1.2. Although the initial results are expectable the model is too unstable to run on large scale and in batch. Therefor a custom made version of WatCAM is created which based on Microsoft Excel and wrapped into a script which allows the user to adapt initial values of the chosen water province. For an in depth description and explanation of the setup of the custom made WatCAM see chapter 6.

4 DATA

4.1 GDP DATA[2]

The gridded GDP data and GDP per capita which are used as drivers within the IMAGE model are used to calculate the urban and industry demands for this study. This data is shared by the Dutch environmental and planning agency (PBL). PBL uses the economical projection as calculated by the OECD (Organization for Economic Co-operation and Development). This chapter will be based on the OECD documentation.

While there is no single theory of economic growth, there is wide support for models in which each country would be expected to converge to its own steady-state trajectory of GDP per capita determined by the interface between global technological development and country-specific structural conditions and policies (so-called conditional convergence). In the long-run, all countries are expected to grow at the same rate determined by the worldwide rate of technical progress, but cross-country GDP per capita gaps would remain, mainly reflecting differences in technology levels, capital intensity and human capital.

The supply side of the economy consists of a standard aggregate Cobb-Douglas production function with constant returns to scale featuring physical capital, human capital and labour as production factors plus technological progress (so-called multi-factor productivity). Multi-factor productivity is measured as the difference between output and total inputs. These components of the production function are projected to 2060 in order to construct measures of potential GDP measured in terms of constant 2005 USD purchasing power parities (PPPs) (see Easterly and Levine, 2001; OECD, 2003; Duval and de la Maisonneuve, 2010 and Fouré et al., 2010 for similar approaches). The projections for all components to 2013 are mostly consistent with the May 2012 OECD Economic Outlook projections, although some elements of the short-term non-OECD projections are taken from IMF (2012). An is the projection of human capital which starts in 2011 as there is no short-term forecast available.

The fiscal side of the model ensures that government-debt-to-GDP ratios stabilize over the medium term via fiscal closure rules for the primary balance which either stabilize debt through a gradual improvement in the primary balance or target a specific (usually lower) debt-to-GDP ratio. Debt service responds to changes in market interest rates, but with lags which reflect the maturity structure of debt. Higher debt levels are assumed to entail higher country-specific fiscal risk premia (e.g. Égert, 2010; Laubach, 2009) A further interest rate adjustment equal across all countries ensures that global saving and investment are aligned.

Private saving rates for OECD countries are determined by demographic factors including old- age and youth dependency ratios, fiscal balances, the terms of trade, productivity growth, net oil balances and the availability of credit (see Kerdrain et al., 2010). Total saving is the sum of public and private saving, although there is a 40% offset of any improvement in public saving from reduced private saving due to partial Ricardian equivalence (e.g.

[2] Section based on OECD economic policy paper (2012)

Röhn, 2010). For non-OECD countries, the total saving rate is modelled by developments in old-age and youth dependency ratios, the terms of trade, the availability of credit, the level of public expenditure (a proxy for public social protection) and productivity growth. Investment projections are backed out from projected capital stocks assuming that depreciation remain stable at recent historical levels. There is no influence from structural policies on investment, except indirectly to the extent that they boost output, although this ignores some evidence to suggest that reforms to product market regulation and employment protection legislation can boost investment rates (Alesina et al., 2005; Egert, 2009; Kerdrain et al., 2010).

Structural policies play an important role in shaping the long-run projections for growth and fiscal and global imbalances presented in this report. The baseline long-run scenario incorporates a number of policy developments in several areas:

- The share of active life in life expectancy is assumed to remain constant, hence the legal pensionable age is implicitly assumed to be indexed to longevity. In addition, recently- legislated pension reforms that involve an increase in the normal retirement age by 2020 are assumed to be implemented as planned.

- Educational attainment continues to converge across countries relying implicitly on an expansion of education systems, particularly in countries with currently low educational attainment levels and; projected labour force participation depends on developments in educational attainment.

- Countries with relatively stringent product market and trade regulations are assumed to gradually converge towards the average regulatory stance observed in OECD countries in 2011. For other countries regulations remain unchanged. This implies faster MFP growth in countries where the regulatory stance is currently more stringent than the OECD average.

- For non-OECD countries, a gradual increase in public spending on social protection is assumed, amounting on average to an increase of 4 percentage points of GDP to a level of provision similar to the average OECD country. It is further assumed that this is financed in a way in which there is no effect on public saving.

- Private credit as a share of GDP is projected on the basis that countries gradually converge on the US level of financial development with the gap assumed to close at 2% per annum. For example, this means that for an average of the BRIC countries, the availability of credit rises from just over one-third of that in the United States in 2010, to around three-quarters in 2060.

Further details of the methodology used to make the long-term projections, including the parameterisation of the links between structural factors and the components of GDP, including via new regression estimates are provided in Johansson et al. (2012).

4.2 POPULATION DENSITY[3]

PHOENIX is a population user support system to explore, develop and analyze future changes (simulation period is 1950-2100) in the population size and structure in relation to the socio-economic and environmental conditions. PHOENIX consists of three components.

1. Demographic Core
The population submodel uses an integrated systems approach, in which the results of the fertility and mortality submodels are structured into pressure, state, impact and response (P-S-I-R) modules:

- A pressure module describing the health determinants, which are divided into both socio-economic factors (income and literacy status) and environmental factors (food and water availability, malaria risk)
- A state module simulating fertility behaviour and population dynamics for disease and disease-specific mortality; both of these serve as input to the population module distinguishing sex and age groups
- An impact module describing the quantitative and qualitative aspects of the state module, such as the burden of disease and life expectancy, and the size and structure of the population
- A response module consisting of population policies influencing the fertility behaviour and health policies influencing the disease processes.

2. Fertility Model
Human fertility is a biological process governed by social, economic, cultural and environmental variables. The effects of these variables on fertility levels are mediated by a set of proximate variables. The relationship between these proximate variables and fertility, which is well understood, forms the core of the fertility model (Bongaarts and Potter, 1983). The main outcome of the fertility submodule is the number of births. The calculation of births is based on the Bongaarts model, which assumes that an average biological maximum total fertility rate of 15.3 children per woman (FERTmax) is reduced by the following four determinants:

- The index of marriage (Cm), based on the average age of marriage and determines the fraction of the reproductive life span spent in stable sexual union;
- Index of contraceptives (Cc), which represents the reducing effects of the use and effectiveness of several methods of birth control on reproduction;
- Index of postpartum infecundity (Ci), which is defined as the fraction of the fertile life span lost for reproduction because of breast feeding and culturally motivated abstinence;
- The index of abortion (Ca), which is a function of the number of induced abortions combined with the fraction of reproductive life span loss because of abortions.

The combination of these factors results in the total fertility rate (TFR), which represents the

[3] Section based on PHOENIX documentation at: http://themasites.pbl.nl/tridion/en/themasites/phoenix/index.html

number of children to which a woman has given birth at the end of her fertile period: `

TFR = Cm x Cc x Ca x Ci x FERTmax

The model adopts the perspective that fertility change is the result of a 'modernization' process. Modernization is seen as a complex of interrelated processes of societal change, driven by gross domestic product, (female) literacy and life expectancy at birth. These are combined into the human development index (HDI) (see, for example, UNDP, 2000), which is used as indicator for the modernization process.
The concept of 'human development' represents an extension of a purely economic view on development. The two main characteristics which have been added to the Bongaarts approach are the linkage of the fertility determinants to the level of socio-economic development and the modelling of contraceptive use (Rosero-Bixby and Casterline, 1993).

3. Mortality Model
The Mortality model simulates the number of persons exposed to various health risks and the number of deaths related to these exposures. The health risks associated with the exposed population are based on the broad and proximate health determinants of the health transition.
The major health determinant is socio-economic status (SES, see e.g. Najman, 1993). The distinction between high and low socio-economic status is derived from the income status and the fraction of the total population that is literate. Further health risks include malnutrition, absence of safe drinking water, occurrence of malaria, habitual smoking and high blood pressure and poor availability of health services. Health risks are clustered into 12 categories on the basis of the empirically estimated contribution to mortality and disease levels in societies, as inferred from international statistics.

4.3 GLOBAL RESERVOIR AND DAMS[4]

The Global Reservoir and Dam Database compiles reservoirs with a storage capacity of more than 0.1 km³. The recent version contains 6.862 spatially explicit records of reservoirs with their respected dams and gives information on their storage volume.

Despite established recognition of the many critical environmental and social tradeoffs associated with dams and reservoirs, global data sets describing their characteristics and geographical distribution have been largely incomplete. To addrress this shortcoming, the Global Water System Project (GWSP) initiiated an international effort to collate the existing dam and reservoir data sets with the aim of providing a single, geographically explicit and reliable database for the scientific community: The Global Reservoir and Dam Database (GRanD).

The development of GRanD primarily aimed at compiling the available reservoir and dam information; correcting it through extensive cross-validation, error checking, and identification of duplicate records, attribute conflicts, or mismatches; and completing missing information from new sources or statistical approaches. The dams were geospatially referenced and

[4] Section based on Global Water System Project (GWSP.org)

assigned to polygons depicting reservoir outlines at high spatial resolution. While the main focus was to include all reservoirs with a storage capacity of more than 0.1 km³, many smaller reservoirs were added if data were available. The current version 1.1 of GRanD contains 6,862 records of reservoirs and their associated dams, with a cumulative storage capacity of 6,197 km³.

4.4 GLOBAL MAP OF IRRIGATED AREAS[5]

The global map of irrigated areas us used to calculate the irrigated area for each water province. The global map of irrigated area is created by the University of Frankfurt. The following piece is based on the documentation of the dataset by Portmann et al.

Agriculture of crops provides more than 85% of the energy in human diet, while also securing income of more than 2.6 billion people. To investigate past, present and future changes in the domain of food security, water resources and water use, nutrient cycles, and land management it is required to know the agricultural land use, in particular which crop grows where and when. The current global land use or land cover data sets are based on remote sensing and agricultural census statistics. In general, these only contain one or very few classes of agricultural land use. When crop-specific areas are given, no distinction of irrigated and rainfed areas is made, whereas it is necessary to distinguish rainfed and irrigated crops, because crop productivity and water use differ significantly between them.

To support global-scale assessments that are sensitive to agricultural land use, the global data set of Monthly Irrigated and Rainfed Crop Areas around the year 2000 (MIRCA2000) was developed by the author. With a spatial resolution of 5 arc-minutes (approximately 9.2 km at the equator), MIRCA2000 provides for the first time, spatially explicit irrigated and rainfed crop areas separately for each of the 26 crop classes for each month of the year, and includes multi-cropping. The data set covers all major food crops as well as cotton, while the remaining crops are grouped into three categories (perennial, annual and fodder grasses). Also for the first time, crop calendars on national or sub-national level were consistently linked to annual values of harvested area at the 5 arc-minutes grid cell level, such that monthly growing areas could be computed that are representative for the time period 1998 to 2002.

The downscaling algorithm maximizes the consistency to the grid-based input data of cropland extent [Ramankutty et al., 2008], crop-specific total annual harvested area [Monfreda et al., 2008], and area equipped for irrigation [Siebert et al., 2007]. In addition to the methodology, this dissertation describes differences to other datasets and standard scaling methods, as well as some applications. For quality assessment independent datasets and newly developed quality parameters are used, and scale effects are discussed.

[5] Section based on MIRCA documentation Portmann et al.

5 CURRENT AND FUTURE WATER DEMANDS

The demands have been calculated for different scenarios. The IPCC adopted four Representative Concentration Pathways (RCP's) which describe the possible climate futures. The four RCP's (2.6 – 4.5 – 6.0 – 8.5) are named after a possible range of radiative forcing values in the year 2100. See Table 4 and Figure 15 for values and pathways of the RCP's. The RCP values are the radiative forcing values relative to pre-industrial values.

Table 4: representative concentration pathways in the year 2100 (source: IPCC)

	Radiative forcing	CO_2 equivalent concentration	Rate of change in radiative forcing
RCP 8.5	8.5 W/m^2	1350 ppm	Rising
RCP 6.0	6.0 W/m^2	850 ppm	Stabilizing
RCP 4.5	4.5 W/m^2	650 ppm	Stabilizing
RCP 2.6	2.6 W/m^2	450 ppm	Declining

Besides the RCP's the Shared Socioeconomic reference Pathways (SSPs) have been developed. The SSPs includes quantitative elements and qualitative narrative descriptions of potential socioeconomic and ecosystem reference conditions that underlie challenges to mitigation and adaptation. See the textbox in Figure 14 for an example of SSP narratives. The SSPs scenarios are defined as can be observed in Figure 13. Each SSP has different socio-economic challenges for mitigation and adaptation to climate change. Figure 14 gives a better idea of the challenges for each SSP.

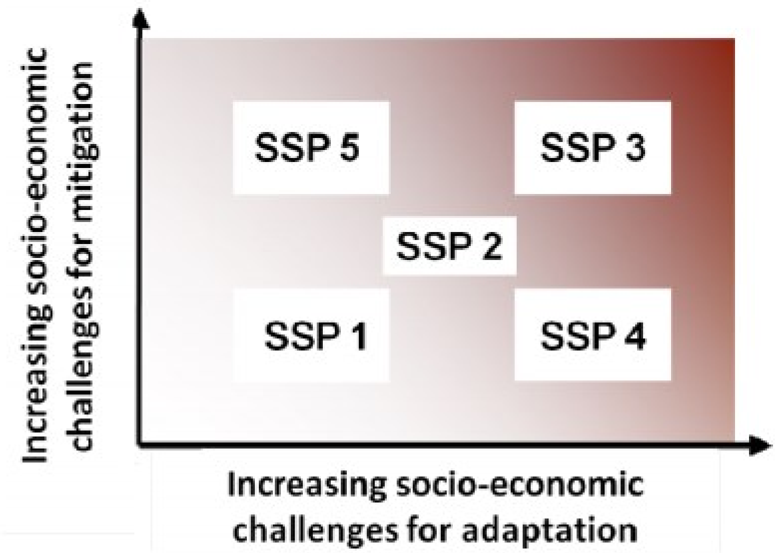


Figure 13: The scenario space to be spanned by SSPs according to the IPCC

- SSP 1, in which the world is reasonably well suited to both mitigate and adapt, could be one in which development proceeds at a reasonably high pace, inequalities are lessened, technological change is rapid and directed toward environmentally friendly processes, including lower carbon energy sources and high productivity of land. An analogue could be the SRES B1 scenario.

- SSP 3, with large challenges to both mitigation and adaptation, could be a world in which unmitigated emissions are high due to moderate economic growth, a rapidly growing population, and slow technological change in the energy sector, making mitigation difficult (as, for example, in SRES A2). Investments in human capital are low, inequality is high, a regionalized world leads to reduced trade flows, and institutional development is unfavorable, leaving large numbers of people vulnerable to climate change and many parts of the world with low adaptive capacity.

- SSP2 would be an intermediate case between SSP1 and SSP3, where future dynamics could follow historical trends similar to e.g. SRES B2 scenario.

- SSP 4, in which mitigation might be relatively manageable while adaptation would be difficult and vulnerability high, could describe a mixed world, with relatively rapid technological development in low carbon energy sources in key emitting regions, leading to relatively large mitigative capacity in places where it mattered most to global emissions. However, in other regions development proceeds slowly, inequality remains high, and economies are relatively isolated, leaving these regions highly vulnerable to climate change with limited adaptive capacity.

- SSP 5 as a world with large challenges to mitigation but reasonably well equipped to adapt, could be one in which, in the absence of climate policies, energy demand is high and most of this demand is met with carbon-based fuels (perhaps similar to the SRES A1FI scenario). Investments in alternative energy technologies are low, and there are few readily available options for mitigation. Nonetheless, economic development is relatively rapid and itself is driven by high investments in human capital. Improved human capital also produces a more equitable distribution of resources, stronger institutions, and slower population growth, leading to a less vulnerable world better able to adapt to climate impacts.

Figure 14: Illustrative example of narratives underlying the SSPs (Source: IPCC)

The calculated input for the water allocation model depends on the RCP, the SSP or is general for all scenarios. The user will be able to select a combination of RCP and SSP for which the model will calculate water availability and shortages among the sectors. See Table 5 for which input files depend on RCP or SSP input.

Table 5: WatCam input files sorted by dependency

General	SSP dependent	RCP dependent
Reservoir Capacity	Demand Domestic	Demand Irrigation
Max kW generation	Demand Industry	Demand Environment
Priority Irrigation		External generated flow
Priority Domestic		Q1
Priority Industry		Q2
Priority Urban		Q3
Priority Groundwater		Internal generated flow
Priority Hydropower		
Hydaulic capacity		
Hydropower efficiency		
Reservoir head		
Groundwater capacity		
Fraction of inflow through hydropower reservoir		
Downstream demand		

5.1 IRRIGATION WATER DEMAND

5.1.1 Irrigation water requirements

Irrigation is the largest water demand worldwide with 70% of the water demands. (Döll et al., 2009). The irrigation water requirement in this study is based on the global map of irrigated areas. (Portmann et al., 2010) this dataset is available at 0.5°. The total irrigation water requirement is calculated by multiplying the irrigated area per cell by the potential evapotranspiration. The potential evapotranspiration is an indication of the amount of water evaporated and transpired when sufficient water resources are available. This results in terms of agriculture in the most optimal yields if there are no other constraints. The ET_{pot} used depends on the RCP. Based on the selected RCP the monthly values will differ. By multiplying the irrigated area by the ET_{pot} it is assumed that the use of irrigated land is possible all year round. In practice this differs from place to place. Therefor a constant factor is used which reflects the use of the irrigated land. This constant value becomes smaller when the irrigation demand increases. The reason behind this is the intensity of the land use and the pressure on the irrigated land. How higher the pressure on the irrigated land the more it will be used over the year.

The Irrigation Water Requirement is calculated as follows:

$$IWR = IEA * ET_{ref} * C$$

Where:

IWR = Irrigation water requirement, calculated
IEA = Irrigation Equipped Area (Portmann et al., 2010)
ET_{pot} = Reference evapotranspiration, resulting from PCRGLOB-WB
C = Constant factor which reflects the use of irrigated land

5.1.2 Irrigation water withdrawal

Assessing the impact of irrigation on water resources requires an estimate of the water effectively withdrawal for irrigation, i.e. the volume of water extracted from rivers, lakes and aquifers for irrigation purposes. Irrigation water withdrawal normally exceeds the consumptive use of irrigation because of water lost in its distribution from its source to the crops. The ratio between the estimated irrigation water requirements and the actual irrigation water withdrawal is usually referred to as "irrigation efficiency". Data on irrigation efficiencies are generally not easily available at field, irrigation scheme or river basin levels and only very scattered and unreliable information is available at country level. The use of the word "irrigation efficiency" is subject of debate. The word "efficiency" implies that all the water that exceeds the irrigation water requirements is wasted. In reality, however, this water can recharge aquifers or it can flow back to the river basin from where it can be re-used. It is for this reason that we use the term "water requirement ratio" (WRR) will be used to indicate the ratio between irrigation water requirements and the amount of water withdrawn for irrigation.

The WRR is calculated as follows:

WRR = IWR / AWW

Where:
WRR = water requirement ratio
IWR = irrigation water requirement, calculated
AWW = total agricultural water withdrawal.

The water requirement ratio will initially be given in the model. Rohwer et al (2007) published a country specific efficiency factor, which accounts for difference between the irrigation water requirement and the irrigation water withdrawal. (e.g. conveyance and application “losses”). The initial water requirement ratio number results from this technical report and on the web-portal the user will be able to specify it further for his specific area.

5.1.3 Future irrigation water withdrawal.

The basis for projection for irrigation is the map with areas equipped for irrigation (Portmann et al., 2010). The user will be able to select the RCP on which the calculation of the irrigation water demand is based. This will account for a seasonal variability as the ET_{pot} varies over the year. The future irrigation water withdrawal will change based on the RCP selected, as temperature and precipitation patterns may change. (Also see Figure 15)

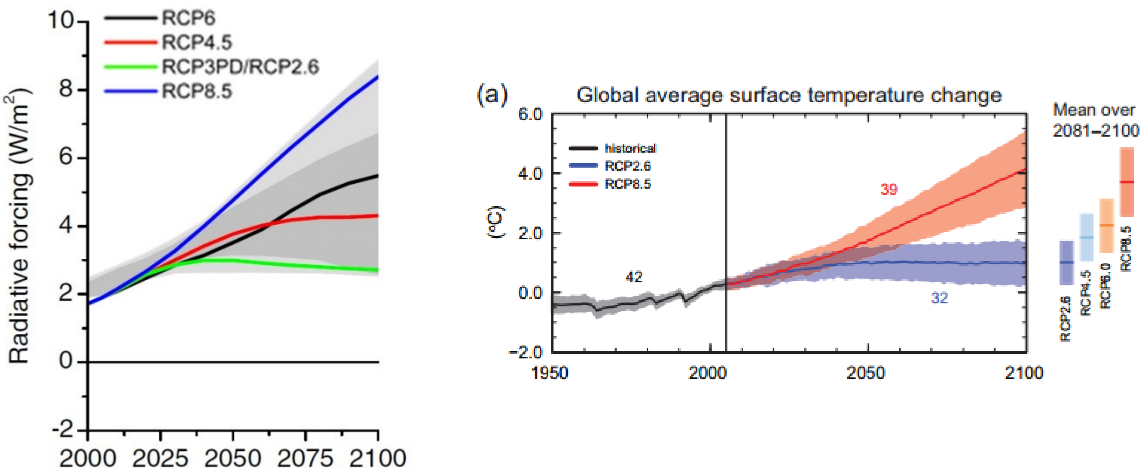


Figure 15: Left: Representative concentration pathways till 2100 (source: van Vuuren 2011) Right: Change in annual mean temperature shown for RCP 2.6 and 8.5 (source: IPCC)

In the current version of the WatCam the initial area of irrigated land is included in a static way. The user will be able to change the amount of irrigated land to calculate how the future irrigation water withdrawal will change, and how this will influence the overall water availability. The choice is made not to increase the irrigated area gradually towards the projected irrigation potential as the concept of irrigation potential is not static. It varies over time, in relation to the country's economic situation or as a result of increased competition for water for domestic and industrial use. In addition, estimates of irrigation potential also are based on renewable water resources, i.e. the resources replenished annually through the hydrological cycle. In those arid countries where mining of fossil groundwater represents an important part of water withdrawal, or where groundwater resources are over-exploited through depletion of the aquifers, the area under irrigation can be larger than the irrigation potential.

5.2 INDUSTRIAL WATER DEMAND

For estimating both industrial and domestic water withdrawals use is made of the SSP projected raster maps created by the Netherlands environmental assessment agency (PBL). PBL translated the RCP's into socioeconomic pathways. The resulting 0.5° raster maps of population and GDP per grid cell are used to calculate the industrial and domestic water demands.

Future industrial water withdrawals (IWW) are a function of the gross domestic product (GDP) and GDP per capita (GDPP) according to the following equation (AQUASTAT, 2010):

$$IWW_y = IWW_{y-1} * GDP_y / GDP_{y-1} * GDPP_{y-1} / GDPP_y$$

where IWW is the industrial water withdrawal. The rationale for this equation is that if a country produces more GDP, but it doesn't get richer per person (constant GDPP), industrial water demands will change equally to GDP. If the country also gets richer per person it is more inclined to safe water. Data on industrial water withdrawals during the reference period are taken from FAO's AQUASTAT database. It is assumed that 20% of the industrial water withdrawals are consumed and the remainders are return flows.

