Groundwater Management and Exploration Package: State of the Art Northern China

GMEP-Project

Groundwater Management and Exploration Package: State of the Art for Northern China

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Preface

This report presents the state of the art of groundwater observation and management tools with particular reference to GRACE satellite monitoring and WEAP planning. Demonstration of the application of these two tools for Northern China is included as well.

This study is undertaken in the context of the GMEP project (Groundwater Management and Exploration Package). GMEP is financially supported by the Dutch Government through its program Partners for Water.

More information on the GMEP project can be found at the project website:
http://www.futurewater.nl/gmep

Consortium:

Dutch project partners:
- FutureWater (Wageningen)
- Delft University of Technology (Delft)
- Water Board Rivierenland (Tiel)

Chinese project partners:
- Shiyang River Basin Management Bureau (Wuwei)
- Hydrology and Water Resources Investigation Bureau (Wuwei)
- Tsinghua University (Beijing)

Contents

1 Introduction

Groundwater can be considered as one of the planet's most important fresh sources of water. Only 2.5% of water on earth is fresh of which 70% is not directly accessible (glaciers, ice caps). Lakes and rivers hold only a tiny 0.3% while groundwater stores about 30% and can therefore be considered as the largest liquid freshwater source available to mankind. However, regions that have sustainable groundwater storages are shrinking by the day.

Groundwater has some unique advantages and opportunities to offer for human development. Groundwater is accessible to a large number of users; it can provide cheap, convenient and individual supplies; it is generally less capital-intensive to develop, and does not depend upon mega-water projects. Groundwater development is also largely self-financing ensuring automatic cost recovery. Compared to surface water, groundwater offers better insurance against drought because of the long lag between changes in recharge and responses in groundwater levels and well yields.

In Northern China, groundwater depletion has reached catastrophic levels. Across the northern half of the country, groundwater over-pumping amounts to some 30 billion cubic meters a year. China's northern and central plains produce roughly 40% of the country's grain. Across a wide area of this region, water tables have been dropping over two meters a year for a decade, even as water demands continue to rise.

China's sustainable development is threatened by this over-exploitation of the scarce water resources. Rapid economic growth has led to overexploitation of available surface water resources, overdraft of groundwater resources and unreliable access to fresh water, all affecting the livelihoods of many predominantly rural and poor people especially in northern China. Particularly unsustainable groundwater management makes the system extremely vulnerable to droughts. It is therefore that the China's new Water Law has been ratified recently, and is currently being refined, interpreted and implemented.

The Chinese government is currently looking for directions to guide this process and a particular interest is expressed in improved groundwater assessment and management tools. The Department of Water Resources (DWR) within the Ministry of Water Resources is responsible for demonstration and nationwide promotion of best practices in Integrated Water Resources Management including groundwater management. The Shiyang River Basin in Gansu province was selected as demonstration case under the new Water Law. Lessons learnt from this demonstration site will be promoted and implemented nation-wide.

The GMEP (Groundwater Management and Exploration Package) project will demonstrate that advanced observations and planning tools can assist decision makers. The package will be demonstrated for two river basins.:

1. The large (795,000 km^2) Yellow River Basin with a schematisation based on limited data;
2. The relatively small (41,600 km^2ha) Shiyang River Basin with a detailed model schematisation.

In this report the a description of the GRACE groundwater monitoring and the WEAP management tool are presented as well as preliminary results of the application of these tools for Yellow River Basin and Shiyang River Basin.

2 Tools included in GMEP

2.1 General

Water resources analysis rely more and more on advanced tools including data assimilation, simulation modeling and remote sensing (Van Loon et al., 2007). Remote sensing has been used extensively to detect land cover and related parameters, where the extension to monitor evaporation is in the transition phase from research to operational application (Immerzeel et al., 2006). Simulation models are commonly used in water resources planning and operation, where understanding processes and evaluating scenarios are the main objectives (Droogers et al., 2008). These tools are increasingly applied in an integrated manner, where remotely sensed observations can be used to calibrate hydrological models (Immerzeel, 2008).

The two main tools included in the Groundwater Management and Exploration Package (GMEP) are GRACE and WEAP. GRACE is a twin-satellite monitoring changes in the earth's gravity field. These changes have a direct correlation to groundwater storage fluctuations. GRACE information will form the base in GMEP to assess current and past groundwater trends. WEAP (Water Evaluation And Planning system) is a user-friendly package able to link supplies and demands in water resources and will be used to evaluate future alternatives in sustainable groundwater management.

2.2 GRACE monitoring tool

The Gravity Recovery And Climate Experiment (GRACE) is a twin-satellite mission, developed to measure changes in the Earth's time-variable gravity field with unprecedented accuracy (Tapley et al., 2004; Tapley and Reigber, 2001). The main mission objective of GRACE is to map changes in mass due to the continental water cycle. On regional scale of a minimum longitudinal and latitudinal magnitude of about 300 km, it can be used to identify mass changes due to variations in water storage, which can assist in determination of groundwater depletion (Rodell and Famiglietti, 2002), ice melt (Velicogna and Wahr, 2006), residual basin-scale estimates of evaporation (Rodell et al., 2004) or validation of hydrological models (Ngo-Duc et al., 2007; Niu et al., 2007; Rodell et al., 2007; Tapley et al., 2004; Wahr et al., 2004).

GRACE consists of 2 polar orbiting satellites that are developed to fly at an altitude ranging from 300 to 500 km and are separated by a distance of about 200 km along track. The Earth's gravity field causes accelerations of the satellites where they approach an area of relatively high mass concentration, and decelerations where they move away from them (see Figure 1). The raw measurements consist of extremely accurate distances between the two satellites, measured by the High Accuracy Intersatellite Ranging System (HAIRS). The acceleration - deceleration behaviour of both satellites causes changes in these distances that can be translated back into mass (or gravity) configurations of the Earth.

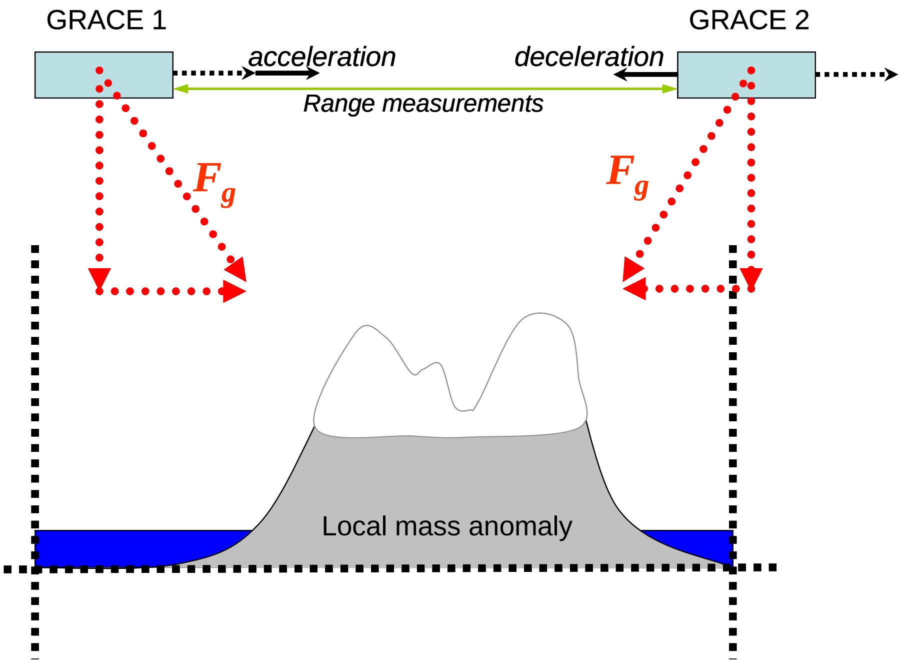


Figure 1: A schematic cartoon of the way in which GRACE measures the gravity field

With only little measurements, the number of possible mass configurations can be numerous, the extreme case being one instantaneous measurement, resulting in an infinite number of mass configurations. The more measurements taken, the lower the amount of possible mass configurations, the higher the resolution that can be reached (one may compare it with GPS positioning, where measurements of only one GPS satellite gives an infinite number of possible locations of a person in its surroundings). Therefore, gravity fields are delivered per month of observation, allowing the satellites to make several passes over each region of the Earth. This reduces the temporal resolution but increases the spatial resolution. Figure 2 clearly shows the trade-off between temporal and spatial resolution. From all range-rate measurements within a month, a monthly-averaged gravity field is deconvoluted by combining Newton's gravitational law and law of motion, assuming that the gravitational force is directed toward the Earth's centre.

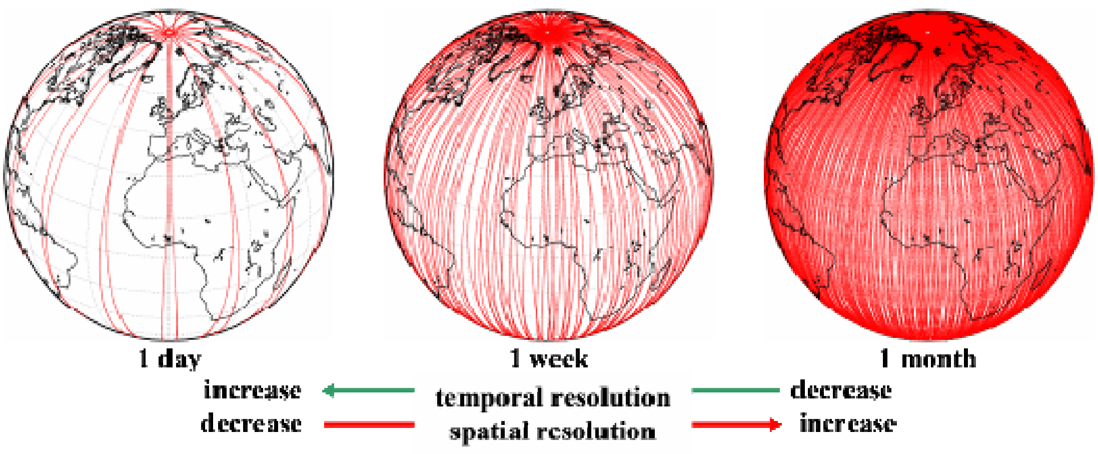


Figure 2: The trade-off between GRACE temporal and spatial resolution (Schmidt et al., 2008).

The gravitational field can best be described as the sum of a set of spherical shaped sine and cosine functions having different frequencies and amplitudes (i.e. deviations from a perfect sphere), also called spherical harmonic coefficients. Spherical harmonics are comparable with Fourier harmonics, but then for a sphere shape instead of a 1-dimensional function. The number of degrees and orders that is derived, determines the resolution of the derived gravity field. Most data centers derive up to degree and order 120, but in practice the last 50 orders represent for the greatest part noise and are therefore discarded.

Changes in mass are caused by many low and high frequency processes, some of the more important ones being gravitational pull by other mass bodies such as the Sun, Moon and nearby planets, atmospheric moisture redistribution, oceanic tides, but also deformation due to the later process and for instance post-glacial rebound. The high frequency processes that are expected to vary a great deal within one month of data acquisition are in the processing of GRACE data corrected for by using several background models, prior to the gravity deconvolution. The most important are an oceanic model and an atmospheric model. The residual gravity signal then represents unmodelled signals such as hydrology, earthquakes and land deformation, and some noise, e.g. from instrumental errors and errors in the background models. The signal that is expected to vary the most on the monthly time scale is hydrology, which comprises terrestrial water storage changes that can be caused by variations in groundwater storage, soil moisture, snow pack and surface water as shown in Figure 3. The hydrology signal is assumed to be constant within the period of observation (i.e. one month) and the time-averaged storage estimates are therefore assumed to be representative for the middle of the month. This means that, with the introduction of GRACE, we now have a first large-scale observation of basin-scale terrestrial water storage available, that can be used as validation for hydrological model structures and parameters.

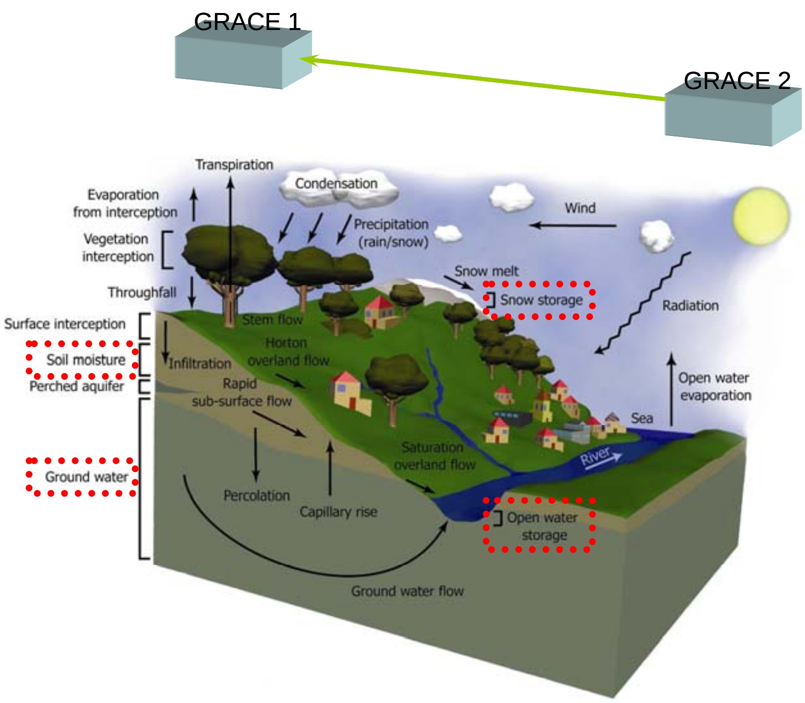


Figure 3: An artist impression of hydrological processes and storages. Storages observed by GRACE are encircled in red (courtesy, TU Delft 2008).

GRACE data are recovered since May 2002. However data before July 2003 are not very accurate because of a relatively high level of noise in the signal. Also the GRACE data of September and October 2004 are of lower quality due to repeated tracks of the satellites. GRACE data are nowadays processed in three data centers: the Center for Space Research Texas (CSR), the GeoForschungsZentrum Potsdam (GFZ) and the Jet Propulsion Laboratory (JPL). The difference in their end-user products is mainly the use of different background models. Delft, University of Technology is developing its own solution procedure, which also allows for an estimation of uncorrelated errors in each monthly solution.

GRACE data products are expressed in mm equivalent water. Two factors are important when evaluating these results from GRACE. Firstly, no distinction between snow cover, soil moisture and deep groundwater storage can be made. Secondly, results are given relative to the long-term average from Apr-2002 to Apr-2006. This means that no absolute values of water storage can be provided and that no spatial differences in water stored can be observed. In other words GRACE detects only changes in stored water.

2.3 WEAP Water Allocation Tool

The WEAP System Model is short for Water Evaluation and Planning System and was developed by the Stockholm Environment Institute to enable evaluation of planning and management issues associated with water resources development. The WEAP System Model can be applied to both municipal and agricultural systems and can address a wide range of issues including sectoral demand analyses, water conservation, water rights and allocation priorities, streamflow simulation, reservoir operation, ecosystem requirements and project cost-benefit analyses (SEI, 2001).

The WEAP tool has two primary functions (Sieber et al., 2004):

- Simulation of natural hydrological processes (e.g., evapotranspiration, runoff and infiltration) to enable assessment of the availability of water within a catchment.
- Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e., consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

To allow simulation of water allocation, the elements that comprise the water demand-supply system and their spatial relationship are characterized for the catchment under consideration. The time step of simulation is one month. The system is represented in terms of its various water sources, (precipitation, surface water, groundwater and water reuse elements), withdrawal, transmission, reservoirs, and wastewater treatment facilities, and water demands (agricultural, domestic and industrial). The data structure and level of detail can be customized (e.g., by combining demand sites) to correspond to the requirements of a particular analysis and constraints imposed by limited data. A graphical interface facilitates visualization of the physical features of the system and their layout within the catchment.

A *Demand Site* in WEAP can be considered as the core of every schematization. Demand calculations are based on a disaggregated accounting for various measures of social and economic activity (number of households, hectares of irrigated agriculture, industrial and commercial value added, etc.). In the simplest cases, these activity levels are multiplied by the water use rates of each activity.

A *Catchment Node* is defined in WEAP as an area within the schematic in which hydrologic processes such as precipitation, evapotranspiration, runoff and irrigation are simulated. There are three different modules to calculate these processes: the Rainfall Runoff method (1), The Irrigation Demands Only version of the FAO Crop Requirements Approach (2) and the Soil Moisture Method (3).

Groundwater Nodes can have natural inflow, infiltration from Catchment Nodes, Demand Site and wastewater treatment plant returns, inflows from transmission and return flow link leakage, river interactions and storage capability between months. A Groundwater Node can be linked to any number of demand sites.

