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# Large-scale hydrological modelling and decision-making for sustainable water and land management along the Tarim River

**Yang Yu**

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Vorsitzende/-r: Prof. Dr. rer. nat. Michael Krautblatter

Prüfende/-r der Dissertation:

1. Prof. Dr. –Ing. Markus Disse

2. Prof. Dr. Bernd Cyffka

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**Abstract:** The debate over the effectiveness of Integrated Water Resources Management (IWRM) in practice has lasted for years. As the complexity and scope of IWRM increases in practice, it is difficult for hydrological models to directly simulate the interactions among water, ecosystem and humans. This study presents the large-scale hydrological modeling (MIKE HYDRO) approach and a Decision Support System (DSS) for decision-making with stakeholders on the sustainable water and land management along the Tarim River.

With the mainstream of 1321 km, the Tarim River is the longest inland river in China. On the northern edge of the Taklimakan desert, the Tarim River Basin is an extremely arid region. Overexploitation and other anthropogenic activities has caused severe environmental problems in the basin. Since 2011, the German Ministry of Science and Education BMBF established the Sino-German SuMaRiO project, for the sustainable management of river oases along the Tarim River. A cross-disciplinary consortium of 11 German and 9 Chinese universities and research institutes joint together for the research on SuMaRiO, focusing on realizable management strategies, considering social, economic and ecological criteria. This will have positive effects for nearly 10 million inhabitants of different ethnic groups in the basin.

A lumped and a distributed MIKE HYDRO model were established separately in the Tarim River Basin. The lumped model focus on evapotranspiration, soil available water, water-saving scenarios and crop type changes. In the distributed model, a land use map was combined with water distribution methods to solve the water allocation problems. The calibration and validation were successful. The comprehensive management of farmland areas and water distribution strategies were investigated in model scenarios. The optimized water allocation strategies help alleviate conflicts among farmers under water scarcity.

DSS is the main outcome of SuMaRiO. The development of the DSS provides links from the outputs of hydrological models with real-time decision making on social-economic assessments and land use changes. The overall goal of the DSS is to integrate all crucial research results of SuMaRiO, also including stakeholder perspectives, into a model based decision support system, to understand ecosystem services (ESS) and integrating them into land and water management in the Tarim River Basin.

The DSS is user-friendly for supporting decision-making progress to the stakeholders and decision-makers. The involvement of stakeholders bridges the gap between hydrological models and engineering practice. Communications with the local residents provide opportunities to gather research data and knowledge, as well as implement research outcomes. Therefore, getting the stakeholders involved in the research process is very crucial to the project. Moreover, local stakeholders and residents will benefit in the long

term from sustainable management practices. The implementation of the DSS provides stakeholders scientific guidance on their management practices. In the meantime, the feedbacks from the users help improve the DSS and gain experience in the future cooperation researches.

**Zusammenfassung:** Die Diskussion über die Wirksamkeit des integrierten Wasserressourcenmanagements (IWRM) in der Praxis dauert seit Jahren an. Da die Komplexität und der Umfang des IWRM in der Praxis zunehmen, ist es für hydrologische Modelle schwierig, die Wechselwirkungen zwischen Wasser, Ökosystem und Menschen direkt zu simulieren. Diese Studie präsentiert eine großräumige hydrologische Modellierung (MIKE HYDRO) und ein Decision Support System (DSS), um gemeinsam mit den Stakeholdern Entscheidungen in der nachhaltigen Wasser- und Landbewirtschaftung entlang des Tarim River zu treffen.

Mit einer Länge von 1321 km ist der Hauptstrom des Tarim Flusses der längste Binnenfluss in China. Am nördlichen Rand der Taklimakan-Wüste gelegen, ist das Tarim-Einzugsgebiet eine besonders trockene Region. Extremer landwirtschaftlicher Wasserverbrauch und andere anthropogene Aktivitäten haben schwere Umweltprobleme im Tarim Becken verursacht. Im Jahr 2011 hat das Bundesministerium für Wissenschaft und Bildung (BMBF) das deutsch-chinesische SuMaRiO-Projekt für nachhaltige Bewirtschaftung von Flussoasen entlang des Tarim-Flusses gegründet. Das interdisziplinäre Konsortium aus elf deutschen und neun chinesischen Universitäten und Forschungsinstituten arbeitet gemeinsam für die SuMaRiO-Forschung, die sich auf realisierbare Managementstrategien konzentriert und dabei soziale und ökologische Kriterien berücksichtigt. Dies wird positive Auswirkungen für fast 10 Millionen Einwohner unterschiedlicher ethnischer Gruppen im Tarim Becken haben.

Im Tarim-Einzugsgebiet wurden ein lokales und regionales MIKE HYDRO-Modell parallel implementiert. Das weitläufige Modell konzentriert sich auf Evapotranspiration, Bodenschutz, wassersparende Szenarien und Veränderungen der landwirtschaftlichen Erträge. Im regionalen Modell wurde eine Landnutzungskarte mit verschiedenen Prozessen der Wasserverteilung kombiniert, um die Probleme der Wasserverteilung zu lösen. Die Kalibrierung und Validierung lieferten gute Ergebnisse. Das umfassende Management von Ackerland und Wasserverteilungsstrategien wurden in Modellszenarien untersucht. Die optimierten Strategien der Wasserverteilung helfen, Konflikte hinsichtlich des begrenzten Wasserdargebotes zwischen den Landwirten zu vermindern.

Das DSS ist das finale Produkt SuMaRiO Projektes. Die Entwicklung des DSS bietet die Verbindung der Ergebnisse der hydrologischen Modelle mit Echtzeit-Entscheidungen über sozial-ökonomische Einschätzungen und Landnutzungsänderungen. Das übergeordnete Ziel des DSS ist es, alle entscheidenden Forschungsergebnisse von SuMaRiO, einschließlich der Ansichten der Stakeholder, in ein modellbasiertes Entscheidungsunterstützungssystem zu integrieren, Ökosystemleistungen (ESS) zu verstehen und sie in die Land- und Wasserwirtschaft im Tarim Becken zu integrieren.

Das DSS ist benutzerfreundlich hinsichtlich der Unterstützung der Entscheidungsfindung für die Stakeholder und Entscheidungsträger. Die Beteiligung der Stakeholder schließt die Lücke zwischen hydrologischen Modellen und der Ingenieurpraxis. Die Kommunikation mit den Anwohnern bietet die Möglichkeit des gegenseitigen Austauschs von Wissen, wodurch die Implementation der Forschungsergebnisse erleichtert wird. Daher ist die Beteiligung der Stakeholder am Forschungsprojekt für das Projekt sehr wichtig. Darüber hinaus werden lokale Akteure und Bewohner langfristig von nachhaltigen Managementpraktiken profitieren. Die Umsetzung des DSS bietet den Stakeholdern wissenschaftliche Leitlinien für ihre Managementpraktiken. Mittlerweile helfen die Rückmeldungen der Benutzer, das DSS zu verbessern und in der Zukunft weitere transdisziplinäre Forschungen durchzuführen.

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## AFFIDAVIT

I hereby affirm that I wrote this PhD thesis independently and on my own without illegal assistance of third parties. To the best of my knowledge, all sources that I used to prepare that thesis are labeled as such. This thesis has not been received by any examination board, neither in this nor in a similar form.

Yang Yu, Mar 30$^{th}$, 2017

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## Author contributions

Chapter 3 to 6 in the thesis have been partially submitted or published in a similar form in the following peer-reviewed journals.

**Chapter 3**

Yu Y., Disse M., Yu R., Yu G., Sun L., Huttner P., Rumbaur C.,2015. Large-Scale Hydrological Modeling and Decision-Making for Agricultural Water Consumption and Allocation in the Main Stem Tarim River, China. Water, 7(6), 2821-2839.

The manuscript was written by Yang Yu and Philipp Huttner. The MIKE HYDRO model was developed and analyzed by Yang Yu and Markus Disse. Data was collected and sorted by Yang Yu, Ruide Yu, Guoan Yu and Lingxiao Sun. Additional information and outcomes from SuMaRiO German side were collected by Christian Rumbaur. Figures and Tables were provided by Yang Yu, Guoan Yu and Markus Disse.

**Chapter 4**

Yu Y., Yu R., Chen X., Yu G., Gan M., Disse M., 2017. Agricultural water allocation strategies along the oasis of Tarim River in Northwest China. Agricultural Water Management, 187: 24-36.

The manuscript was written by Yang Yu and revised by Markus Disse. The distributed MIKE HYDRO mode was developed and analyzed by Yang Yu, with revisions by Markus Disse. Data was collected and sorted by Yang Yu, Ruide Yu, Xi Chen, Guoan Yu and Miao Gan within the SuMaRiO project.

**Chapter 5 and 6**

Yu Y., Hinnenthal M., Yu R., Huttner P., Rumbaur C., Chen X., Disse M., 2017. A Model Based Decision Support System for Sustainable Land Management and Socio-economic Assessments, on submission.

Yang Yu contributed the manuscript, links from MIKE HYDRO and data inputs into the DSS, design of the DSS scenarios and analysis of the DSS outputs. The design and contents of the DSS was generated by Markus Disse. The programming of the DSS was mainly conducted by Marie Hinnenthal, and the revisions were made by Yang Yu. The groundwater MODFLOW model was created by Philipp Huttner. Data was collected and sorted by Yang Yu, Ruide Yu, Xi Chen and Christian Rumbaur. The implementation and modification of the DSS was conducted by Yang Yu. The research work was supervised and revised by Markus Disse.