5.3 DOMESTIC WATER DEMAND

The domestic water demand is a function of the population and the GDPP. First a relation is identified between per capita domestic water withdrawal and the GDPP per country (Figure 16). The rationale behind this is that with increasing prosperity the domestic water withdrawals per capita will also increase (washing machines, bathrooms, watering gardens, swimming pools, etc.). The increase in water withdrawals is not linear but the growth rate reduces with increasing GDPP. Once the GDPP reaches 70.000 US$ it is assumed that the per capita water consumption remains constant. Theoretically it is possible that once people get very rich there will also be substantial investments in water saving technologies and per capita domestic water withdrawals would decrease. To date this has hardly observed in even rich and technologically advanced countries in the world and therefore we assume this not to be the case.

For the USA the per capita domestic water use decreases only marginally, due to water saving washing machines, toilets etc. But the decrease is very slow and there is also a counter effect that people use more water for showering, washing cars, swimming pools and watering gardens. The advances in technologies do not outweigh the increase.

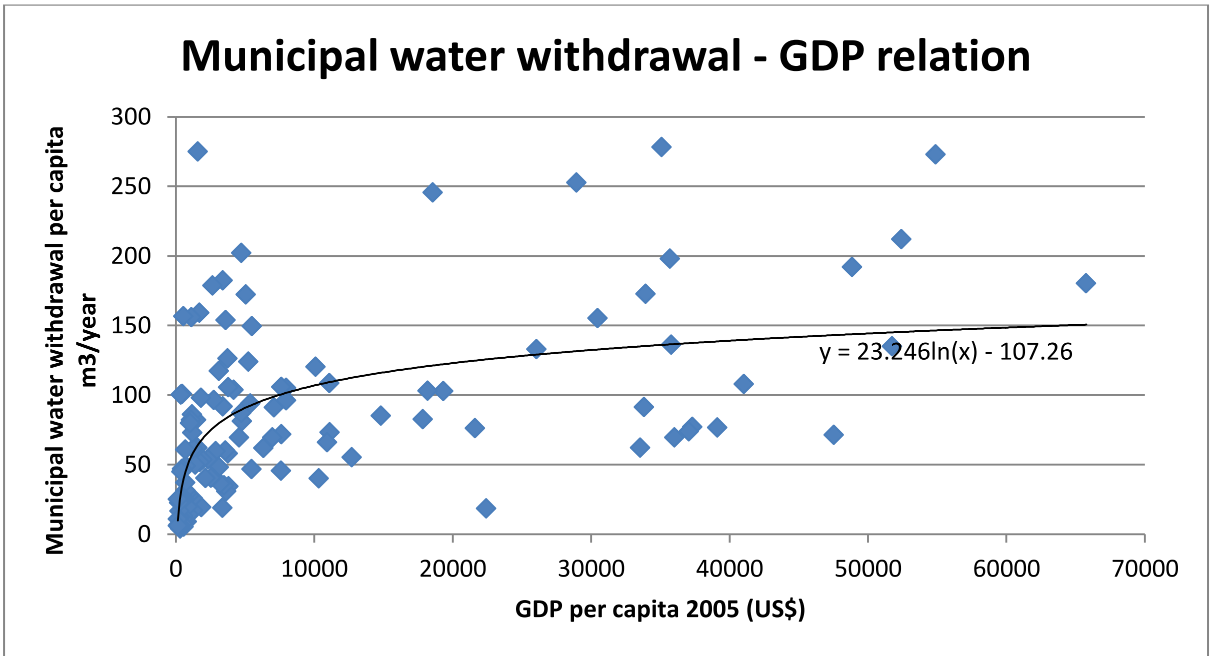


Figure 16: Relation between per capita domestic water withdrawals and GDPP

FAO country per capita water uses and per capita GDP are used to plot the graph. Formula from this graph is used to calculate the water demands for the WP's. A correction is carried out to correct the FAO domestic water demands per country to the water demand based on the grid as calculated by PBL. The 0.5° grid based water demands give a much better spatial variation. The values resulting from the GDPP, water withdrawal relation as given in

Figure 16 approach the domestic water demands as given by FAO. To maintain the variation a correction is made based on the gridded water withdrawal. Therefor the value given by the formula y = 23.246*ln(x) - 107.26 is multiplied with the deviation to this formula based on the gridded summed water withdrawal for each water province in 2010. In this way it is assumed that the deviation to this formula given domestic water withdrawal will be constant for the whole running period.

5.4 ENVIRONMENTAL AND DOWNSTREAM WATER DEMAND

The demands for downstream water provinces and environmental flow are enabled in the water allocation model. However no global information is available on water treaty agreements between countries. For this reason the user will be able to enter a fixed flux which has to be allocated to the downstream water province. The environmental demand depends largely on the ecosystem services within the water province as well as on the absolute value of the fluxes. Initially the environmental demand has been set on 20% of the total pristine inflow, which consists of the internal and external generated flows. The user will be able to change this according to the local situation. The factor Environmental use is also enabled for users. This is a fraction of the environmental flow which is consumed or used for eco-system services. The factor Environmental use is set on zero by default.

5.5 RESERVOIR CAPACITY[6]

The Global Reservoir and Dam Database, Version 1 (Revision 01) contains 6,862 records of reservoirs and their associated dams with a cumulative storage capacity of 6,197 cubic km. The dams were geospatially referenced and assigned to polygons depicting reservoir outlines at high spatial resolution. Dams have multiple attributes, such as name of the dam and impounded river, primary use, nearest city, height, area and volume of reservoir, and year of construction (or commissioning). While the main focus was to include all dams associated with reservoirs that have a storage capacity of more than 0.1 cubic kilometers, many smaller dams and reservoirs were added where data were available. The data were compiled by Lehner et al. (2011) and are distributed by the Global Water System Project (GWSP) and by the Columbia University Center for International Earth Science Information Network (CIESIN).

The reservoir capacity is aggregated per water province based on the GRanD database. The value used for the reservoir capacity is static and will remain the same for the whole running period.

5.6 GROUNDWATER CAPACITY

Groundwater capacity is based on the soil water storage which results from the PCRGLOB-WB model. The number given by the model is the amount of water stored in the soil layer 0.3-1.3 meter below surface level. For WatCAM it is assumed that groundwater can be stored in 50 meters of soil, and that soil properties remain comparable as in the layer 0.3-1.3 meter below surface level.

[6] Based on GranD documentation

5.7 DEMAND VALIDATION

5.7.1 Irrigation

The irrigation water demands have been validated based on the irrigation water use as used on country base by Wada et al. 2014. The scatter in Figure 17 shows that the demands as used in WatCAM are comparable to the ones which are used within the global modelling. Both calculation methods are different as within this study a higher level of detail is required due to the water provinces. Therefor the irrigation water use is based on the highest resolution rasters of irrigated area and evapotranspiration. Within WatCAM this potential irrigation water use is multiplied with certain efficiency, irrigation reuse and infiltration factors, which finally define the irrigation water demand.
The validation is based on the average of the five models used to calculate the irrigation water use by Wada et al 2014. The standard deviation of these models is plotted as well.

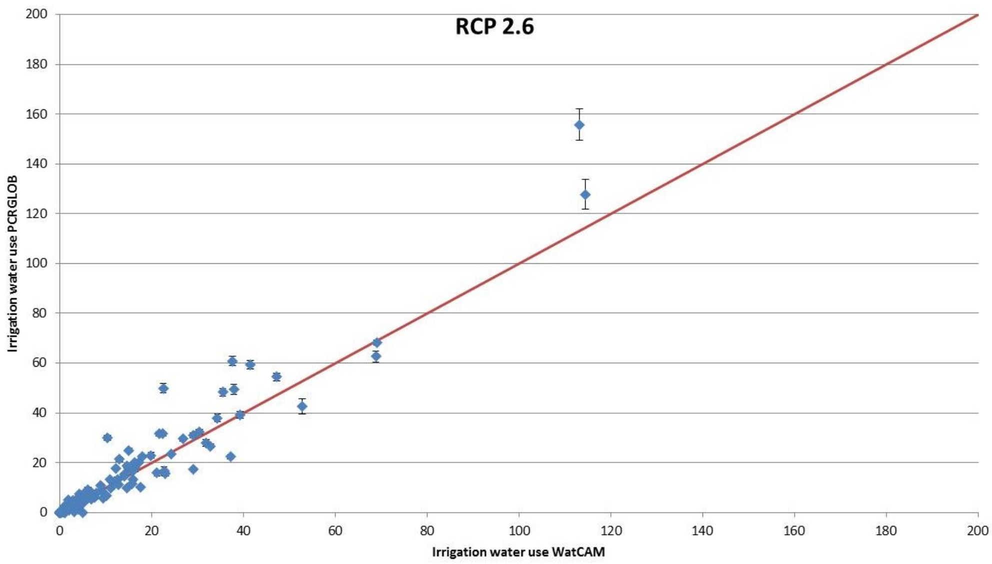


Figure 17: Irrigation water use per country in mm/y, average 2010-2039. Example of RCP2.6 other RCP's give similar plots.

5.7.2 Urban and Industry

The urban and industrial demands are based on the FAO database. The 2010 country data have been downscaled to the water provinces based on the raster maps given by the Netherlands Environmental Assessment Agency (PBL). These rasters give a better spatial variation which is needed to calculate the demands per water province.

6 WATCAM SETUP

Watcam has been set up with the major task to allocate the available water within the water provinces to the prioritized demand sites. Based on the priorities given by the user the model will calculate how much water is available in a monthly time step from streams, reservoirs or ground water and allocate the available water. The model will calculate the amount of internal generated water and the amount of water which is entering the water province from external sources. If the available stream flow is not sufficient to cover all demands additional water may be extracted from reservoir or groundwater. The user can define which fraction of the available stored water can be used by the demand sites within a monthly time step. The Demands include efficiency factors, and reuse factors. Efficiency for the urban or industrial demands is the fraction of consumed water by the sector. The other part is either returning upstream and will be available within the same water province again or will return to the stream and leave the water province. For Irrigation a fraction of the water will infiltrate to the groundwater and two other fractions will return upstream or downstream. Also see the flowchart in Figure 18.

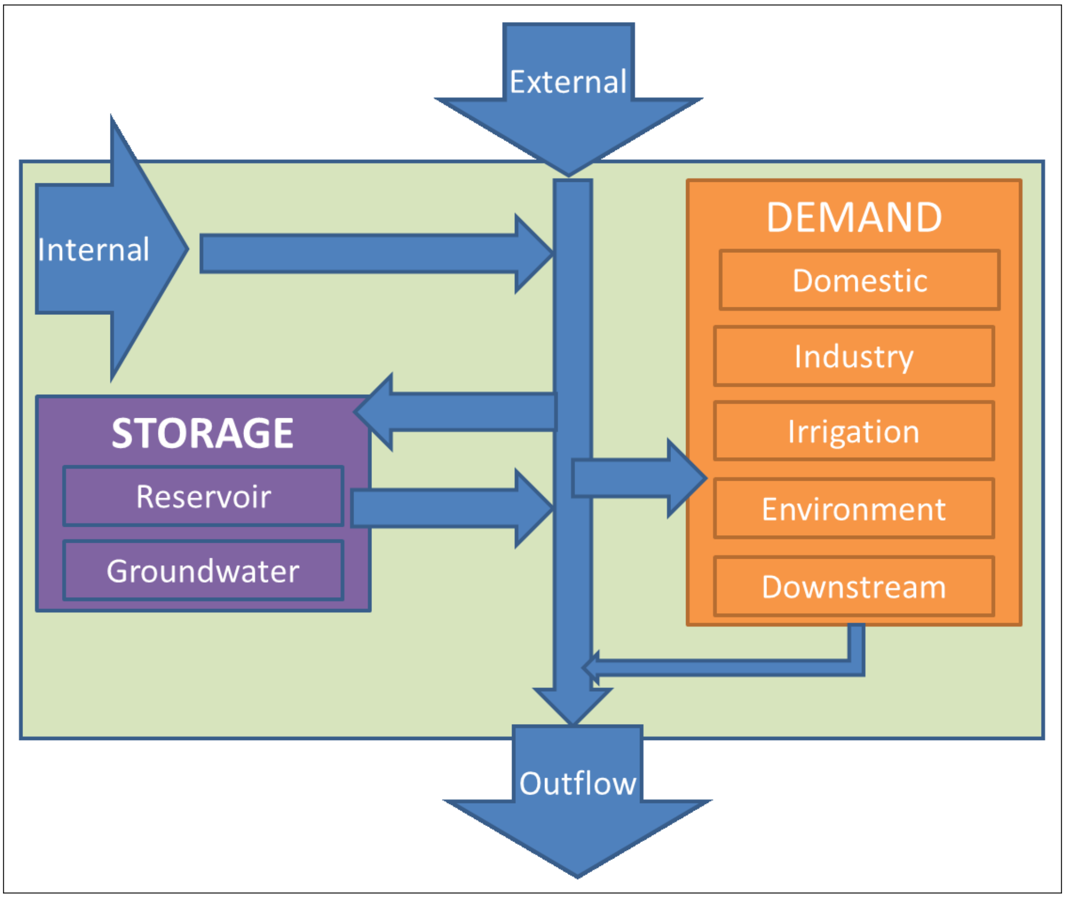


Figure 18. Concept of water demand-supply analysis for one Water Province.

6.1 WATCAM FUNCTIONALITY

The main Watcam requirements are:

- Possibility to select a water province

- Load the corresponding data based on selected RCP SSP combination
- Calculate the available water in the water province
- Calculate demands based on user given efficiency fractions.
- Calculate the amount of water going to a specific downstream water province
- Allocate the water based on the availability and user given priorities
- Calculate unmet water demands
- Calculate hydropower generated
- Give actual reservoir and groundwater storage
- Run in batch

Based on these requirements the formulas as used in the WEAP model are used to program a custom made water allocation model. This water allocation model consists of several parts of which the WatCamE_09.xls is the main WatCAM module where the water allocation is calculated. This WatCAM module is wrapped within several scripts which automates the process and includes the correct parameters for each water province and the parameters given by the users. The output of the model is a .csv file for each water province, giving the time series for the demands, supply, unmet demands, total supply, supply per water source, actual groundwater and reservoir storage and hydropower generation.

6.2 WATCAM OPERATIONAL SETUP

6.2.1 Files

WatCAM consist of 4 pieces of which the main module is the WatCamE_v09.5.xls, the four pieces are:

1. WatCamE_v09.5xls
2. RunWatcamE_v04.1.py
3. WatCamConfig.cfg
4. WatProv_02

Apart from these four WatCAM modules there are several input files with which the scripts communicate to extract the correct information for the selected water province.

The most important input files are:

General

- WatProvPar.csv
- Reservoir capacity
- Groundwater capacity
- Historical flow
- Irrigated area

RCP dependent

- Reference evapotranspiration
- Internal generated flow
- External generated flow (output and input from model)

SSP dependent

- Population
- Domestic water use (l/p/d)
- Industrial demand

6.2.2 Running

To run WatCAM for a selected set of water provinces make sure that in the file WatProv_02 the water provinces to be calculated are set to Y (yes) in the column B.

In the file WatCamConfig.cfg it is possible to select the desired input and output folders. The input folders depend on the selected RCP-SSP combination. In this file it's also possible to select the time slot for which the model should run. As default the model runs from 2006-2099.

After these two steps the model is ready to run. To run the model run the script RunWatcamE_v04.1.py. The output files are saved as .csv files for the selected water provinces.

6.2.3 Change parameters

To run custom scenarios or a pre-defined set of adaptation measures it is needed to change some input parameters. All parameters which have to be changed to run the eight selected measures can be changed in the file WatProvPar.csv. (See

Name	Description	Unit
CALC		
DOM_GRO	Domestic gross demand	m3/mo
DEM_DOM	Domestic demand, inc. effiency and reuse	m3/mo
IRR_GRO	Irrigation gross demand	m3/mo
DEM_IRR	Irrigation demand, inc. effiency and reuse	m3/mo
DEM_TOT	Demand total	m3/mo
FLO_TOT	Flow available total	m3/mo
GRW_REC	Groundwater recharge	m3/mo
INFORM_SUP	Informal extration and supply	m3/mo
FLO_AVA	Total available water	m3
RES_ACT	Reservoir actual storage	m3
GWT_ACT	Groundwater actual storage	m3/mo
RES_AVA	Reservoir flow available	m3/mo
GWT_AVA	Groundwater flow available	m3/mo
AVA_TOT	Water available total	frac
AVA_DOM	Water fraction available domestic	frac
AVA_IND	Water fraction available industry	frac
AVA_IRR	Water fraction available irrigation	frac
AVA_ENV	Water fraction available environment	frac
AVA_DWN	Water fraction available downstream	m3/mo
DOM_SUP	Domestic supply	m3/mo
IND_SUP	Industrial supply	m3/mo
IRR_SUP	Irrigation supply	m3/mo
ENV_SUP	Environment supply	m3/mo

DWN_SUP	Downstream supply	m3/mo
SUP_TOT	Total supply	m3/mo
FLO_EXT	Flow extracted from surface water	m3/mo
RES_EXT	Flow extracted from reservoir	m3/mo
GWT_EXT	Flow extracted from groundwater	m3/mo
RES_INF	Reservoir inflow	m3/mo
RES_NEW	Reservoir new storage	m3
GWT_NEW	Groundwater new storage	m3/mo
FLO_OUT	Outflow	m3/mo
IND_GRO	gross indstry demand	m3/mo
DEM_IND	Industry demand, inc. effiency and reuse	m3/mo

Table 8) This file has all the static parameters for the water provinces. WatCAM automatically copies the correct set of parameters belonging to the selected water province to the WatCamE_v09.5.xls module, based on the WatProv_02.csv.

6.3 WATCAM PARAMETERS

Table 6. Input variables

Name	***Description***	***Unit***	***Source***
INPUT			
YY	Year	int	
MM	Month	int	
AREA_WP	Area	km2	Watprovpar.csv
POP	Population	int	population.tss
DOM_DEM_org	Demand domestic original	L/C/day	dom_l_p_day.tss
DOM_DEM_sce	Demand domestic scenario	L/C/day	
DOM_EFF	Domestic efficiency	frac	Watprovpar.csv
DOM_REU	Domestic reuse	frac	Watprovpar.csv
IND_EFF	Industry efficiency	frac	Watprovpar.csv
IND_REU	Industry reuse	frac	Watprovpar.csv
IND_DEM_org	Industrial demand original	m3/mo	denIndustry_m3.tss
IND_DEM_sce	Industry demand scenario	m3/mo	
IRR_ARE_org	Irrigated area original	m2	Irr_area_m2.tss
IRR_ARE_sce	Irrigated area scenario	m2	Watprovpar.csv
ET_REF	Reference evapotranspiration	mm/mo	ETrefmm.tss
IRR_EFF	Irrigation efficiency	frac	Watprovpar.csv
IRR_REU	Irrigation reuse	frac	Watprovpar.csv
ENV_DEM	Environmental Demand	m3/mo	Calc from ENV_FRC
DWN_DEM	Downstream Demand	m3/mo	zero
DWN_DEM_User	Downstream demand user given	m3/mo	Watprovpar.csv
FLO_INT_org	Internal generated flow	m3/mo	Q1_km3.tss+Q2_km3.tss+Q3_km3.tss
FLO_INT_cali	Internal generated flow calibrated	m3/mo	
FLO_EXT	Flow External	m3/mo	from upstream outflow
FLO_EXT_User	Flow external user given	m3/mo	Fraction of historical flow
RES_FLO	Flow fraction into reservoir	frac	constant
RES_CAP_org	Reservoir capacity original	m3	Watprovpar.csv
RES_CAP_new	Reservoir capacity scenario	m3	
GWT_CAP	Maximum groundwater capacity	m3	GW_cap.tss

RES_MAX	Maximum extraction from reservoir	frac	constant
GWT_MAX	Maximum extraction from groundwater	frac	constant
HIS_FLO	Historical pristine flow	m3/mo	Hist_flo_m3.tss
ENV_FRC	Fraction of flow required for environment	frac	Env_flow_frac.tss
DOM_PRI	Domestic priority	1-100	Prior_Domestic.tss
IND_PRI	Industrial priority	1-100	Prior_Industry.tss
IRR_PRI	Irrigation priority	1-100	Prior_Irrigation.tss
ENV_PRI	Environmental priority	1-100	constant
DWN_PRI	Downstream priority	1-100	constant

Table 7: WatCAM calculation variables. Also see WatCamE_9.5.xls.

Name	Description	Unit
CALC		
DOM_GRO	Domestic gross demand	m3/mo
DEM_DOM	Domestic demand, inc. effiency and reuse	m3/mo
IRR_GRO	Irrigation gross demand	m3/mo
DEM_IRR	Irrigation demand, inc. effiency and reuse	m3/mo
DEM_TOT	Demand total	m3/mo
FLO_TOT	Flow available total	m3/mo
GRW_REC	Groundwater recharge	m3/mo
INFORM_SUP	Informal extration and supply	m3/mo
FLO_AVA	Total available water	m3
RES_ACT	Reservoir actual storage	m3
GWT_ACT	Groundwater actual storage	m3/mo
RES_AVA	Reservoir flow available	m3/mo
GWT_AVA	Groundwater flow available	m3/mo
AVA_TOT	Water available total	frac
AVA_DOM	Water fraction available domestic	frac
AVA_IND	Water fraction available industry	frac
AVA_IRR	Water fraction available irrigation	frac
AVA_ENV	Water fraction available environment	frac
AVA_DWN	Water fraction available downstream	m3/mo
DOM_SUP	Domestic supply	m3/mo
IND_SUP	Industrial supply	m3/mo
IRR_SUP	Irrigation supply	m3/mo
ENV_SUP	Environment supply	m3/mo
DWN_SUP	Downstream supply	m3/mo
SUP_TOT	Total supply	m3/mo
FLO_EXT	Flow extracted from surface water	m3/mo
RES_EXT	Flow extracted from reservoir	m3/mo
GWT_EXT	Flow extracted from groundwater	m3/mo
RES_INF	Reservoir inflow	m3/mo
RES_NEW	Reservoir new storage	m3
GWT_NEW	Groundwater new storage	m3/mo
FLO_OUT	Outflow	m3/mo
IND_GRO	gross indstry demand	m3/mo
DEM_IND	Industry demand, inc. effiency and reuse	m3/mo

Table 8. Parameters of which most can be changed by user (see Watprovpar.csv)

Parameter	Description	Unit
WatProvID	Waterprovince ID	int
RES_INIT	Initial reservir storage	frac
GWT_INIT	Initial Groundwater storage	frac
GWT_RECH	Groundwater recharge	frac
INFORMAL	Informal	frac
RES_FLO	Reservoir flow	frac
RES_MAX	Reservoir maximum extraction capacity	frac
GWT_MAX	Groundwater maximum extraction capacity	frac
ENV_FRAC	Fraction of flow as environmental demand	frac
DOM_EFF	demestuc efficiency	frac
DOM_REU	Domestic reuse	frac
IRR_REU	Irrigation Reuse	frac
IND_EFF	Industry efficiency	frac
IND_REU	Industry Reuse	frac
ENV_USE	Environmental Use	frac
AREA_WP	Water province area	km2
HP_ELV	Hydropower average turbine drop	m
HP_FAC	Hydropower factor	frac
HP_EFF	Hydropower efficiency	frac
RES_extra	Additional reservoir created	MCM
DESAL	Water desalinated	MCM
DOM_PRI	Domestic priority	1-100
IND_PRI	Industry priority	1-100
IRR_PRI	Irrigation priority	1-100
ENV_PRI	Environmental Priority	1-100
DWN_PRI	Downstream priority	1-100
IRR_EFF	Irrigation efficiency	frac
URB_DEM	Urban demand fraction	frac
IND_DEM	Industry demand fraction	frac
IRR_AREA	Irrigation demand fraction	Frac
Ext_User	External flow user given (frac of historical)	Frac
DWN_DEM	Downstream demand (frac of historical)	Frac
Calibration	Calibration factor	Fact
IRR_COR	Irrigated land use factor	Fact

6.4 WATCAM FORMULA'S

The setup of the water allocation model made in Excel is based on the WEAP formulas and documentation. The formulas as used are given in the sections underneath, for a more detailed description please see the WEAP manual at: http://www.weap21.org/downloads/WEAP_User_Guide.pdf

6.4.1 Water demand

The calculation of the demands is described in more detail in chapter 5.