The WEAP model essentially performs a mass balance of flow sequentially down a river system, making allowance for abstractions and inflows. To simulate the system, the river is divided into reaches. The reach boundaries are determined by points in the river where there's a change in flow as a consequence of the confluence with a tributary, or an abstraction or return flow, or where there is a dam or a flow gauging structure. Typically, the WEAP model is applied by configuring the system to simulate a recent "baseline" year, for which the water availability and demands can be confidently determined. The model is then used to simulate alternative scenarios (i.e., plausible futures based on "what if" propositions) to assess the impact of different development and management options. The model optimizes water use in the catchment using an iterative Linear Programming algorithm, whose objective is to maximize the water delivered to demand sites, according to a set of user-defined priorities. All demand sites are assigned a priority between 1 and 99, where 1 is the highest priority and 99 the lowest. When water is limited, the algorithm is formulated to progressively restrict water allocation to those demand sites given the lowest priority. WEAP calculates on a monthly time step. More details of the model are available in Sieber et al. (2005) and SEI (2005).

WEAP consists of five main views: Schematic, Data, Results, Overviews and Notes (Figure 4). A typical stepwise approach will be followed to develop WEAP for a particular area: (i) create a geographic representation of the area, (ii) enter the data for the different supply and demand sites, (iii) compare results with observations and if required update data, (iv) define scenarios and (v) compare and present the results of different scenarios. In general, the first three steps will be done by technical experts like hydrologists, while for the last two steps input and exchange with stakeholders, water managers and policy makers is essential.

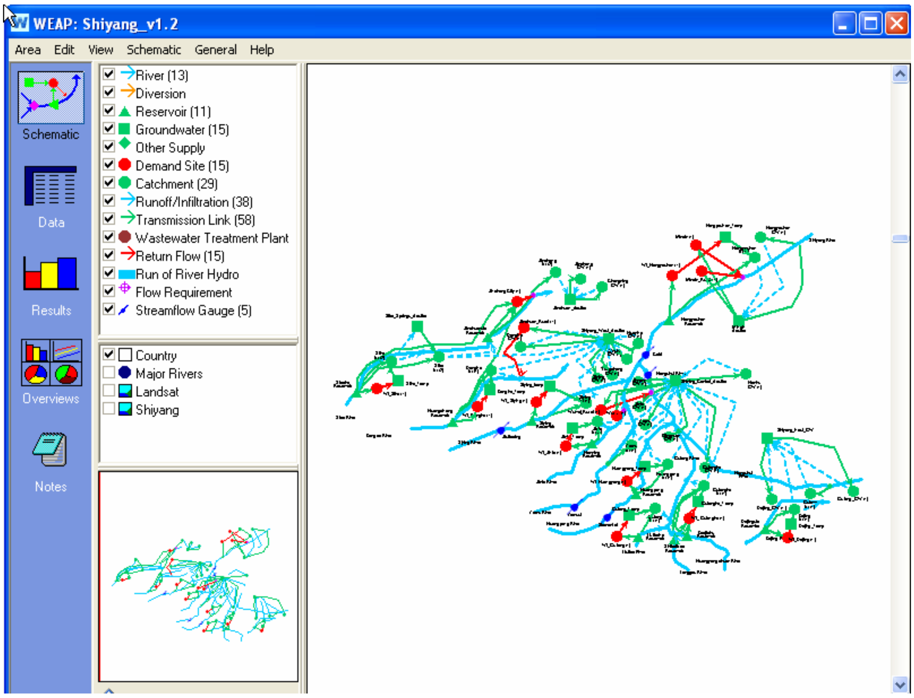


Figure 4: User interface of WEAP with on the left the five main views.

3 Yellow River Basin

3.1 Introduction

The Yellow River (Huang He in Chinese) is with 5.400 km the second longest river in China (after Yangtze River). The Yellow River Basin area is 795,000 km^2. The river originates in the Bayangela Mountains in Western China. The river can be divided into three reaches (see Figure 5). The upper reach drains about half of the basin area. It begins in a high moisture plateau. As it moves northward into the desert plain evaporation is several times that of precipitation, resulting in a largely reduced river flow.

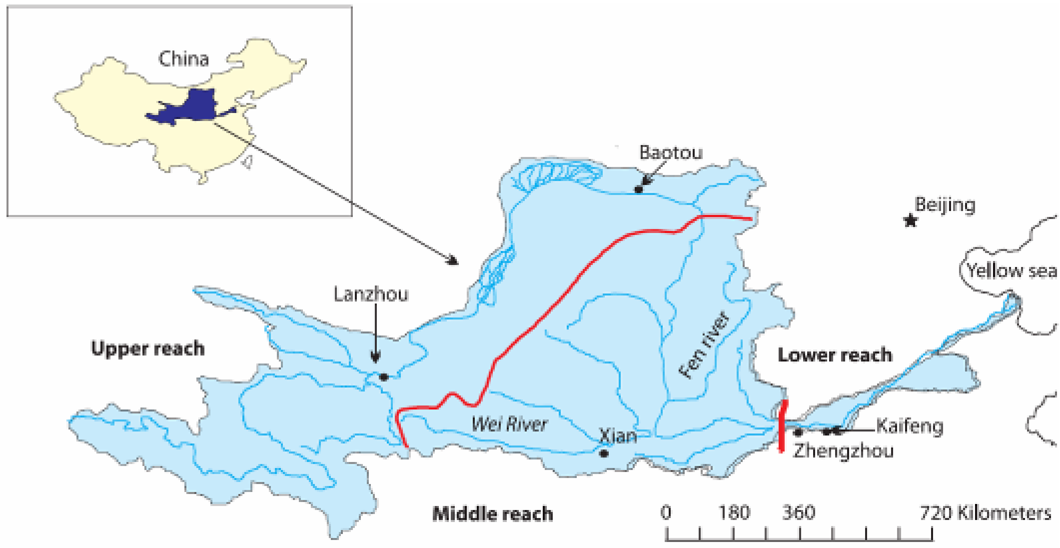


Figure 5: The Yellow River Basin (Source: Giordano, 2004)

In the middle reach the river turns south through the Loess Plateau resulting in massive sediment loads. The lower reach is one of the most unique river segments in the world. As the river spills onto the flat North China plain the sediments begin to settle. The silts elevate the channel bed and to hold the river channel levees were constructed and raised. Over time, the process has created a “suspended” river, in which the channel bottom is above ground level, sometimes by as much as 10 meters (Liu, 2002). The “suspended” river brings in severe flood threats if the levees break. In addition rainfall on surrounding lands cannot drain into the river nor can tributaries enter it. With almost no inflow, the contribution of the lower reach accounts for only 3% of basin total runoff.

The yearly averaged rainfall during 1956-2000 was 372 mm in the upper reach, 523 mm in the middle reach, 671 mm in the lower reach, and 454 mm over the entire basin (YRCC, 2002). Figure 6 gives an impression of the distribution of the precipitation during the year.

Groundwater has been extensively utilized in the basin since tubewell usage began in the late 1950s. Agriculture is by far the largest consumer of water. Currently the basin has a total irrigated area of 7.5 million ha (9.4% of the total area).

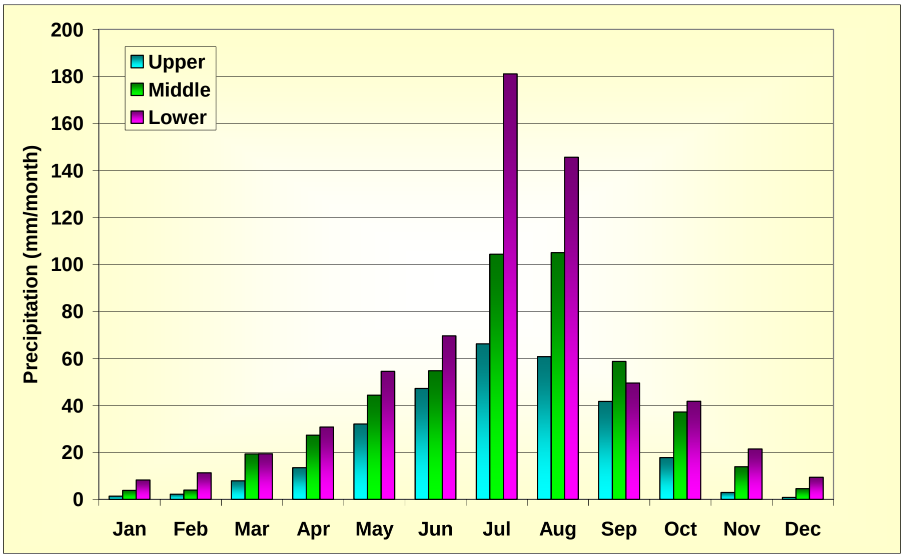


Figure 6. Monthly average precipitation (1990-2002) for the three reaches

3.2 GRACE

In Figure 7 the monthly terrestrial storage difference with respect to an average is shown for the Yellow River basin and its sub-basins. This figure shows clearly the seasonal variations in water storage in the Yellow River Basin. In general most water is found in September/October/ November and April/May/June water storage is least. If we regard the sub-basins separately the lower reach basin shows the largest variety with approximately 100 mm equivalent water depth difference between the annual wet and dry period. If the storage of snow, open water and soil moisture is neglected and assuming an average specific yield of 10% the seasonal groundwater variation is approximately 1 m.

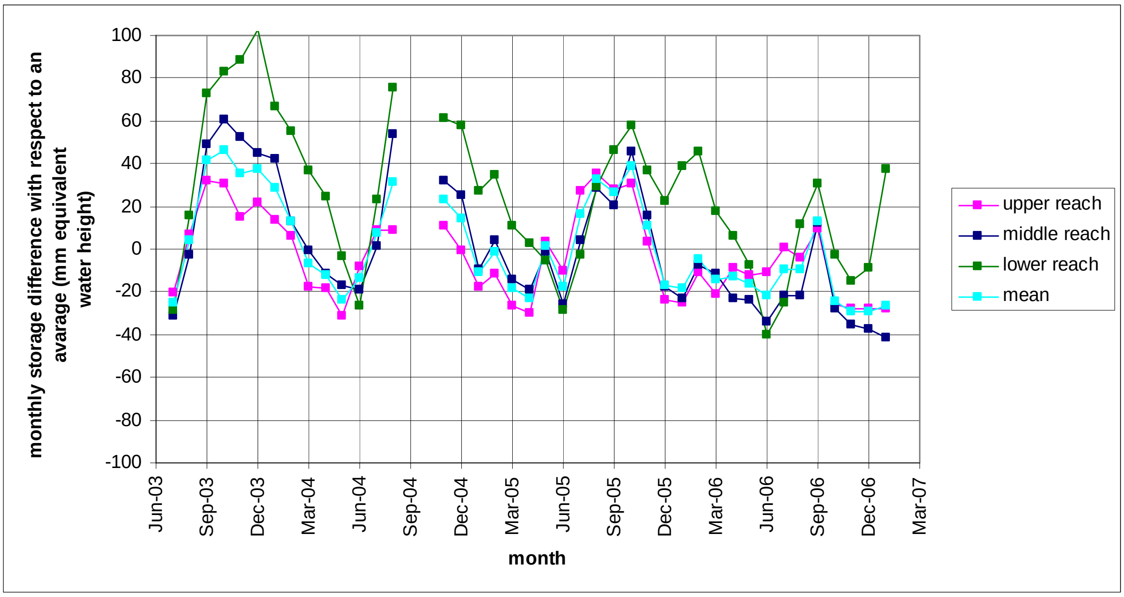


Figure 7: Monthly changes in water storage (soil moisture, groundwater and snow cover) relative to the long term average (mm equivalent water depth) for the Yellow River Basin and it's sub- basins.

The years 2003-2006 show an annual downward trend (Figure 7). This trend is most pronounced in the lower reach sub-basin where most water is used for irrigation purposes.

In Figure 8 the storage differences between May 2004 and October 2003 are presented. This figure gives an impression of the spatial distribution of the seasonal variation in terrestrial water storage. In the North-Eastern and in the Western part of the basin the seasonal difference is relatively low with 0 to 60 mm equivalent water depth. The largest seasonal difference of more than 100 mm equivalent water depth is found in an irrigation area in the South.

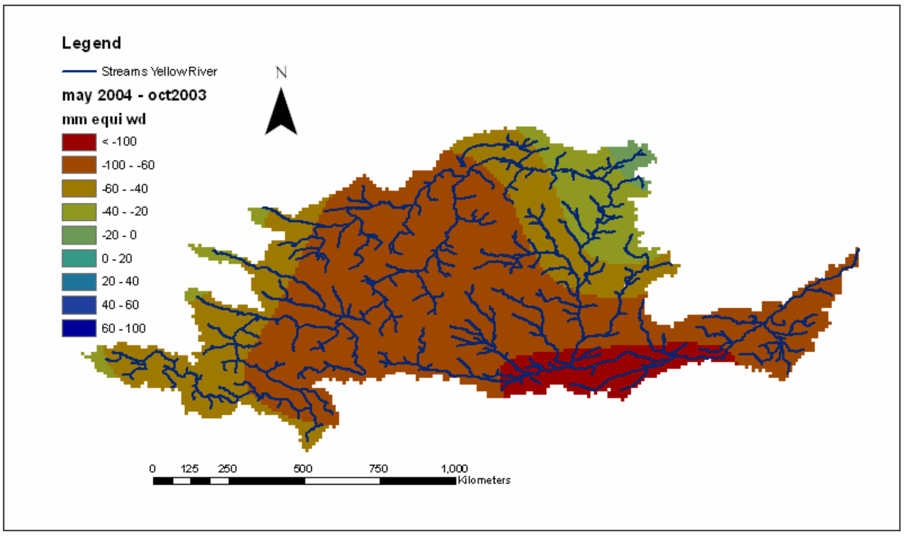


Figure 8: Storage difference between October 2003 and May 2004 expressed in mm equivalent water depth (negative indicates dryer conditions in May).

In Figure 9 the relative water storage is shown for the month of June for respectively the years 2004, 2005 and 2006. These figures show clearly that in the central part of the Yellow river basin June is getting dryer over these years, while in the South-Western part of the basin June is getting wetter over these years. In a next phase of this research monthly spatial distributed precipitation data will be included. It is expected that these precipitation data will give more insight in these spatial and temporal variations in terrestrial water storage.

In Figure 10 the relative water storage is shown for the month of October for respectively the years 2003, 2005 and 2006. The relative water storage for October 2004 is not presented; due to repeated tracks of the satellites the quality of this month’s data is low. Figure 10 shows that the wet month of October is getting dryer every year.