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## List of Abbreviations

The following abbreviations are used in this thesis:

| | |
|---|---|
| CAS | Chinese Academy of Sciences |
| CTC | Crop Type Change |
| DEM | Digital Elevation Model |
| DEV | Crop Growing Development Stage |
| DHI | Danish Hydraulic Institute |
| DIUM | Drip Irrigation Under Mulch |
| DSS | Decision Support System |
| ES | Equal Shortage |
| ESF | Ecosystem Functions |
| ESS | Ecosystem Services |
| GCMs | Global Climate Models |
| GUI | Graphical User Interface |
| GW | Groundwater |
| HS | Hotspot |
| INI | Crop Growing Initial Stage |
| IWRM | Integrated Water Resources Management |
| LAT | Late Season |
| LUCCs | Land Use/Cover Changes |
| LUD | Land Use Decrease |
| LUI | Land Use Increase |
| MEECAL | Management of Ecosystems and Environmental Changes in Arid Lands |
| MID | Mid-season |
| Ph.D | Doctor of Philosophy Degree |
| PS | Provisioning Services |
| RAW | Readily Available Water |
| RCMs | Regional Climate Models |
| RS | Regulating Services |

| | |
|---|---|
| SC | Sub-catchment |
| SC1 | Alar-Xinqiman Sub-catchment |
| SC2 | Xinqiman-Yingbaza Sub-catchment |
| SC3 | Yingbaza-Qiala Sub-catchment |
| SC4 | Qiala-Taitema Lake Sub-catchment |
| SIA | Sustainability Impact Assessment |
| SL | Spray Loss |
| SS | Supporting Services |
| SuMaRiO | Sustainable Management of River Oases along the Tarim River |
| SW | Surface Water |
| TAW | Total Available Water |
| TUM | Technical University of Munich |
| WB | Work Block |
| WF | Wetting Fraction |
| WP | Work Plan |
| WS | Water Saving |
| YS | Yield Stress |

## List of Symbols

| Symbol | Unit | Definition |
|---|---|---|
| a | ($m^2$) | cell size in the DSS |
| A(BP) | (t) | aggregated biomass production by riparian forest |
| A(CA) | (ha) | aggregated crop area |
| A(CP) | (RMB) | aggregated cotton income |
| A(FP) | (RMB) | aggregated fruit income |
| A(OC) | (RMB) | aggregated income of other crops |
| A(WD) | ($m^3$) | aggregated irrigation water demand |
| BP | (t/ha) | biomass production of riparian forest of cell |
| C(RC) | (RMB) | aggregated cost of running cotton |
| C(RF) | (RMB) | aggregated cost of running fruits |
| C(RO) | (RMB) | is aggregated cost of running other crops |
| CK1 | (h) | time constant 1 for routing overland flow |
| CK2 | (h) | time constant 2 for routing overland flow |
| CKBF | (h) | time constant for routing base flow |
| CKIF | (h) | time constant for routing interflow |
| CKLOW | (h) | time constant for routing lower base flow |
| CQLOW | (%) | lower base flow, recharge to lower reservoir |
| CQOF | (-) | overland flow runoff coefficient |
| Db | (%) | distribution of biomass production each year |
| DBH | (m) | diameter at breast height of the tree |
| DI | (ha) | aggregated drip irrigation area |
| DIS | (%) | drip irrigation share in the farmlands |
| DP | (mm) | deep percolation |
| Dr | (mm) | root zone depletion |
| $ET_a$ | (mm) | actual evapotranspiration |
| $ET_c$ | (mm) | crop evapotranspiration |
| $ET_o$ | (mm) | reference evapotranspiration |
| f(i) | (%) | fraction of irrigation water distribution over months |

| | | |
|---|---|---|
| FI | (RMB) | farmers' income |
| ht | (m) | tree height of cell |
| I (t) | ($m^3/s$) | inflow |
| IRR | (mm) | irrigation depth |
| $IRR_c$ | (mm) | irrigation water from the channel |
| $IRR_{GW}$ | (mm) | irrigation water from groundwater pumping |
| $IRR_R$ | (mm) | irrigation water from reservoirs |
| K | (h) | Muskingum routing travel time |
| Kcb | (-) | basal crop coefficient |
| $K_e$ | (-) | water evaporation coefficient in soil evaporation |
| Ks | (-) | water stress coefficient |
| Ky | (-) | yield response factor |
| $L_{max}$ | (mm) | maximum water content in root zone storage |
| MH | (m) | maximum height |
| Nm | (number/ha) | mean number of trees per ha in high density cell |
| Nr | (number) | number of riparian forest cells |
| NSE | (-) | Nash-Sutcliffe efficiency |
| P | (mm) | precipitation |
| Q(t) | ($m^3/s$) | outflow |
| RD | (mm) | root depth |
| $R_{GW}$ | (mm) | root transpiration water from groundwater |
| RMSE | ($m^3/s$) | root mean square error |
| RSR | (-) | RMSE-observations standard deviation ratio |
| RWD | (%) | Relative Water Deficit |
| RWDD | (%) | Reduction of Water Demand Deficit |
| S(C) | (%) | cotton share in the farmlands |
| S(DI) | (RMB/ha) | subsidy for drip irrigation |
| S(F) | (%) | fruit share in the farmlands |
| S(t) | ($m^3$) | storage |
| t | (s) | time interval |
| TG | (-) | root zone threshold value for groundwater recharge |

| | | |
|---|---|---|
| TIF | (-) | root zone threshold value for interflow |
| TOF | (-) | root zone threshold value for overland flow |
| $U_{max}$ | (mm) | maximum water content in surface storage |
| Wr | (mm) | water depth |
| WS | (mm) | water supply for crops |
| WU | (mm) | water use |
| X | (-) | Muskingum routing weighting coefficient |
| $Y_a$ | (t/ha) | actual harvest yield |
| $Y_c$ | (t/ha) | cotton production |
| Ym | (t/ha) | maximum harvest yield |
| $\Delta S$ | (mm) | change of storage water in the soil |
| $Q_{obs}$ | ($m^3/s$) | observed discharge |
| $Q_{sim}$ | ($m^3/s$) | simulated discharge |

# 1 Introduction

The first chapter includes research background of the Tarim River Basin, introduction of project SuMaRiO, problem statement and research objectives, and outline of this Ph.D thesis.

## 1.1 Research background

Located on the fringe of Taklimakan Desert in Northwest China, Tarim River Basin is one of the most arid region in the world, known worldwide for its extreme climatic situation and vulnerable ecosystem. Tarim River is the longest inland river in China, 5th in the world. It flows across the northern part of the Taklimakan desert in Xinjiang, with an extremely arid desert climate (Figure 1.1). Widespread attention has been paid to the river due to its unique landscape and ecological environment. The ecological system of the Tarim is extremely vulnerable due to the lack of sustainable water supply management of the oases (Chen et al., 2003). Since the 1950’s when large-scale land reclamation in the basin started, the stress on the water body becomes too much to bear. More than 80 percent of the flow is withdrawn each year. Water interception and serious environmental problems have been caused by anthropogenic activities. The uneven temporal and spatial distribution of water resources result in more severe water scarcity issues.

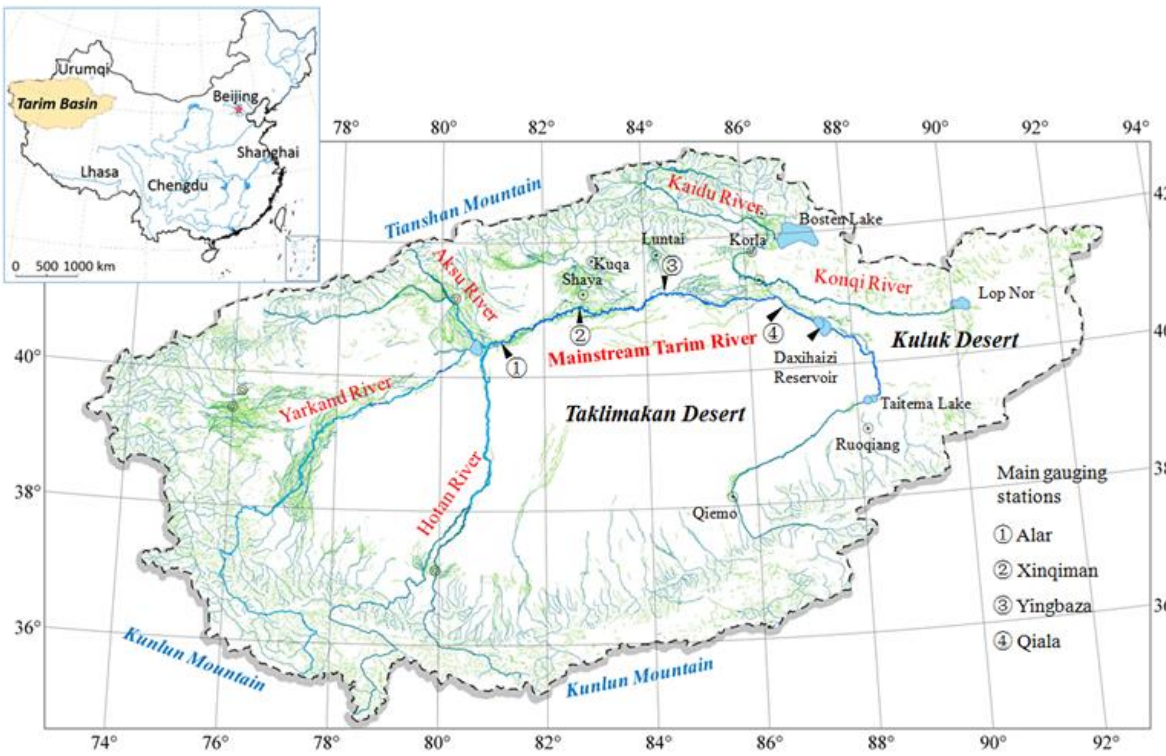



**Figure 1.1:** Tarim River Basin in the Northwest of China.

The climate of the Tarim River Basin is extreme dry with large temperature amplitude. The monitored highest and lowest temperatures were 43.6 °C and -27.5 °C respectively. From the statistical data in Alar, which was acquired from meteorological stations in Xinjiang, the annual mean temperature has a slightly increase during the past decades (Figure 1.2). Located in the hinterland of the Eurasia continent, the basin has a typical temperate continental climate. Average daily temperature difference is around 14 °C to 16 °C each year. Summer is dry and hot, with average temperature between 20 °C to 30 °C in July. Winter is long and cold, with average temperature between -20 °C to -10 °C in January. The temperature has an increasing trend from the mountainous regions towards the desert and lower reaches of the Tarim River.

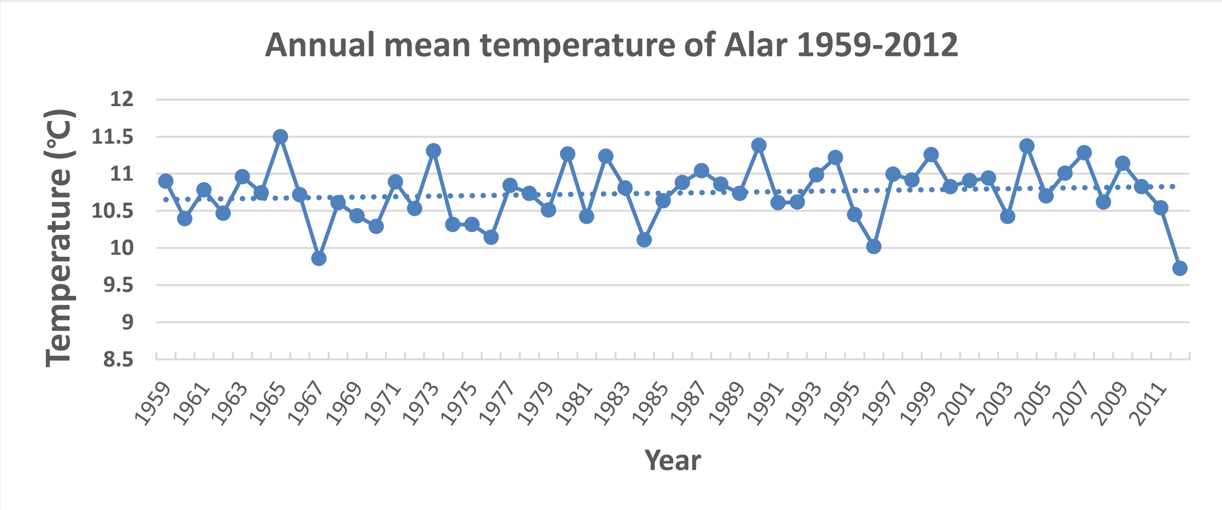



**Figure 1.2:** Annual mean temperature in the upper reaches of the Tarim River Basin.

Due to the far distance from the ocean and surrounded by mountains and desert, the annual precipitation is low with large difference between mountainous region and the central area in the basin. Although the annual precipitation in the mountainous headwater regions can reach up to 200-500 mm, it is only 50–80 mm in the mainstream region (and only 10 mm in the central desert area) (Chen et al., 2009), while annual potential evaporation amounts to 2100–3000 mm or even higher (Feng and Cheng, 1998). Annual mean precipitation has a slightly increase during the past decades. The surface runoff of Tarim River is mainly fed by snowmelt and glacier-melt in Tianshan and Kunlun Mountains, rather than from local precipitation. Natural ecosystem and human activities in this hyper-arid basin heavily relies on water resources from the Tarim River. Precipitation data was acquired from Alar meteorological station records since 1959 to 2012 (Figure 1.3).