Irrigation water requirement (IWR) = IEA * ET_{pot}
Industrial - IWWy = IWWy-1 * GDPy / GDPy-1 * GDPPy-1 / GDPPy
Domestic – DWWy = 23.246*ln(x) - 107.26

6.4.2 Water availability

$$AVA\_TOT = FLO\_TOT + RES\_AVA + GWT\_AVA$$

$$FLO\_TOT = FLO\_INT + FLO\_EXT$$

$$RES\_AVA = RES\_ACT * RES\_MAX$$
$$GWT\_AVA = GWT\_ACT * GWT\_MAX$$

6.4.3 Demand – supply balance

Available fraction as function of demand and availability
$$AVA\_FRAC = MIN(1, AVA\_TOT/DEM\_TOT)$$

$$SUP\_TOT = DEM\_TOT * AVA\_FRAC$$

Extract water first from stream, than from reservoir, than from groundwater
$$FLO\_EXT = MIN(FLO\_TOT, SUP\_TOT)$$
$$RES\_EXT = MIN(SUP\_TOT - FLO\_EXT, RES\_AVA)$$
$$GWT\_EXT = MIN(SUP_{TOT} - FLO_{EXT} - RES\_EXT, GWT\_AVA)$$

Update reservoir and groundwater
$$RES\_INF = \min(RES\_CAP - RES\_ACT, FLO\_TOT - FLO\_EXT$$
$$RES\_NEW = RES\_ACT - RES\_EXT + RES\_INF$$
$$GWT\_INF = \min(GWT\_CAP - GWT\_ACT, (FLO\_TOT - FLO\_EXT) * GWT\_RECH)$$
$$GWT\_NEW = GWT\_ACT - GWT\_EXT + GWT\_INF$$

6.4.4 Reuse and efficiency

$$DEM_{ADJ} = \frac{DEM}{EFF} - \left(\frac{DEM}{EFF} - DEM\right) * REUSE$$

6.4.5 Allocation optimalization

WatCAM will optimize the water which is available. This will happen based on the priorities which are given by the user. The optimization will happen within the water province so that the available water will be allocated according to the user's requirements. The water allocation is not optimized over the whole basin or over time. This allows the user to evaluate the direct impacts of adaptation measures within his own water province. The priorities for each demand site can vary from 1 to 99, for which 99 is the highest priority and 1 the lowest. The water will be allocated based on the relative ratio of the five demands. There are three pre-defined set of priorities which the user can select apart from making custom priorities.

When Equal priorities are selected:

- DOM_PRI = 99
- IND_PRI = 99
- IRR_PRI = 99
- ENV_PRI = 99
- DWN_PRI = 99

When Default priorities are selected:

- DOM_PRI = 99
- IND_PRI = 75
- IRR_PRI = 50
- ENV_PRI = 25
- DWN_PRI = 25

When Downstream demand is selected:

- DOM_PRI = 1
- IND_PRI = 1
- IRR_PRI = 1
- ENV_PRI = 1
- DWN_PRI = 99

6.5 VALIDATION AND CALIBRATION OF WATCAM

This chapter gives a description of the validation of WatCam, based on data from the Global Runoff Data Center (GRDC). For this purpose 17 basins have been selected, which have been run for multiple scenarios to carry out sensitivity analysis. See Table 9 for the selected basins, GRDC stations used and the corresponding water provinces from WatCam.

Table 9: selected basins and water provinces

River	GRDC_Stat	Country	DS_WP
CONGO	1147010.mon	Congo	434
ORANGE	1159100.mon	Zambia	1103
NILE	1362100.mon	Egypt	992
YANGTZE	2181900.mon	China	1538
INDUS	2335950.mon	Pakistan	673
MEKONG	2569005.mon	Vietnam	874
KRISHNA	2854300.mon	India	718
AMUR	2906901.mon	Russia	197
SYR DARYA	2916203.mon	Uzbekistan	1432
AMU DARYA	2917110.mon	Turkmenistan	183
CHAO PHRAYA	2964130.mon	Thailand	392
ORINOCO	3206720.mon	Venuzuela	1119
AMAZONAS	3629000.mon	Brasil	153
MISSISSIPPI RIVER	4127930.mon	US	911
PO	6348800.mon	Italy	1193
RHINE	6435060.mon	NL	1211
DANUBE RIVER	6742900.mon	Romania	458

Initially a set of selected parameters from the WatProvPar.csv files have been changed one by one to see which parameter is most sensitive.
Changing the Demands, Use and Reuse does not have a large influence. It became clear that by running without any demand the “natural” flow is 15,094.8m3/s for the Mekong. For this run about 2 % of the total demand is used for urban-industry-irrigation against 98% for the environmental flow. By turning the environmental fraction down from 20% of the historical pristine flow to 0, a flow of 14,919.8m3/s was simulated. The sensitivity analysis shows that environmental demand and environmental use should be clearly distinguished. In a new version of WatCamW_9.5 the environmental use factor is multiplied with the total environmental demand, after calculating and optimizing the water demands. This bring the average outflow for the Mekong on 13,566.7m3/s with a 0% environmental water use.

The results of the calibration can be seen in Table 10. A specific calibration factor is made for each basin to match the GRDC output. This calibration factor is multiplied with the internal generated flow. This calibration factor is made based on the yearly average flows in m3/s. The timing of the water availability can hardly be changed by WatCAM as the water supply and evaporation is calculated with the PCRGLOB-WB model. Table 10 shows the measured GRDC outflow of the basins, the un-calibrated simulated outflow and the calibrated outflow. The last column shows the calibrated outflow as fraction of the measured GRDC outflow. Within the scope of this study a specific calibration factor is made for these 17 basins. For the other basins an average calibration factor is used, which is based on these 17 basins.

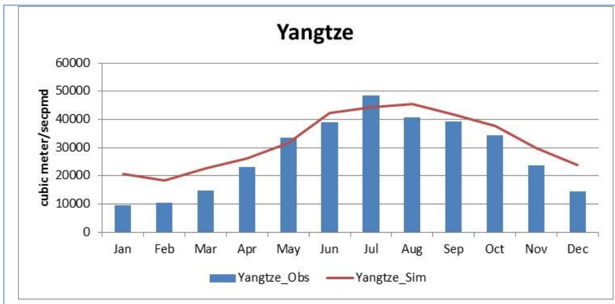
Table 10: Annual average Flows in m3/s for the selected basins.

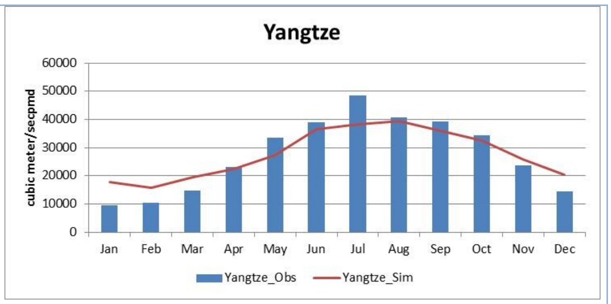
River	GRDC	Un-calibrated	Calibrated	Fraction of GRDC
Congo	42,586.6	35,237.8	42,701.9	100.3%
Orange	170.2	199.1	171.5	100.8%
Nile	1,251.3	1,364.9	1,270.7	101.5%
Yangtze	27,623.0	32,116.0	27,217.0	98.5%

Indus	2,112.1	3,788.1	2,086.2	98.8%
Mekong	13,297.2	13,886.5	13,566.7	102.0%
Krishna	1,032.1	1,358.6	1,032.8	100.1%
Amur	10,238.6	9,987.4	10,182.0	99.4%
Syr_Darya	84.3	89.5	82.9	98.4%
Amu_Darya	1,534.8	1,542.7	1,540.5	100.4%
Chao_Phraya	292.0	1,119.6	295.0	101.0%
Orinoco	30,861.2	41,822.3	30,117.6	97.6%
Amazone	171,486.1	197,336.0	169,516.6	98.9%
Mississippi	14,181.1	11,954.6	14,233.1	100.4%
Po	1,526.5	1,303.5	1,576.7	103.3%
Rhine	2,280.3	1,399.3	2,285.6	100.2%
Danube	6,565.1	4,699.1	6,628.8	101.0%

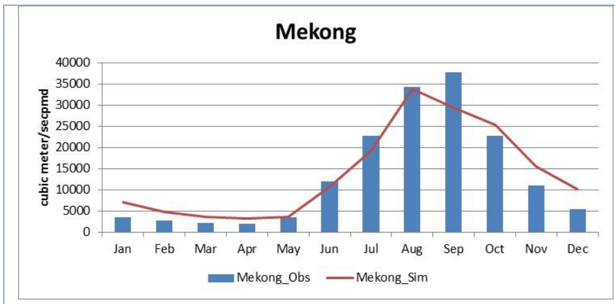
On the following pages the results for some of these 17 basins will be shown. Firstly the monthly averaged outflow, measured vs simulated. Secondly the yearly average flow is shown in the graphs, original run on top and calibrated run underneath. The remaining graphs are shown in the annex.

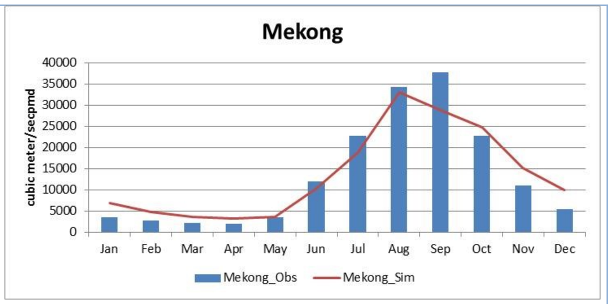
6.5.1 Yangtze



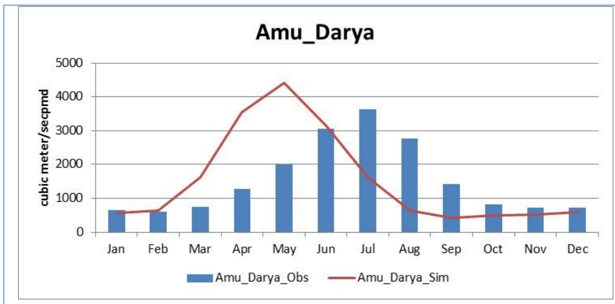


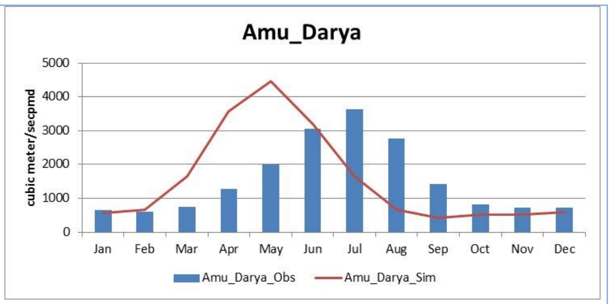
6.5.2 Mekong



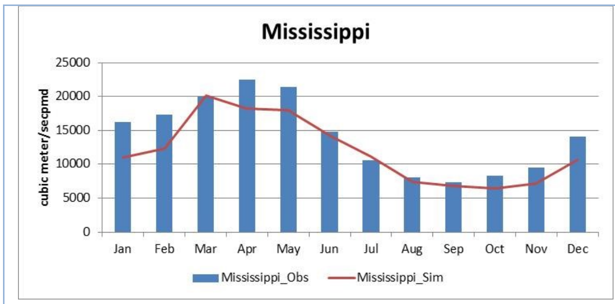


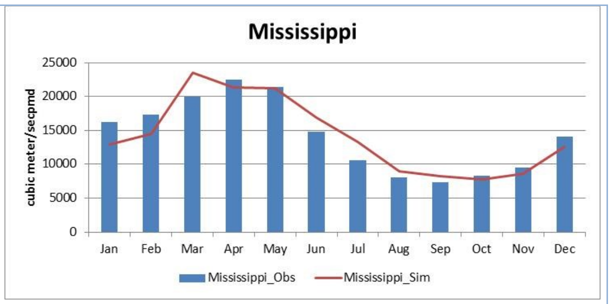
6.5.3 Amu_Darya





6.5.4 Mississippi





6.5.5 Hydropower

The hydropower generation can be a reason to expand reservoir capacity which serves multiple purposes as it may also benefit water availability over the years. Within WatCAM the hydropower generated within a water province is calculated. Little information is available on hydropower generation around the world, and especially not on water province scale. Therefor Switzerland is used as an example as the whole country is about one water province. See Figure 19 for the graph, reference versus simulated. The reference is a fixed number, and the simulated is of course depended on the amount of water passing through a hydropower reservoir. Within WatCAM the fraction of water passing through a reservoir is implemented as a fraction of the total inflow. It is assumed that all water passing through a reservoir will benefit hydropower generation.

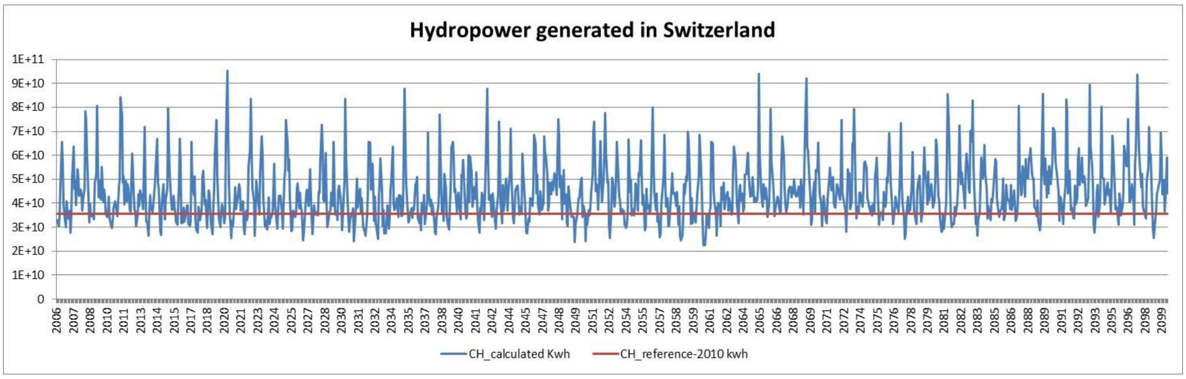


Figure 19: The reference generated hydropower is shown in red and is slightly lower than the calculated hydropower generated. The calculated hydropower generation fluctuates because of the amount of water flowing through the power plant.

7 RESULTS

7.1 CURRENT CLIMATE

The distributed hydrological model was used to determine the renewable water resources including external renewable water resources for the current and future climate. These outputs in combination with sectorial water demands are fed into the WatCAM water allocation model that is used to assess water demand on a monthly basis. The allocation model links supply and demand for each country, sector and supply source. So the hydrological model provides monthly time series of surface water and natural groundwater recharge to the water allocation model. The water allocation model is subsequently used to assess the effects of different supply and demand options.

The following maps give an overview of the input and output datasets of WatCAM under the current climate. For the current situation, the time period 2006-2015 was used.

- **Available water**: Figure 20 to Figure 22, show the internal, external and total available water resources (including groundwater). The global map of the internal water resources shows the flow generated within each water province. The pattern is as expected mainly a function of the global precipitation pattern. The external water resources show a different pattern, especially in the larger river basins where many water provinces are in cascade. The downstream water provinces show high values generally, although in some of the larger basins with high water demands this pattern is less obvious (as the Nile and the Volta for example).
- **Demands**: Figure 23 - Figure 28 show global maps of domestic, industrial and irrigation and environmental demand and the totals. The demands are shown in mm, to allow interpreting the spatial patterns. Demand maps expressed in volume (m3) have the disadvantage that the size of the WP becomes very relevant in interpreting the maps. The maps showing the separate components of demand have all the same legenda classes to allow inter-comparison. Domestic and industrial demands follow mainly population patterns. Irrigation demand is highest in the water scarce semi-arid areas. The total of human-induced demand (domestic, industrial and irrigation) is also shown (Figure 26). Total demand (Figure 28) including environmental demand (Figure 27) makes clear that the majority of the demand for most of the water provinces is downstream environmental demand.
- **Unmet demand**: Figure 29 shows the global unmet demand as simulated by WatCAM. The main areas that are highlighted are California (U.S.), downstream Nile, Ganges, Brahmaputra, and parts of China, among others. The global patterns are coherent with other studies, but still some improvements are foreseen in the near future, mainly in irrigation demand, that will affect these patterns (both relatively as absolutely).
- **Intensity of water use**. Figure 30 shows the intensity of water use, which is defined here as the total demand divided by the internal water resources. So the coefficient expresses which part of the demand can potentially be met with internal water flow. Values higher than 1 indicate reliance on external water resources and/or unmet demand.

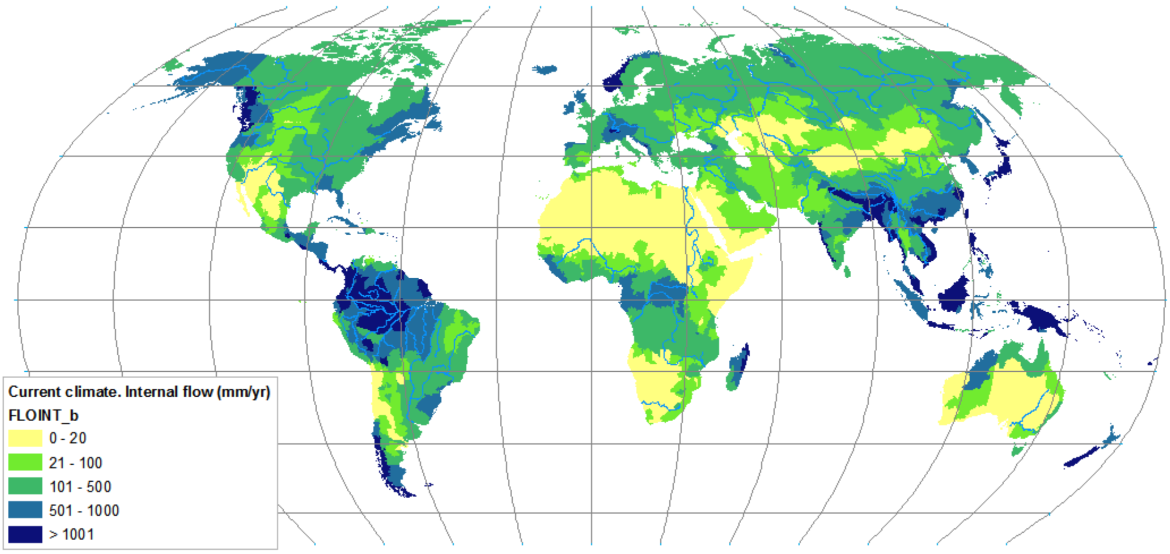


Figure 20: Internal flow (mm/yr) with the current climate

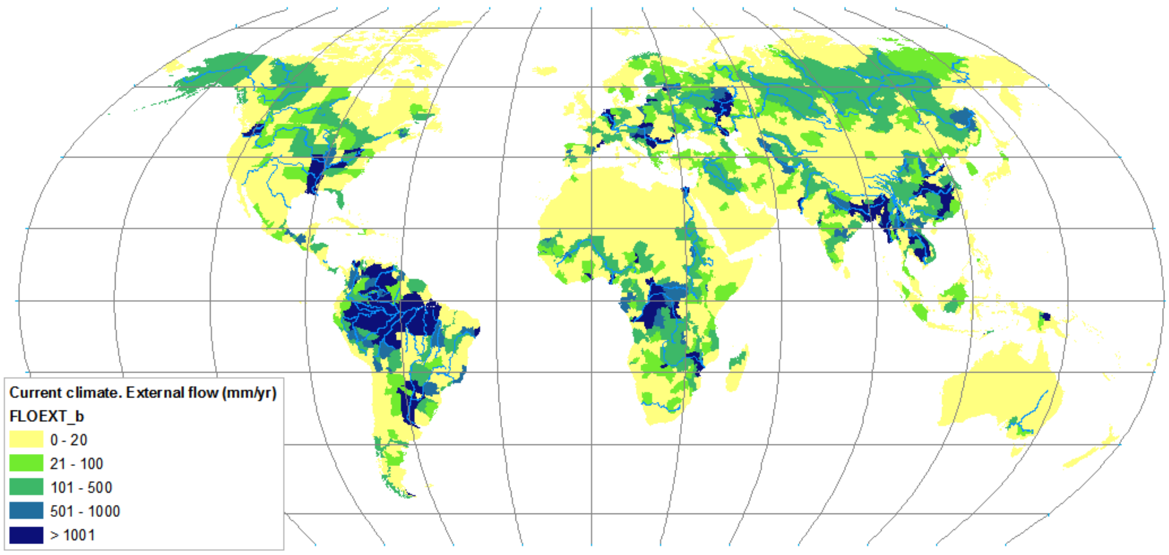


Figure 21: External flow (mm/yr) with the current climate

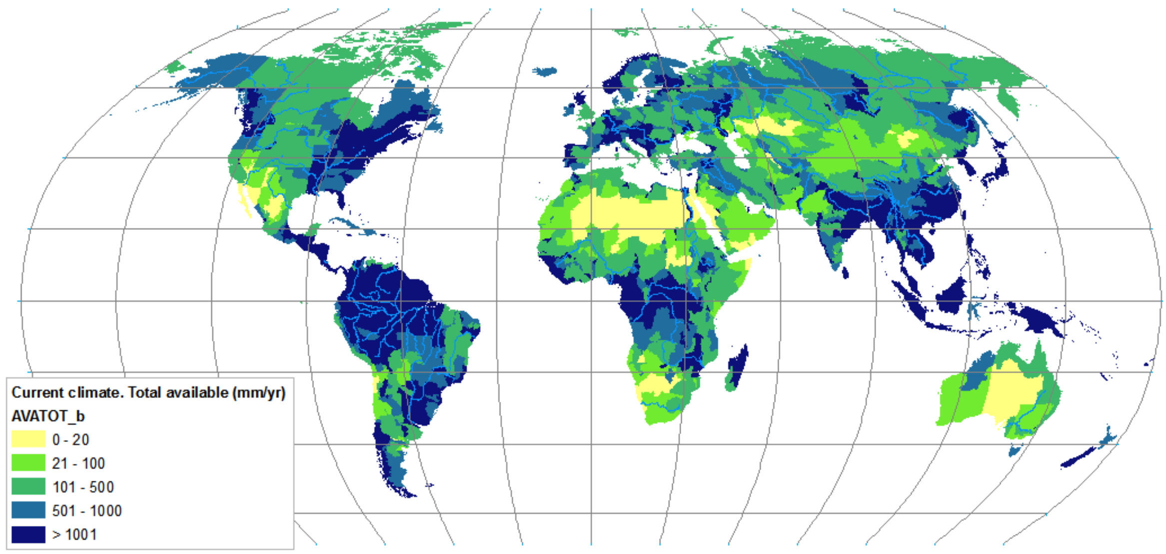


Figure 22: Total available water (mm/yr) with the current climate (total of internal and external water resources)