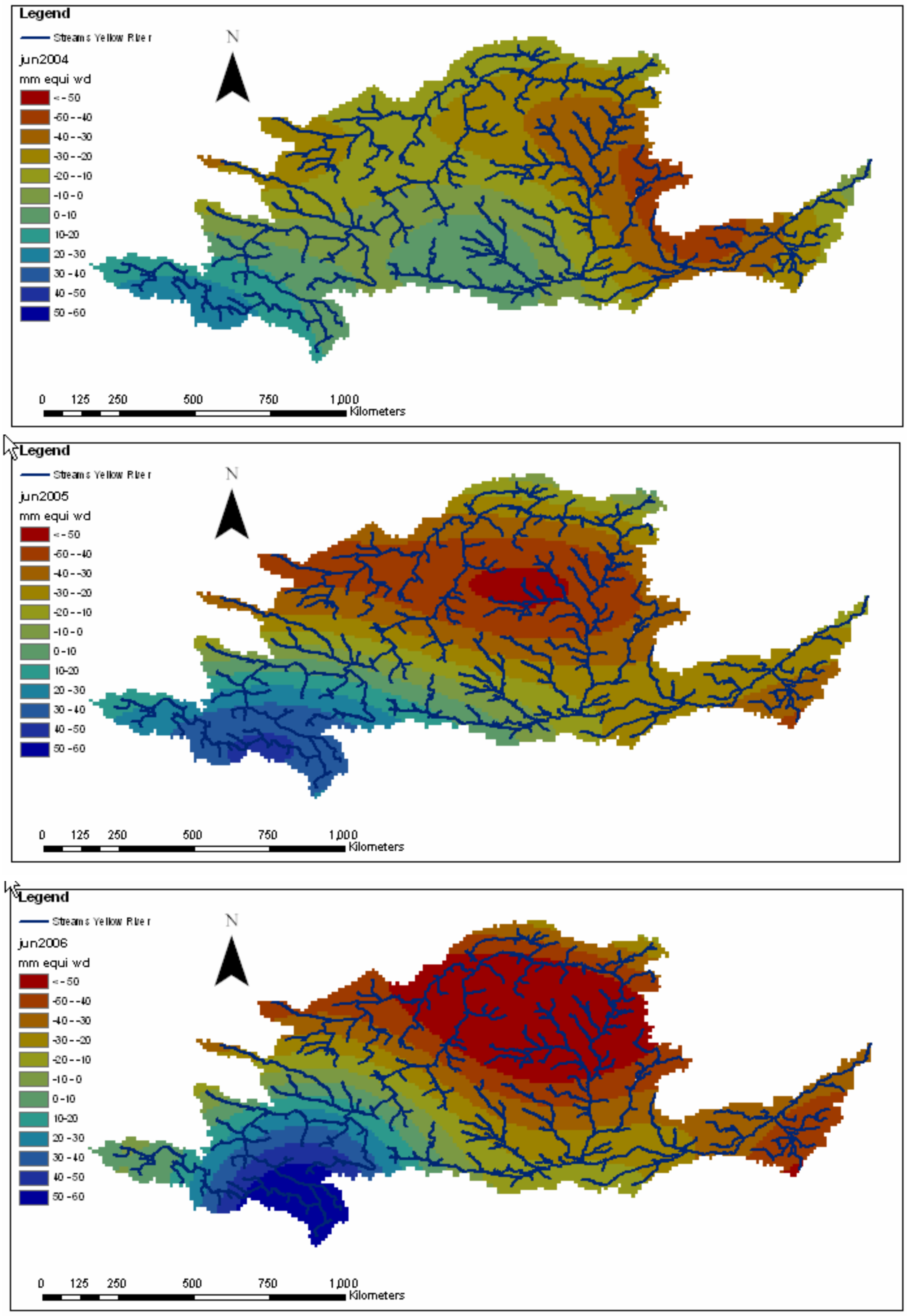


Figure 9. Changes in water storage (soil moisture, groundwater and snow cover) relative to the long term average (in mm equivalent water depth) for the Yellow River Basin in June 2004 (a), June 2005 (b) and June 2006 (c)

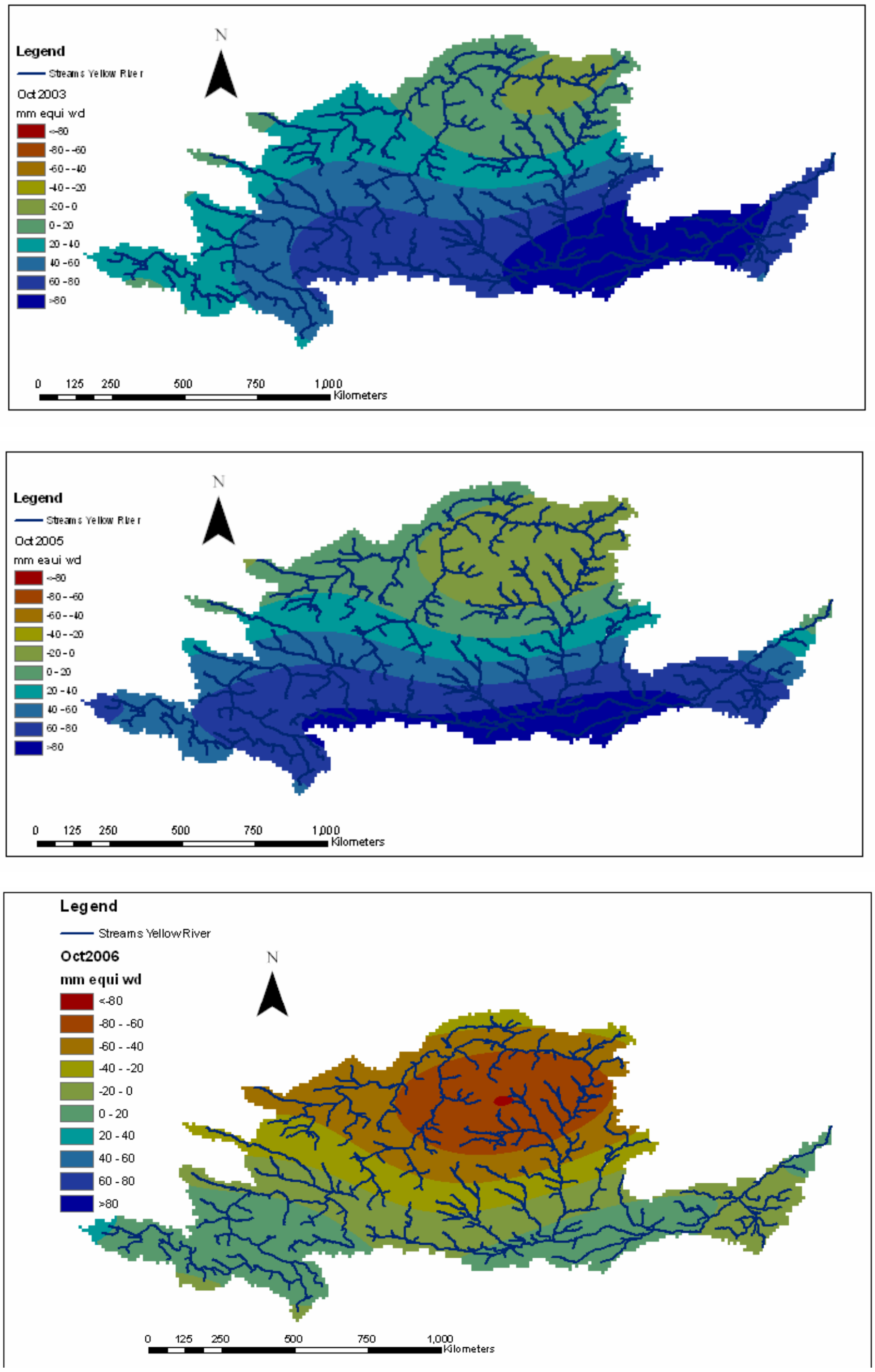


Figure 10: Changes in water storage (soil moisture, groundwater and snow cover) relative to the long term average (in mm equivalent water depth) for the Yellow River Basin in October 2003 (a), October 2005 (b) and October 2006 (c)

3.3 WEAP

3.3.1 Data collection

3.3.1.1 General

The Yellow River Conservancy Commission (YRCC) divides the Yellow River in three reaches: upper, middle and lower (see Figure 5). The downstream gauging stations of these sub areas are (Figure 13): Toudaoguai (also referred to as Hekouzhen) for the upper reach, Huayuankou (also referred to as Taohuayu) for the middle reach and Lijin (BoHai see) for the lower reach.

Based on reports from the YRCC several authors (e.g. Zhu et al., 2003 and 2004; Giordano, 2004) have compiled data on the water supply and demand of the Yellow River basin. Although in principle straight forward, many complications in terms of terminology (e.g. withdrawal vs. consumption, reuse, total water vs. utilizable, overall evapotranspiration (ET) vs. ET from irrigation) and double counting, this water accounting is much more complex. One of the major problems in these water accounting approaches is that no clear indication of the spatial extent one refers to is provided: entire basin, only (irrigated) agriculture, or only surface water.

Based on records of 1998 (if not available other periods), assuming that no changes in storages occur, simplified water balances for the entire basin, surface water only and groundwater only have been derived (Table 1). Although these water balances are based on many assumptions, it is one of the few attempts to include all water resources into the equation.

Table 1. Rough estimate of Yellow River water accounting for the entire basin, surface water only and groundwater only. Data reflects the situation from around 1998 (based on qualitative data) and assuming no changes in storage.

Inflow (BCM y^{-1})		Outflow (BCM y^{-1})	
Basin			
Rainfall	335	ET agriculture	68
		ET other	253
		Industry/domestic	8
		Outflow to sea	6
Surface Water			
Runoff	43	Irrigation	32
		Industry/domestic	5
		Outflow to sea	6
Ground Water			
Recharge	13	Irrigation	10
		Industry/domestic	3

In this table a total evapotranspiration, either by natural vegetation or by agriculture, of about 321 BCM is estimated as the closure term of the basin's water balance. The basin produces about 75 million ton grains. Using a rough estimate of Water Productivity of 1.1 kg m^{-3} (Zwart and Bastiaaanssen, 2004) shows that agriculture consumes about 68 BCM.

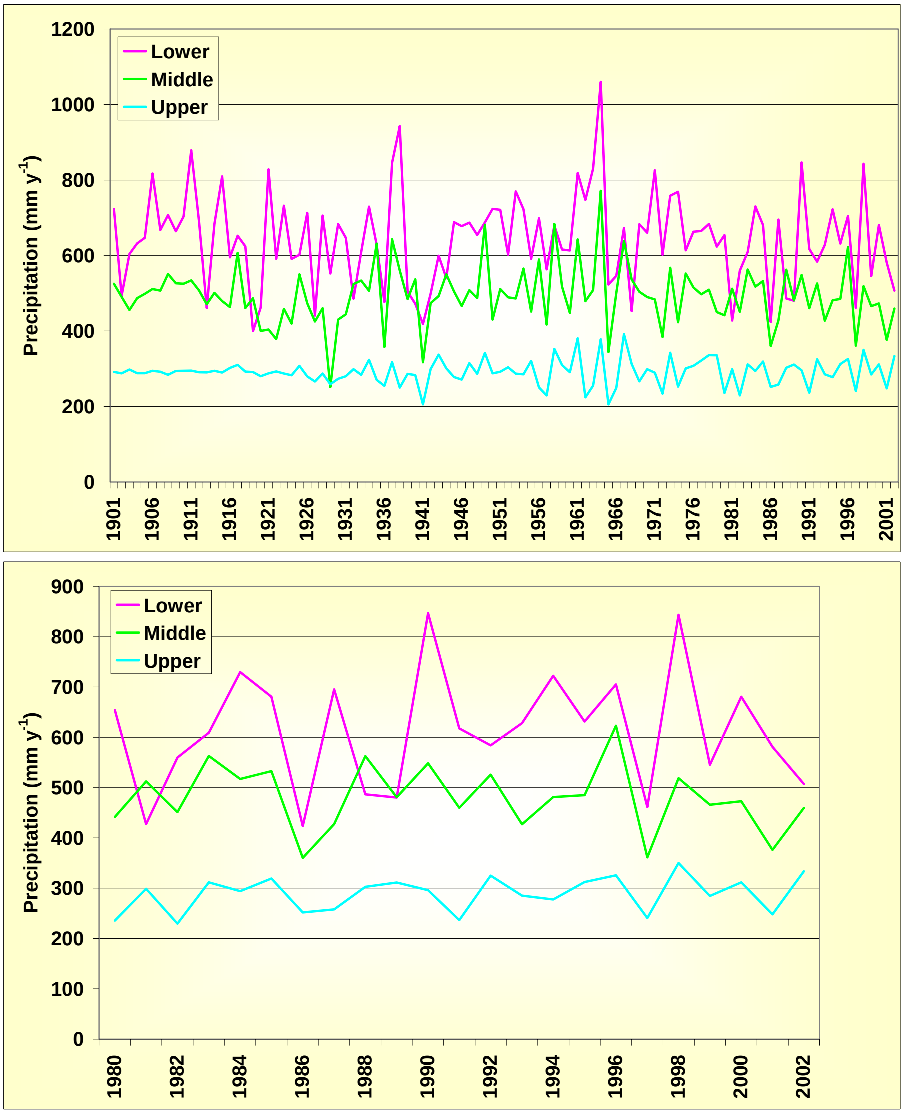


Figure 11. Annual precipitation for the three reaches of the Yellow River according to the GRU global data set.

3.3.1.2 Precipitation

Accurate meteorological data for this initial WEAP analysis were not yet available at a high spatial resolution. Therefore the high resolution Climate Research Unit (CRU) global data set of the University of East Anglia was obtained. The CRU TS 2.1 dataset comprises 1200 monthly grids for the period 1901-2002, and covers the global land surface at 0.5° × 0.5° resolution (Mitchell and Jones, 2004). The dataset comprises: cloud cover, diurnal temperature range, precipitation, temperature and vapor pressure. The CRU dataset is based on raw station data, which are scarce in some regions and periods. A method called 'relaxation to the climatology' was used to create continuous grids. This implies that, for some areas or regions, data are less accurate.

For the Yellow River a total of 397 CRU points (Upper 217, Middle 149, Lower 31) were extracted and average values for each reach were used. For this initial phase of the model only precipitation data were used. In a following-up phase temperature and potential evapotranspiration might be used as well. In Figure 11 annual precipitation for the three reaches is plotted for the entire 1901-2002 period. Figure 12 shows the monthly averaged precipitation for the period 1990-2002. The Lower Reach receives more rainfall than the Upper Reach and wettest months are July and August.

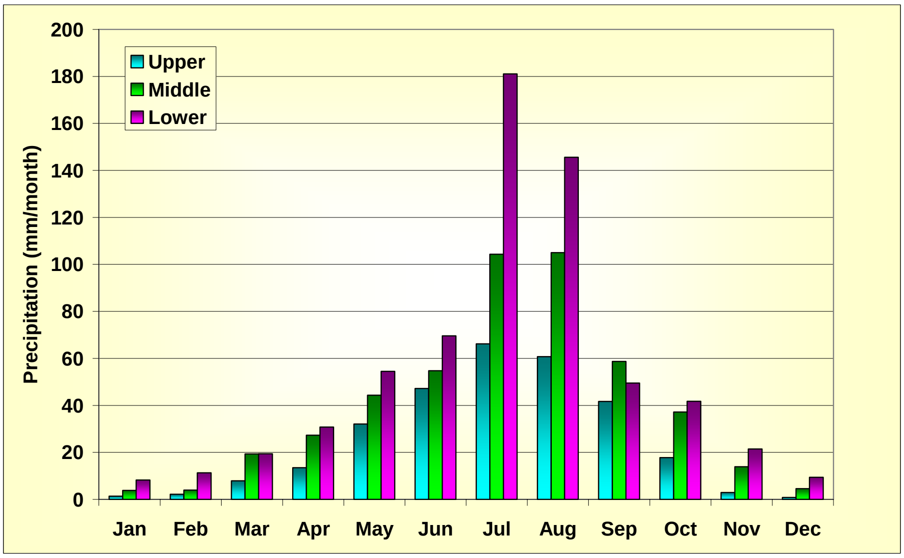


Figure 12. Monthly average precipitation (1990-2002) for the three reaches.

3.3.1.3 Discharge

Discharge data have been obtained from the Global Runoff Data Centre in Koblenz, Germany (GRDC, 2007). Monthly runoff data from nine stations in the Yellow River Basin were available from GRDC, of which five stations were located on the main stream of the Yellow River (see Figure 13):

- Sanmenxia (1953 – 1988)
- Shanxian (1919 – 1958)
- Tanglai qu (1978 – 1997)
- Huangheyan (1978 – 1997)
- Huayuankou (1946 – 1988)

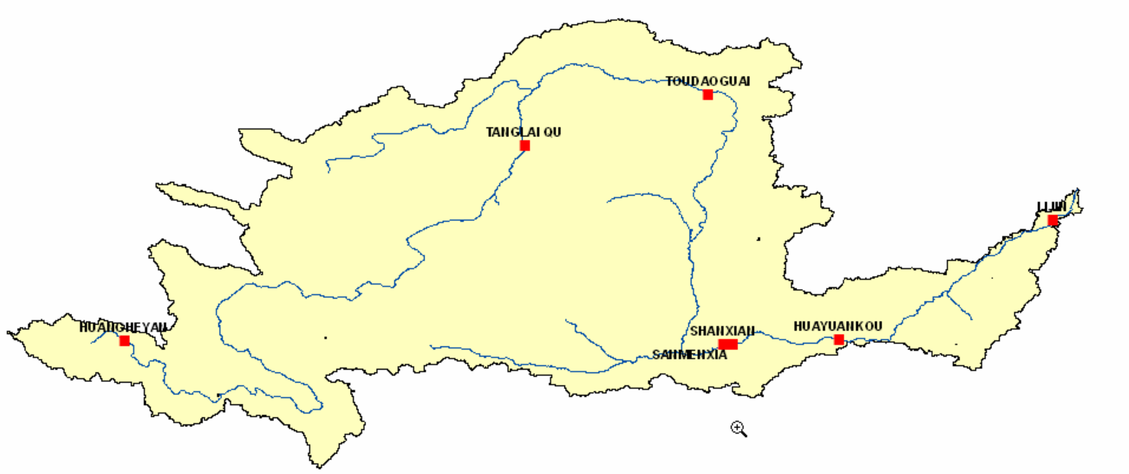
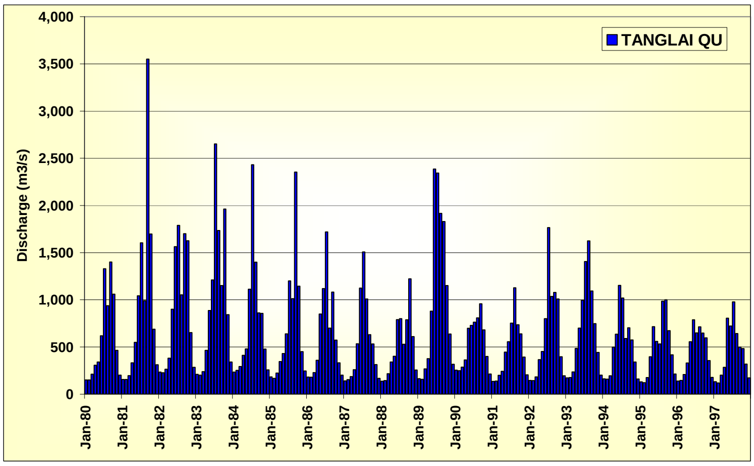


Figure 13. Overview of the major gauging stations.