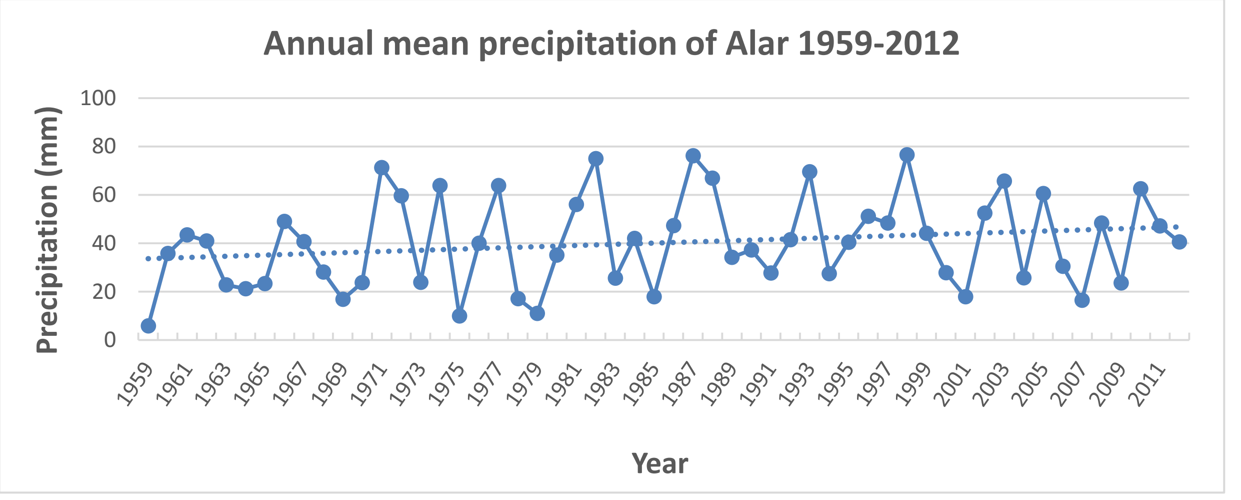



**Figure 1.3:** Annual mean precipitation in the upper reaches of the Tarim River Basin.

The Tarim Basin is surrounded by Tianshan Mountain on the northern edge, and Kunlun Mountain from the southern and western edge. The highest peaks of Tianshan and Kunlun Mountain are 7444 m and 7649 m, respectively. Both mountains have perpetual snowline in the summer, with large amount of glacier storage. Due to low precipitation in the central area of the basin, the Tarim river is mainly fed by the snow and glacier melt water from Tianshan Mountain and Kunlun Mountain in south of Xinjiang (Figure 1.4).

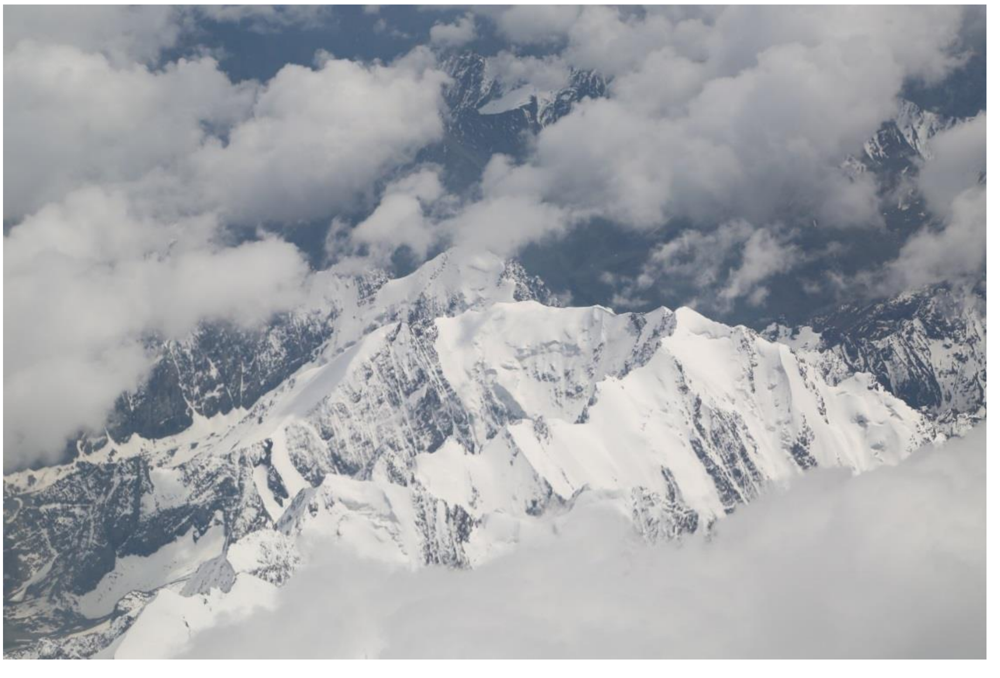


**Figure 1.4:** Mountains surrounding the Tarim River Basin. Snow and glacier melt water provide most of the surface runoff of the Tarim River.

The Tarim River originates at the confluence of the Aksu, Yarkand, Hotan and Kaidu-Konqi rivers, and flows into the Taitema Lake, east of Xinjiang. With a main stem of 1321 km, it is the longest inland river in China. Average annual discharge in the mainstream during the last 60 years is approximately $4.5 \times 10^9$ $m^3$. The differences of the discharges between upper and lower reaches indicate large water consumptions in the upper and middle reaches in the Tarim River Basin. Since the year 2000, Chinese government initiated the ecological water conveyance project, to transfer intermittent water from Bosten Lake to the lower reaches of the Tarim River. The implementation of this water conveyance project has reversed the decreasing trend of discharge in the lower reaches. Discharge data was acquired from gauging stations in Alar (discharge of upper reach) and Qiala (discharge of lower reach) since 1950 to 2013 (Figure 1.5).

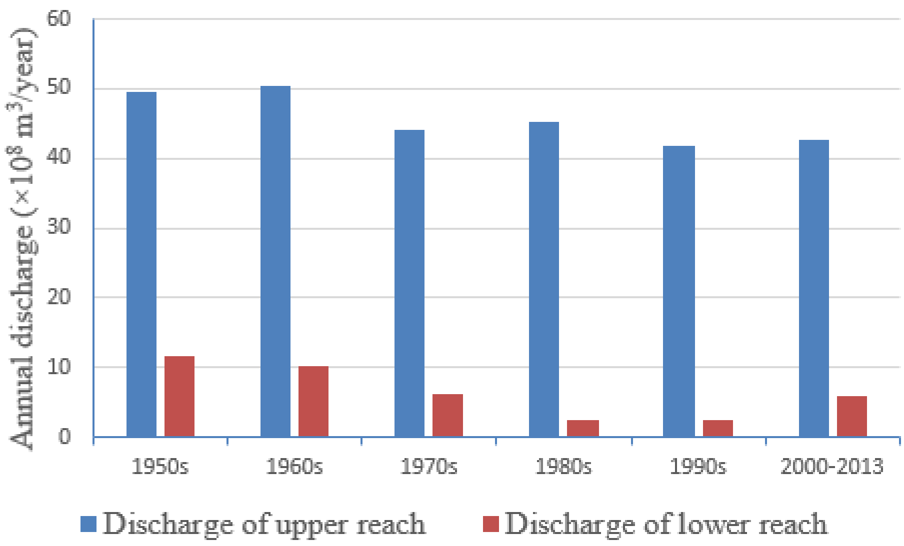



**Figure 1.5:** Annual discharge of the mainstream Tarim River in the past 6 decades (Yu et al., 2015).

The river is a typical seasonal river in the arid land, with floods in the summer and dry season in spring, autumn and winter. In July, when summer floods come, the river becomes unstable. The river network system has disintegrated from a historically '(quasi) centripetal' system with nine tributaries into several isolated river systems, which have mainly developed since the 20th century. Currently, only four tributaries flow into the main stem river, which is dominated by braided channel patterns in the upper reaches and meandering (typically with distorted bends) patterns in the middle reaches. With the obvious decrease in runoff into the river during the last five decades, there has been increased annual occurrence of low flow events and a fluctuating and gentle decrease in moderate-high flow events and sediment loads. Consequently, the mean channel width of the current channel gradually decreased, the braiding intensity of the braided reach also descended, while the sinuosity index of the meandering reach exhibited a gentle increase (Guoan et al., 2016).

The total area of the Tarim River Basin is $1.02 \times 10^6$ $km^2$, with the desert area of $3.7 \times 10^5$ $km^2$. The basin contains 42 counties and cities, with a total population of $8.26 \times 10^6$

in 2001. More than 80% of the total population is comprised of Uyghurs, who are one of 55 officially recognized ethnic minorities in China. The basin has become the most important source of cotton in China. Due to relatively low rainfall in the region, irrigation is the primary source of water for agriculture along the Tarim River (Thevs, 2011). Although the volume of flow from the river's headwaters is sensitive to precipitation (Chen et al., 2006), the main stem of the river is dominated by human activities such as agricultural irrigation (Hao et al., 2008). Water allocations specify the amount of water that can be extracted each year by license holders. During the past six decades, as conflicts among the water users from upstream to downstream has continuously been severe, and intensive exploitation of water resources has caused serious environmental problems in the basin, a comprehensive spatial-temporal assessment of variability in flows and water allocation is imperative to work towards sustainable management of water resources on the Tarim River.

The Tarim River Basin has evolved a vast, unique and beautiful natural landscape during the long history. The world's largest natural *Populus euphratica* is distributed in the basin oases. The Taklimakan desert is the second largest desert in the world, and the mysterious Lop Nor is always attractive to the adventurers. Furthermore, the basin has a number of nature reserve for rare species of wild animals, e.g. Tianshan Swan nature reserve. The ancient Silk Road went through the basin, with many ancient sites left today. From the desert in the center area, the basin is inclined to the mountains on the edge. More than 140 rivers are originated from the surrounding mountains towards the basin each year. However, most of the outflow is lost after the consumption of river oases and vast desert area. The largest water user in the upper reaches of Tarim River is Aksu catchment. Aksu River contributes more than 70% of the mainstream Tarim River. The overexploitation of water resources in the upstream oases has attracted the attention from local government and water administrations. Located in the northeast of the basin, Bosten Lake is the largest inland freshwater lake in China. Due to water interception problems in the lower reaches of the Tarim River, Chinese government started the ecological water conveyance project from year 2000, to transfer intermittent water from Bosten Lake to the lower reaches of the Tarim River.