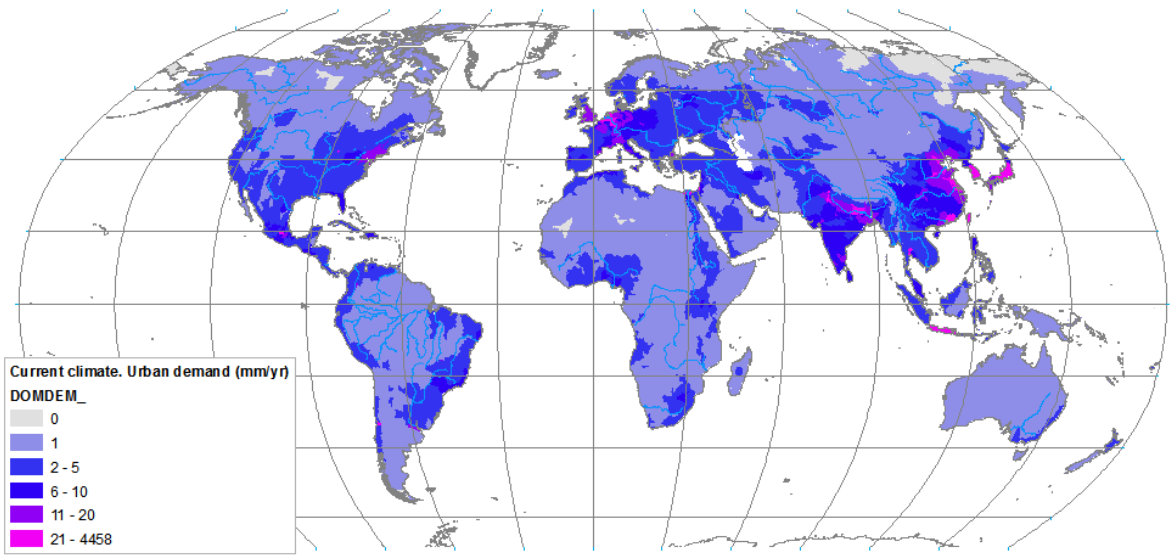


Figure 23: Total domestic demand (mm/yr)

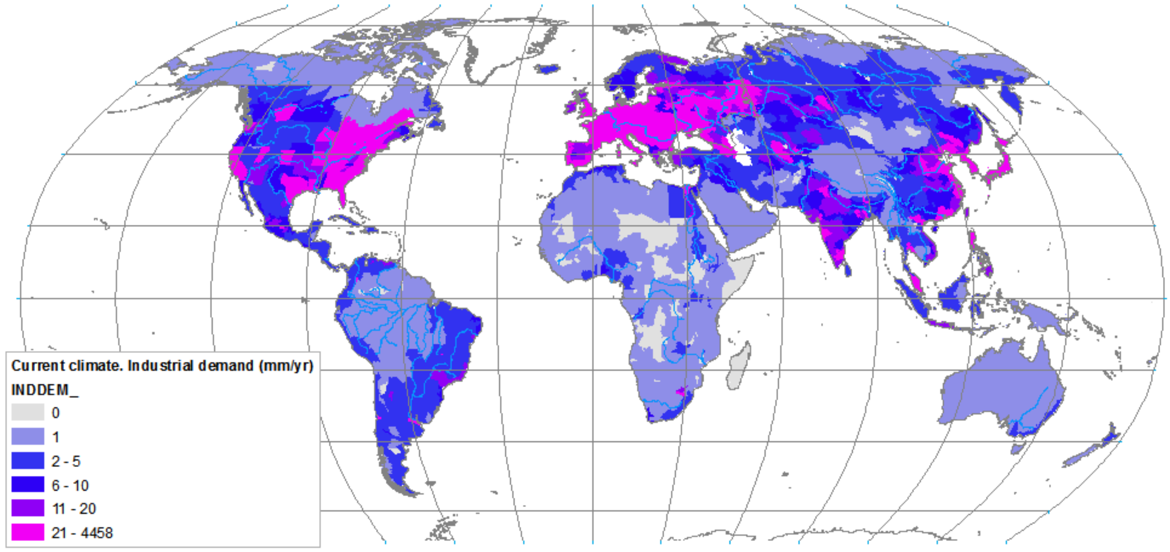


Figure 24: Total industrial demand (mm/yr)

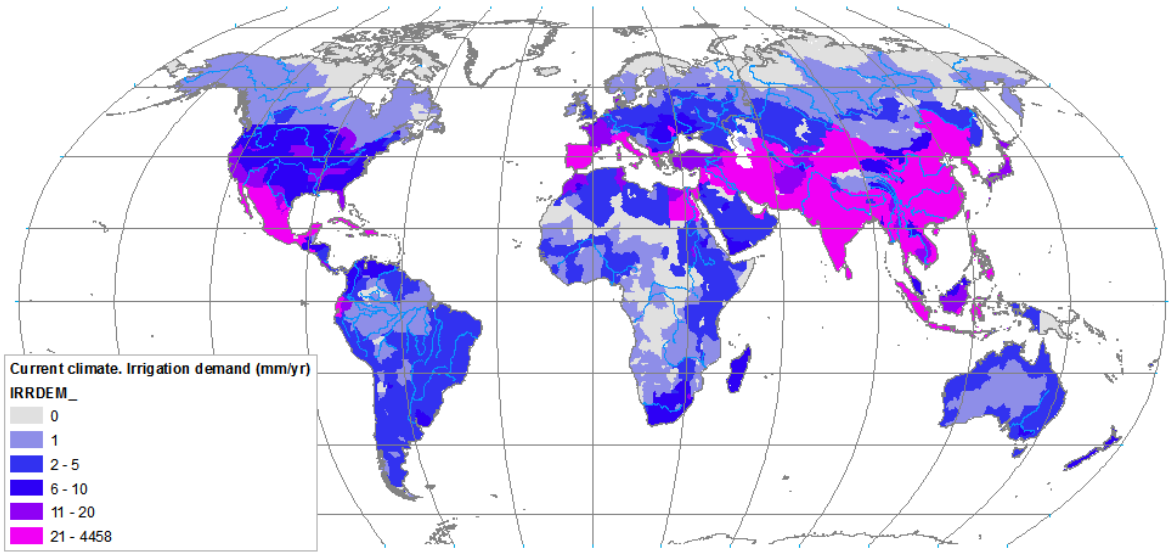


Figure 25: Total irrigation demand (mm/yr)

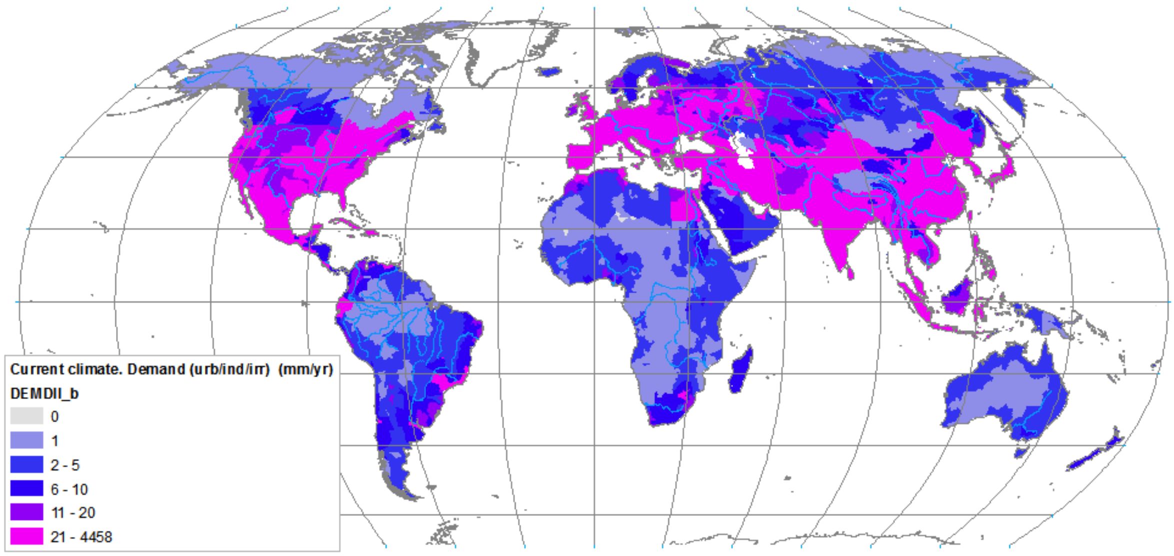


Figure 26: Total urban, industrial and irrigation demand (mm/yr)

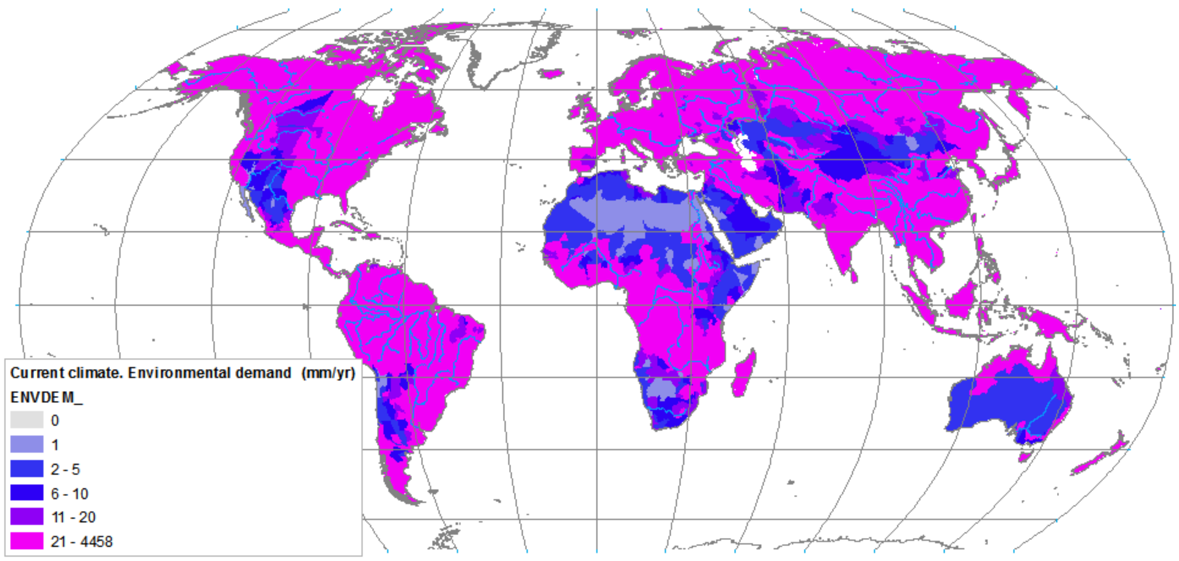


Figure 27: Environmental demand (mm/yr)

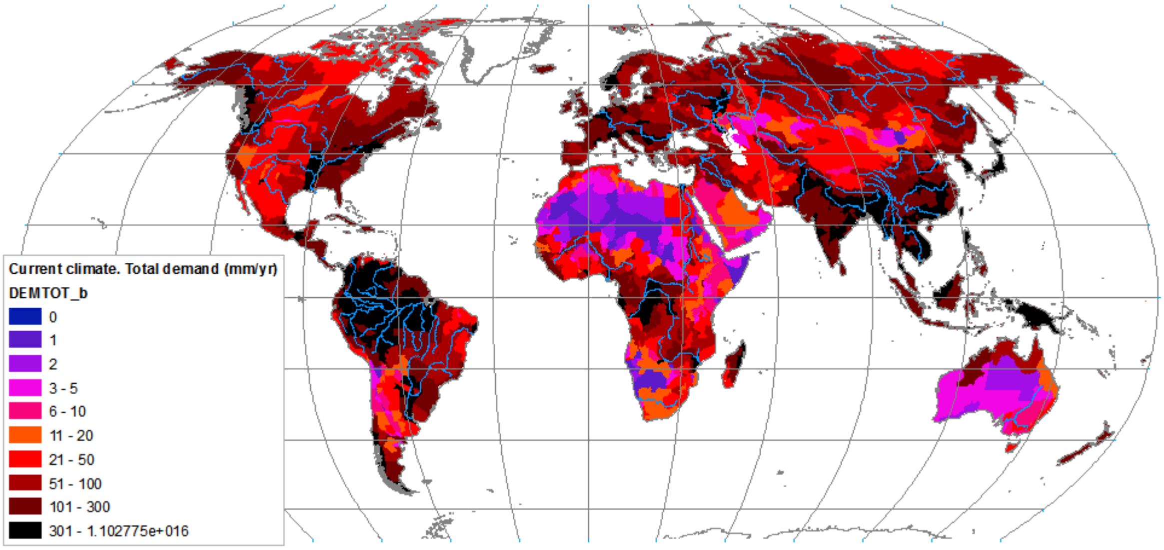


Figure 28: Total demand (mm/yr) with the current climate. In many areas the majority of the demand corresponds to environmental demand (see also next figure)

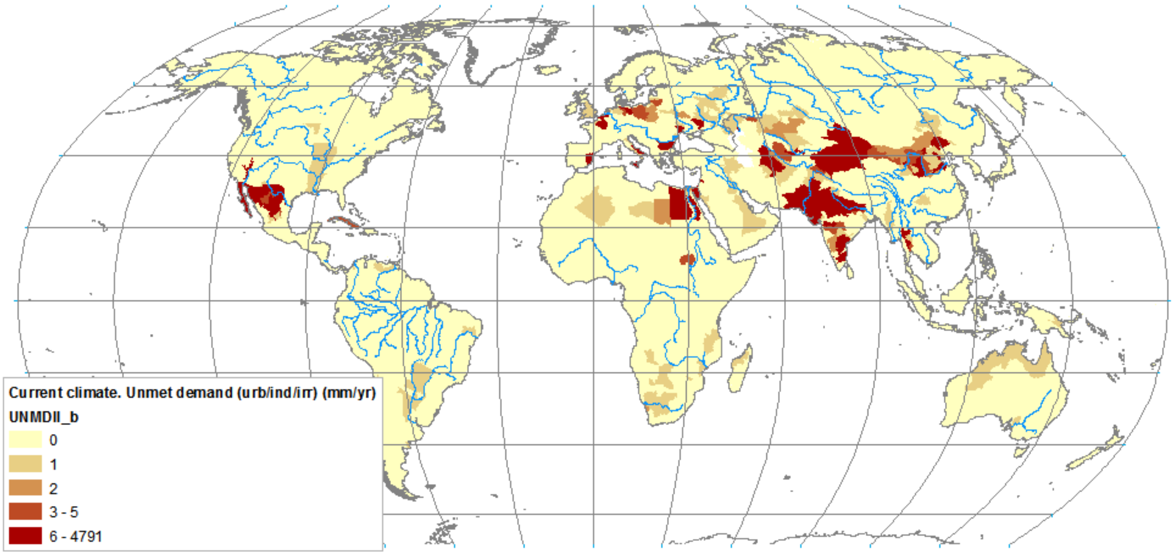


Figure 29: Unmet demand (mm/yr) with the current climate for urban, industrial and irrigation demand, excluding environmental demand

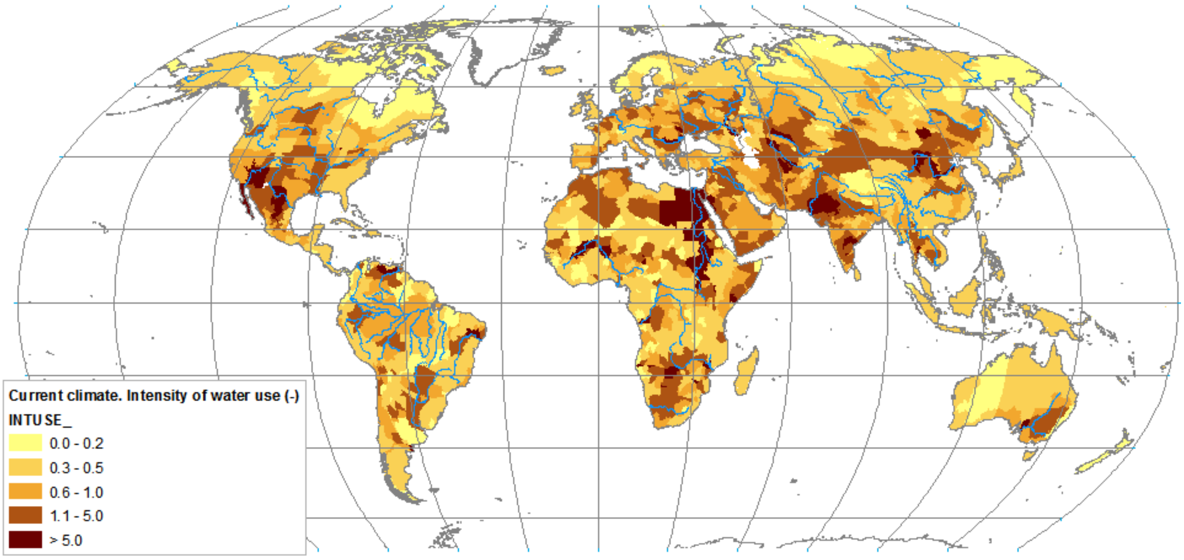


Figure 30: Intensity of water use (total demand divided by internal water resources). Values higher than 1 indicate external reliance.

7.2 FUTURE CLIMATE

Worldwide climate change scenarios were used from the Coupled Model Intercomparison Project (CMIP5), the climate change projections from the IPCC fifth Assessment Report (AR5). These data are bias corrected and used to assess the future water availability based on the PCR-GLOBWB global hydrological model (Van Beek et al. 2011). Then the impacts of the future changes on water demand is analyzed across the irrigation, industrial and domestic sectors using a water allocation model WatCAM.

WatCAM calculates the water demand and supply from 2010 until 2100. The user is able to select the combination of an RCP and SSP for which the calculation will be carried out instantly. This way, decision makers can better understand the impacts of climate change on their water resources, including the uncertainties among the several Representative Concentration Pathways (RCP) and Shared Socioeconomic reference Pathways (SSP's).

This section will give an overview of the maps resulting from the RCP 2.6-SSP 1 combination being a relatively low impact scenario, and the RCP 8.5-SSP 5 combination, a relatively high impact scenario. The following maps show an overview of the changes in supply, demand and the gap between supply and demand that are predicted for both scenarios. All the maps correspond to the period 2070-2099, compared to the baseline situation (2006-2015).

- **Change available:** Figure 31 shows the relative change in internal water resources per water province, for the two RCP-SSP combinations. The maps show very high divergence among each other: in many WPs, the direction of change can be both positive as well as negative.
- **Change demand:** Figure 32 shows relative demand change (domestic, industrial and irrigation). Increase is highest in Africa, but also Asia and South-America have considerable demand change, especially under the high impact scenario (SSP3).

- **Unmet demand:** unmet demand is predicted to increase mainly in California U.S., the MENA region, India and some parts of China. Other areas are South-Africa, Australia and some parts of Europe.

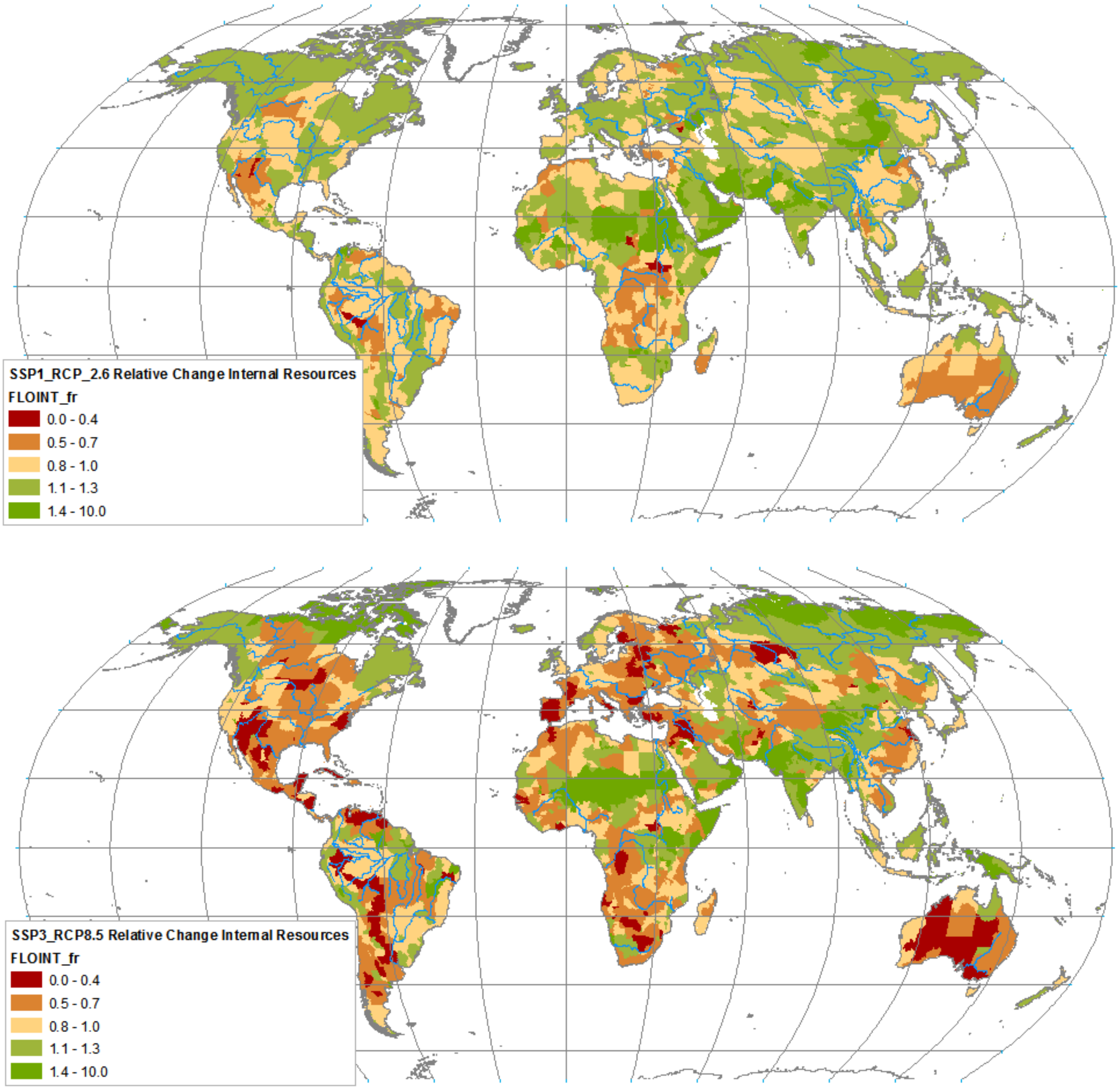


Figure 31: Relative change (future divided by baseline) in total available water for the low impact scenario RCP2.6-SSP1 (up) and a high impact scenario RCP8.5 – SSP3 (down)