Unfortunately, no records of the stations Toudaoguai or Lijin were available and only data from Huayuankou could be used to represent the Middle Reach. Figure 14 shows that there is a clear downward trend in discharge indicating that historic data are an unreliable estimate for the current situation. More recent data on 3 stations are only available for the year 2000 as expressed in total annual flow (Zhu et al.,2003).



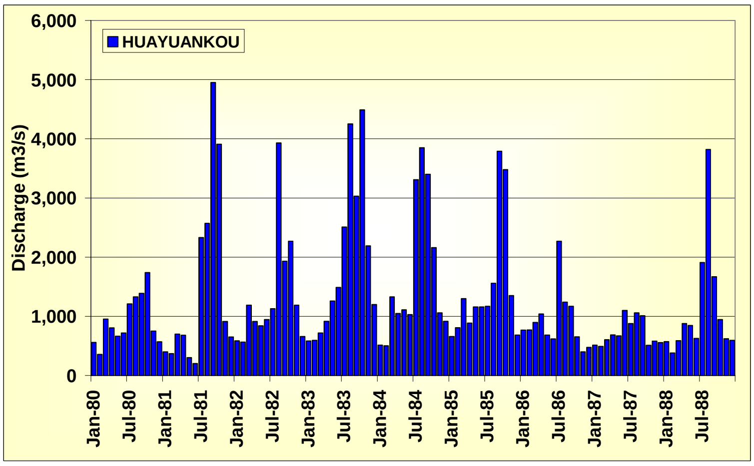


Figure 14. Discharge data for two stations from the GRDC data.

3.3.2 Schematisation

3.3.2.1 General

The diversion in three reaches is also used in the initial setup for WEAP. For each reach one Catchment Node, two Demand Sites and one Groundwater Node were included to represent the entire water resources of Yellow River (Figure 15).

The Catchment Node receives precipitation and evaporation is simulated. Part of the precipitation that is not evaporated infiltrates to the Groundwater Node; part of is run-off to the River. For each reach there’s one Demand Sites specified which receives water from the river and one Demand Site which receives water from the Groundwater Node.

As a base year used in the calibration 1998 was used. In this initial WEAP version of the Yellow River the simulation period is 1998-2000.

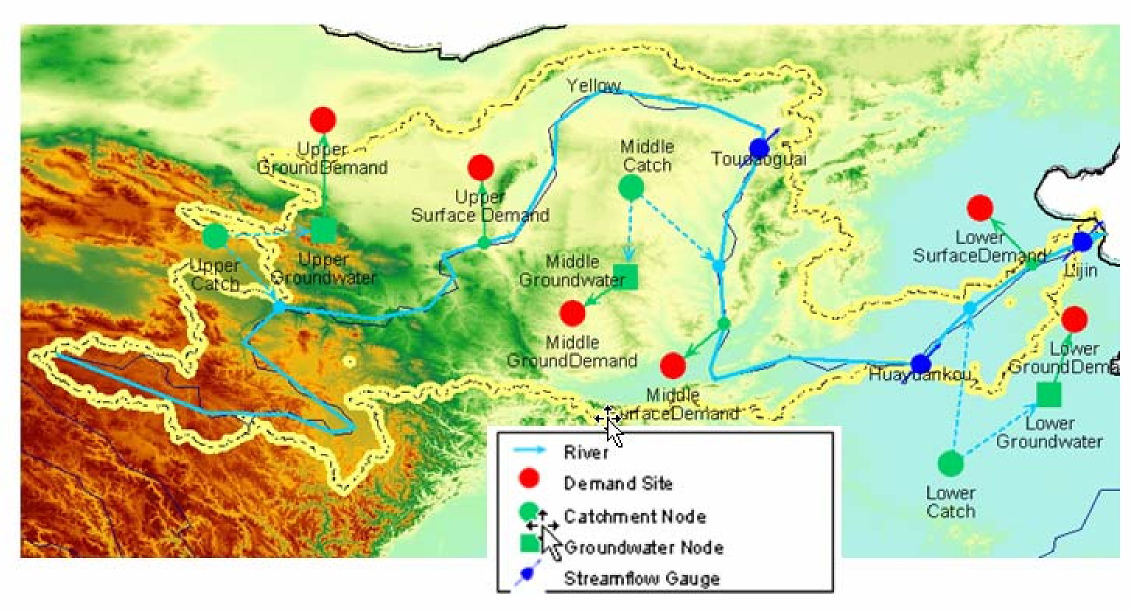


Figure 15. Schematization of the Yellow River Basin in WEAP.

3.3.2.2 Catchment Nodes

As described in section 3.3.1.2 the monthly rainfall is based on the CRU dataset. Figure 16 gives an overview of the precipitation input for the different reaches. Evaporation is estimated using a fixed percentage of precipitation available for evapotranspiration (see Figure 17). The remainder is the effective precipitation and was estimated as a result of the calibration (see section 3.3.3).

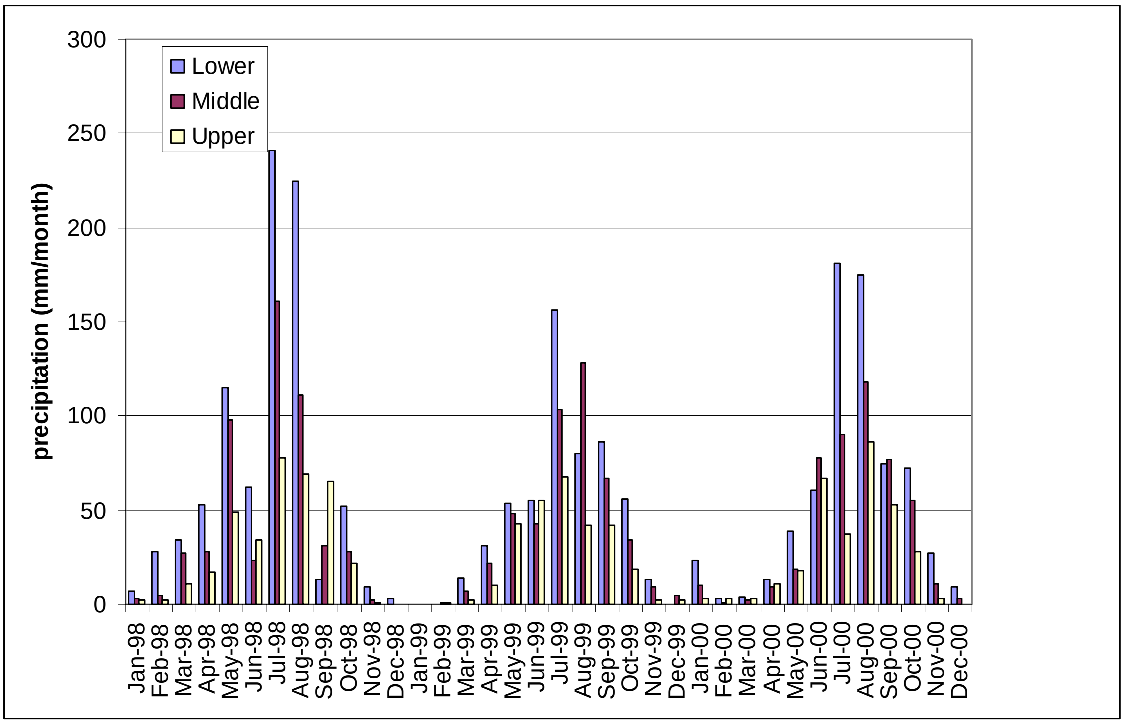


Figure 16: WEAP-input: Monthly precipitation for the period 1998-2000 according to the CRU dataset for the three reaches.

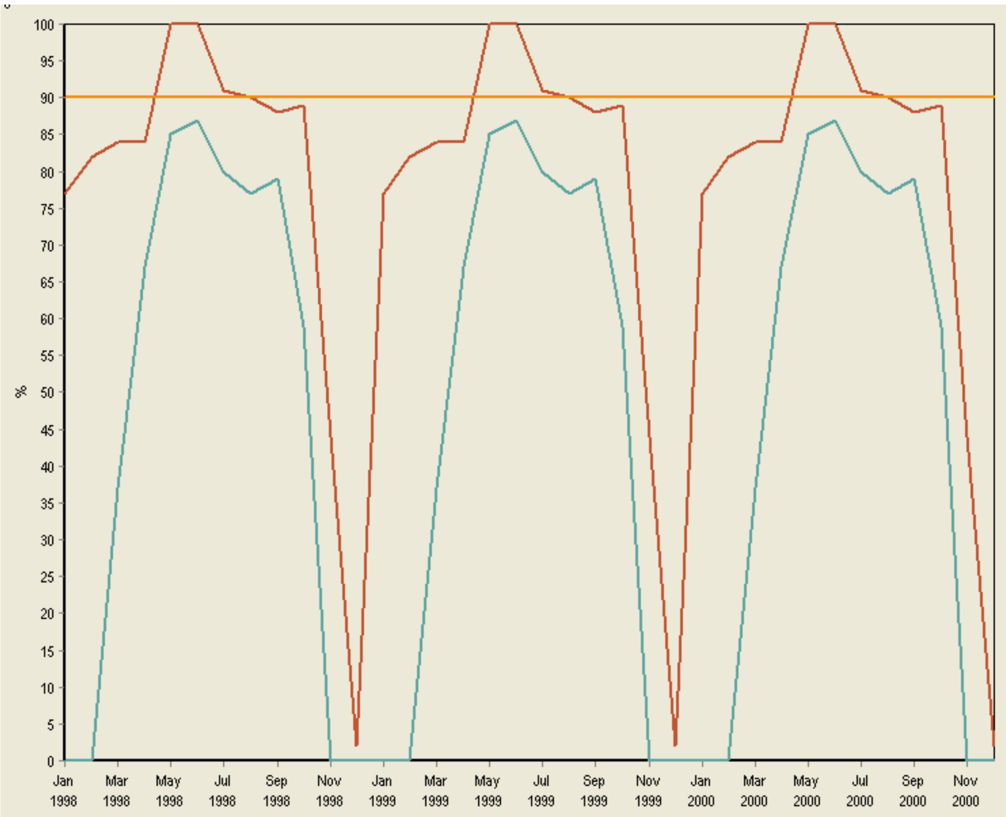


Figure 17: Weap input: percentage of precipitation available for evapotranspiration for the period 1998-2000 as estimated as a result of the calibration.

For calculating the Runoff the Rainfall Runoff approach has been selected. This is a simple method that computes the sum of runoff and groundwater recharge as the difference between precipitation and evapotranspiration. The runoff fraction was based on the data presented by Zhu et al. (2003) and Giordano et al (2004): 94% is runoff to the river, 6% is groundwater recharge.

3.3.2.3 Water Demand Sites

WEAP is able to deal with complex water demand and use issues. Given the demonstration nature of this study and the lack of reliable data, a constant water demand was assumed based on the data presented by Zhu et al., (2003) and Giordano et al. (2004). For the entire river basin those data are mentioned in the water balances of the ground water and the surface water (Table 1). Only one average annual value was provided (see Figure 18) per Demand Site. No difference is made in water demand for domestic, industrial or irrigation purposes. For each reach there's one Demand Sites specified which receives water from the river and one Demand Site which receives water from the Groundwater Node. Additionally for the Surface Water Demand Sites a monthly variation was assumed that follows the precipitation records variation (see Figure 19).

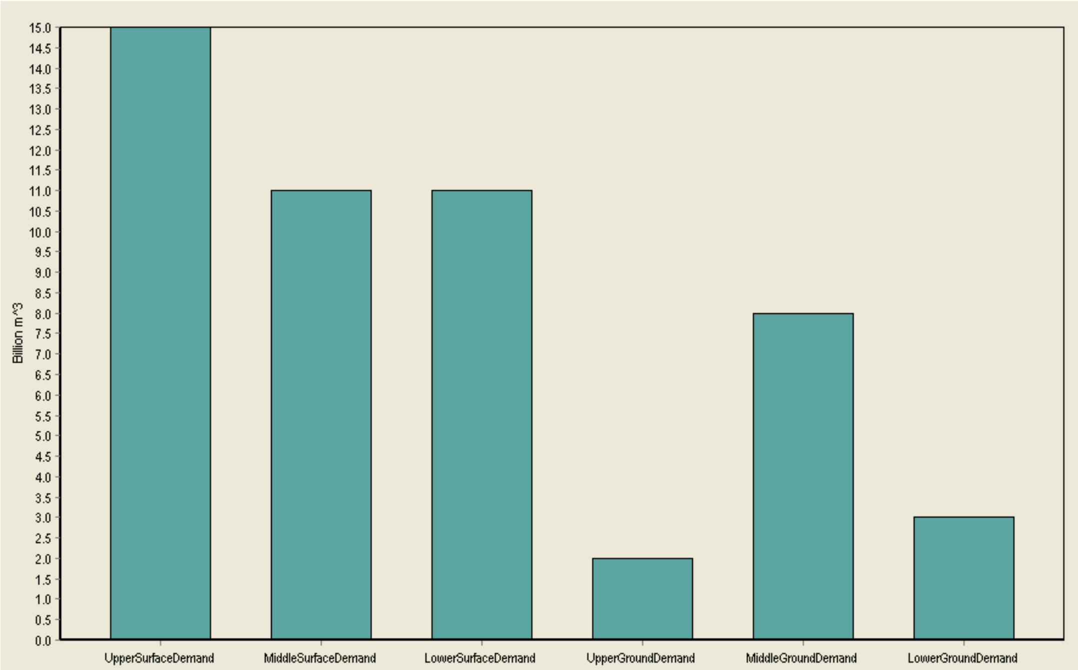


Figure 18: WEAP input: Annual water demand (billion m^3) for the six Demand Sites.

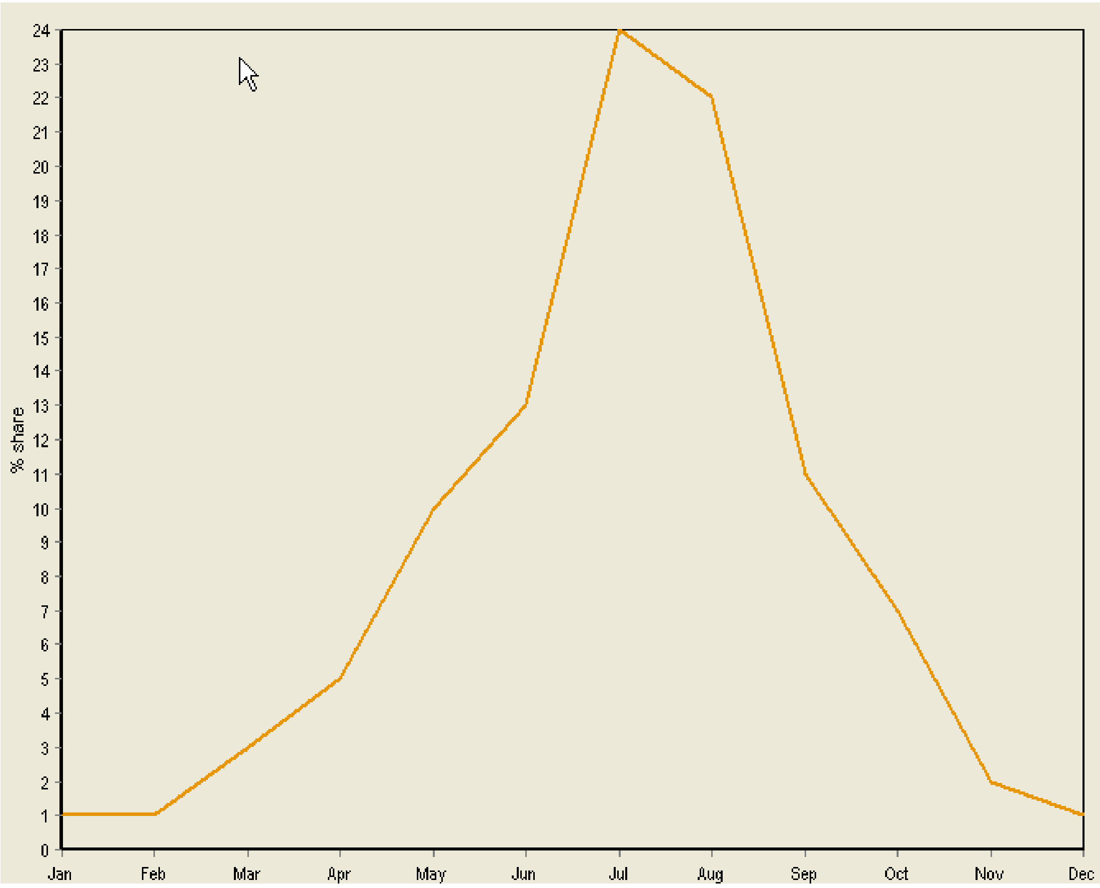


Figure 19: WEAP input: Monthly share of annual surface water demand (billion m^3) for the six Demand Sites.