The economic development of the Tarim River Basin is far behind the eastern part of China. The basin is dominated by agriculture and grazing. Most regions are distant from railway and the transportation road is a long distance from the cities. In recent years, petroleum exploration and petrochemical industry have developed greatly, but most residents have not been benefited from this development. Since the year 2000, Chinese central government has initiated the western development strategy, and huge amount of investments were used to develop the western regions in China, including the Tarim River Basin. New railways are under constructions and basin economy are developing rapidly.

Under such circumstances, utilization of water resources and protection of ecological environment are more important than ever before. In the mainstream of the Tarim River, the economic development are not evenly distributed. Most population in the river oases is located in the upper reaches.

Research in the upper reaches is mainly conducted on farmland and human activities. Most farmland areas are cultivated in this region, due to abundant water supply and better soil moisture conditions (Figure 1.6). Approximately 10% of the world's cotton is produced in China, and about 60% of the Chinese cotton are produced in Xinjiang each year. As the largest cotton production base in China, the Tarim River Basin has a reputation of producing high quality cotton. Cotton is suitable to grow under abundant sunshine and water conditions, which cause high evapotranspiration and water losses. Solar radiation is intense in the basin, with 2500 to 3500 sunshine hours each year. Due to its unique climate and soil conditions, the basin is also producing considerable quantity of long-staple cotton, which requires more strictly growth environment on the water, soil and climate conditions. In recent years, the local governments start to organize farmers to develop characteristic agriculture, and search for substitution of cotton (e.g. Apocynum, Chinese jujube) with higher water productivity. This agricultural transformation is being investigated and may last several decades under discussions, but currently cotton still remains the major crop in the basin.

**Figure 1.6:** New cultivated farmland in the upper reaches.

The largest *Populus euphratica* (commonly known as Euphrates poplar or desert poplar) nature reserve park in the world is located in this region, with a total area of $4 \times 10^5$ ha. The nature reserve is within Yuli and Luntai county of the Tarim River Basin. The region has flat terrain, with elevation from 800 to 940m. Alluvial plain and desert comprised most of the land. Alluvial plain has been formed centuries ago, consisting of perennial flood water depressions, terraces, ancient riverbed, and intermittent river plain. On the edge of the desert, the geomorphic unit provides the growth and succession environment of riparian forest, e.g. *Populus euphratica* and *Tamarix* shrubs.

The Tarim River provides uneven distributed surface flow in a year, and it is insufficient for the forest. Summer floods last for 2 to 3 months, and yet contains 80% of the yearly runoff. Dry season is a long period each year with severe water shortage. Groundwater also provides water supply for the irrigation and natural vegetation. In the upper and middle reaches, groundwater recharge mainly comes from seepage of irrigation water and natural flooding. In the lower reaches, groundwater recharge is mostly supplied by river leakage. Within 1 km from the river, groundwater level is mostly within 4 to 7 meters in the middle reaches. Groundwater depth is directly related to the plant species and surface soil desertification.

*Populus euphratica* is an ancient tree species, which appeared on earth from 135 million years ago. The research in the middle reaches is mainly conducted on the riparian forest (mostly *Populus euphratica*). The tree can endure hyper-arid conditions, and the growth is mainly dependent on groundwater conditions. *Populus euphratica* is favor of arid continental climate, with intense and long hours of sun radiation, extreme heat and drought conditions. It has resistance on wind, sandstorm and soil salinity. *Populus* trees have been used to arid environment with poor growth in humid climates and sticky soils. The trees have growth requirements of sandy soil and water supply near the desert. The change of the river courses near the desert are quite frequently, so does the living traces of *Populus* trees. The deeper the ground-water depths were, the lower the leaves water potential of *Populus euphratica* was, the more serious drought stress *Populus euphratica* suffered from (Fu et al., 2006). For a comfortable living environment of *Populus euphratica*, the groundwater level should be not lower than 4 meters. If the groundwater fell below 10 meters, the trees will be less productive with low transpiration rates (Gries et al., 2003).

Lower reaches of the Tarim River starts from Qiala, through Qiala Reservoir and Daxihaizi Reservoir, and reaches the ending point of Taitema Lake. River width is largely narrowed down from over 1 km in the upper reaches, to less than 100 m in the lower reaches. River banks are usually very low or without clear banks. Due to overexploitation of water resources in the upper and middle reaches, the Tarim River had interception problem for many years. Especially since 1970s, the river often cannot reach its natural ending point of Taitema Lake even in flood seasons. Since the beginning of this century, Chinese government kicked-off the ecological water conveyance project, to transfer water from Bosten Lake to the lower reaches of the Tarim River each year. Large area of natural vegetation has gained benefit from this water conveyance.

Fruit planting is also very common in the Tarim River Basin. Fruits include grape, pear, pomegranate, melons, figs, Chinese wolfberry, and Chinese jujube from the basin are quite famous in China and provide steady income for orchard workers. Due to hot and dry climate in summer, fruits usually contain high portion of sugar. On the other hand, the contradiction between high evapotranspiration of fruit trees and water scarcity in the basin has forced the workers to use more water-saving technics in the orchard.

Desertification has become more and more serious since 1950s (Figure 1.7). Land reclamation, overgrazing, deforestation and unreasonable utilization of water resources are the main reasons for desertification. These activities are driven by the population increase, commercial interest and policy mistakes, which are obviously on the contrary of sustainable management in the basin. Land desertification has led to rising temperature, intense drought, strong wind and sand storm, vegetation decline, buried roads, farmlands and villages, which are serious threats to the survival of the residents and development of the river oases.

**Figure 1.7:** Land desertification in the lower reaches.

Due to hyper-arid climate, natural vegetation (besides *Populus euphratica*) are mainly comprised of low bushes, including *Achnatherum splendens*, Apocynum, *Chinese Tamarisk*, *Halimodendron halodendron*, *Kalidium foliatum*, and *Nitraria tangutorum*. These drought-endurable plants can alleviate desertification conditions to a certain extent. On the arable lands, soil types are mainly loamy sand. Because of high evapotranspiration, irrigation water shortage and poor drainage systems, soil salinization has been aggregated in recent years. Statistic data show that 38% of the fields have suffered from salinization (Xu et al., 2008). The most serious salinization contaminated area is mainly in the middle and lower part of the Tarim River (Xu et al., 2014). Mineral dissolution and evapotranspiration are the main mechanisms of salt accumulation in groundwater. Reduced recharge from the river has resulted in a distinctive zoning pattern in groundwater salinity (Pang et al., 2010).

The water resources sustainability largely depends on the proper management and efficient utilization of agricultural water (Fasakhodi et al., 2010). The conjunctive use of surface water and groundwater resources cannot only solve the problem of water shortages but also improves the water use efficiency and regional environment of irrigated areas (Liu et al., 2013). Therefore, the optimization of water allocation strategies and combined simulation of surface and subsurface water resources play an important role in river basin management models, as well as in decision-making process for water administrations and stakeholders. The water authority must carry out a comprehensive management on the entire river basin. Xinjiang Tarim River Basin Management Bureau is such a management authority which is in charge of the water resources management in the entire Tarim River Basin. The bureau was established in 1990 and reports directly to the Xinjiang autonomous district government. Before that, water management decisions were made by counties and regiments along the river. According to the discussions with decision-makers from the bureau, adjustment of farmland area and water allocation strategies are matters of cardinal significance for the sustainable management of water resources.

Since the beginning of this century, the Xinjiang Tairm River Bureau has set up a bunch of water policies to regulate water-related activities in the Tarim River Basin. The aim of these water regulations are to utilize the water consumptions, maintain ecosystem balance, and implement sustainable management on ecology and society along the river oases. Protecting ecosystem and increasing water use efficiencies are the key points in the regulations. In the basin, any land reclamation without permission will be stopped and punished. The bureau takes the responsibility of the supervision on water resources in the whole basin. At least two conferences will be held each year to summarize the working progresses and make the future work arrangements. Along the river, grazing will be strictly controlled, and riparian forest will be protected with more attentions and efforts. *Populus euphratica* is particularly mentioned in the policies, and its importance in maintaining the ecosystem balance is emphasized. Digging wells and cutting trees are forbidden in the forest area. According to the situations of drought, precipitation, flood, reservoir storage, ecological water consumption, irrigation and other water use conditions, the bureau can control the water valves and reservoirs, to make a comprehensive coordination on water abstractions.

The water policies also include a number of punishments on the groups or individuals who disobey the water law. For overexploitation of water resources within 10%, water prices will be charged twice as much. Between 10% and 20%, water price will be 4 times than the usual price. If unauthorized water use of more than 20 %, water price will be charged 6 times of the common price. For the activities of digging wells without permission, a penalty will be charged between 20000 to 10000 RMB. Many other illegal activities are illustrated and will be punished accordingly, including providing electricity and water to unauthorized land reclamation, stealing of water resources, and refusing to take orders from the bureau.

However, water scarcity and poor economic development are still key issues in the river basin. The uneven temporal and spatial distribution of water resources intensify water shortage in this arid region. The problem remains on how to conduct the water policies and how to implement sustainable management along the river oases. Hydrological models and decision-support tools will assist on the management practices.

## 1.2 Project SuMaRiO

Since 2011, the German Ministry of Science and Education BMBF established the Sino-German Sustainable Management of River Oases along the Tarim River (SuMaRiO) project, to provide scientific basis for water and land management practices in the Tarim River Basin (www.sumario.de). A cross-disciplinary consortium of 11 German and 9 Chinese universities and research institutes joint together for the research on SuMaRiO and DSS. The SuMaRiO project focus on realizable management strategies, considering social, economic and ecological criteria. This will have positive effects for nearly 10 million inhabitants of different ethnic groups.

The land management decision to reclaim large areas for agricultural fields in the Tarim River Basin and grow cotton resulted in high yields of economic benefits for many people in Xinjiang. However, from the 1950s to present two thirds of all riparian forests have been destroyed, directly through logging and conversion into fields and indirectly due to water shortage. The lower reaches of the Tarim River was even dry for 30 years after 1970, which resulted in severe degradation of riparian forests and complete destruction of reed beds and grasslands. Thus, this land management decision resulted in a great loss of Ecosystem Functions and Ecosystem Services provided by the natural riparian ecosystems (Disse, 2016).

The major driver for land management in the Tarim River Basin is water allocation. The irrigation agriculture, i.e. cotton, directly abstracts river water into the irrigation channels.