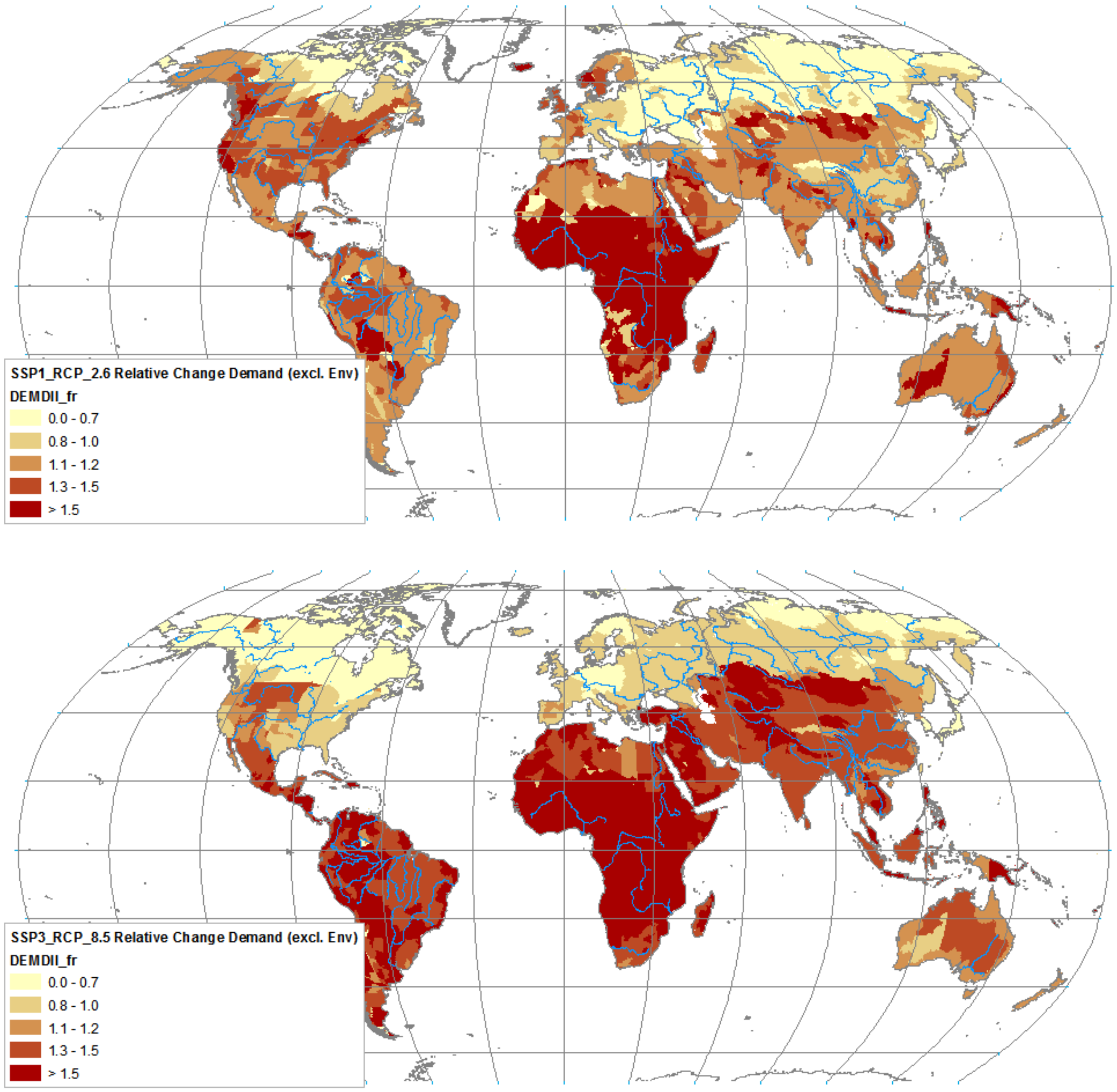


Figure 32: Relative change (future divided by baseline) in total demand for the low impact scenario RCP2.6-SSP1 (up) and a high impact scenario RCP8.5 – SSP3 (down)

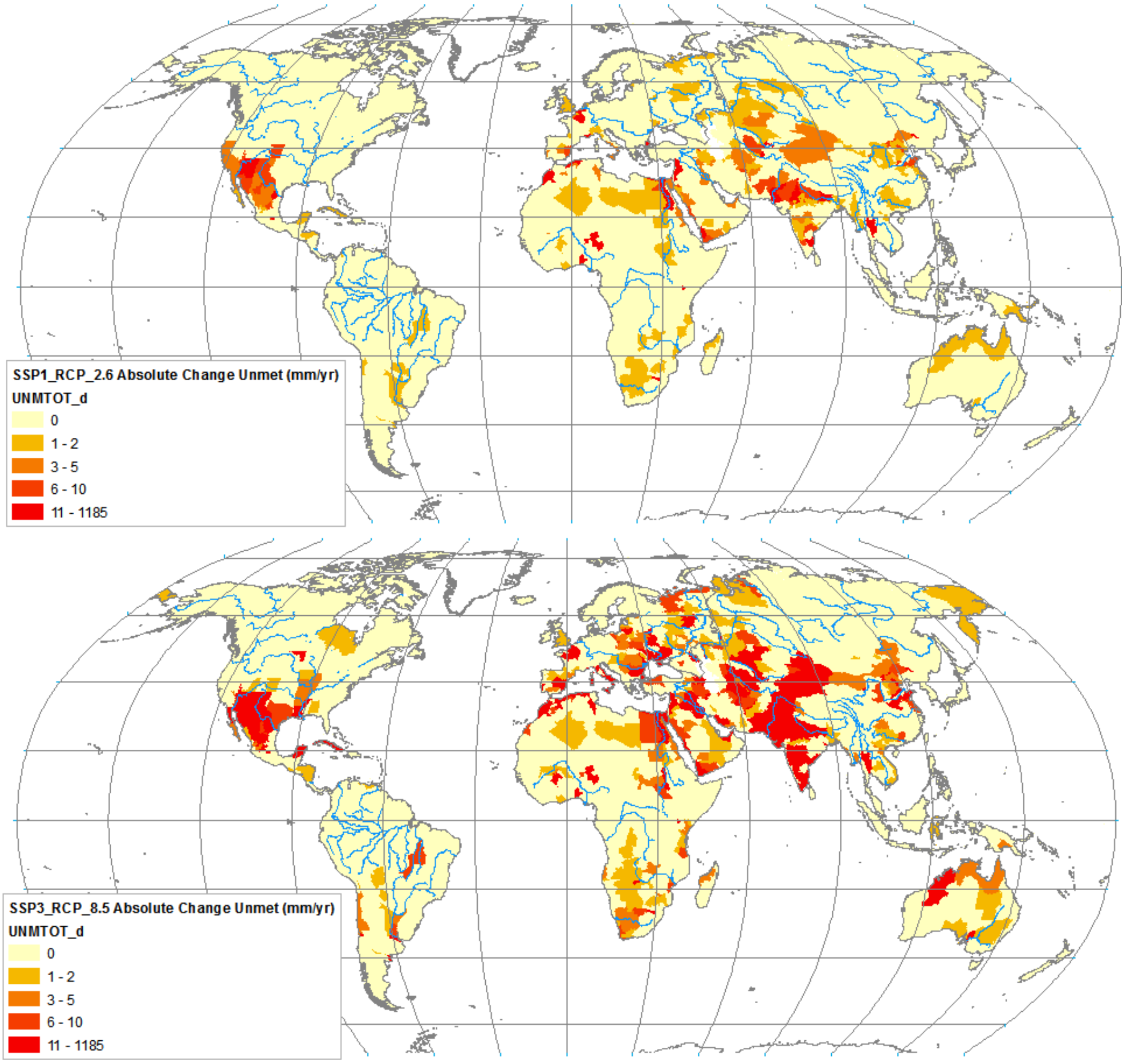


Figure 33: Absolute change (future minus baseline) in total unmet demand (mm/yr) for the low impact scenario RCP2.6-SSP1 (up) and a high impact scenario RCP8.5 – SSP3 (down). A positive number means an increase in unmet demand

7.3 CASE STUDIES

This section shows some case studies, on the water province level, for several selected basins in the world. It shows the main output components of WatCAM, and its functionality. The tool allows studying impacts of upstream changes to downstream areas, taking into account changes in demand and supply due to climate change and adaptation actions.

For these case studies, three future periods were used to show the impacts over time:

- Foreseeable Future (2020-2039)
- Long-term Future (2050-2069)
- Far Horizon Future (2080-2099)

This section shows results for the future scenario combination SSP 3 and RCP8.5.

7.3.1 Nile

For the Nile basin, two water provinces are selected, indicated in the below figure. The first is the Nile delta (992), the second a water province in the Upper Nile (1006 – South Sudan). The arrows below indicate the links from upstream areas contributing water to these two areas. The percentages indicate the part of the total flow leaving the water province that goes to this particular water province.

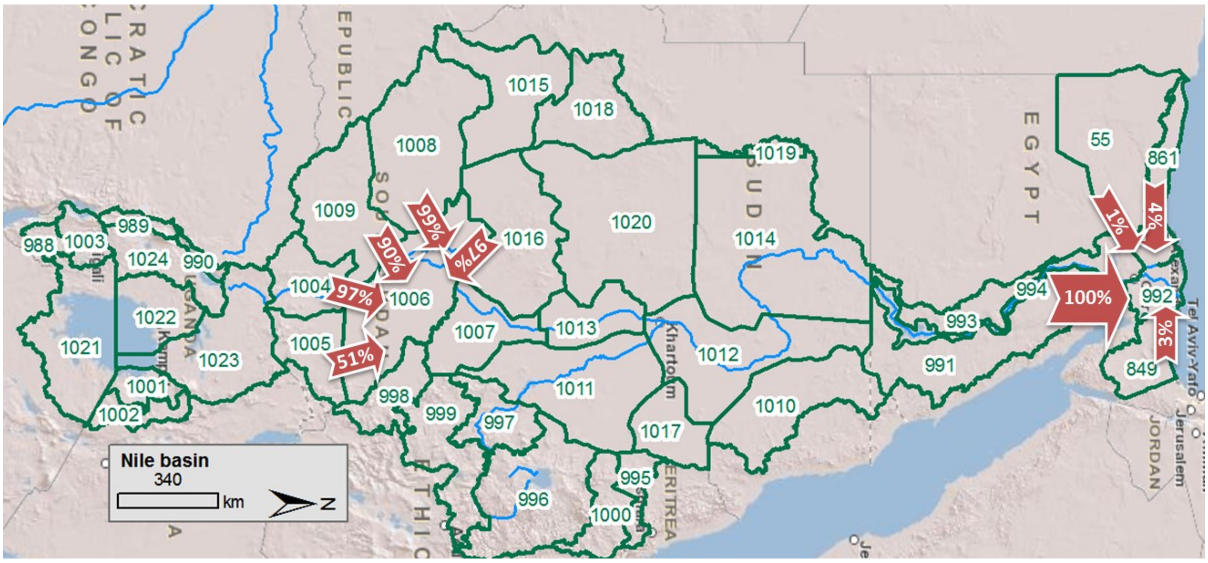
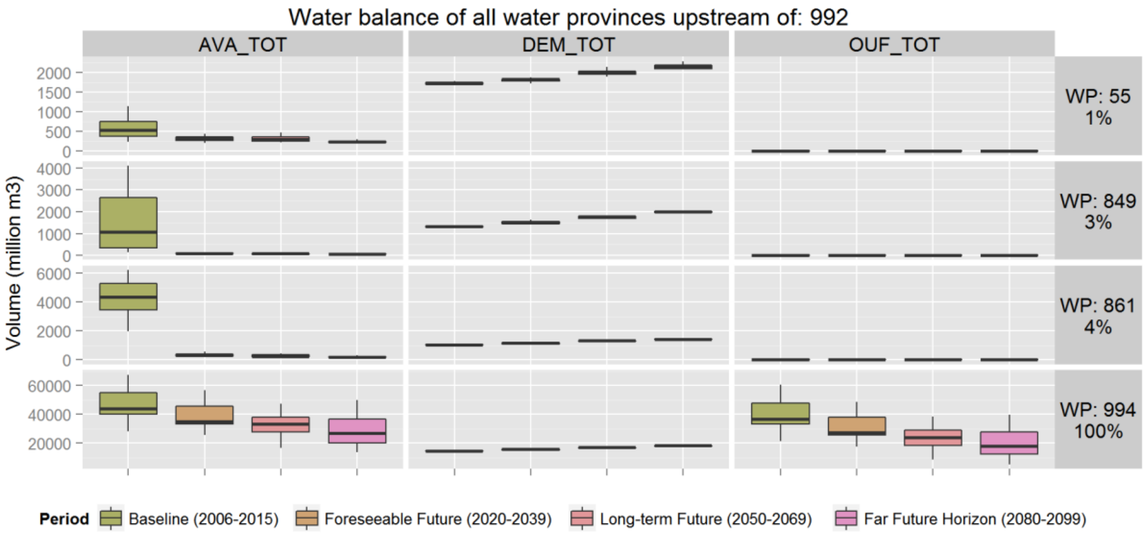


Figure 34: Water provinces IDs of Nile basin, rotated so upstream on the left, downstream on the right.

Figure 35 shows the water balance of the upstream water provinces, and the water province itself for the Nile delta (992). Clearly, the vast majority of the water is coming from the upstream water province on the Nile (994). The upper figure shows a clear impact of climate change on the outflows of this water province. This affects the external flow of the water province 992 (lower figure) leading to a higher unmet demand in the future. Also the demand is increasing for all water provinces in this area.

The lower figure stresses the need for supply-demand gap assessments on the monthly level. For example for the Foreseeable Future horizon, the average supply is much higher than the average demand. However, the variability shown in the boxplot indicates also that there may be months where the available water is lower than the demand. This is confirmed in the most right panel with unmet demand.



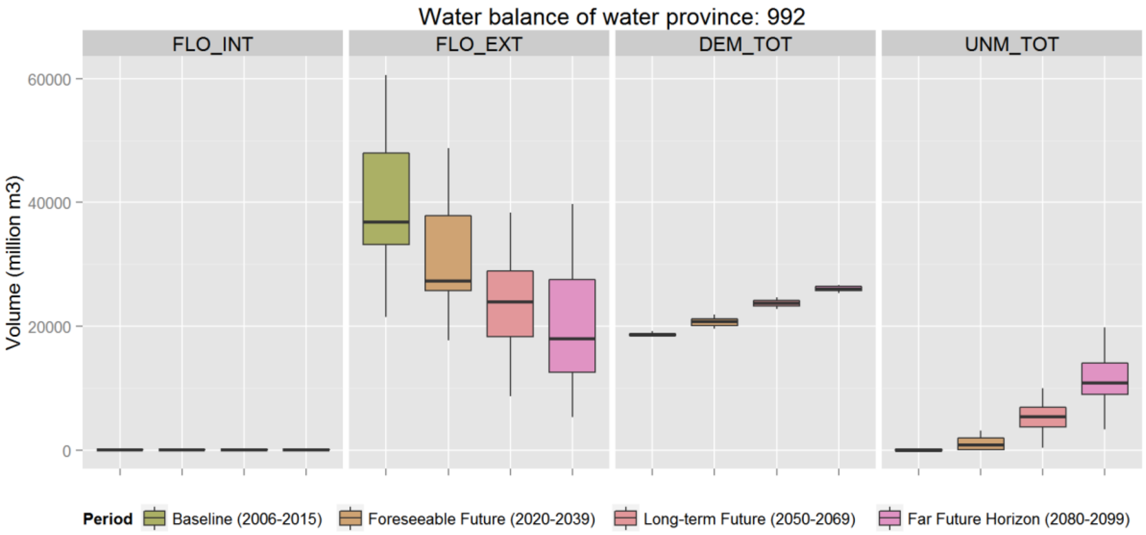
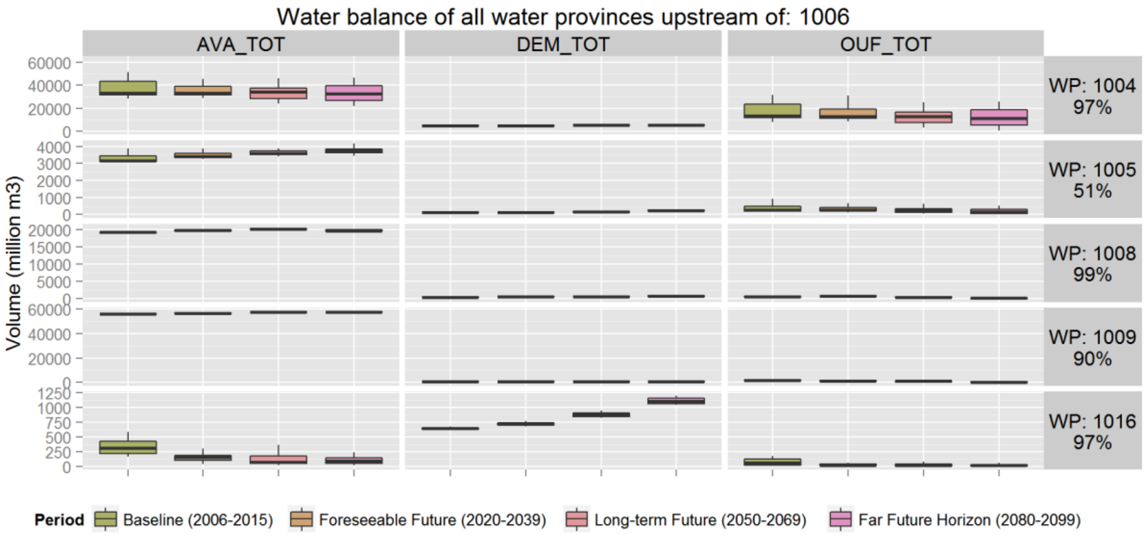


Figure 35: Upper: total available, total demand and outflow from upstream water provinces of water province 992 (Nile delta). Lower: water balance (internal and external flow, demand and unmet demand) of water province 992.

Figure 36 shows the same figures for a water province in the Upper Nile (South Sudan, 1006). In total 5 water provinces provide water to this water province. For some of these water provinces, impacts under this climate change scenario are limited, for others more severe. In total, the flow received by the water province (external flow in the lower figure) is highly reduced. This, together with an increase in demand, this leads for the Far Future Horizon to an unmet demand.



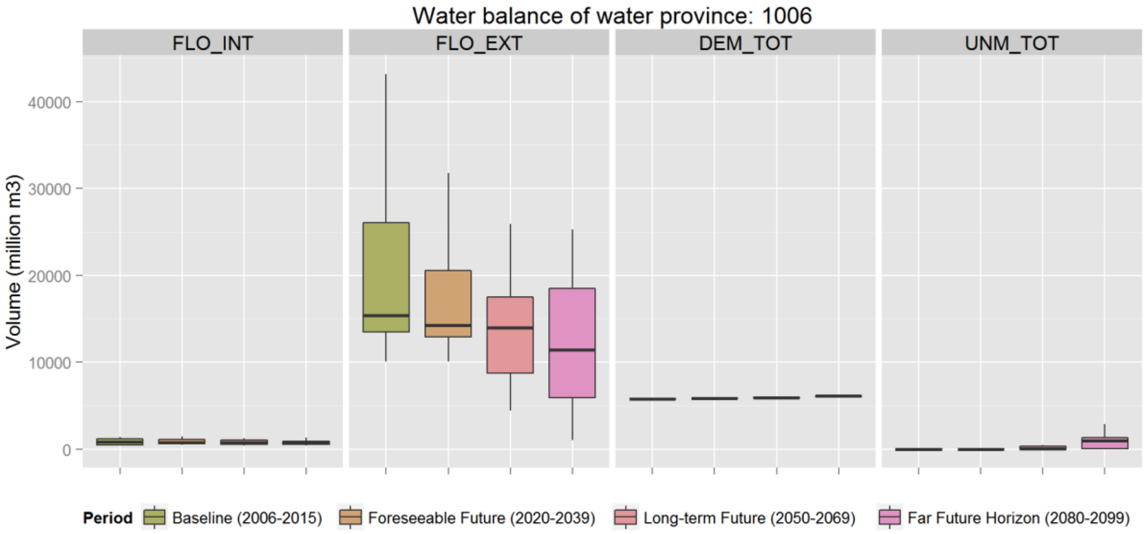


Figure 36: Upper: total available, total demand and outflow from upstream water provinces of water province 1006 (South Sudan). Lower: water balance (internal and external flow, demand and unmet demand) of water province 1006.

7.3.2 Red River

The following case study is for the Red River basin, Vietnam. The map below shows all the links, and the part of the outflow that flows to the selected water province (637). Figure 38 shows that most of the water comes from the upstream water province on the Red River, 636 (99% of outflow of this area).

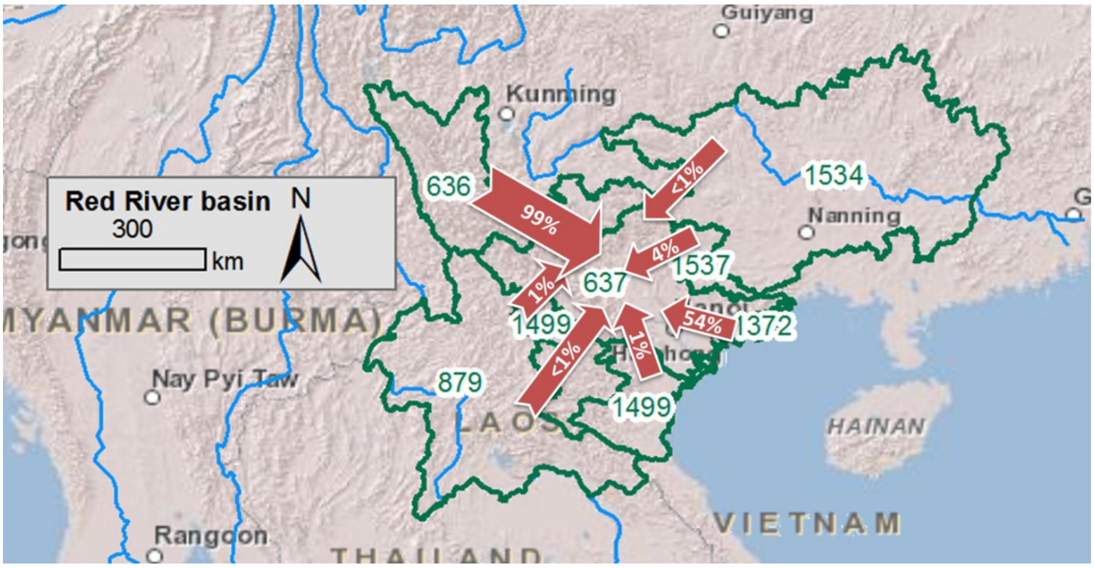
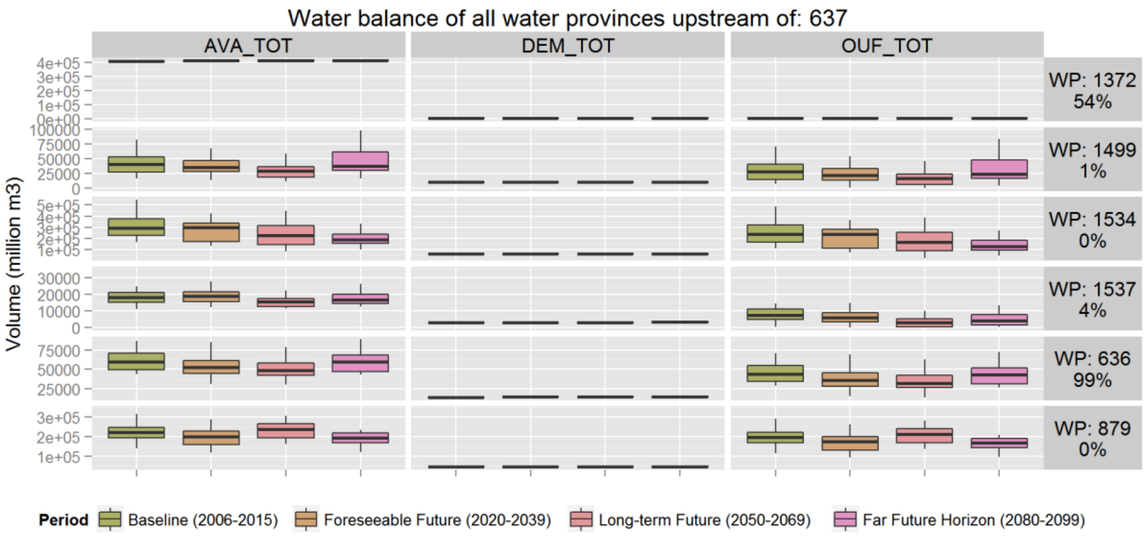


Figure 37: Water provinces IDs of the Red River basin and connected water provinces

The future trend under climate change in terms of flows is negative, although for the far horizon future an increase is again predicted under this particular scenario. This is mainly due to an increase in water being received from the upstream water province 636. Demand increases under this scenario in most of the water provinces, although the changes are small compared to those in available water.