3.3.2.4 Groundwater Nodes

No information regarding the absolute storage capacity of the aquifers was available and therefore a dummy value of 5 BCM was assumed. Main objective of this Groundwater Node was to mimic fluctuations in groundwater to be able to compare results to GRACE monitoring data.

3.3.2.5 Streamflow gauges

Streamflow gauges have been added to the WEAP schematization in order to compare calculated and observed river discharges. The total annual flow data for the year 2000 presented by Zhu et al. (2003) were adjusted to reflect monthly variation using the variation as the GRDC data at Huayuankou over the period 1980-1988. This discharge pattern was assumed to be constant over the period 1998-2000. Figure 20 presents these "observed" data for the three Streamflow gauges.

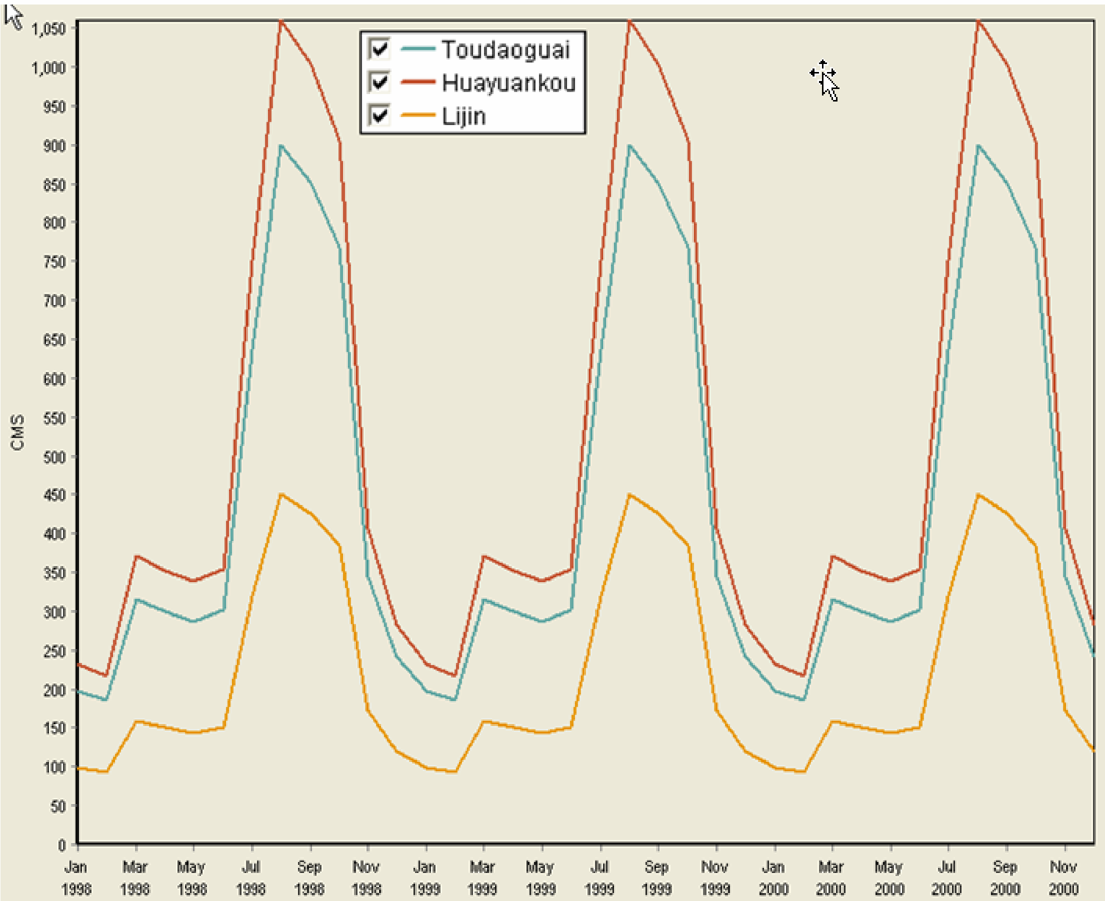


Figure 20: WEAP input: monthly discharge for the period 1998-2000 for the three Streamflow gauges. Input is based on annual observed Yellow River flows in the year 2000 and a monthly distribution according to GRDC data at Huayuankou over the period 1980-1988.

3.3.3 Calibration

A very initial calibration procedure has been performed for the year 1998 using the following factors:

- Effective precipitation: percentage of precipitation that becomes runoff or groundwater recharge.
- Runoff fraction: fraction of effective precipitation as surface water runoff and as groundwater recharge.

Since only qualitative calibration data were available a very basic calibration was performed. A typical example is shown in Table 2, where two parameters were optimized by taking estimated streamflow, demand shortage and groundwater fluctuation from qualitative information. Calibration was performed by comparing observed and simulated discharge and simultaneously considering the overall water balance as presented in Table 1.

Table 2. Example of initial calibration for the Upper Reach, using two parameters.

Parameter	*Run1*	*Run2*	*Final run*
Effective Precipitation (%)	25	23	Monthly (inverse of Figure 17)
Runoff Fraction % to Surface water	94	94	94
WEAP-results 1998			
Runoff (BCM)	32.2	29.6	30.7
Unmet Groundwater Demand (BCM)	0	0	0
Unmet Surfacewater Demand (BCM)	1.4	1.8	2.1
Streamflow (BCM)	16.6	14.6	16

3.3.4 Results

This section should be considered as a demonstration of the options WEAP offers to evaluate water resources in a transparent way. Results presented are based on assumptions and simplifications and should therefore only be considered as indicative. These simplifications are mainly in the restricted number of Nodes (only three reaches with each one Catchment Node, one Groundwater Node and two Demand Sites). In terms of assumptions insufficient discharge and water demand data were available. However this section provides a nice overview of what can be done with WEAP to evaluate water resources, including scale issues and all components of the water balance, in a comprehensive framework.

WEAP offers the opportunity to present model results in a wide-range of output: graphs, tables, maps and exported to excel. Results can be aggregated in space (e.g. all demand sites) or in time (annual totals, monthly averages etc.). As typical examples the following output is provided:

- Figure 21: Fluctuations in groundwater storage. Absolute values of aquifer storage were unknown and therefore an initial storage capacity of 5 BCM was assumed for the three aquifers. Values shown in the Figure reflects therefore relative changes in storage.
- Figure 22: Observed and simulated streamflow for the Upper Reach and Middle Reach of Yellow River Basin. Based on the initial calibration as mentioned above, a good match between observed and simulated streamflow was obtained.

- Figure 23: Water balance of the Middle Reach. A substantial part of the total available water resource (= precipitation) is consumed before reaching the river or recharging the groundwater.
- Figure 24: Graphical representation of simulated streamflow for the year 1999. In reality supply and withdrawals will be spatially more distributed.
- Table 3: Groundwater balances for three years. For the Lower Reach substantial extractions and relatively low recharge levels can be seen.

Some options WEAP offers were not presented here. One of the most important one is scenario analysis (what…, if…). WEAP is extremely suitable to evaluate the impact of a certain change and how to respond to this. Typical examples that can be included are impact of reservoir construction, changes in agricultural practices, increased demand for industry, climate change, drought management, etc.

A second option of WEAP not demonstrated is the use of multi-year trend analysis. WEAP is extremely strong in evaluating water resources demands and supplies over tens of years. Especially in the case of Yellow River, with increasing demands over the last decades, a thorough evaluation could lead to a better understanding of past water resources that might assist decisions making for the future.

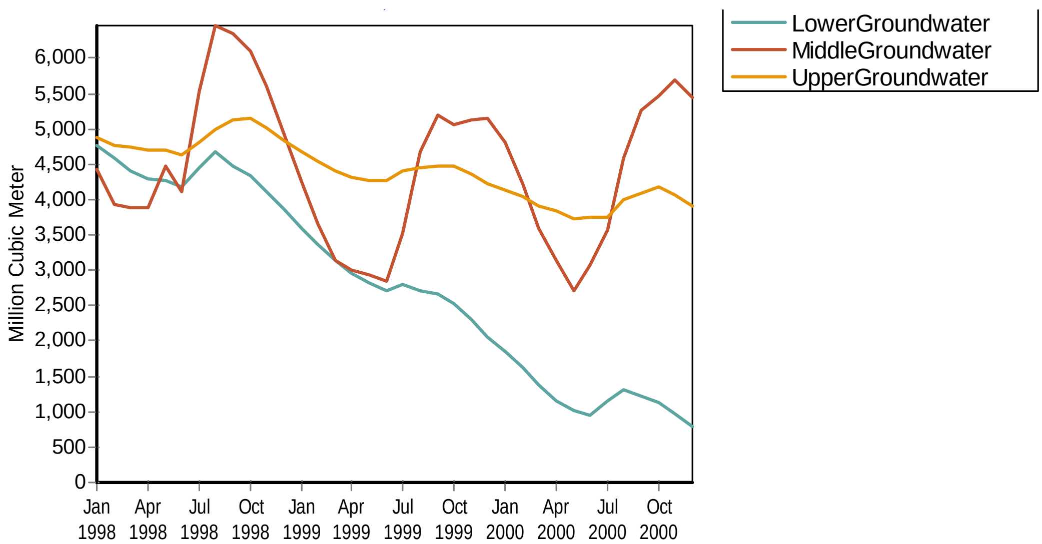
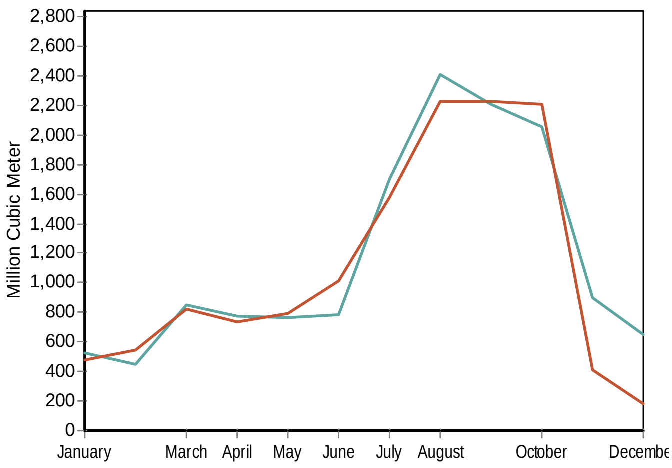


Figure 21. Groundwater storage fluctuation for the three aquifers. Initial storage is set to a dummy value of 5 BCM.



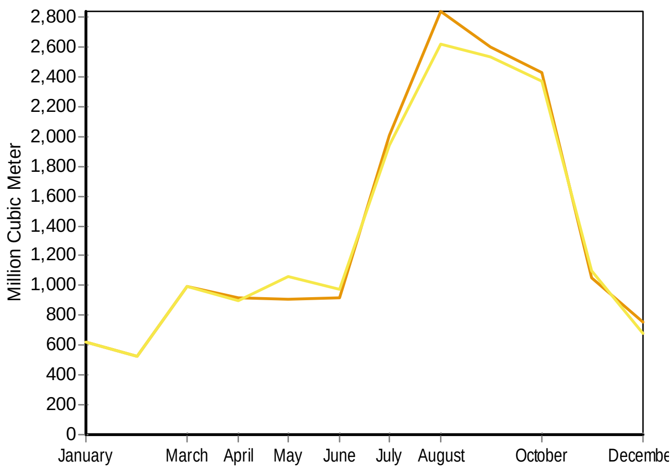


Figure 22. Observed (blue, orange) and simulated (red, yellow) streamflow for Upper Reach (top) and Middle Reach (bottom). Monthly averages over the period 1998-2000.

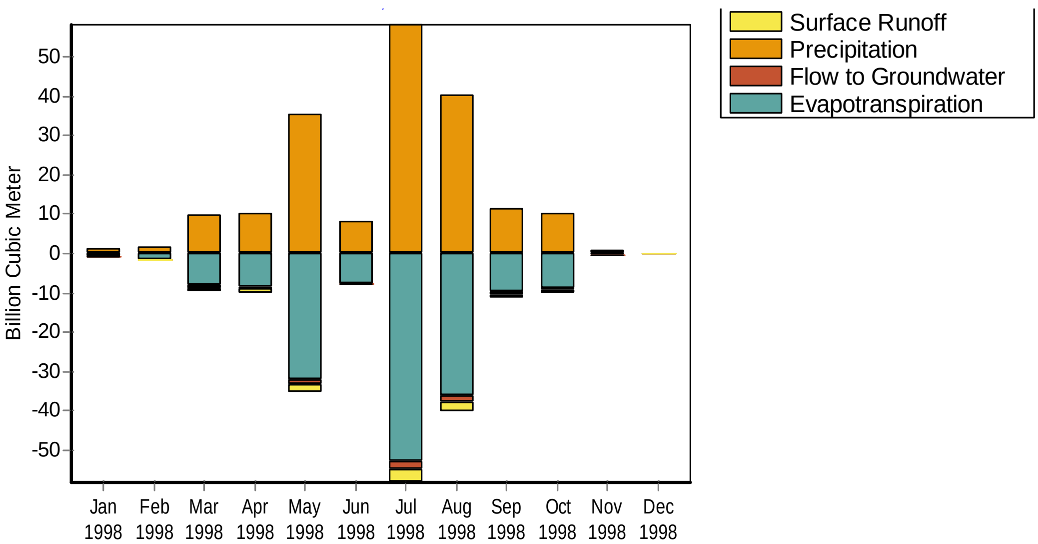


Figure 23. Water balance of the Middle Reach catchment.

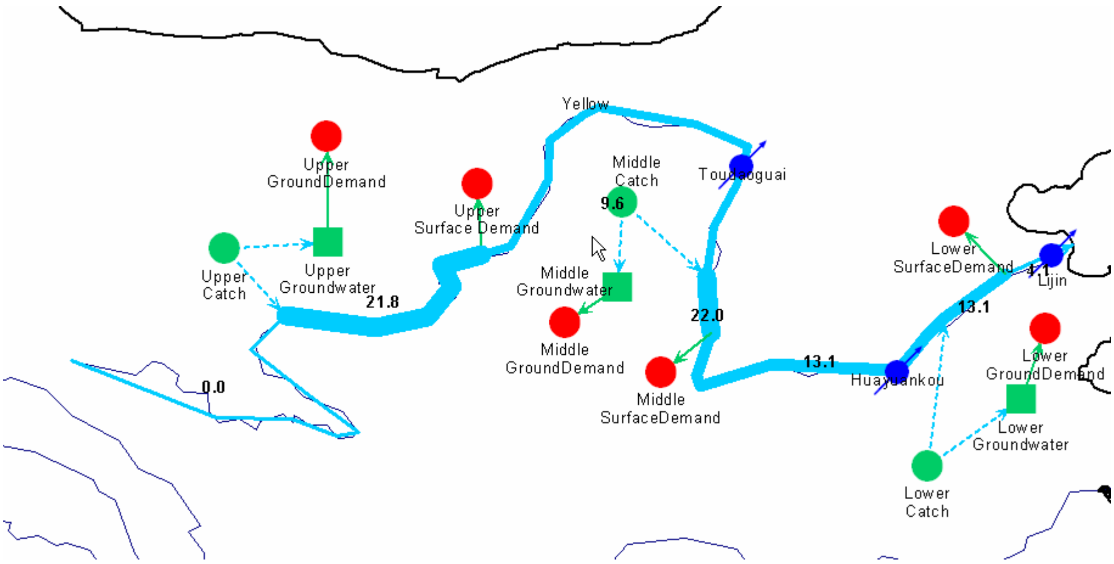


Figure 24. Streamflow in 1999 as simulated by WEAP (units: BCM).

Table 3. Groundwater balances resulting from WEAP runs.