Due to lacking of surface water supply, a fraction of the irrigation water is pumped from the groundwater, mostly in depths of 10-100 m. The natural vegetation mainly rely on summer floods and groundwater in the shallow aquifer, which is recharged by the river, floods, and irrigation fields. Due to high evapotranspiration and low precipitation, little groundwater recharge is generated from rainfall. Research on water balance is a key issue in the project. The interactions between the surface and groundwater need to be investigated. The water demand and supply have to be studied for further researches along the river oases.

Decision Support System (DSS) is the main outcome of SuMaRiO. The overall goal of the DSS is to integrate all crucial research results of SuMaRiO, also including stakeholder perspectives, into a model based decision support system, which allows a Sustainability Impact Assessment (SIA) within regional planning. This SIA will take into account the perspectives of all relevant actors in the problem field of land and water management in the Tarim River Basin, to understand ecosystem services (ESS) and interactions with water, land use and human activities. The DSS is an indicator based tool that enables stakeholders and decision-makers to evaluate the consequences of their intended actions, which helps to implement sustainable land and water management measures in the upcoming development plans (Disse, 2016). The major research work of this Ph.D study is within SuMaRiO project.

The Sino-German Joint research Center for the Management of Ecosystems and Environmental Changes in Arid Lands (MEECAL) was established by scientists of the Technical University of Munich, Bundeswehr University of Munich and the Xinjiang Institute of Geography and Ecology, Chinese Academy of Sciences. MEECAL conduct research works on the sustainable water and land management, as well as the maintenance of ecosystems in SuMaRiO project.

## 1.3 Problem statement and research objectives

Water scarcity and ecosystem stability are the most obvious and sensitive issues in the Tarim River Basin. During the past six decades, due to overexploitation and other anthropogenic activities, water interception and severe environmental problems have been caused along the river oases (Figure 1.8). In this region, agricultural water consumption and allocation management are crucial to address the conflicts among irrigation water users from upstream to downstream (Yang et al., 2015), which cause severe water scarcity problems on ecosystem (Liu and Chen, 2006) and sustainable land management (Feng et al., 2001; Liu and Meng, 2011).

**Figure 1.8:** River interception in the middle reaches during dry season.

The coordination of water consumption between upstream and downstream water users is another issue along the river oases. Excessive use of water in the upper reaches has lasted for several decades, resulting in a reduction of available water resources downstream. High evapotranspiration and high groundwater salinity are environmental reasons which intensify the water shortage. Moreover, unregulated people's activities, including overgrazing, firewood collection, farmland expansion, all accelerated the desertification in the lower reaches.

Since 2001, the Chinese Government has been promoting the development of western China. The demographic development and socio-economic change has led to a rapid increase of farmland areas in the Tarim River Basin and has substantially affected the quantity and quality of arable soil, surface water, and groundwater (Zhao et al. 2009; Zhang et al. 2014; Rumbaur et al., 2015). These changes in soil and water have large impacts on the crop production and natural vegetation (Chen et al., 2015; Zhang et al., 2015). Water conservation and ecosystem rehabilitation are imperative in recent years.

Different scenarios for water resource management, as well as water distribution and allocation in a more efficient and water-saving way, in order to obtain optimal benefit for society, economy and natural environment in a sustainable manner, are the target outcomes of this research. For addressing water allocation, conjunctive use, water inflow and outflow issues and irrigation water use in this research, large-scaled water-balance model MIKE HYDRO (DHI, 2014) is employed to meet these objectives. The basic steps of the modeling include data collection, pre-modeling, modeling, calibration, and the development, implementation and modification of the DSS (Figure 1.9).

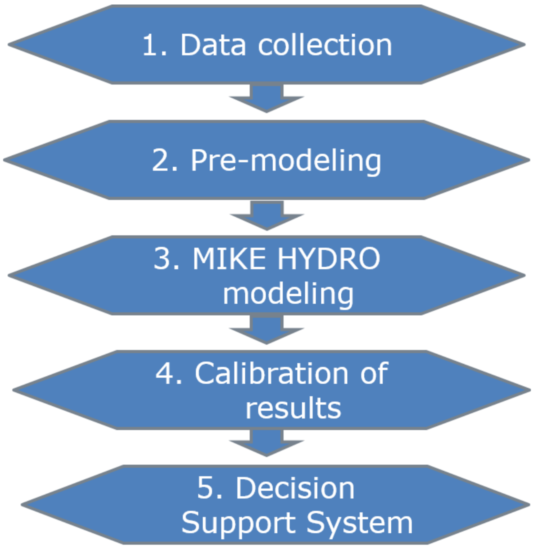



**Figure 1.9:** Basic steps of modeling work.

The aim of this PhD research is to establish the hydrological model and the DSS to support decision makers, stakeholders and engineers to find right measures in the Tarim river area for the further development of the region. Water and land management issues require the simulation of water supply and consumption along the river oases, and the conjunctive use of surface water and groundwater resources.

Research hypothesis of this Ph.D work includes the following major points: (1) water reallocation could assist decision-making process and alleviate water sharing conflicts along the river oases; (2) hydrological models and the DSS could provide scientific basis to improve sustainable management in the basin even with data scarcity problems; (3) the goals and requirements in the water and land management could be fulfilled by applying practical problems into the models; (4) although the DSS integrates cross-disciplinary research topics and the structures were simplified, the model is still able to provide reliable results for the well-being of human in a sustainable way. These hypothesis would be testified after the models being established and the results being implemented in the research area.

Aiming to solve water allocation problems and assist stakeholders with decision-making on sustainable land management in this arid region, 10 research problems are defined to be addressed in this study: 1) How are the water balances, and how much water deficits exist on the irrigation fields? 2) How to distribute water resources in a more efficient manner? 3) Where and how much farmland should be cultivated each year? 4) How to save more irrigation water to guarantee ecological water for nature vegetation? 5) How a DSS is developed to assist decision-making on sustainable land management? 6) Why and how are the hydrological models linked with DSS? 7) How to test management alternatives in the DSS to make goals and strategies? 8) Why and how to involve stakeholders in the research to integrate their knowledge and problem perceptions in the scientific process? 9) How to demonstrate the ecological and socio-economic consequences of the decisions from the DSS users? 10) How the DSS can be further developed?

To answer the questions and solve the problems, a number of research aspects are included in the modeling stage. The major research focus are summarized in Figure 1.10.

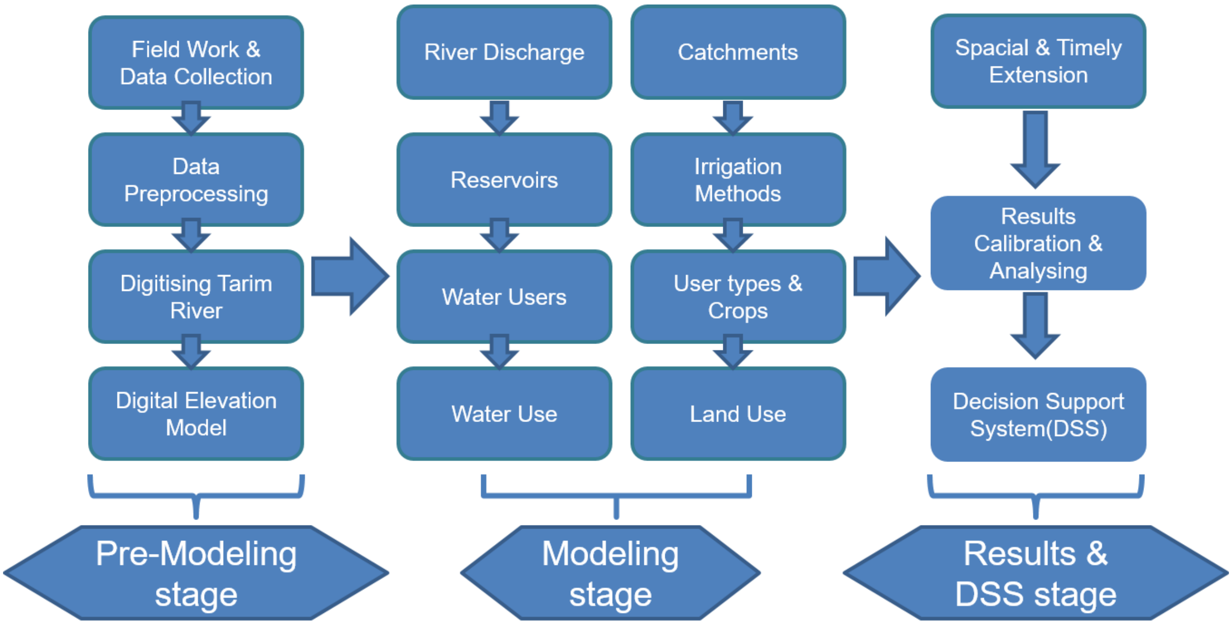



**Figure 1.10:** Modeling stages of the Ph.D. work.

## 1.4 Thesis outline

This dissertation is structured into seven chapters. Chapters 1 and 2 give an introduction on the background and literature review; Chapter 3 and 4 demonstrate the lumped and distributed hydrological model; Chapters 5 and 6 illustrate the development and implementation of DSS with feedbacks from stakeholders; Chapter 7 makes the conclusion and further suggestions. More specifically:

Chapter 1: the first chapter is the introduction chapter, including research background, introduction of project SuMaRiO, problem statement and research objectives and the outline of thesis.

Chapter 2: this chapter presents literature review on three major research topics: studies on the Tarim River Basin, water allocation models in arid lands, and decision support system for sustainable land and water management.

Chapter 3: this chapter demonstrates a lumped MIKE HYDRO model. From data collection, model introduction and background, to model setup, the discharge and calibration, then to model scenarios, afterwards to the results and discussions, and finally summarized the conclusion. The lumped MIKE HYDRO model is established and analyzed on a sub-catchment level.

Chapter 4: this chapter demonstrated a distributed MIKE HYDRO model. Compared with the lumped MIKE HYDRO model, the distributed model gives more insights in the sub-catchments and handles water allocation problems on a hotspot level. From model introduction, to land use and hotspots, then to the analysis of water balance and key modules, to model calibration and validation, later to model scenarios and results, and in the end presented with concluding remarks.

Chapter 5: this chapter presents the development of the DSS in the mainstream Tarim River Basin. The distributed MIKE HYDRO model provides water consumption and water balance for the DSS on the surface flow, and MODFLOW is linked with DSS on groundwater simulations. The content, structure and logics in the DSS are introduced. The Graphical User Interface of (GUI) the DSS is presented. Simulation results of land use changes, downstream outflow and socio-economic outputs are analyzed and summarized in conclusion.

Chapter 6: The implementation of the DSS is discussed in this chapter. Through a number of application activities, the feedbacks were gathered from stakeholders. These feedbacks are helpful to improve the DSS. Uncertainties of the DSS are also discussed.

Chapter 7: the final chapter presents the summary of the Ph.D work and outlook for further research.

# 2 Literature review

Literature review includes three major research topics: studies on the Tarim River Basin, water allocation models in arid lands, and decision support system for sustainable land and water management.