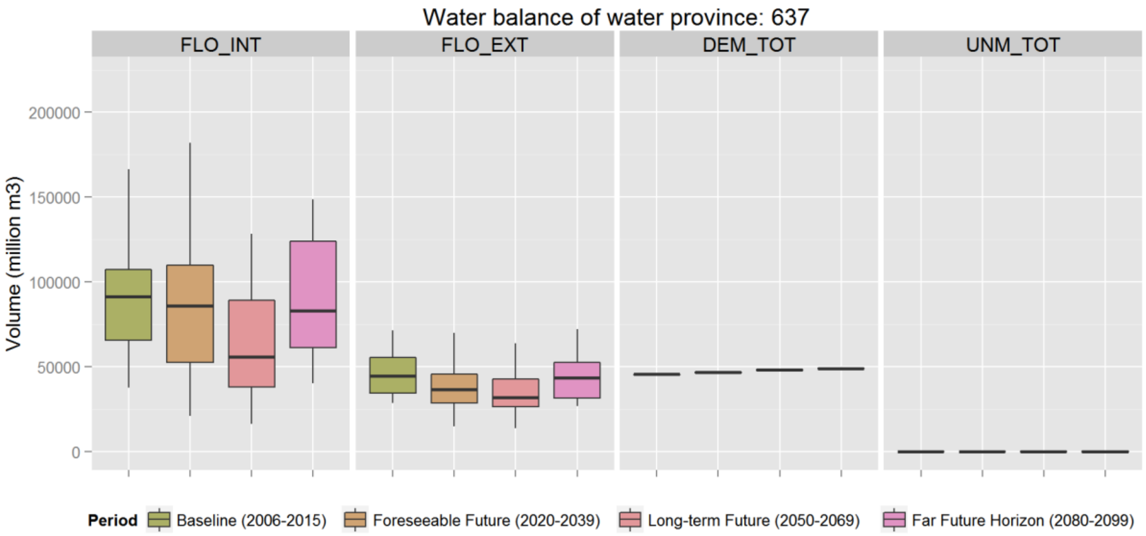


Figure 38: Upper: total available, total demand and outflow from upstream water provinces of water province 637 (Red River, downstream). Lower: water balance (internal and external flow, demand and unmet demand) of this water province.

7.3.3 Indus

For the Lower Indus (water province 673), the map in Figure 37 shows the links with the upstream water provinces and the part of their outflows contributing to the external flow received by 673.

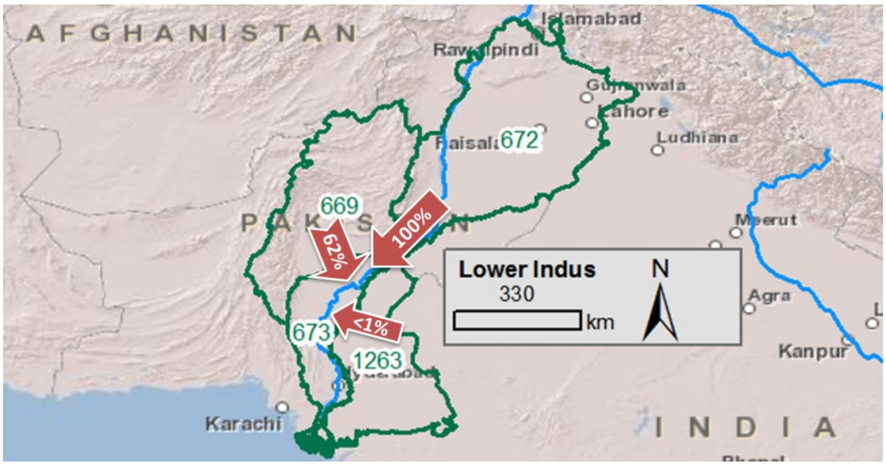
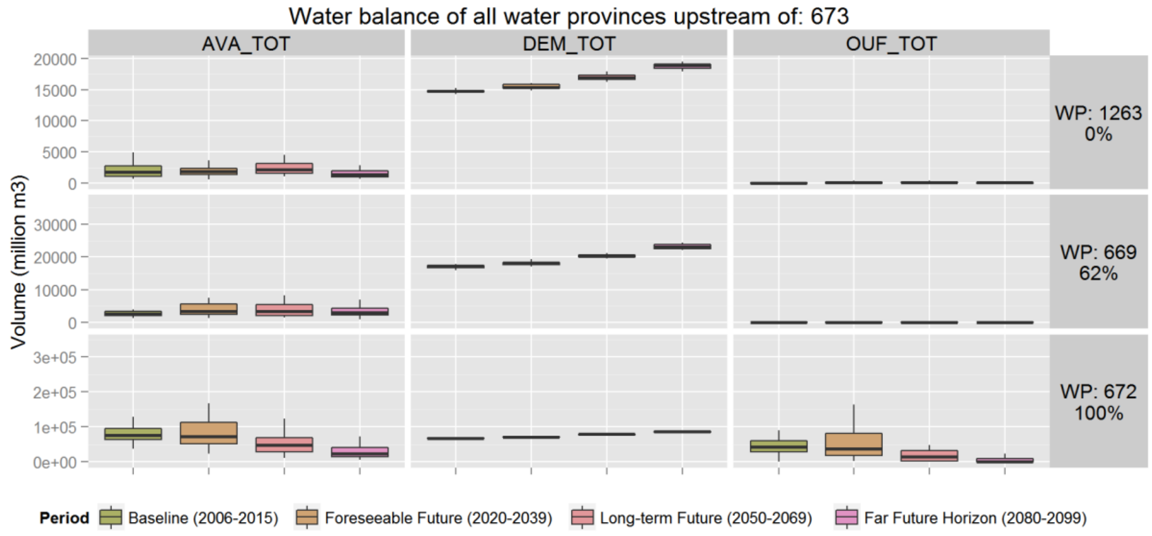


Figure 39: Water provinces IDs and connections to 673 in the Lower Indus basin.

Figure 38 shows how the changes in water availability of the contributing upstream water provinces and changes in demand, affect the outflows of these water provinces and thus the flows received (FLO_EXT) by the water province 673. The unmet demand is predicted to increase considerably under this scenario (SSPP3 and RCP8.5), also due to changes internal demand (DEM_TOT in the lower figure).



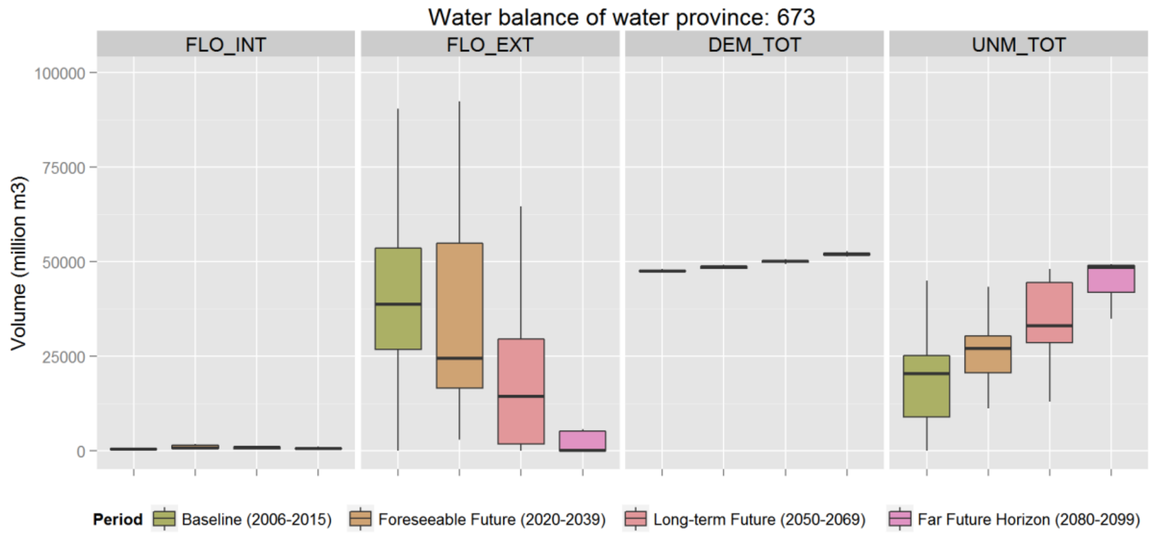


Figure 40: Upper: total available, total demand and outflow from upstream water provinces of water province 673 (Lower Indus). Lower: water balance (internal and external flow, demand and unmet demand) of this water province.

7.3.4 Mekong

For the Mekong river basin, the functioning of WatCAM is represented here in a different way, showing the interactions of several water provinces in cascade. For all water provinces of the Upper Mekong (see lower map) the main incoming and outgoing components of the water balance are shown. For the incoming this corresponds to internal and external resources (differences in reservoir and groundwater storage are not shown here) and for outgoing this corresponds to supplied water and water leaving the water province as outflow.

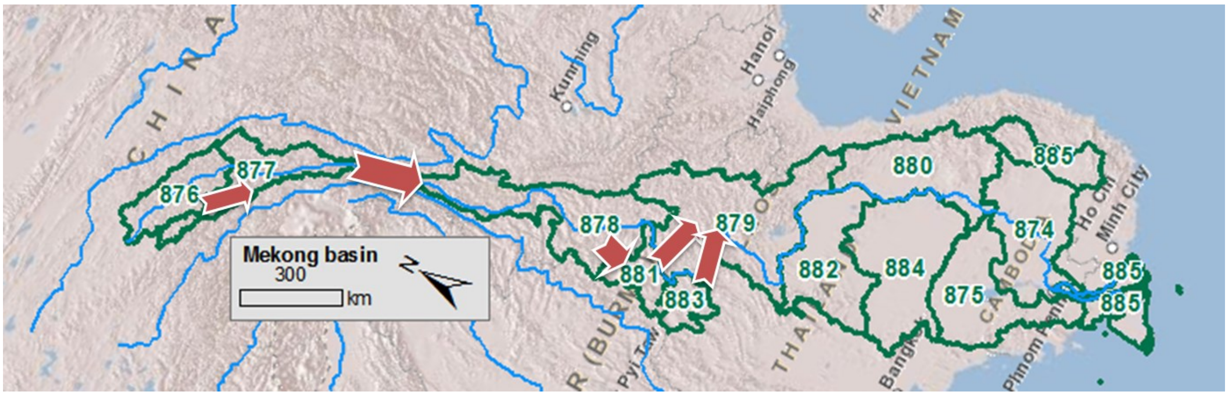


Figure 41: Water provinces IDs of Mekong basin, rotated so upstream on the left, downstream on the right.

From Figure 42 it can be seen that outflows from one water province feed into the downstream water province as external flow. Also the figure shows how changes in upstream flows propagate to downstream water resources availability. The upper panels show the outcomes for the current climate, the panels in the middle for a low impact scenario (SSP1 RCP2.6), and the lower panels for a high impact scenario (SPP3, RCP8.5)

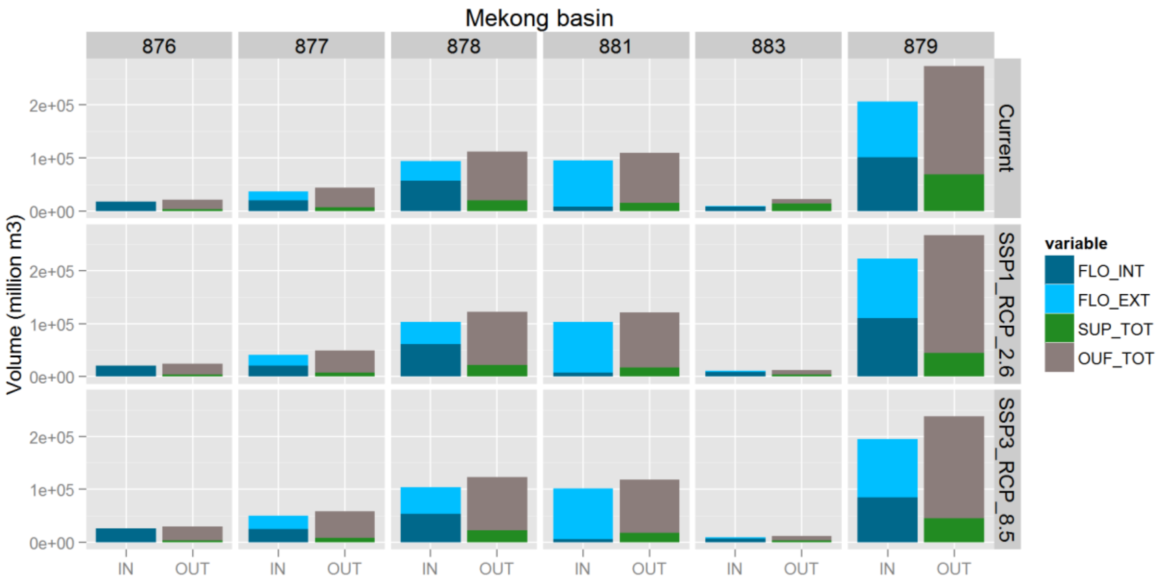


Figure 42: Main components of incoming (internal and external flow) and outgoing (supply and outflow) of the water balance under three climate scenarios: current (upper panels) and low and high impact future scenarios (resp. middle and lower panels). From left to right a selection of the water provinces from upstream to downstream.

7.3.5 SE-Spain

The Water Province covering southeastern Spain includes two basins: Segura and Jucar. To show the flexibility of WatCAM and the possibility to adapt the tool by including local data, this section shows the changes in output after several modifications of the default parameters and inputs of WatCAM for this particular water province (ID: 1400). Figure 43 shows the selected WP in the Water2Invest web-interface.

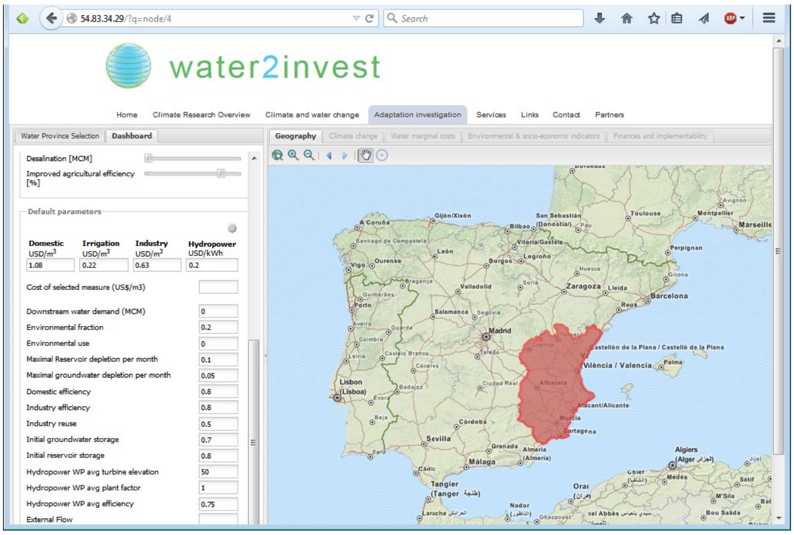


Figure 43. Water province 1400, SE-Spain, and default parameters as in the web-interface

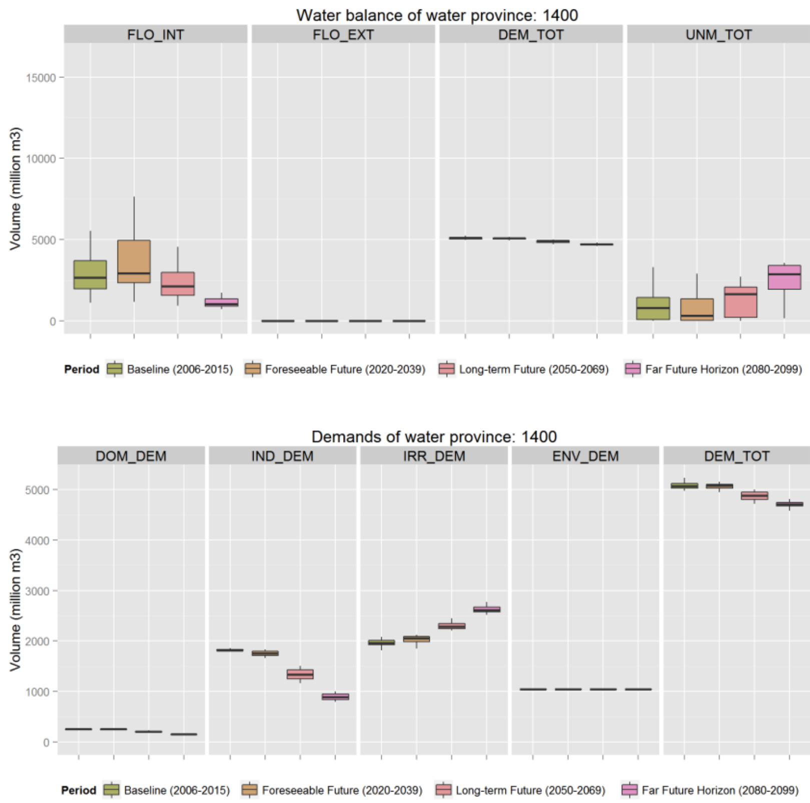


Figure 44. The water balance of water province 1400, SE-Spain, from a run based on the default parameters in WatCAM.

The default configuration for this water province does not include an inter-basin water transfer (trasvase Tajo-Segura) from the Upper Tagus to the Segura basin. On average, around 300 MCM/yr, are transferred from the Tagus to the Segura basin. This external flow can be added to WatCAM by modifying the file that determines the water province topology (WatProv.csv). For this case study, it was assumed that on average 30% of the water in the Upper Tagus becomes external flow of the SE-Spain water province.

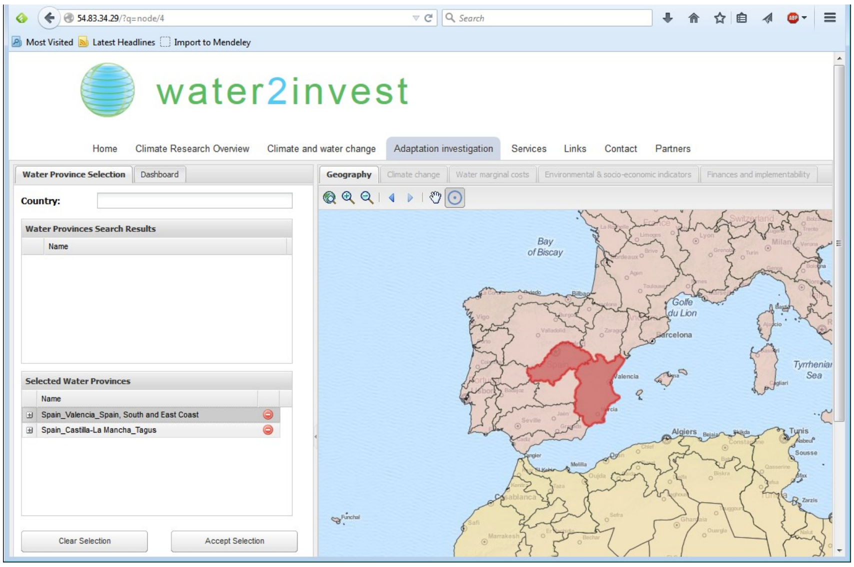


Figure 45. The SE-Spain water province and the connected Upper Tagus water province in the web-interface

Comparing data for demands with the two River Basin Management Plans currently in vigor (2010), the irrigation demands resulted to be under-estimated using the global estimation approach, while the industrial demands were over-estimated. These input variables were changed in the corresponding input files (for resp. irrigated area and monthly industrial demand). The following table shows the original baseline values of some of the parameters and variables of WatCAM, and the local data that was used to change the parameters and input variables in WatCAM.

Source	WatCAM default (Segura/Jucar)	Local (Segura RBMP)	Local (Jucar RBMP)	WatCAM local (Segura/ Jucar)
Domestic demand	**252**	105	548	**653**
Industrial demand	**1827**	50	83	**133**
Irrigation demand	**1974**	1400	2528	**3928**
Total demand	**4053**	1555	3159	**4714**
External from Tagus	**0**	300	0	**300**

The impacts on the water balance of the modified inputs are shown in Figure 46, predicting higher demands in general. The external flow is around 300 MCM for the baseline, but is predicted to be reduced drastically under this particular RCP-SSP scenario. Unmet demands are also higher than in the run with the default parameters.

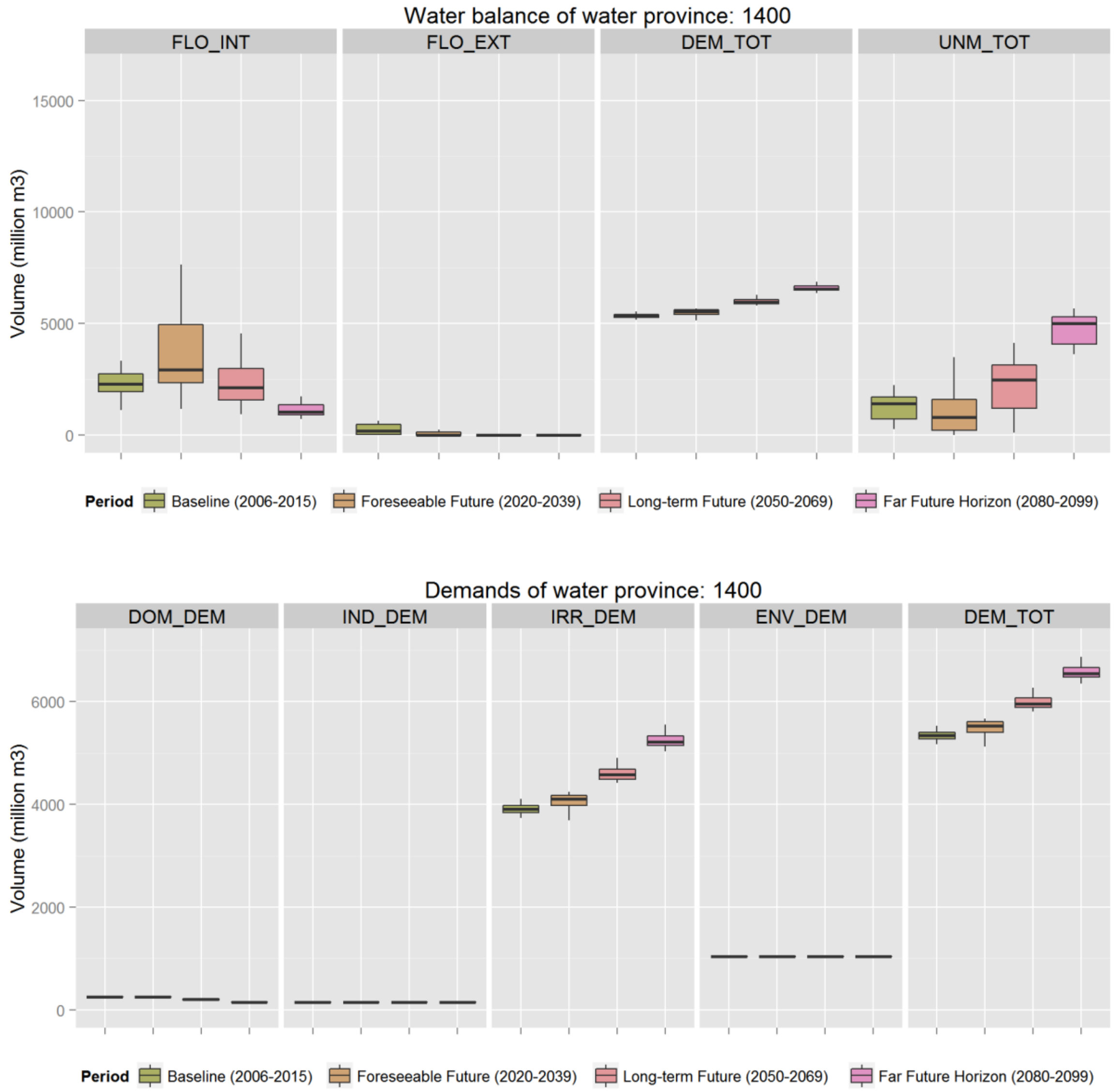


Figure 46. The water balance of water province 1400, SE-Spain, from a run based on the locally modified parameters in WatCAM.