	1998 BCM	*1999 BCM*	*2000 BCM*	*1998 mm*	*1999 mm*	*2000 mm*
Upper						
Recharge	1.843	1.392	1.672	5.0	3.8	4.5
Extraction	2.000	2.000	2.000	5.4	5.4	5.4
Storage change	-0.157	-0.608	-0.328	-0.4	-1.7	-0.9
Middle						
Recharge	7.934	8.225	8.291	21.9	22.7	22.9
Extraction	8.000	8.000	8.000	22.1	22.1	22.1
Storage change	-0.066	0.225	0.291	-0.2	0.6	0.8
Lower						
Recharge	1.852	1.199	1.500	84.2	54.5	68.2
Extraction	3.000	3.000	2.755	136.4	136.4	125.2
Storage change	-1.148	-1.801	-1.500	-52.2	-81.9	-68.2
Basin						
Recharge	11.629	10.815	11.464	15.5	14.4	15.2
Extraction	13.000	13.000	12.755	17.3	17.3	17.0
Storage change	-1.371	-2.185	-1.291	-1.8	-2.9	-1.7

3.4 Integration of GRACE and WEAP

The integration of GRACE and WEAP as described in this report is very preliminary. First of all because the period simulated in WEAP differs from the period for which GRACE data are available. Another item that complicates the comparison is that WEAP presents groundwater storage differences where in GRACE storage differences include groundwater as well as soil moisture and snow cover. Finally the WEAP results are based on minimal datasets and should therefore only be considered as indicative. Nevertheless Figure 25 and Figure 26 show the (ground)water storage differences (with respect to an average) per month according to WEAP and GRACE respectively for the three reaches.

It's clear that for the upper and middle reach the seasonal variations in groundwater storage according to WEAP are about a factor 10 lower than water storage according to GRACE. Part of this difference can be explained by the fact that GRACE measures not only groundwater storage differences but also differences in soil moisture and snow cover. But still, the seasonal fluctuation according to WEAP in these reaches seems to be quite underestimated. In the lower reach the possible seasonal fluctuation in groundwater according to WEAP is overruled by a very pronounced downward trend. GRACE is showing a downward trend in terrestrial water storage for this reach as well. However over three years, WEAP is showing a drop in groundwater storage which is about five times as high as according to GRACE. In WEAP there's no downward trend visible over the three years of simulation for the upper and middle reach. Where as GRACE is also showing for these reaches a downward trend in terrestrial water storage, though less pronounced as the trend for the lower reach.

In summary the comparison between WEAP and GRACE shows substantial differences that can be explained by the following points:

- WEAP was setup with very limited data and information
- In WEAP it was assumed that groundwater extraction was constant during the year
- GRACE results include groundwater, soil moisture and snow cover

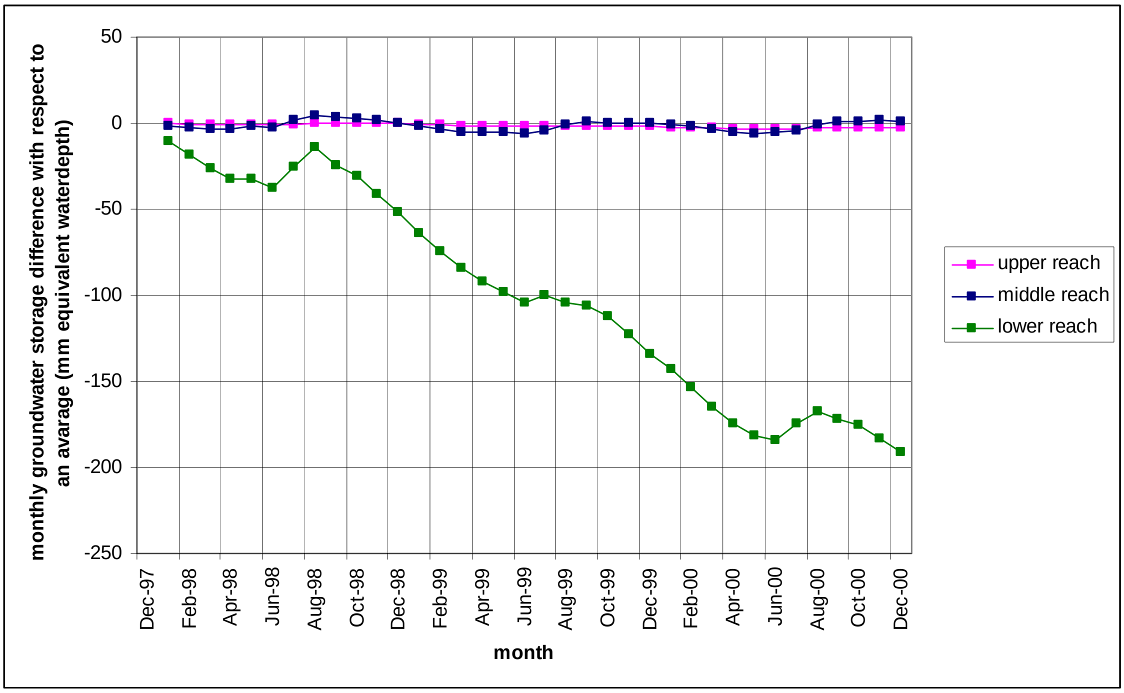


Figure 25: Monthly changes in groundwater storage relative to an average (mm equivalent water depth) for the sub-basins of the Yellow River Basin according to WEAP.

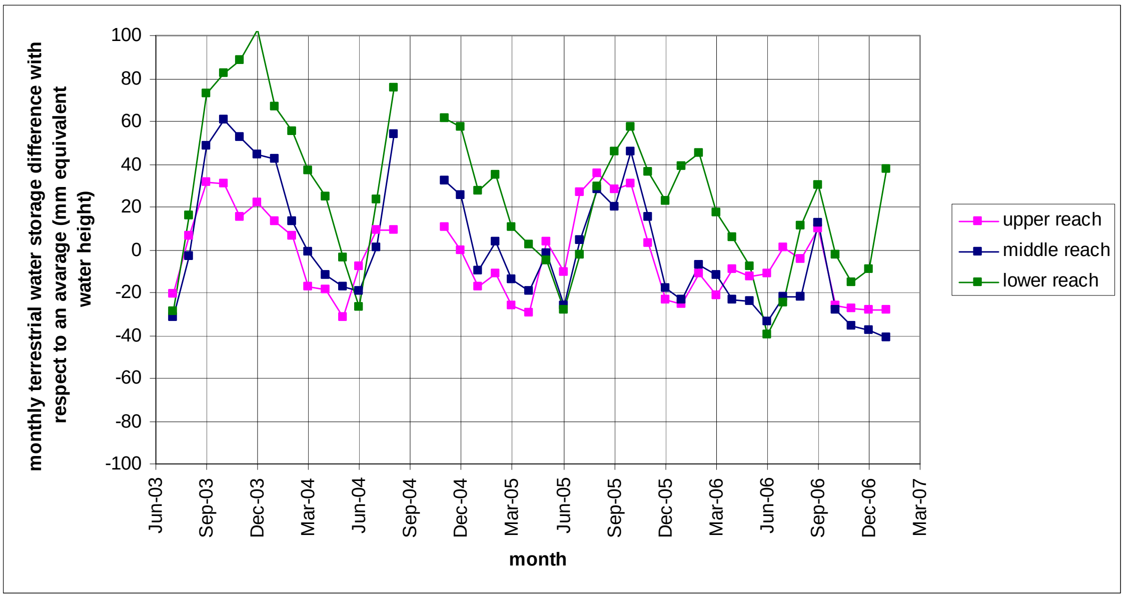


Figure 26: Monthly changes in water storage (soil moisture, groundwater and snowcover) relative to the long term average (in mm equivalent water depth) for the sub-basins of the Yellow River Basin according to GRACE.

4.1 Introduction

The Shiyang River Basin has an area of some 41,600 km^2. Eight tributary stream from the Qilian mountains in the south and flow out over alluvial fans into the plain and towards the Badanjilin Desert in the north (Figure 27). To the east is the Tenggeli Desert. These eight streams all join the Shiyang River in the middle basin, which then flows through the Minqin oasis before terminating in the Quing Tu lake. The Quing Tu lake dried up in the early 1960s following construction of the Hongyashan Reservoir, and extension of irrigation in the Minqin oasis.

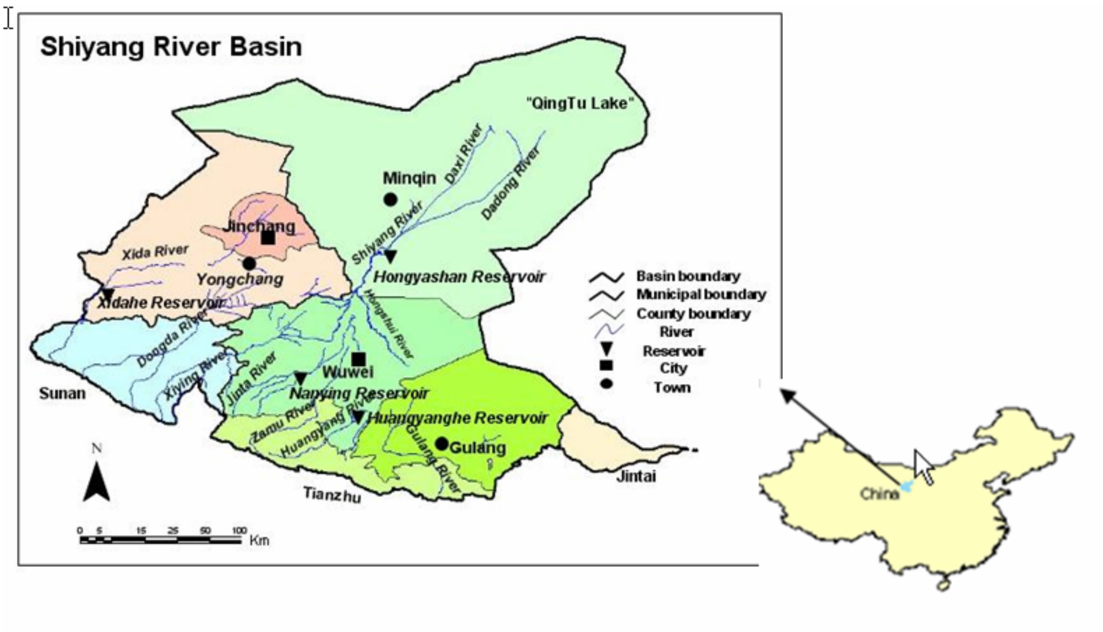


Figure 27. The Shiyang River Basin (DFID, 2004).

Precipitation occurs mainly over the mountains in the south, and is of the order of 600 mm annually. In the North of the Shiyang River Basin, average annual precipitation is of the order of 60 mm. Precipitation is highest in July, August and September. Most runoff is thus generated in the mountains in the South, and much of it is from snow and glacier melt in the spring and summer. In the mountains in the southwest there's natural vegetation cover, but north and east of the mountains vegetation exists only in the river corridors where there is irrigation.

4.2 GRACE

The spatial resolution of the derived GRACE product is limited to 50 x 50 km. The Shiyang River Basin is therefore represented by only twenty points. In Figure 28 the monthly storage difference with respect to the long-term average is shown for the Shiyang River Basin. These data are derived from the gravity observations. Figure 28 shows clearly the seasonal variations in water storage in the Shiyang River Basin. In general most water is present in September and least in March/April. The seasonal variety is approximately 60 mm equivalent water depth. If the storage of snow, open water and soil moisture is neglected and a specific yield of the aquifer of 10% is assumed, this is equivalent to a seasonal groundwater variation of approximately 0.60 m. Figure 28 shows a difference in water storage for the Shiyang River Basin: 2004 is dryer than 2003 and 2005. However there's no pronounced trend for the observations over the short period 2003-2006.

Figure 29 shows the storage difference between October 2003 and May 2004. This figure gives an impression of the spatial distribution of the seasonal water storage difference. This seasonal variation is the lowest (40-60 mm equivalent water depth) in the Western part and the highest (>80 mm) in the Eastern part of the basin.

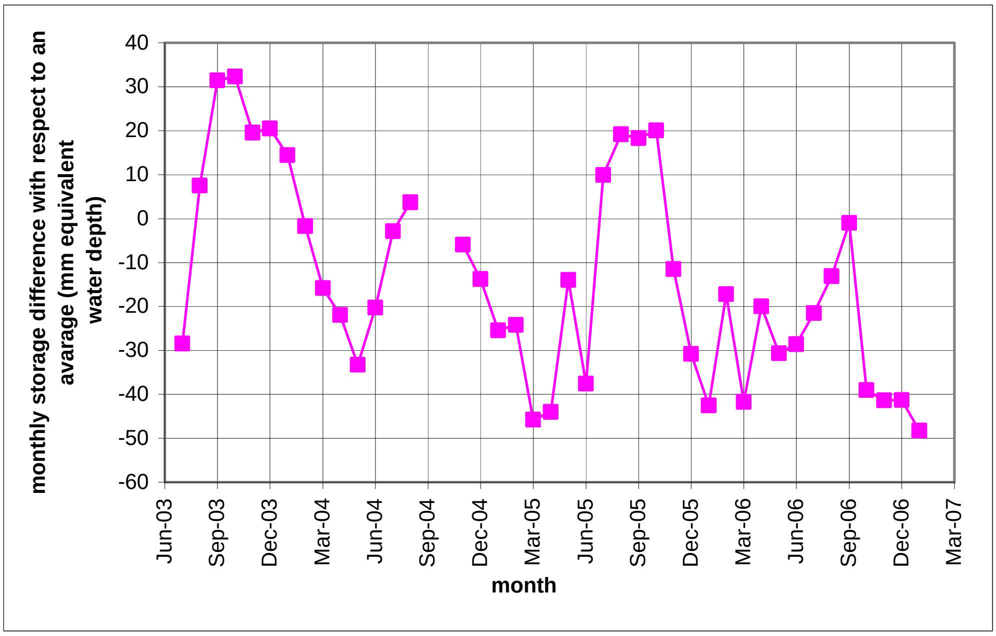


Figure 28: Changes in water storage (soil moisture, groundwater and snow cover) relative to the long term average (in mm equivalent water depth) for the Shiyang River Basin.

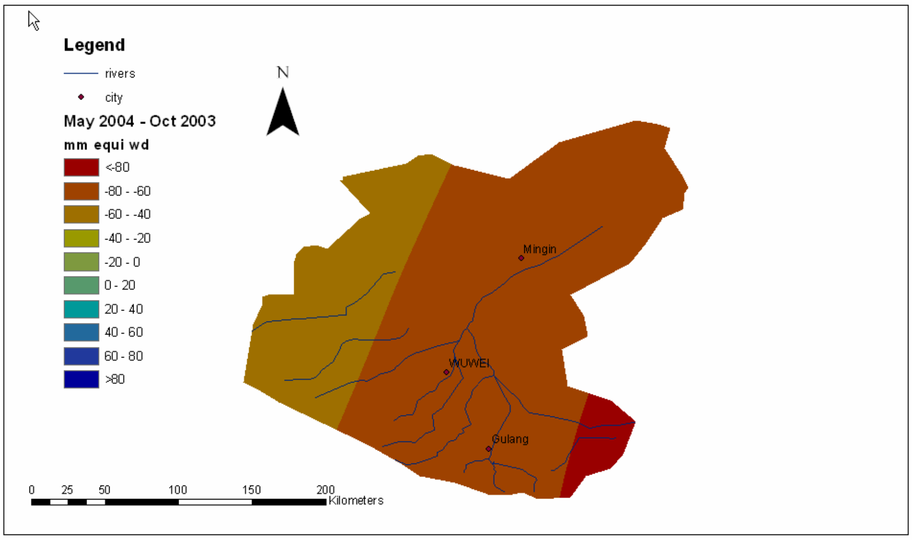


Figure 29: Storage difference between October 2003 and May 2004 expressed in mm equivalent water depth (negative indicates dryer conditions in May).