## 2.1 Studies on the Tarim River Basin

Previous studies show that, due to the effects of climate change, annual runoff in the river's headwaters has significantly increased since the 1950s. Average air temperature experienced a significant increase in the last few decades, and average annual precipitation increased by 6–8 mm per decade (Chen et al., 2006). However, surface runoff in the main stem has dramatically decreased in the 1970s, 1980s and 1990s (Hao et al., 2008). Tarim River is a purely dissipative inland river producing no runoff, and completely relies on water supply from its headstreams in the mountains around the Tarim Basin (Yu et al., 2009). Tarim River Basin is characterized by both rich natural resources and fragile environments (Jiang et al., 2007). Since the 1970s, less than 1/4 of the discharge from the main stem of the Tarim River has been reaching the downstream areas in the average year. However, the lower reach of the river serves as the "Green Corridor" in protecting the natural environment from encroachment by the Taklimakan and Kuluk Desert. The "Green Corridor" is an essential ecological corridor for maintaining ecosystem balance in the lower reach. Its area has sharply reduced because of serious wind erosion, land desertification and degeneration of natural vegetation (Chen et al., 2004). This indicates the challenge of maintaining sustainable water resources in the river oases. In this extremely arid region close to Taklimakan Desert, water is the key factor in maintaining local ecosystems.

Studies on climate change and hydrological processes rely on the data acquired from meteorological and hydrological stations. Observed discharge data are acquired from mountain stations and stations along the main channel of the Tarim River. The meteorological data are acquired from weather stations, including daily observations of six variables: precipitation, temperature, relative humidity, sunshine duration, actual vapour pressure, and wind speed. The geographical distribution of hydrological and meteorological stations are demonstrated in Figure 2.1 (Tao et al., 2011).

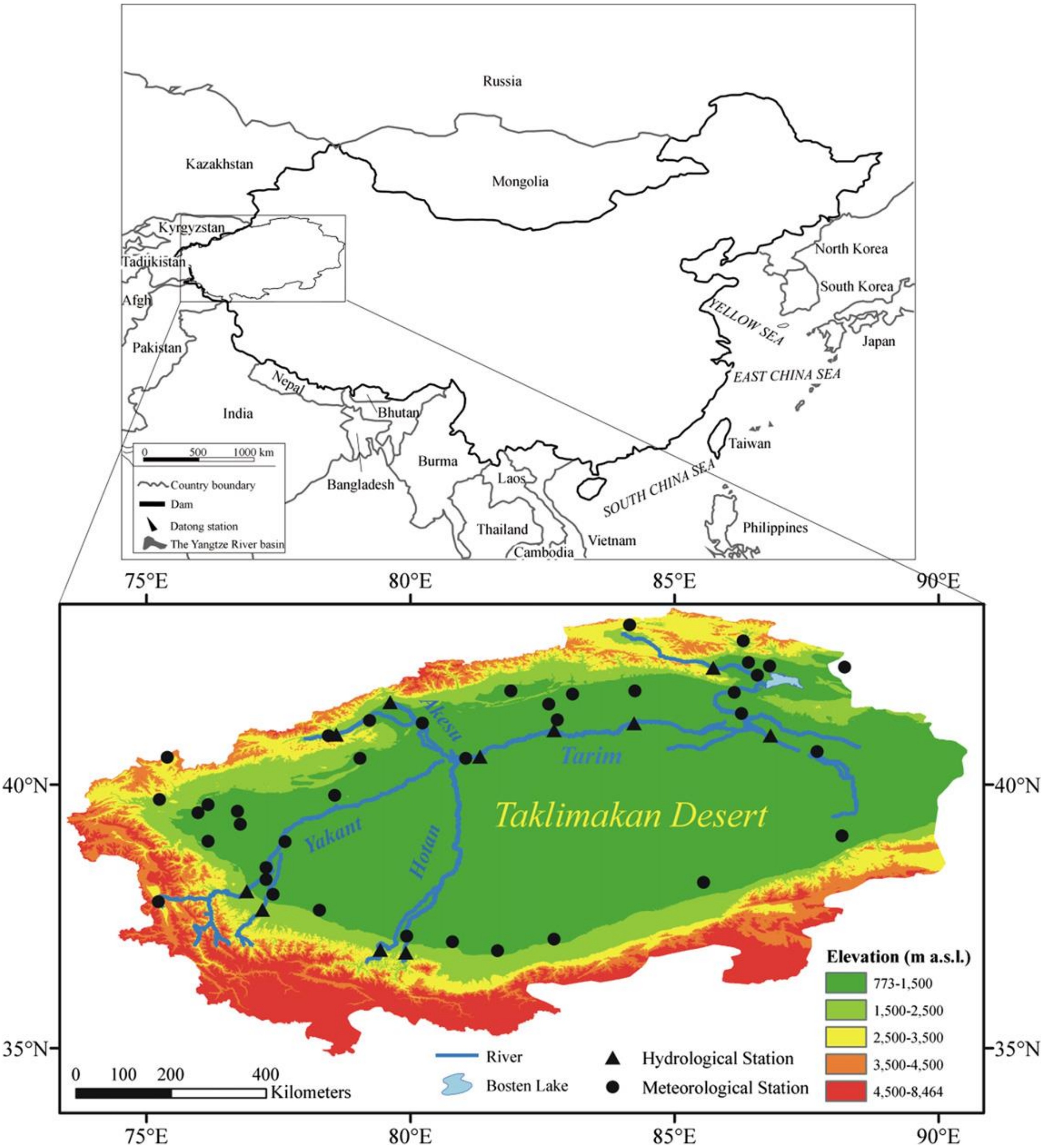



**Figure 2.1:** The geographical distribution of hydrological and meteorological stations in the Tarim River Basin (Tao et al., 2011).

In spite of the large influence of climate change on the environmental evolution (Xu et al., 2004; Chen et al., 2005; Chen et al., 2009; Zhang et al., 2010), it was recognized that agricultural development was the major reason for the water resource crisis in the mainstream of Tarim River Basin (Zhu et al., 2001; Hao et al., 2008; Duan et al., 2009; Tao et al., 2011; Zuo et al., 2014; Yu et al., 2016). Increased farming and water use since the 1950s have led to significant hydrological and environmental degradation (Feng et al., 2001; Qi et al., 2005; Hao et al., 2006; Chen et al., 2011; Ling et al., 2013; Huang et al., 2015). In this context, water saving and higher crop irrigation efficiencies are crucial to the future allocation of water resources. The management of irrigation water use continues to pose increasing challenges to decision-makers and planners in developing countries, particularly those facing limited water resources. The Tarim River is one of the largest inland rivers in the world and located in the northwest of China, known worldwide for its extreme climatic situation and vulnerable ecosystem. With the high-intensity and large-scale exploitation of water resources at the upper reaches of the Tarim River, the water curtailment downstream has brought great negative effects for the ecosystem in the Tarim River Basin (Chen et al., 2004; Chen and Xu, 2005).

Limited data is a key issue for the researches in the Tarim River Basin. Many researchers have faced data scarce problems. Li and Williams (2008) found some research results lack of solid physical basis when they were conducting snowmelt runoff modeling in the basin. The difficulties were large data requirements, especially in data-scarce mountain watersheds. After many years' of research in the Tarim River Basin, Chen and Xu (2005) still claimed limited data being the reason for the unclear long-term trend of climate and water resources. Many researches had been hampered to reach a further step due to limited data (Hao et al., 2008; Zeng et al., 2011; Liu et al., 2012). Thevs et al. (2008) has made an investigation on the runoff of the Yingbaza station, but the data was based on monthly values, and the investigation period was before 2003 (Figure 2.2). Further research with better quality data will be used in this Ph.D research for deeper and more reliable investigations.

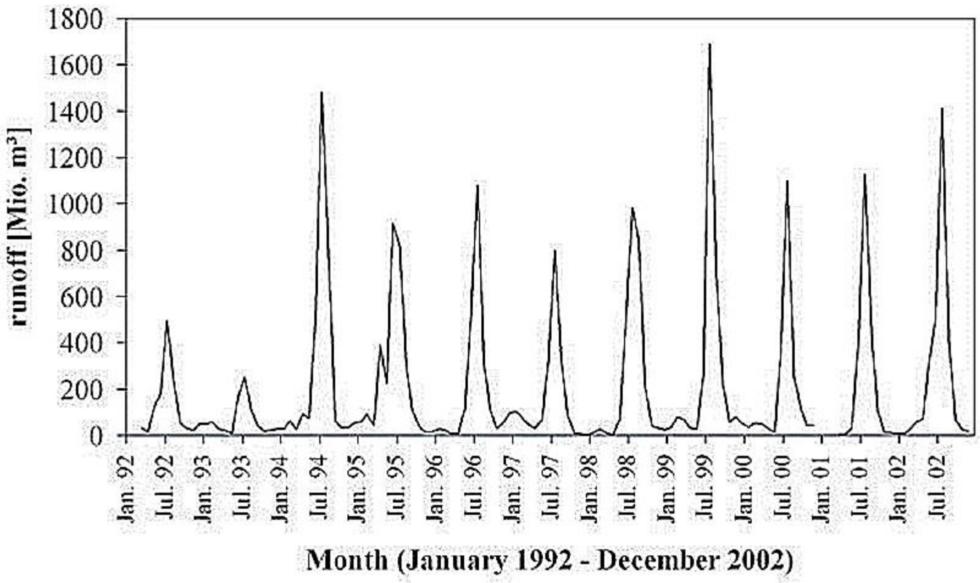



**Figure 2.2:** Monthly runoff of the Tarim River's middle reaches (hydrological station Yingbaza) (Thevs et al., 2008).

A particular research was conducted on the glacier area and headwater of the Tarim River (Duethmann et al., 2016). The study presents an analysis of future climate change impacts on glaciers and surface water availability for headwater catchments of the Aksu River, the most important tributary to the Tarim River. A glacier-hydrological model was applied based on daily discharge variations and glacier mass changes. Three different emission scenarios, nine global climate models (GCMs) and two regional climate models were considered, and different hydrological model parameters were derived from the multi-objective calibration. The simulation results indicated overall discharge in the Aksu headwaters was expected to be increased in the period 2010–2039 due to climate change, but decreased in 2070–2099 due to glacier retreat. Seasonally, projections showed an increase in discharge in spring and early summer throughout the 21st century. The research findings from this study was used in this Ph.D work for the future climate scenarios.

The environmental degradation of the Tarim River Basin has attracted the attention from the local government and water bureau. Human intervention and recovery measures have since been adopted (Zhu et al., 2016). The restriction on farmland expansion and convention from farmland to forest has some initial achievements (Hu et al., 2015). The ecological degradation was obviously reversed within a certain region of the water channel (Xu et al., 2008). Since the year 2000, Chinese government started the ecological water conveyance project, to transfer intermittent water from Bosten Lake to the lower reaches of the Tarim River. Chen et al. (2009) investigated the effects of ecological water conveyance on groundwater dynamics and riparian vegetation in the lower reaches, and concluded that the water recharges considerably lifted the groundwater table on both sides of the river course, but no significant influence of the water recharges on herbaceous plants was observed this time. Hao and Li (2014) made another examination, and found a general rise in the groundwater table and improved soil moisture conditions. They also pointed out that the water conveyance directly affected vegetative cover and the phenology of herbs, trees, and shrubs. Aishan et al. (2015) analyzed the monitoring data of 7 years, and concluded that some eco-morphological parameters of the *Populus Euphratica* trees have different levels of response to the ecological water diversion. A similar result was reported by Peng (Peng et al., 2014), who examined the areas of *Populus euphratica* forest, and obtained the conclusion of a positive correlation between water supply and forest area.