7.4 WATER MARGINAL COST CURVES

7.4.1 Introduction

The cost-effectiveness of various measures to close the supply-demand gap will be compared in this study by means of the “water-marginal cost curve”, similar to the approach of the 2030 Water Resources Group (2009), and similar to the so-called marginal abatement cost curves widely used in evaluations on measures to reduce emissions of greenhouse gases. This cost curve shows the cost and potential of a range of different measures- spanning both productivity improvements and supply expansion – to close the gap. Such a water-marginal cost curve is estimated for each water province to assess the total costs to close the supply-demand gap projected under various climate change scenarios.

Each of these measures is represented as a block on the curve. The width of the block represents the amount of incremental water that becomes available from adoption of the measure. The wider a measure, the larger its net impact on water availability. The height of the block represents its unit cost[7] in US$ per m^3. The vertical axis measures the financial cost –or savings- per unit of water released by each measure. This is the annualized capital cost, plus the net operating cost compared to business as usual. The unit costs are ordered from the lowest costs to the highest on the cost curve.

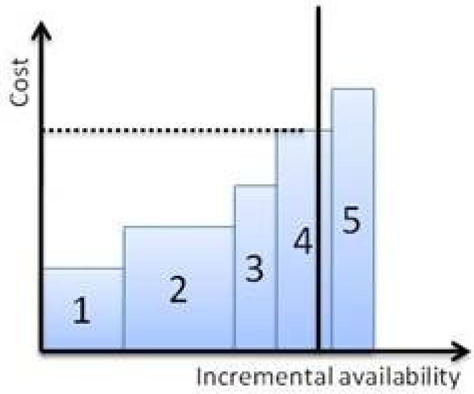


Figure 47. Schematic representation of the cost curve.

In applying the cost curve in the various water provinces, the net impact of each measure on water availability is estimated, taking into account return flows. This is especially important for drip irrigation, as at farm level it can have massive efficiency impacts but at an aggregate level the impact could be different: by reducing return flows, this measure could actually reduce the supply available to others and therefore diminish the true aggregate impact on closing the gap.

It is important to note that the cost curve's use is limited to comparing measures' financial cost and technical potential to close the gap. It does not include or evaluate policies that would be used to enable, incentivize, or enforce the adoption of those measures such as pricing, standards, and behavioral changes. Rather, it provides information on what the cost would be of adopting a set of technical measures, which in turn can be used to inform policy design. Of course, cost is not the only basis on which choices are made, but shedding light on the cost and technical potential of measures allows these to be compared and evaluated in a common context. The cost curve, then, is not prescriptive: it does not represent what the plan for closing the supply-demand gap ought to be. Rather, it should be considered as a tool to help decision-makers understand and compare different options for closing the gap under a given demand scenario. It is therefore important to emphasize that the estimates generated by the cost curve are not explicit predictions, but approximate guides to decision-making.

7.4.2 Adaptation measures and costs

The challenge is to become sustainable by closing the gap between projected future water demand and current supply. Three core ways of matching water supply and demand are distinguished:

[7] All values are annualized and presented as US$ 2010 prices.

- increasing the productivity of existing water use;
- expanding supply; and
- reducing demand by shifting the economy towards less water-intensive activities.

Increasing the water productivity of existing activities entails here producing the same output with less water. The following seven potential measures are assessed in this study:

Increasing the productivity:
- A: Improved agricultural practice (including crop varieties)
- B: Increased reuse of water from domestic and industry
- C: Increased reuse of irrigated agriculture

Expanding supply:
- D: Expanding reservoir capacity
- E: Desalinisation

Reducing demand:
- F: Reduce irrigated areas
- G: Reduce domestic and industrial demand

The total annual costs for the combined set of measures can be calculated by multiplying the specified deficit by the unit cost of each block required to close the gap. The considered unit cost of each measure is presented below. As there are a large number of measures and a lot of uncertainty about the costs of these measures in the various countries in the future, some crude assumptions have to be made in this study.

A) For **improved agricultural practices** that increase the productivity of water a unit cost of 0.02 $\$/m^3$ is considered. There are varies kinds of improved agricultural practices, such as drip and sprinkler irrigation, no-till farming and improved drainage, utilization of the best available germplasm or other seed development, optimizing fertilizer use, innovative crop protection technologies and extension services. Costs of such measures vary, but are relatively cheap compared to the water supply measures. Some of the productivity measures can even result in a net cost saving, when operating savings of the measures outweigh annualized capital costs. The 2030 Water Resource Group shows that the majority of the costs of such measures are in the range of 0.02 $\$/m^3$ to 0.03 $\$/m^3$. Converting this to costs per hectare (assuming on average 1000 mm of water consumption per hectare) is US$ 200 to US$ 300 per hectare per year.

Obviously, these costs can vary and are measure dependent. For example, for the Irrigation Improvement Project (IIP) in Egypt the average IIP improvement costs were exceeding LE 6,000 per feddan on average. This is about US$ 2500 per hectare[8]. Taking into account depreciation costs on investment of 25 years gives annualized capital costs of about US$ 100 per hectare.

[8] one Feddan is 4200 m2, one LE is US$ 0.17

B) The unit cost of **increased reuse of domestic and industrial water** depends on the treatment level. According to the 2030 Water Resources Group the unit cost of municipal and industrial waste water reuse is on average **0.30 $/m^3 (**see Exhibit 24 on Page 77).

C: The unit costs of **increased reuse of irrigation water** are assumed to be 0.04 $/m^3 (2030 Water Resources Group, Exhibit 23 on Page 75). These costs are relatively low as it was assumed that this water is only reused for agricultural purposes so that no additional treatment is necessary. The price of 0.04 $/m^3 is based on

- Reuse of 50 mm = 500 m^3 per ha / year
- Investment costs of $ 1000 /ha
- Annualized capital costs (investment over 10 years) $ 100 / ha / year; for 500 m^3 = 0.02 $/m^3
- Annual operational costs (maintenance, pumping) of 0.02 $/m^3

D): The costs of **expanding reservoir capacity** are taken to be 0.04 $/m^3 . this is an average of the price for large and small reservoir strucutres. (2030 Water Resource Group, Exhibit 7, page 48). Obviously these costs can vary from region. For example according to Di Prima (2007), who reviewed experience with sand dams in Kitui District, Kenya, their construction cost is relatively high: currently around US$ 10,000 for each dam to provide an average of 5-8,000 cubic meters of water each season for (potentially) 50 years or more. This means 0.04 $/m3 (World Bank, 2010)

The Aslantas Dam in Turkey is an example of a large dam. The annual recovery charge on investment of the Aslantas Dam is estimated on $ 350 per ha per year. Assuming a 1000 mm per year (10,000 m3 per ha) means 0.035 $/m3 (World Commission on Dams, p. 48)

E) The costs of **desalination by means of concentrating solar power (CSP)** for seawater desalination are assumed to decrease over time from currently 1.50 $/m^3 to 0.90 $/m^3 in 2010 and 2050 (Trieb and Muller-Steinhagen, 2008; Trieb et al., 2011). It is assumed that installed capacity is only sufficient for domestic water in 2030, and for industrial use as well in 2050.
The potential additional costs due to externality costs, such as costs used for mitigation against environmental impacts, and subsidies for example of energy cost, are partly taken into consideration but varies from country to country (Trieb et al., 2011).
The costs of **desalination by means of fossil fuel** is assumed to be 1.00 $/m^3 currently and will increase to 1.20 $/m^3 in 2050. In the case of reverse osmosis and fossil fuel half of the costs consist of energy costs (Trieb et al., 2011). There is, however, uncertainty about both the energy price as well as energy requirements in the future among others as a result of the development of crude oil prices and technological breakthrough. Within this study an average price is used of 1.20 $/m^3

F) The unit cost of **reduced irrigated areas** is assumed to be of 0.10 $/m^3, as the value of irrigation water ranges usually between 0.05 $/m^3 and 0.15 $/m^3 (Hellegers, 2006) and foregone benefits can be considered as unit costs. This value is, of course, strongly dependent on the price of agricultural products, which in turn are strongly affected by interventions of governments and trading blocs.

G) The unit cost of **reduced domestic and industrial demand** is assumed to be 2.00 $/m^3$. While drinking water is a necessity of life, its value can be expected to be very high. The other uses of water within households, which make life more comfortable, and industry can be expected to have lower values (Young, 2005) The foregone benefits of moving for instance towards less water-intensive industries can be considered as unit costs of reduced industrial demand.

7.4.3 Case study examples

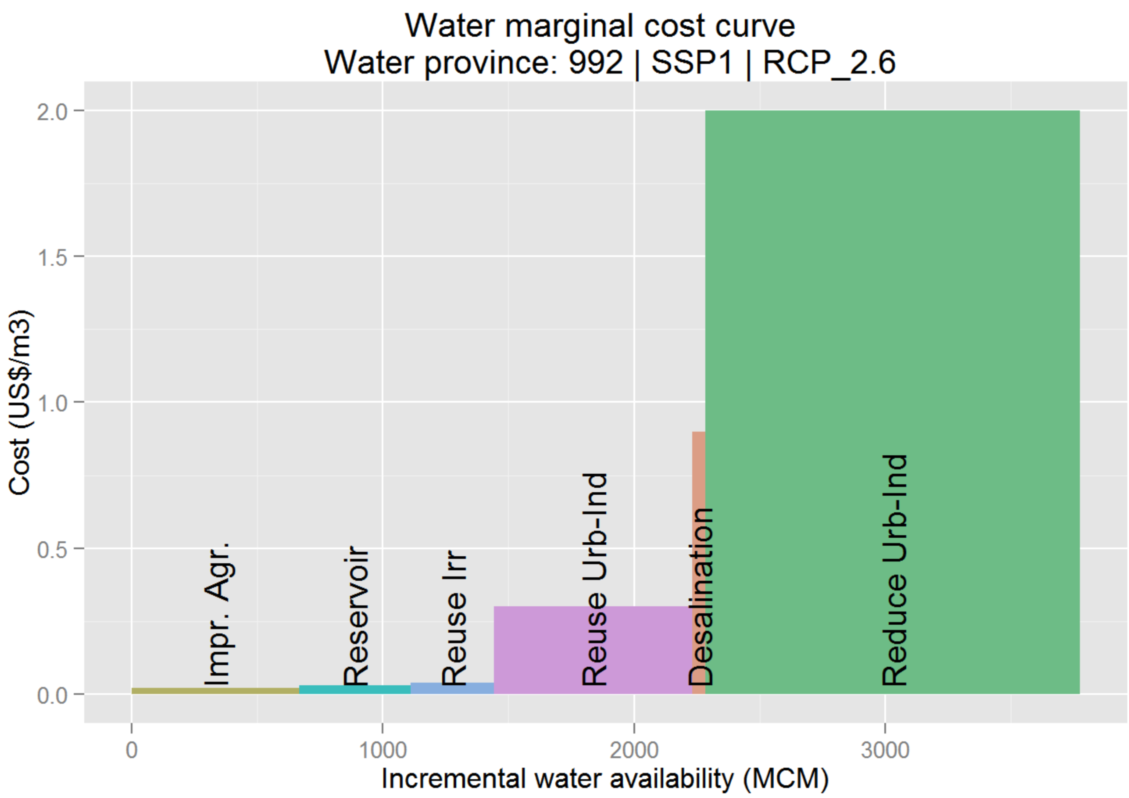
Within the web tool the water marginal cost curve is created for the user. To avoid superposition among the measures a set of runs will be conducted, starting from the cheapest and adding one more measure at a time. The extra water availability will be assigned to the measure added. This section shows some examples of the water marginal cost curves for some of the case studies presented earlier.

The following examples are based on global values for costs and need to be taken with caution. The WatCAM approach allows more detailed assessments with a higher spatial resolution and local information on costs and possibilities for adaptation. The web-user-interface allows changing costs and other default parameters.

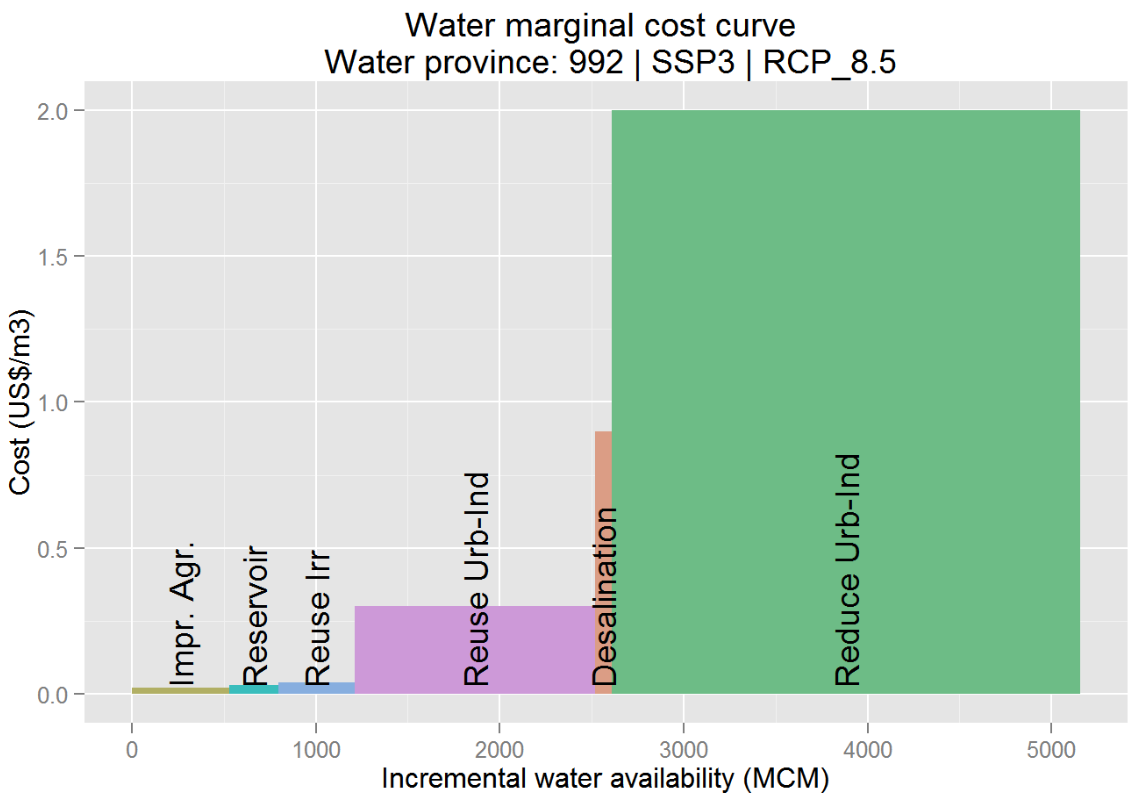
Some discussion on the below examples:

- The examples in the Nile basin show that if all measures are implemented, unmet demand can be reduced with around 50%, for both studied RCP-SSP scenarios. So the studied adaptation options here are not able to balance supply and demand completely if only action is taken in the water province itself. The results suggest that upstream adaptation options should be included and a cross-boundary (water province-wise at least) strategy is necessary.
- For the Red River example, under the low impact RCP-SSP scenario, the adaptation measures are able to balance supply and demand completely, without the need to implement the most costly measure (reduction of urban and industrial demand). For the high impact scenario this measure is necessary and still some unmet demand remains.
- For the Mekong example, only the first adaptation measure (Improved agricultural practices) is necessary to take away unmet demand and balance supply and demand.

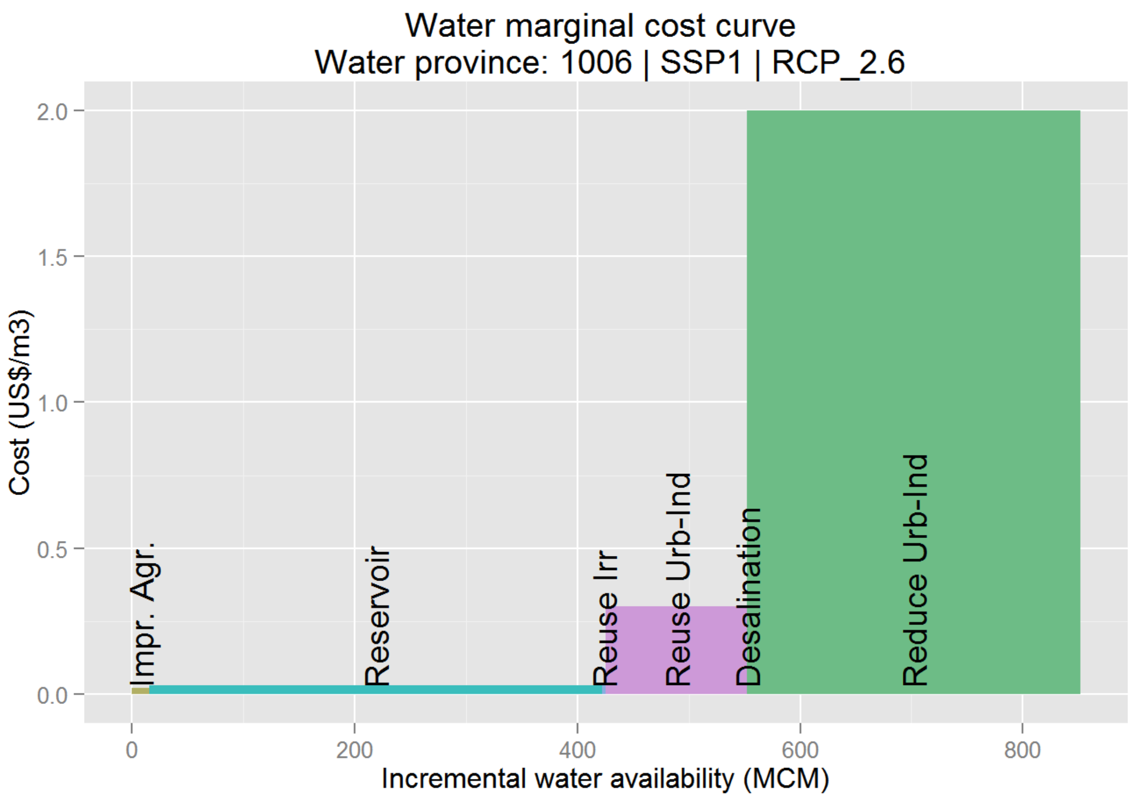
Nile delta water province (992) with low impact scenario (SSP1, RCP2.6)		
Measure	Incremental water availability (MCM)	Total Unmet Demand (cumulative) (MCM)
Business as usual	0	6523
A: Improved agricultural practices	666	5857
B = A + Expanding reservoir capacity	443	5414
C = B + Increased reuse of irrigated agriculture	334	5079
D = C + Increased reuse domestic and industrial	787	4291
E = D + Desalinisation	53	4237
F = E + Reduce domestic and industrial demand	1489	2748



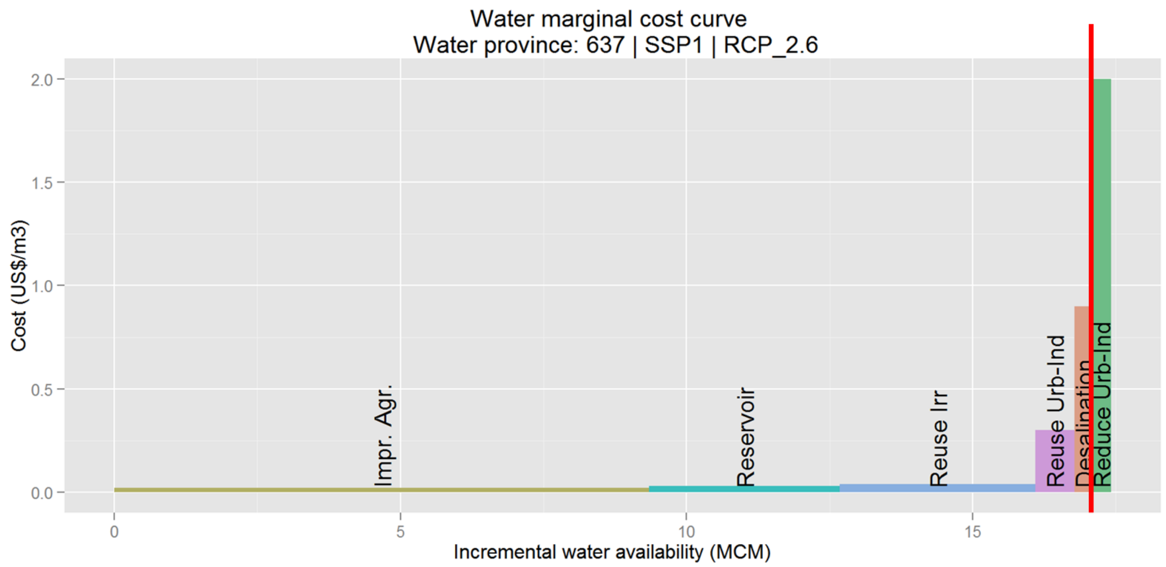
Nile delta water province (992) with high impact scenario (SSP3, RCP8.5)		
Measure	Incremental water availability (MCM)	Total Unmet Demand (cumulative) (MCM)
Business as usual	0	11528
A: Improved agricultural practices	528	11000
B = A + Expanding reservoir capacity	267	10732
C = B + Increased reuse of irrigated agriculture	414	10318
D = C + Increased reuse domestic and industrial	1309	9008
E = D + Desalinisation	88	8919
F = E + Reduce domestic and industrial demand	2548	6371



Upper Nile, south Sudan, water province 1006, low impact scenario (SSP1, RCP2.6)		
Measure	Incremental water availability (MCM)	Total Unmet Demand (cumulative) (MCM)
Business as usual	0	1475
A: Improved agricultural practices	15	1459
B = A + Expanding reservoir capacity	406	1052
C = B + Increased reuse of irrigated agriculture	3	1049
D = C + Increased reuse domestic and industrial	126	922
E = D + Desalinisation	0	922
F = E + Reduce domestic and industrial demand	299	623

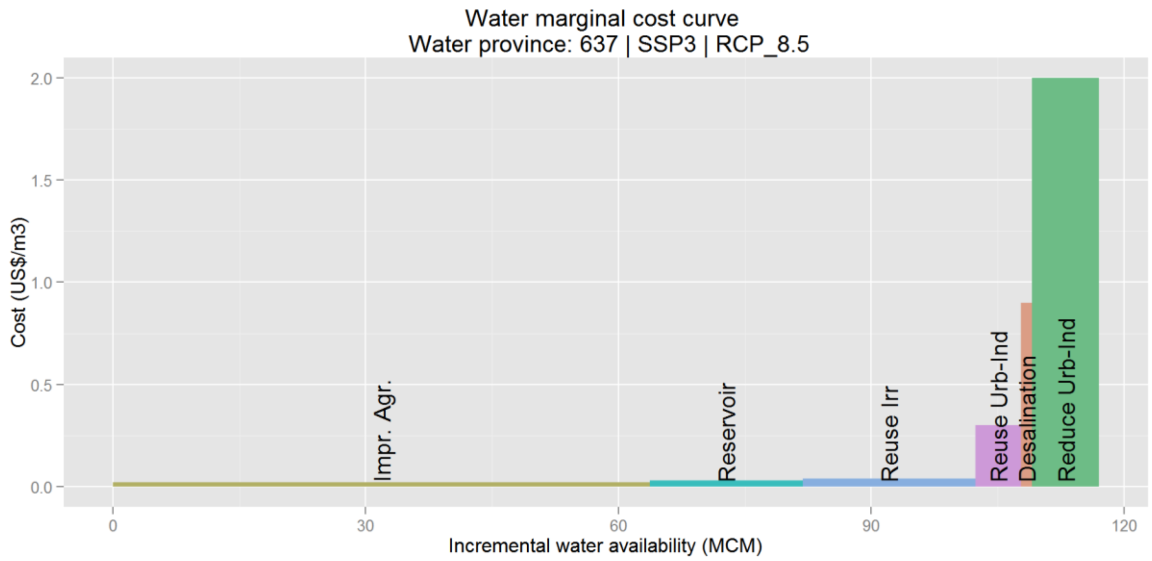


Red River, water province 637 with low impact scenario (SSP1, RCP2.6)		
Measure	Incremental water availability (MCM)	Total Unmet Demand (cumulative) (MCM)
Business as usual	0.0	17.4
A: Improved agricultural practices	9.3	8.0
B = A + Expanding reservoir capacity	3.3	4.7
C = B + Increased reuse of irrigated agriculture	3.4	1.3
D = C + Increased reuse domestic and industrial	0.6	0.6
E = D + Desalinisation	0.3	0.3
F = E + Reduce domestic and industrial demand	0.3	0.0