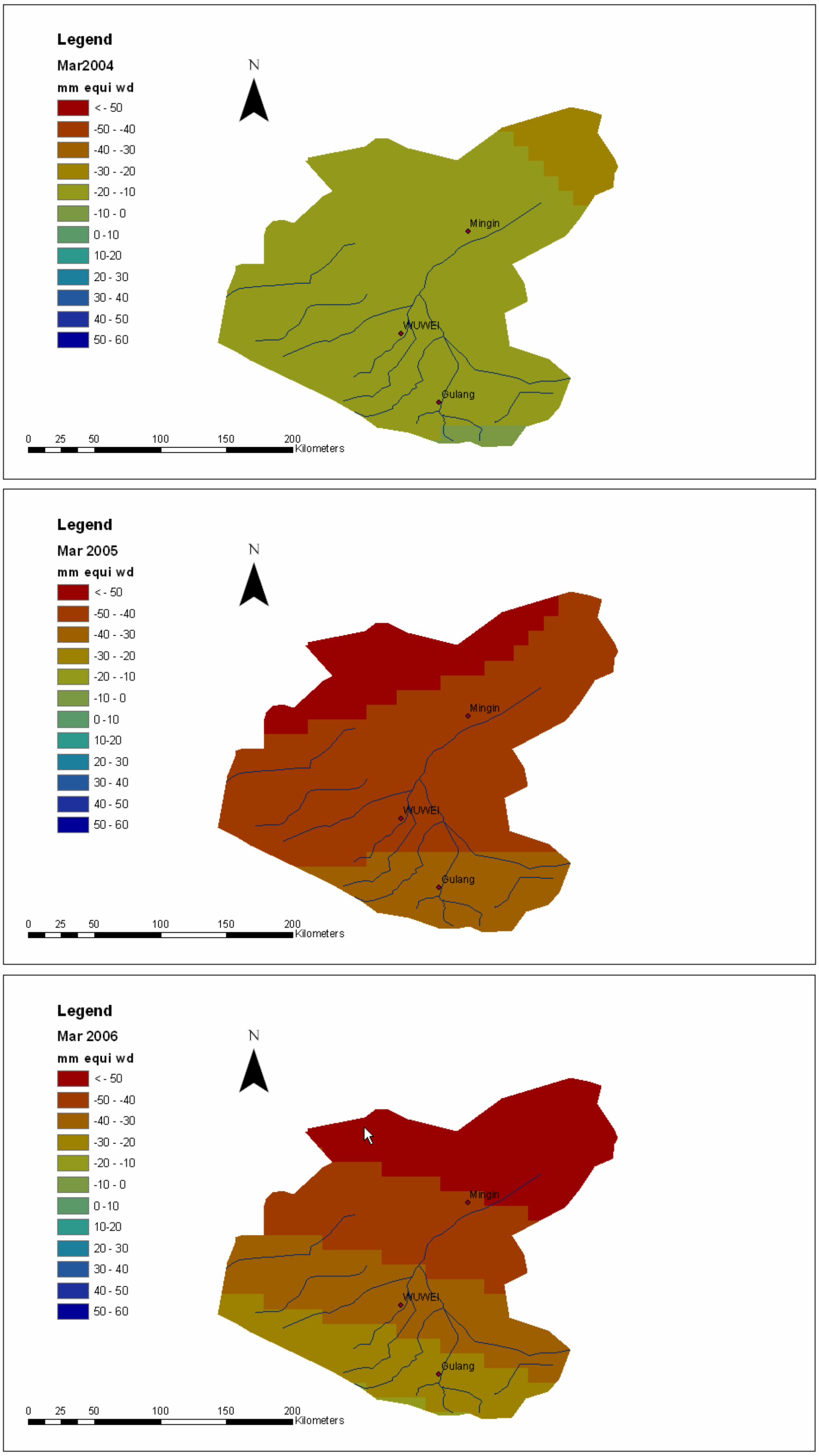


Figure 30. Changes in water storage (soil moisture, groundwater and snow cover) relative to the long time average (in mm equivalent water depth) for the Shiyang River Basin in March 2004 (a), March 2005 (b) and March 2006 (c)

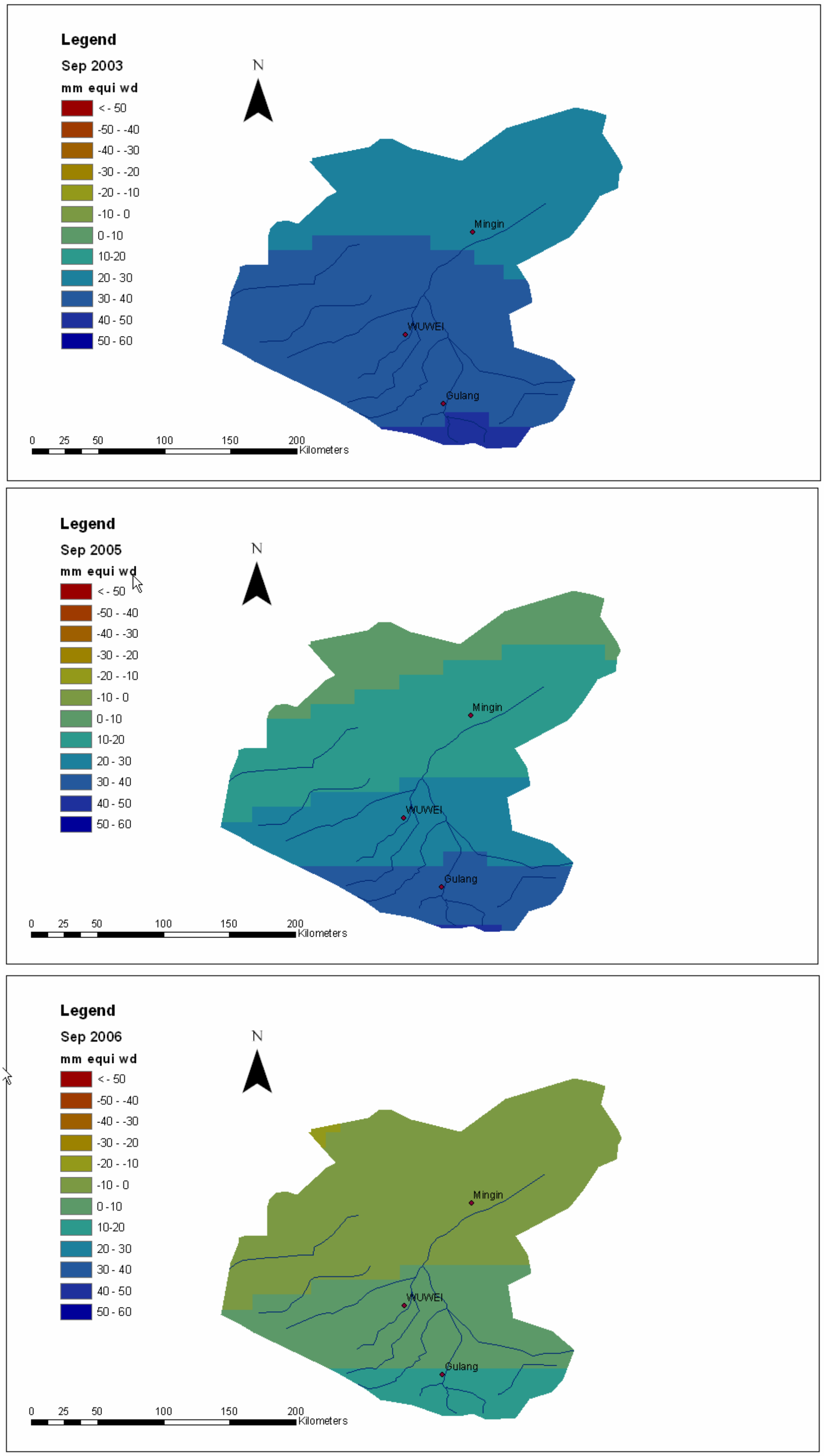


Figure 31. Changes in water storage (soil moisture, groundwater and snow cover) relative to the long time average (in mm equivalent water depth) for the Shiyang River Basin in September 2003 (a), September 2005 (b) and September 2006 (c)

In Figure 30 the relative water storage is shown for the month of March of respectively the years 2004, 2005 and 2006. These figures show that the north of the basin is getting dryer every year. However, in the central and the southern part of the basin the year 2005 is the driest year. In a next phase of this research monthly spatial distributed precipitation data will be included. It is expected that these precipitation data will give more insight in these spatial and temporal variations in terrestrial water storage.

In Figure 31 the relative water storage is shown for the month of September of respectively the years 2003, 2005 and 2006. The relative water storage for September 2004 is not presented; due to repeated tracks of the satellites the quality of these data is low. These figures clearly show a downward trend for the whole river basin.

4.3 WEAP

4.3.1 Schematisation

The WEAP model was configured for the Shiyang River Basin as part of the Water Resources Demand Management Assistance Project (DFID, 2004). This was used as the starting point for the current study. The WEAP schematisation (Figure 32) of the Shiyang River Basin is much more detailed than that of the Yellow River Basin as described in section 3.3.2. Details on data collection and schematisation can be found elsewhere (Mott MacDonald, 2006; Droogers, 2007).

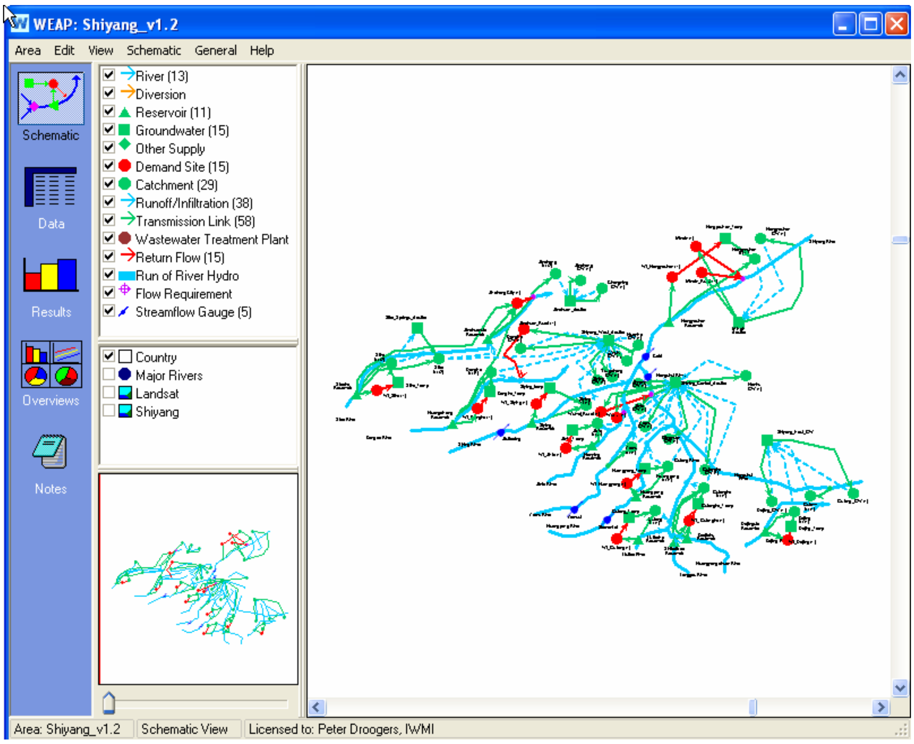


Figure 32: Schematic view of the Shiyang River Basin WEAP model

4.3.2 Results

Details regarding output analysis can be found elsewhere (Droogers, 2007) and therefore only most important model output options will be discussed here.

4.3.2.1 River flow

One of the first actions in any hydrological modeling will be to evaluate stream flows. For two rivers (Shiyang and Hongshui) observed and simulated flows were compared (Figure 33). Note that observations before 2000 for Hongshui river might be unreliable. Overall the performance of the model is quite good, especially considering that neither calibration nor validation was carried out.

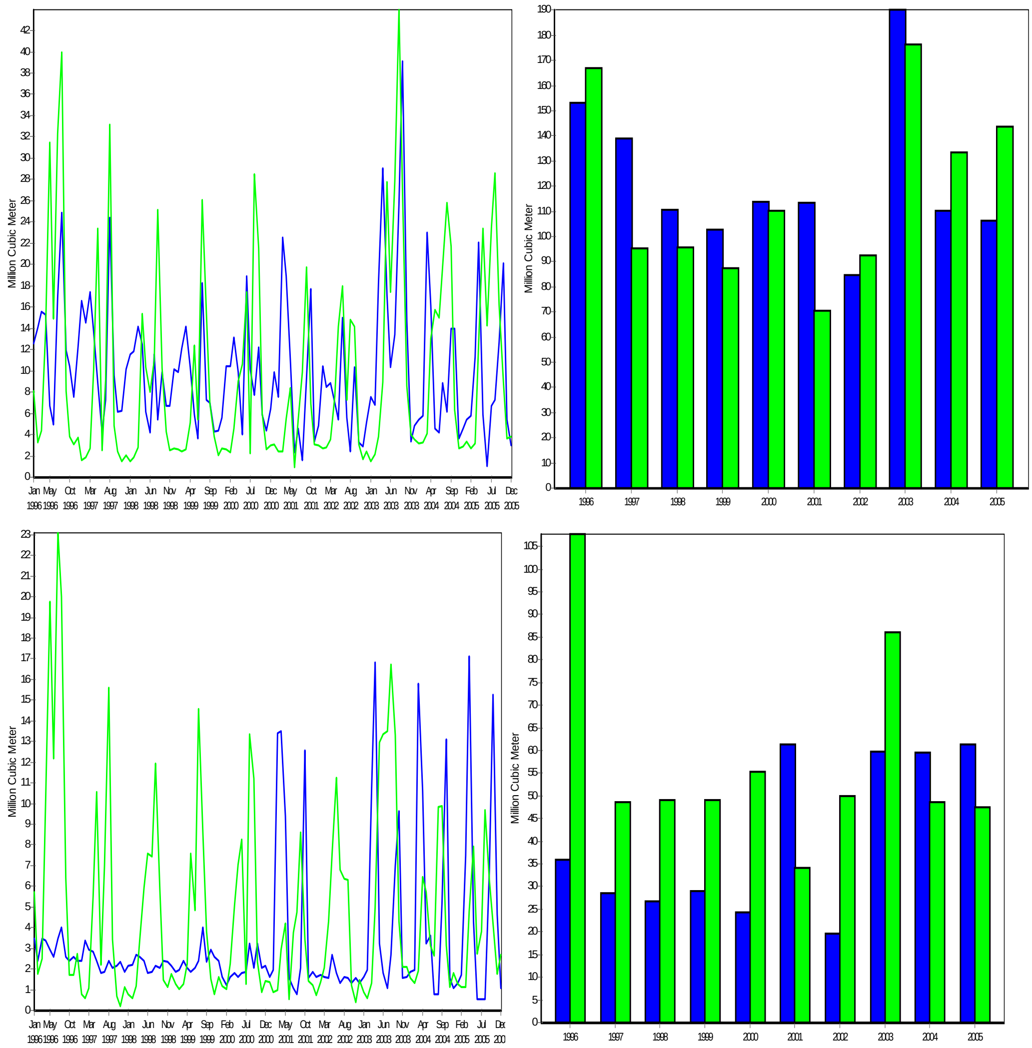


Figure 33. Comparison between observed (blue) and simulated (green) monthly and annual flows for the Shiyang river (top) and the Hongshui river (bottom).

4.3.2.2 Urban demand, supply and consumption

In total six urban water demands have been defined in the SRB-WEAP model (Wuwei, Jinchang, Minqin, Wuwei Rural, Jinchang Rural, Minqin Rural). As an example of the analysis water shortages (Unmet Demand in WEAP terminology) for Wuwei are presented in Figure 34 and Figure 35.

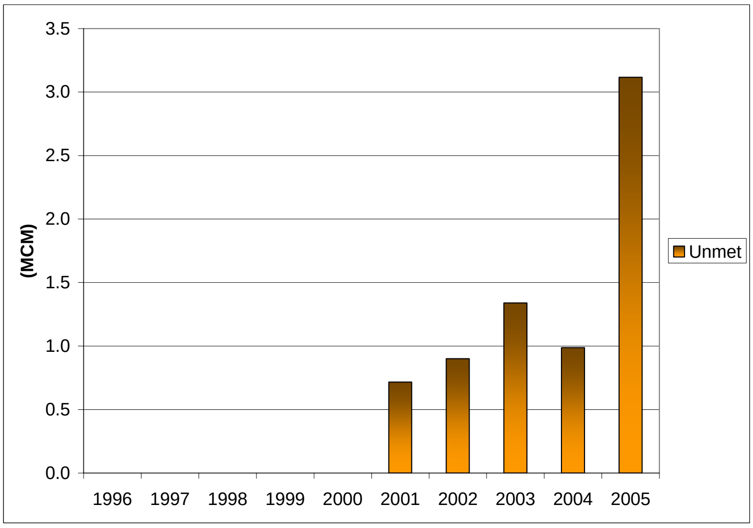


Figure 34. Annual shortage of water delivery for Wuwei.