Land use changes caused by climate change and human activities in the Tarim River Basin are investigated in recent years. Land use/cover changes (LUCCs) have been widely investigated by different remote sensing satellites. In a particular study by Zhang et al. (2015), temporal and spatial patterns over the past 20 years in the middle reaches were investigated. Results indicated that the transformation and changes of land use/covers and landscape occurred more and more frequently from 1989 to 2009. From 1998 to 2009, farmland, heavy saline land and the undeveloped land have increased, and the other types of land use/cover have decreased. The gravity center of each land use/cover types has been shifted. The spatial patterns of heavy saline land have been largely changed between 1989 and 1998. Sun et al. (2016) collected multi-temporal remote sensing images beginning in 1994, a year that captured the initial effects of the period of rapid farmland expansion. They concluded that, over the past two decades, the area subject to farmland expansion was significantly larger than that experiencing farmland abandonment. A widely accepted belief is that rapid farmland expansion and the subsequent abandonment of the farms would lead to soil salinization and desertification, and prohibit the sustainable management along the river oases. The land use changes on the mainstream of Tarim River in the past several decades were demonstrated by Zhao et al. (2013), which had clear evidence for the farmland extension and vegetation degradation in the lower reaches before 2005 (Figure 2.3). Land use change in recent years is an important topic for future researches. Moreover, land use change in future scenarios based on management alternatives is a more crucial and complex task for sustainable land management along the river oases, which will be discussed in the next chapters.

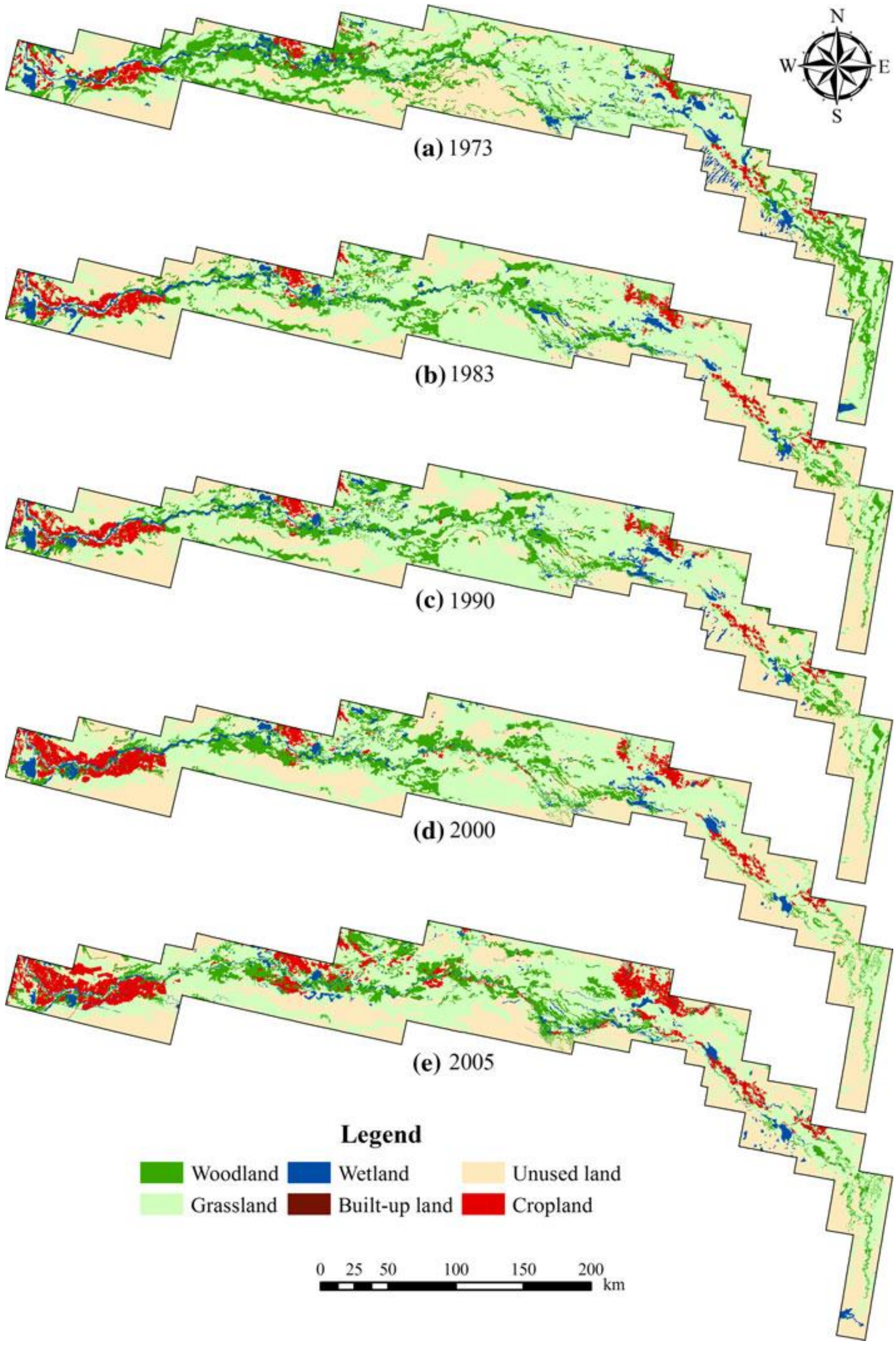



**Figure 2.3:** Land use changes in the mainstream Tarim River from 1973 to 2005 (source: Zhao et al., 2013).

So far most studies about the Tarim River Basin focused on individual factors or driving forces of water scarcity, such as climate change (Chen et al. 2006), population increase (Zuo et al. 2014), agricultural development (Feike et al. 2015), excessive water exploitation and ecosystem degradation (Feng et al. 2001; XU et al. 2008; Ye et al. 2014).

There is a lack of studies addressing the management practice of water allocation strategies along the mainstream of the Tarim River at macro-spatial and temporal scales.

Liu et al. (2013) conducted an analysis on the relationship between historical land-use change and water availability in the lower reaches, and found farmland has been gradually relocated to the upstream regions. This has led to reduced flows from the upper Tarim stream, which subsequently accelerated the dropping of the groundwater level downstream in the basin. Thevs et al. (2015) developed a water quota system aim at assessing the water consumption through irrigated agriculture, mainly cotton. The work was conducted in the headwater catchment of the Tarim River. Though more and more integrated models were developed and applied in the region (Meng et al., 2009; Huang et al., 2010; Xu et al., 2010; Rumbaur et al., 2015; Liu et al., 2015), comprehensive management (water, earth, ecosystem, economy, society, human activities) issues are still remained unclear and unsolved. In general, the studies on arid river basins are still much less in amount and poor in depth, if compared to perennial rivers in humid regions (Tooth, 2000a; Nanson et al., 2002; Thomas, 2011). There remains much difficulties for those studies since related gauging and surveying in arid areas are usually not so persistent and systematic, due to tough natural environments, infrequent nature of events (e.g. precipitation, runoff), problems of monitoring networks establishment over large areas where rainfall and runoff are highly variable (Bull and Kirkby, 2002), and lacking of due attention in the past. Hence, despite the increasing interest, studies on arid river basins may still in its infancy. More significance should be attached to rivers in arid areas in future (Yu et al., 2016).

## 2.2 Water allocation models in arid lands

Water scarcity is expected to increase in the dry regions of Asia (Schmitz et al., 2013). Increasing population and farming practices will increase the stress on water resources in these arid regions. The needs of natural ecosystems have become another source of competition that increases pressure on water resources in the future (Cai and Rosegrant, 2004). A hydrological model for making water allocation strategies needs to consider both spatial and temporal variables, including land use, surface water routing, groundwater movements, water extractions, irrigation, and their interactions. On the other hand, an increasing number of model parameters often leads to high computational complexity, which enhance the difficulty on the analysis of simulation results and future scenarios. With the conjunctive use of groundwater and surface water, the agricultural water management models have evolved to include a framework of both natural and anthropogenic components of groundwater and surface water resources (Hanson et. al, 2015).

Traditional water conflict resolution approaches such as the judicial systems, state legislatures, commissions and similar governmental instruments mostly provide approaches in which one party gains at the expense of the other (Nandalal, 2003). When the number of interdisciplinary research topics (e.g. hydrology, geography, ecology, and socio-economic factors) increases, the conflict resolution process would become rather complicated. Improved water management, conflict resolution and cooperation could ameliorate such conflicts. A good source of selected disciplinary approaches for water conflict resolution process is presented by Wolf (2002). Since the last century, Bender and Simonovic (1995) had proposed the active involvement of stakeholders would be helpful to identify problems, share information and where possible, develop mutually acceptable solutions.

Currently there are many catchment water allocation tools, such as CWAM, (Wang et al., 2008), REALM (George et al., 2011), MIWA (Dai and Li, 2013), CaWAT (Cai, 2014). These models often face difficulties in balancing model complexity and processing time in large basin modeling. For instance, CaWAT was developed to aid rural water resources planning for agriculture in small watersheds. The inputs to water resources management were dominated with small scale interventions such as small storages development, local diversions, on farm management practices which were much easier for famers to adopt. Small watershed including fewer villages was also a scale which enable better negotiations and collaborations among upstream and downstream users (Cai, 2014), which means the model would fail in dealing with large-scale basin problems with more model complexity. One of the fundamentals of water allocation is that any form of abstraction, transfer, storage or other influences on natural stream has effects on the entire downstream river system (CAP-NET, 2008). Large-scale hydrological models have been used to assess the impacts of land use changes and other human activities on water resources (Arnold et al., 1998; Biancamaria et al., 2009; Paz et al., 2010). These models represent a compromise between the limited insight obtained from a lumped model and the large amount of data and computational power required from a distributed model. Consequently, a more suitable approach would be a semi-distributed model wherein the overland flow and unsaturated zone are represented by their lumped-parameter semi-empirical counterparts to simplify the overall analysis (Gunduz, 2004). Furthermore, the integrated use of optimization models has been recently preferred for solving the problems of surface and ground water management because the optimal solutions of conjunctive management problems may not be achieved using either simulation or optimization techniques alone (Ajay,2014).

Based on the limited data, Thevs et al. (2011) was able to generate a skeleton frame for the water allocation along the Tarim River (Figure 2.4). Within each river stretch, quotas are fixed for the amount of water diverted into irrigation, oil exploitation, and water left for the natural vegetation. But the research did not combine land use map, and therefore did not deal with land management issues. Without simulations on the irrigation fields, channels, natural vegetation, the research was conducted on a conceptual level and failed to describe the details on hydrological processes. To provide guidance on the management practices, the interactions among water, soil, crops, reservoirs and climate changes need to be further investigated. Future management scenarios have to be established on deeper knowledge and more distributed models.