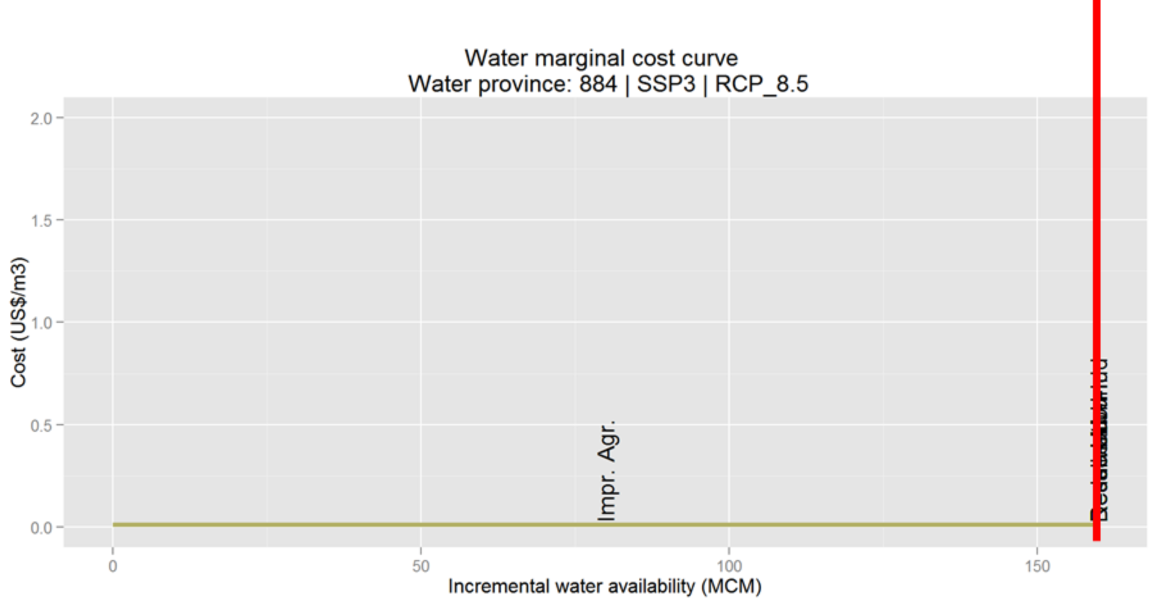


The red line indicates the total unmet demand under the baseline scenario.

Red River, water province 637 with high impact scenario (SSP3, RCP8.5)		
Measure	Incremental water availability (MCM)	Total Unmet Demand (cumulative) (MCM)
Business as usual	0	184
A: Improved agricultural practices	63	120
B = A + Expanding reservoir capacity	18	102
C = B + Increased reuse of irrigated agriculture	20	82
D = C + Increased reuse domestic and industrial	5	76
E = D + Desalinisation	1	75
F = E + Reduce domestic and industrial demand	7	67



Mekong basin, water province 884 with high impact scenario (SSP3, RCP8.5)		
Measure	Incremental water availability (MCM)	Total Unmet Demand (cumulative) (MCM)
Business as usual	0	159
A: Improved agricultural practices	159	0
B = A + Expanding reservoir capacity	0	0
C = B + Increased reuse of irrigated agriculture	0	0
D = C + Increased reuse domestic and industrial	0	0
E = D + Desalinisation	0	0
F = E + Reduce domestic and industrial demand	0	0



8 CONCLUSIONS AND RECOMMENDATIONS

The methodological setup for this study and for the Water2Invest web-interface uses a two tier modeling approach. First an advanced distributed hydrological model (PCR-GLOBWB) is used to determine the internal water resources for the current and future climate. Second, a water allocation model (WatCAM) assesses multi-sectorial water demand on a monthly basis, linking supply and demand for each water province. The tool allows studying adaptation options that influence the balance between supply and demand on the water province level and the impacts on downstream areas. This two-tier approach is something commonly used for basin-level studies, but this study has confirmed it to be useful also for global assessments.

The water marginal-cost curve is added to this decision tool to allow identifying cost-effective solutions to close the gap between projected demand and existing supply by comparing the different measures. So, the combination of the two models and the cost curve facilitates the comparison of the measures' financial cost and their technical potential to close the supply-demand gap. A common critique on the use of this type of curves that measures can interact creating synergies and conflicts. This means that the cumulative outcomes of two measures can be more than the sum of its parts, or less. Therefore, for this tool it was decided to generate these curves by running the adaptation measures cumulatively, adding to each subsequent run a more costly measure.

The main potential improvement of using water marginal cost curves however originate from the estimation of costs: financial implementation costs for most measures concern the majority of total costs, but for other measures there may be more complex hidden or indirect costs and benefits that can be related with implementation barriers, positive feedback mechanisms, socio-economic costs and benefits, and others. It is therefore important to emphasize that the estimates generated by the cost curve are not explicit predictions, but approximate guides to decision-making.

For this study, several water allocation models were evaluated. The final WatCAM tool is based on equations and concepts used in these mainstream water allocation models. The numerical tool was scripted to allow scenario analysis over a wide range of study dimensions (climate, socio-economic, measures, local vs global data, amongst others) and is flexible to be adapted to more local and detailed studies. Still, some improvements are foreseen in the computational efficiency of the programmed tool.

The input data used for this global assessment tool were all from public domain and validated datasets. The validation of the tool shows that it performs well on the global level, but for basin-level assessments improved data would generate robust outcomes. Especially for irrigation demand, local data can improve significantly the outcomes of the tool. Other improvements are also foreseen in the topology between the water provinces: the number of connections can be reduced for some areas while for other areas, some additional ones can be added where inter-basin transfers occur.

Overall, the developed methodology is flexible in its design and provides guidance to decision makers on the cost-effectiveness of climate adaptation measures. Moreover, the methodology is unique that its focus is on the water manager at Water Provincial scale. Based on data provided, he/she can perform already impact and adaptation analysis. And, equally important, these water managers can improve accuracy by including more local data and explore an unlimited amount of adaptation strategies

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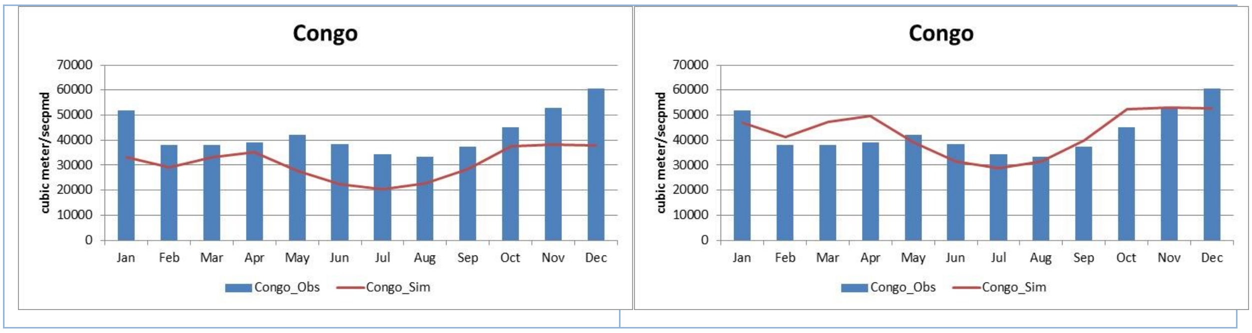
10 ANNEX

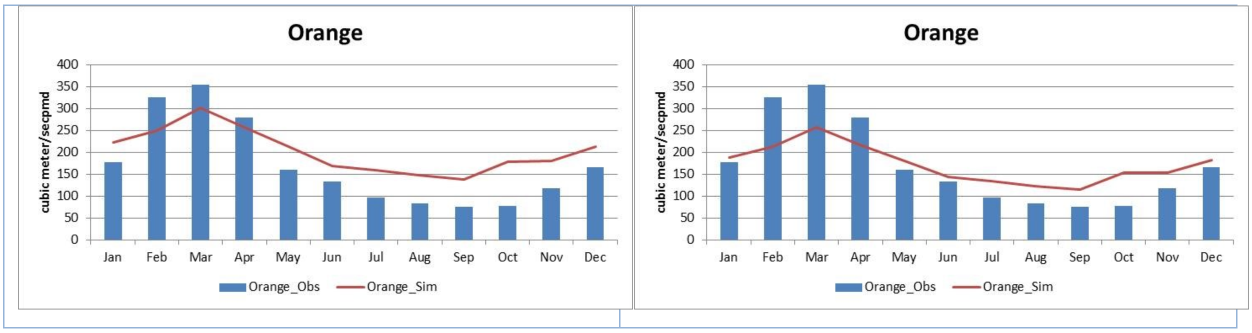
10.1 VALIDATION WATCAM RESULTS

On the following pages the results for the remaining of these 17 basins will be shown. The monthly averaged outflow, measured vs simulated.

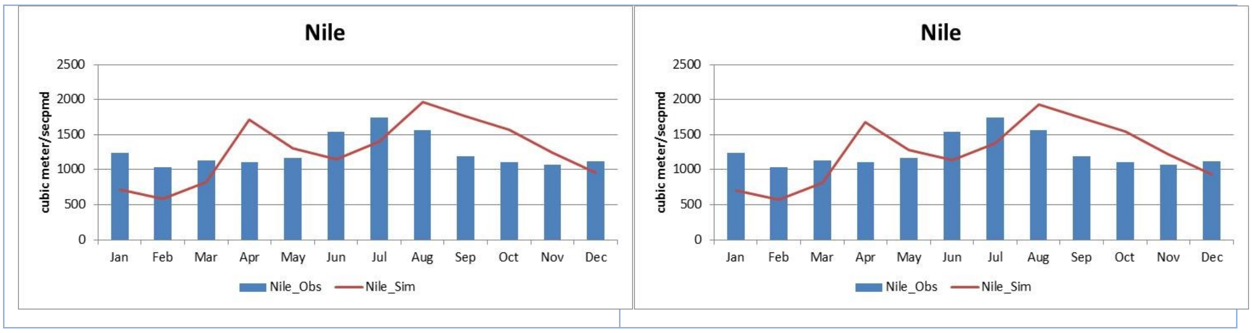
10.1.1 Congo



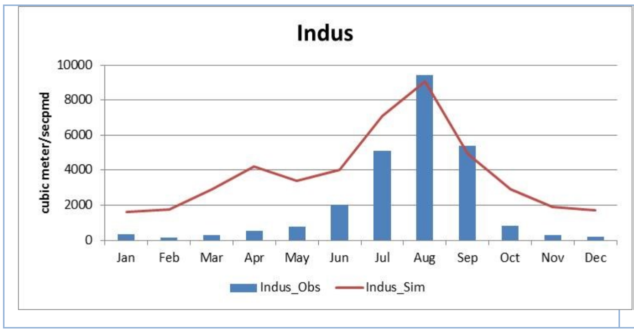
10.1.2 Orange

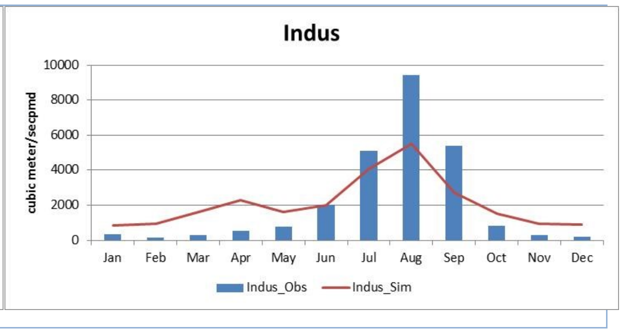


10.1.3 Nile

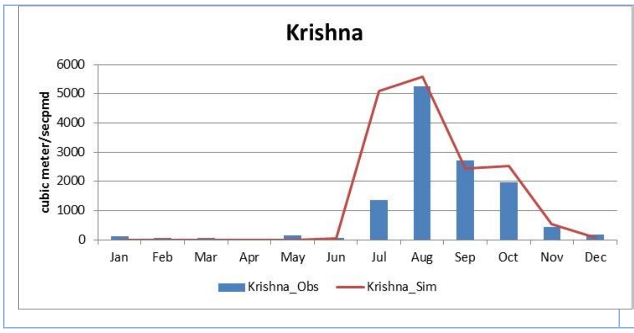


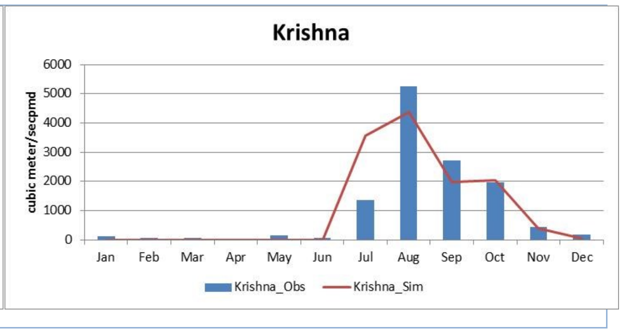
10.1.4 Indus



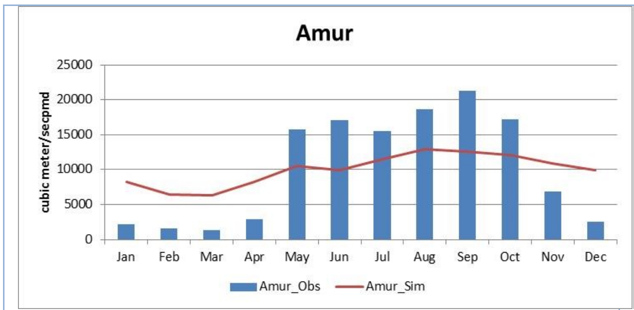


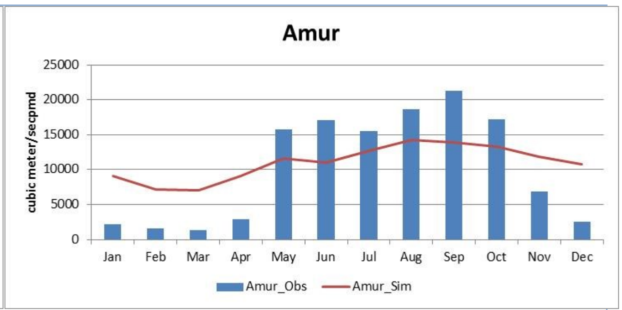
10.1.5 Krishna



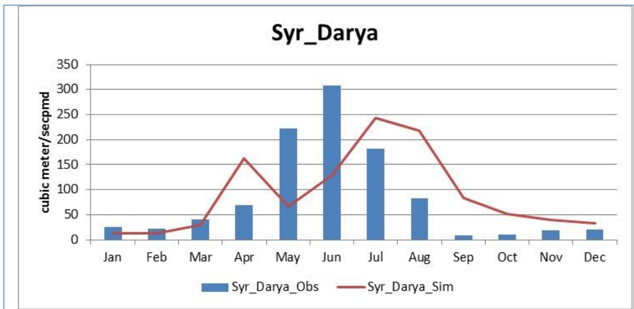


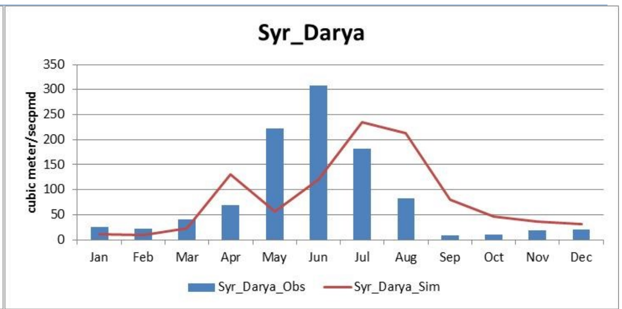
10.1.6 Amur



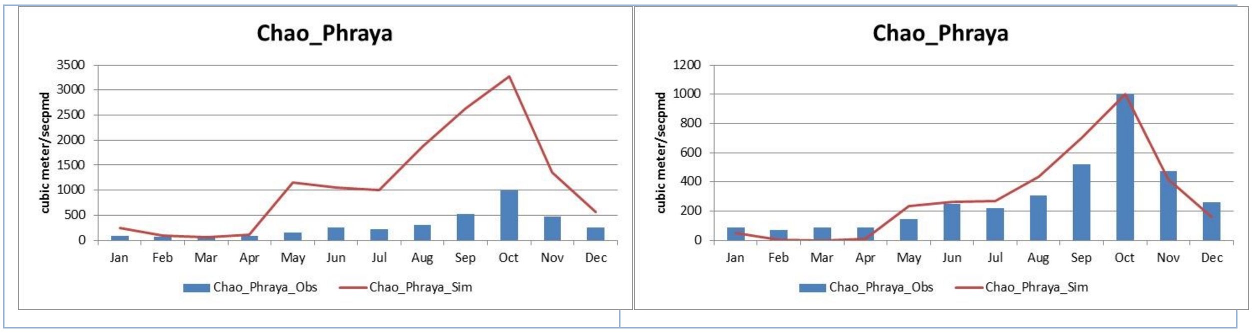


10.1.7 Syr_Darya

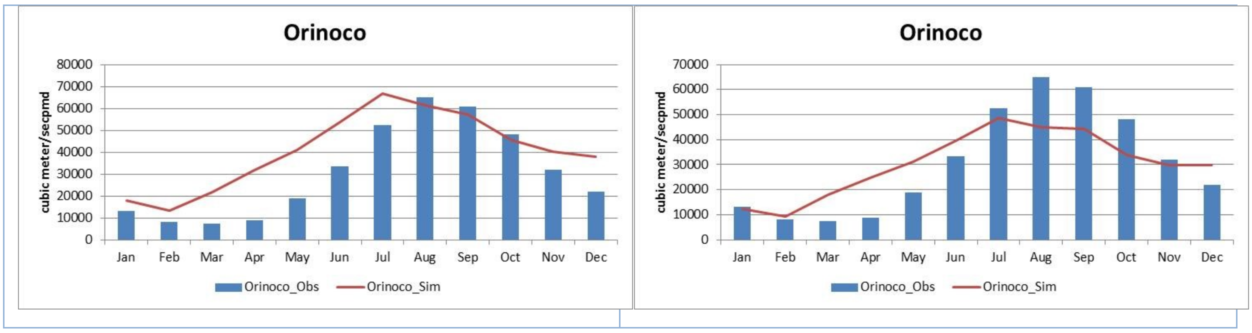




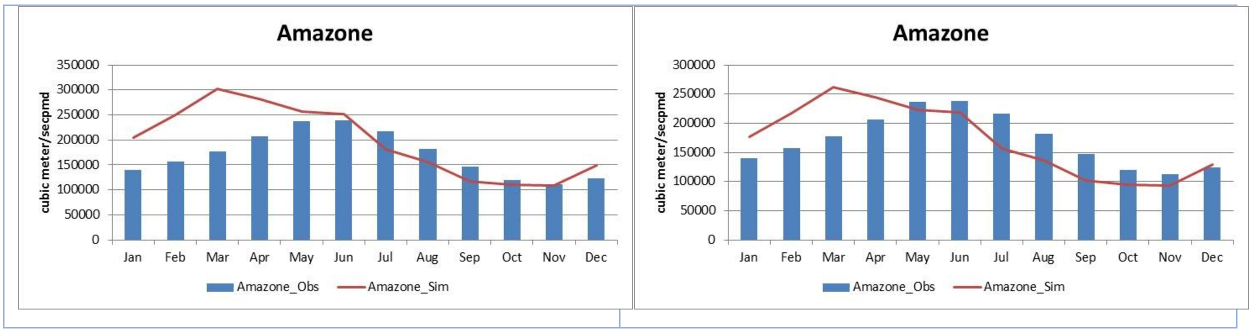
10.1.8 Chao_Phraya



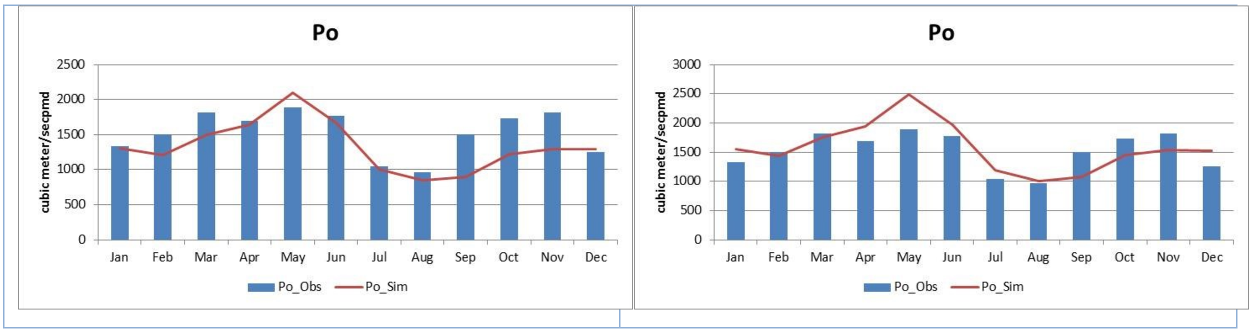
10.1.9 Orinoco



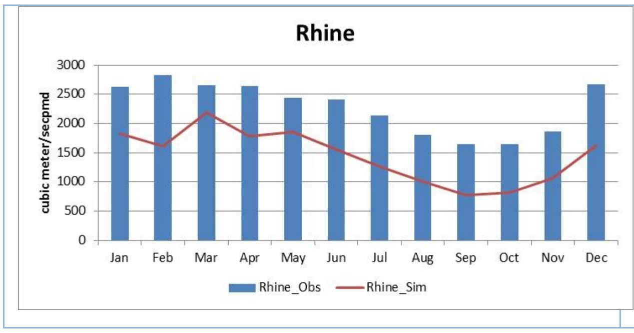
10.1.10 Amazone

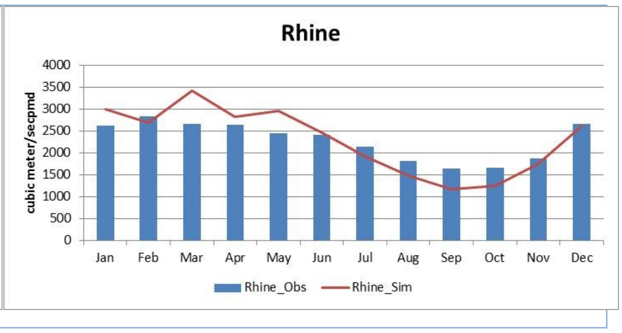


10.1.11 Po



10.1.12 Rhine





10.1.13 Danube