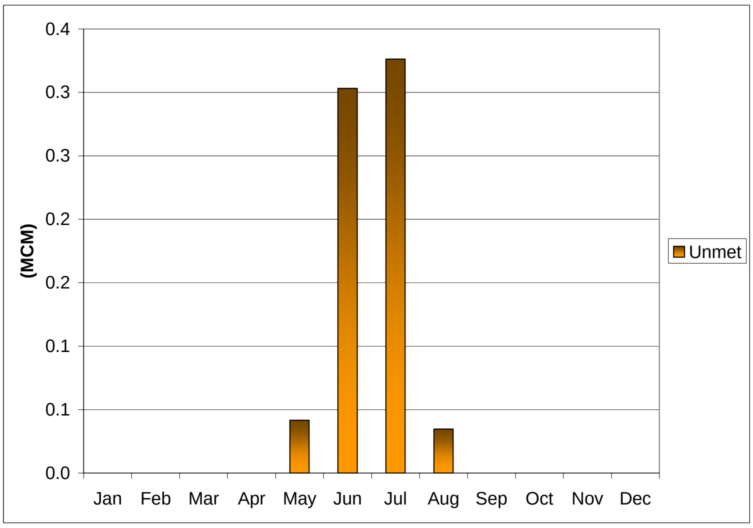


Figure 35. Average monthly (1996-2005) shortage of water delivery for Wuwei.

4.3.2.3 Agricultural demand, supply and consumption

A total of 44 irrigation systems have been defined in the SRB-WEAP model. To demonstrate the model's capacity of analyzing water demand and supply for irrigated areas, results for the Jinchuan Irrigation System are presented here. Interesting is that WEAP offers the opportunity to provide output in various level of aggregation in space as well as in time. For example, Figure 36 present the entire water balance for the Jinchuan system at an annual base, while Figure 37 presents for the same system output as monthly averages over 12 years.

Total water shortage (Unmet Demand) for the entire basin can be presented by WEAP as a map (Figure 38). Such a map is very useful to discuss with stakeholders in an interactive way where critical issues in terms of water resources are.

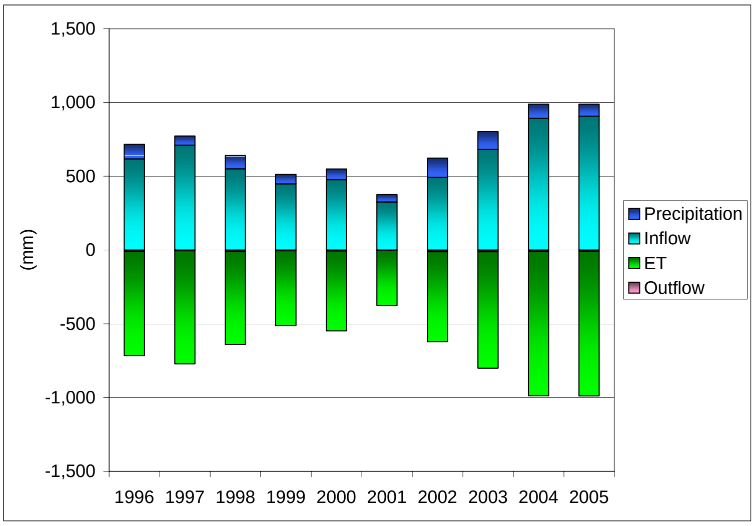


Figure 36. Annual water balance Jinchuan irrigation system in mm.

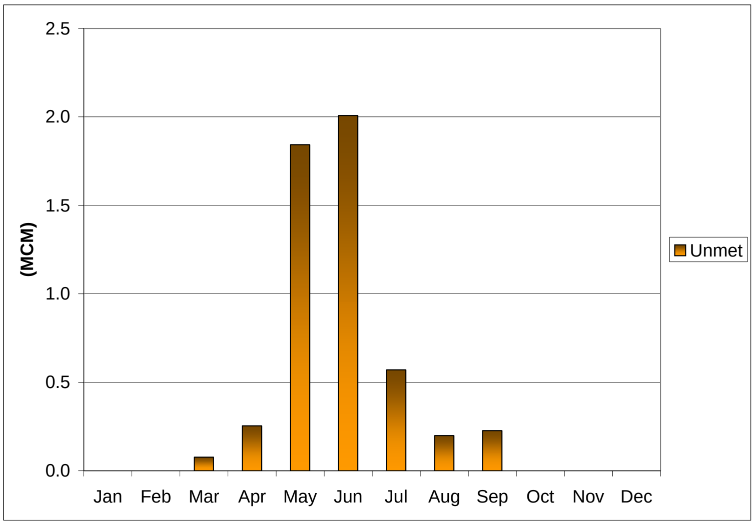


Figure 37. Average monthly (1996-2005) water shortage Jinchuan irrigation system in MCM.

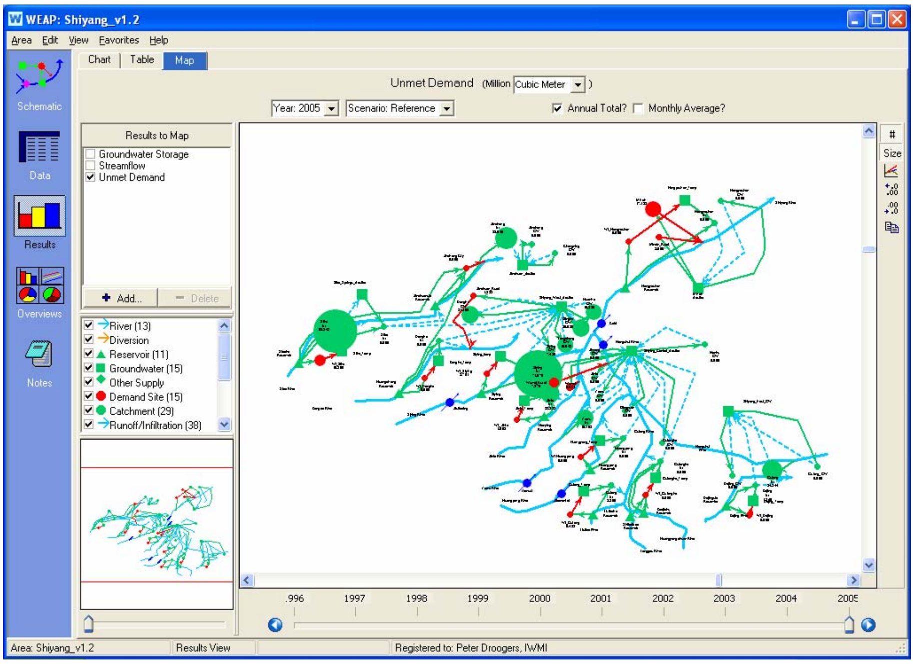


Figure 38. Graphical display of water shortages for the year 2005.

4.3.2.4 Groundwater

The entire aquifer system in the SRB-WEAP model is represented by six aquifers (Figure 32). Output of WEAP as presented in Figure 39 indicates that aquifers were heavily exploited resulting in falling water tables. The different behavior of the aquifer systems can be explained partly by the different nature of the abstractions and inflows. Probably the most important reason is that aquifers are not connected. This will be done in the future using a groundwater model and probably including a simple leveling method.

shows the balance of all aquifer systems based on SRB-WEAP model output. Striking is the enormous overdraft of 330 MCM and the contribution of river seepage to the aquifers.

Finally Figure 39 shows that a substantial year-to-year variation exists in the basin.

Table 4. Water balance for the six aquifers. Annual average over 1996-2005.

Inflow	MCM	Outflow	MCM
Return Flows Urban	14	Abstractions Urban, Industry	169
Recharge Irrigation	37	Abstractions Irrigation	992
Seepage Irrigation canals	152		
Seepage River	617		
Natural Recharge	12		
Total	832	Total	1,162

Storage Decrease	330

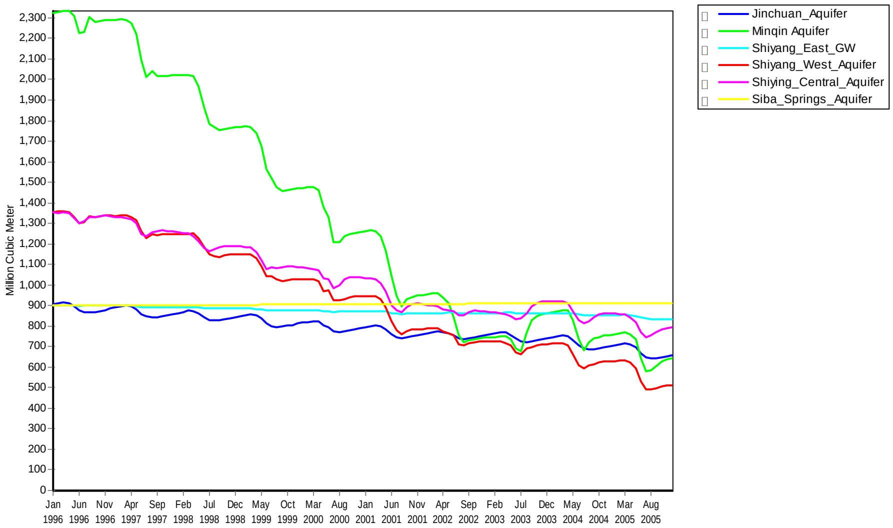


Figure 39. Changes in groundwater storage period 1996-2005.

4.3.2.5 Reservoirs

Reservoirs are the dominant source of water in the basin. In Mot MacDonald (2006) is described in detail how reservoir data were obtained and used in the model. Table 5 shows the annual inflows and outflows for all reservoirs. Evaporation of reservoirs was relatively low with a maximum of 3% of the inflow.

Table 5. Reservoir inflows and outflows.

	Inflow (MCM)	Outflow (MCM)	Evaporation (MCM)	Storage Change (MCM)
1996	1,577	-1,735	-47	-205
1997	1,464	-1,489	-48	-73
1998	1,474	-1,446	-37	-9
1999	1,306	-1,314	-34	-42
2000	1,556	-1,482	-25	48
2001	1,113	-1,125	-25	-36
2002	1,308	-1,256	-31	21
2003	2,191	-2,039	-33	119
2004	1,686	-1,662	-45	-21
2005	1,802	-1,770	-43	-11
Average	1,548	-1,532	-37	-21

4.3.2.6 Water balance Shiyang River Basin

Based on output generated by the SRB-WEAP model as described in the previous sections the entire water balance of Shiyang River Basin can be produced (Table 6). Also some key indicators of the overall performance of the basin have been defined and can be obtained from the SRB-WEAP (Table 7).

Table 6. Average water balance for the entire Shiyang River Basin (1996-2005).

In	MCM	Out	MCM
Precipitation	396	Domestic	75
River headflow	1,608	Irrigation	1,814
Aquifer storage change	369	Rivers outlet	114
Reservoir storage change	58	Reservoirs evap	37
		Irrigation canals[(1)]	360
		Drainage canals[(1)]	29
Total	2,431	Total	2,429

[(1)] Un-accountant losses

Table 7. Key indicators of basin performance (average 1996-2005).

Key Indicators	
Unmet Total (MCM)	138
Unmet Total (%)	7
Unmet Urban/Industry (MCM)	22
Unmet Urban/Industry (%)	23
Unmet Irrigation (MCM)	116
Unmet Irrigation (%)	6
Aquifer Exploitation (MCM)	-369
Total Yield (million kg)	2,243
Gross Revenue (million Yuan)	3,694
Water Productivity (Yuan/m3)	2.09

4.4 Integration of GRACE and WEAP

In this stage of the project the integration of GRACE and WEAP is only executed by comparing results from the two approaches. Comparison is difficult because WEAP presents changes in groundwater storage where GRACE measures changes in the sum of groundwater, soil moisture and snow cover. Nevertheless Figure 40 shows the monthly changes in water storage relative to an average according to WEAP and GRACE.

It's clear that the seasonal changes in groundwater storage according to WEAP are about a factor 5 lower than changes in water storage according to GRACE. Another difference is that GRACE storage is highest in September/October and lowest for March/June while according to WEAP groundwater storage decreases from maximum values in March to minimum values in July. This can be explained by the fact that WEAP presents only groundwater storage and GRACE present also soil moisture storage and snow cover.

From March until May groundwater is abstracted for irrigation leading to a shift of groundwater to soil moisture. In WEAP this leads to a decrease in calculated aquifer storage while GRACE observes total water which remains constant. Water storage according to GRACE start to rise from June/July because of precipitation. According to WEAP water storage rises about a month later than according to GRACE. This can be explained by the time required for precipitation to reach the groundwater.

Based on a very limited period from July 2003 until December 2005 according to WEAP we could say that groundwater storage is lower each year. However, GRACE indicates that 2004 is dryer than 2003 and 2005.

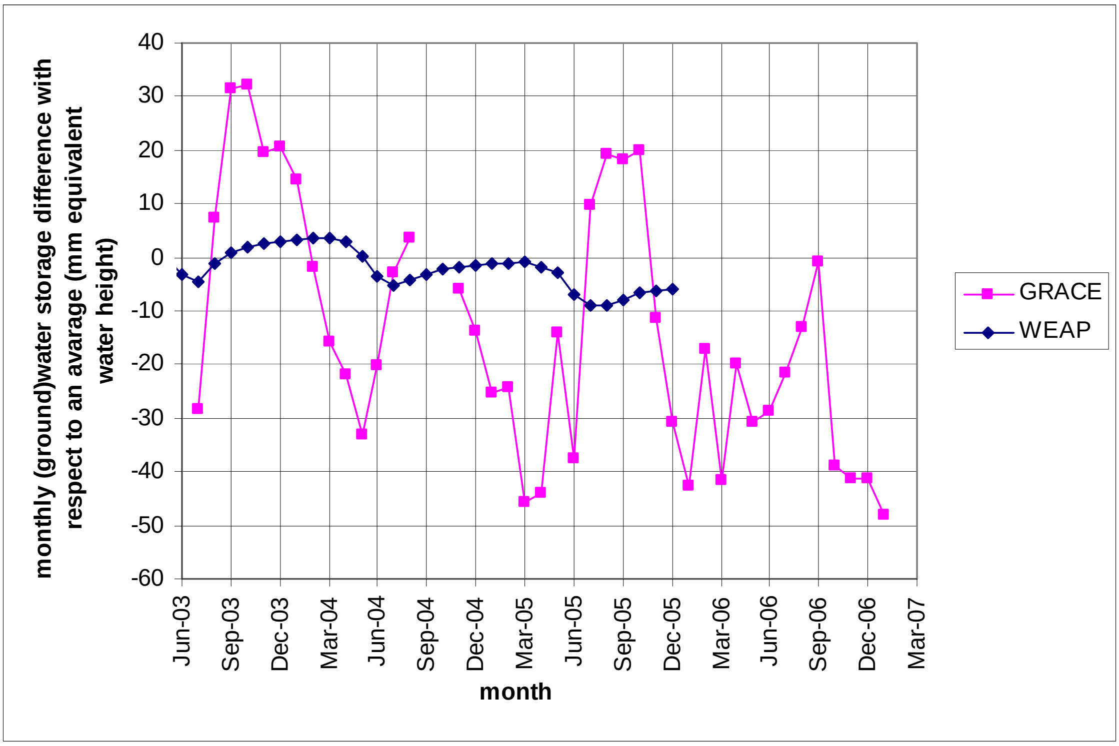


Figure 40: Monthly changes in water storage relative to an avarage (in mm equivalent water depth) for the Shiyang River Basin according to WEAP and GRACE. In WEAP the storage term includes only groundwater. In GRACE the storage term includes groundwater, soil water and snow cover.

5 Conclusions and Recommendations

These preliminary results as presented in this report are only meant to demonstrate the potentials the GRACE satellite monitoring tool and the WEAP evaluation tool might offer in groundwater management. Time, resources, data and information are too limited to provide more accurate results for the moment.

However, based on these preliminary results the following conclusions can be drawn:

- GRACE offers the unique opportunity to detect changes in (ground)water storage over large areas;
- WEAP is a user friendly Water Allocation model which can be applied on different levels of detail and data availability;
- The combination of GRACE and WEAP provides a much better understanding of natural hydrological processes and the impact of human water use;
- GRACE can be implemented to calibrate and validate the WEAP model;
- GRACE provides information on historic groundwater observations;
- WEAP can provide information on future trends;
- WEAP can be applied to support policy makers in evaluating different scenario's.

Some recommendations for future improvements are:

- Isolating the changes in groundwater storage from the total GRACE signal by estimating changes in soil moisture storage and snow cover storage. This might be possible by including passive (AMSR-E) and active (ERS) soil moisture satellite information.
- Including spatial distributed precipitation data. These data will be applied to improve the WEAP models and will be supportive in analyzing GRACE results.
- Improving the Yellow River WEAP model by making a more detailed schematization with more accurate data on water supply and water demand.
- Processing of an improved GRACE dataset including data until August 2007.
- Develop a tool to analyze spatial trends on GRACE-data.

The GMEP project will continue working on these issues. Recent updates can be found on the GMEP website: http://www.futurewater.nl/gmep

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