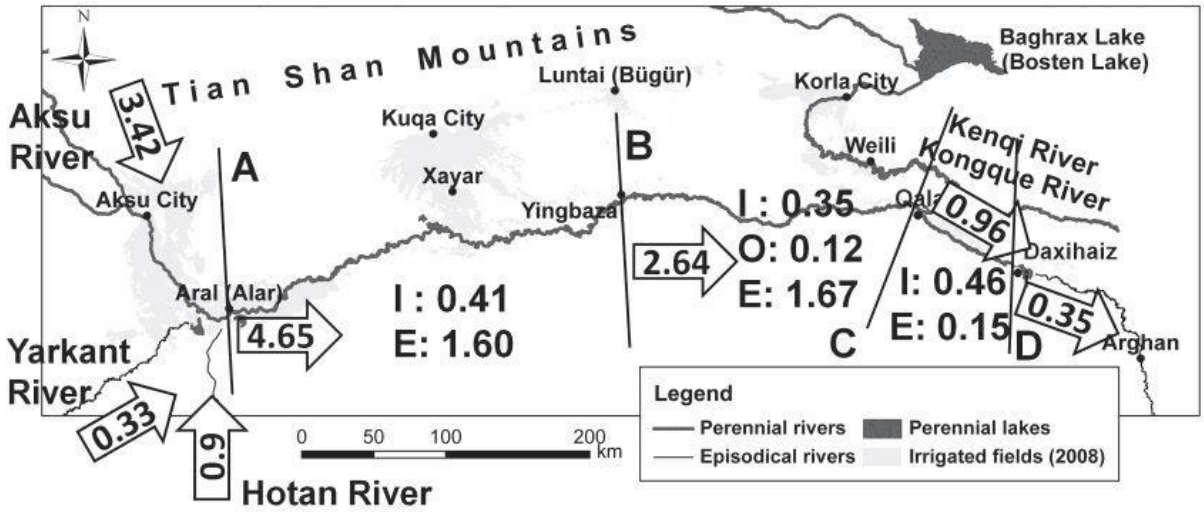



**Figure 2.4:** The Quota System for Water Allocation along the Tarim River. I: irrigation and industry, E: environmental flow, O: oil exploitation. A–B: Tarim upper reaches, B–C: middle reaches, C–D: upper section of lower reaches, D and below: lower reaches (Source: Thevs et al., 2008).

It is evitable that some water allocation models have to deal with crops and water productivities. Sharma et al. (2015) explained in detail the concept and measurement of "water-use efficiency" and "water productivity" as applied at plant, field, farm, basin and national level through traditional and remote sensing based estimations. Further, the methods for improving water productivity under irrigated, water scarce conditions, paddy fields and large river basins were discussed. Furthermore, they pointed out that appropriate water accounting procedures need to be put in place to identify the opportunities for water savings. As pressure on the available land and water increases, higher water productivity is the only solution to providing the food that will be needed with the water that is available. To identify whether a strong increase in water price may lead to a wiser agricultural water use along Tarim River, 128 farmers were interviewed with structured questionnaire by a study by Mamitimin et al. (2015). Multinomial logistic regression was employed to explain the factors influencing farmers' reaction towards a strong increase in water price. Their results indicated that under increased water price less than half of the interviewed farmers would opt for decisions that lead to improved water use efficiency. Moreover, the price increase might lead to a further expansion of groundwater exploitation in the region, because farmers may dig their own wells for water pumping. Although the punishment for digging personal wells is severe, due to lacking of supervision, it is difficult to prevent all the farmers from taking the risk. Fruit farmers, as well as farmers with less land and less cash income are reluctant to adopt advanced irrigation technology or improve their crop production in reaction to increased water price. The experience of slight water shortage in the past created awareness by farmers to use water more wisely. In the end, they concluded that the sole increase of water price is not a viable option. An integrated approach is necessary, in which creation of awareness and improving agronomic skills of farmers play a key role to overcome the water scarcity and realize a more efficient use of water.

A recent-developed software MIKE HYDRO provides a possible solution for managing water allocation problems in macro scale. MIKE HYDRO is an integrated, multipurpose, map-based decision support tool developed by the Danish Hydraulic Institute (DHI). The Basin model type is the MIKE HYDRO module used for a variety of model applications, covering integrated water resources management (IWRM), water resources assessment, water allocation, reservoir operation and other types of analysis (DHI, 2014). It enables detailed simulations of water resources and land use in the catchment areas. MIKE HYDRO has the advantage of conjunctive simulation of spatial and temporal variables within low computational time, and thus beneficial for IWRM in a large-basin project. IWRM has become a popular concept in recent years, but its track record in the application of more efficiently managed macro-scale water projects has been dismal (Biswas, 2008). It is difficult for water allocation models to provide practical and scientific solutions on a large basin scale. MIKE HYDRO was developed from MIKE BASIN, which is a modeling package for water allocation scenario modelling, reservoir operation, and irrigation assessments. The irrigation module of MIKE BASIN was depicted by Doulgeris et al. (2015) in Figure 2.5, which had been comprehensively improved in the new version of MIKE HYDRO (DHI, 2014). MIKE BASIN was coupled with ArcGIS, while MIKE HYDRO has a new developed user-friendly GUI, in which water users can be explicitly distinguished and distributed in the watershed. Besides the original irrigation module from MIKE BASIN, new climate models and soil models are also embedded in MIKE HYDRO.

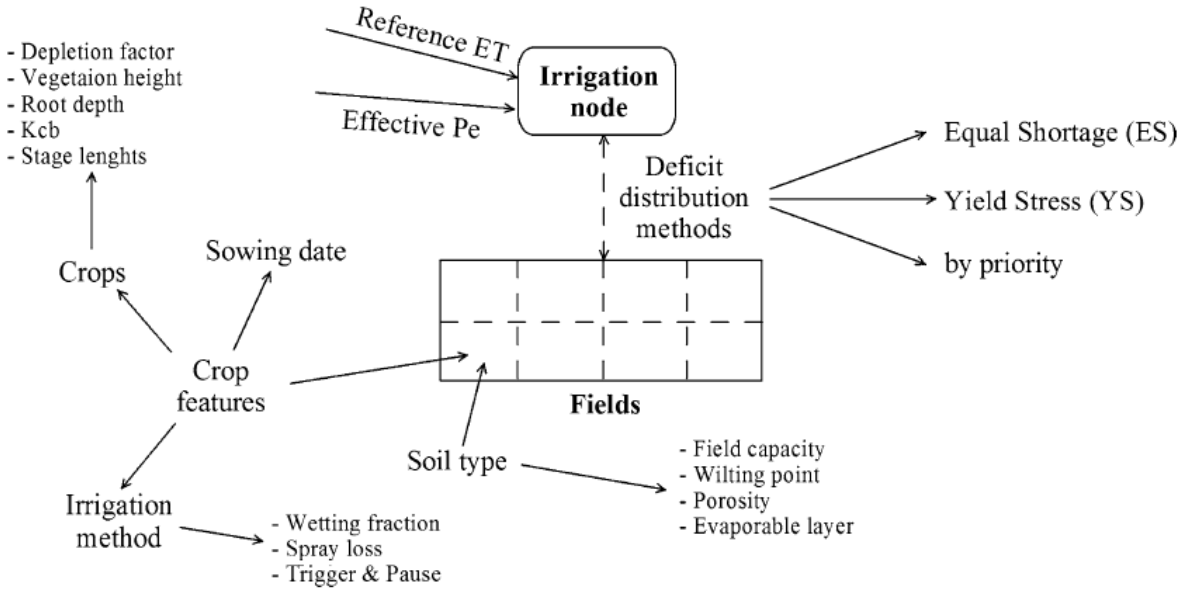



**Figure 2.5:** Irrigation module of MIKE BASIN. MIKE HYDRO was developed from MIKE BASIN (source: Doulgeris et al., 2015).

Butterworth and Soussan (2001) pointed out that it is easier to identify the failings of past approaches than to specify new directions forward. Indeed, there are concerns that the IWRM approach was too complex to be readily understood or implemented, and was potentially disabling in terms of providing a basis for effective change. The need to relate this or any resource-based approach to a human development paradigm is of paramount importance and a major challenge. Operation on the reservoirs is a good example. The reservoirs are often controlled by human beings based on constant changing situations, rather than government policies or certain rules. If a change on the water scarcity situation is considered to be necessary by a decision-maker, then the reservoir would probably release a certain storage. This process may be difficult to reproduce in a hydrological model. There is also a feeling that the IWRM approach is not suited for addressing real, urgent needs and priorities. In addition, some of most important causes of persisting water supply system failures were demonstrated (Table 2.1).

**Table 2.1:** Some of the principal causes of water supply system failures (Butterworth and Soussan, 2001).

| Causes of water shortages | Examples |
|---|---|
| Physical constraints not properly addressed during planning | • poor aquifer with limited storage<br>• arsenic/ fluoride risks<br>• potential competition with other uses, especially irrigation, not addressed |
| Engineering shortcomings | • reticulation systems that are too expensive to operate and maintain |
| Institutional/ management failure | • illegal connections to water supply systems and consequent problems in tail-end villages<br>• overexploitation of groundwater under conditions of open access<br>• poor cost recovery leading to lack of investment/maintenance<br>• lack of maintenance e.g. hand pumps<br>• poor institutional organization for the communal facilities |
| Corruption | • incentives for some to maintain and profit from water shortages e.g. vendors, tanker operators, kick-backs associated with large engineering contracts |
| Rising demands | • increasing population<br>• incentives to use water inefficiently especially for irrigation<br>• changing patterns of water use with changes to lifestyles |
| Social Factors | • social barriers to access to water supply facilities (e.g. caste, restrictions on women) |

## 2.3 Decision support systems for sustainable land and water management

The debate over the effectiveness of Integrated Water Resources Management in practice has lasted for years (Jeffrey and Gearey, 2006; Biswas, 2008; Quevauviller, 2010; Giordano and Shah, 2014). As the complexity and scope of IWRM increases, the difficulties of hydrological modeling is shifting from the model itself to the links with other cognate sciences, to understand the interactions among water, earth, ecosystem and humans. Decision support system (DSS) is a technical tool to provide sufficient and valid information to decision-makers. The development of a DSS can be quite useful to link the outputs of hydrological models with real-time decision making on social-economic assessments and land use management. DSS can assist the decision-making in a qualitative manner based on the outputs of hydrological models and knowledge of experts in cross-disciplinary fields. The DSS can bridge the gap between research and IWRM in practice. IWRM is a process where information, technologies, natural processes, water users, societal preferences, research and water administrations, and policy actors are subjected to gradual or rapid change. A typical DSS for IWRM includes five main components: data acquisition system, user-data-model interface, database, data analysis tools, and a set of interlinked models (Georgakakos, 2007). The processes of gathering knowledge in the DSS, input into the DSS, and output of information to support the planning and management decisions are illustrated in Figure 2.6.

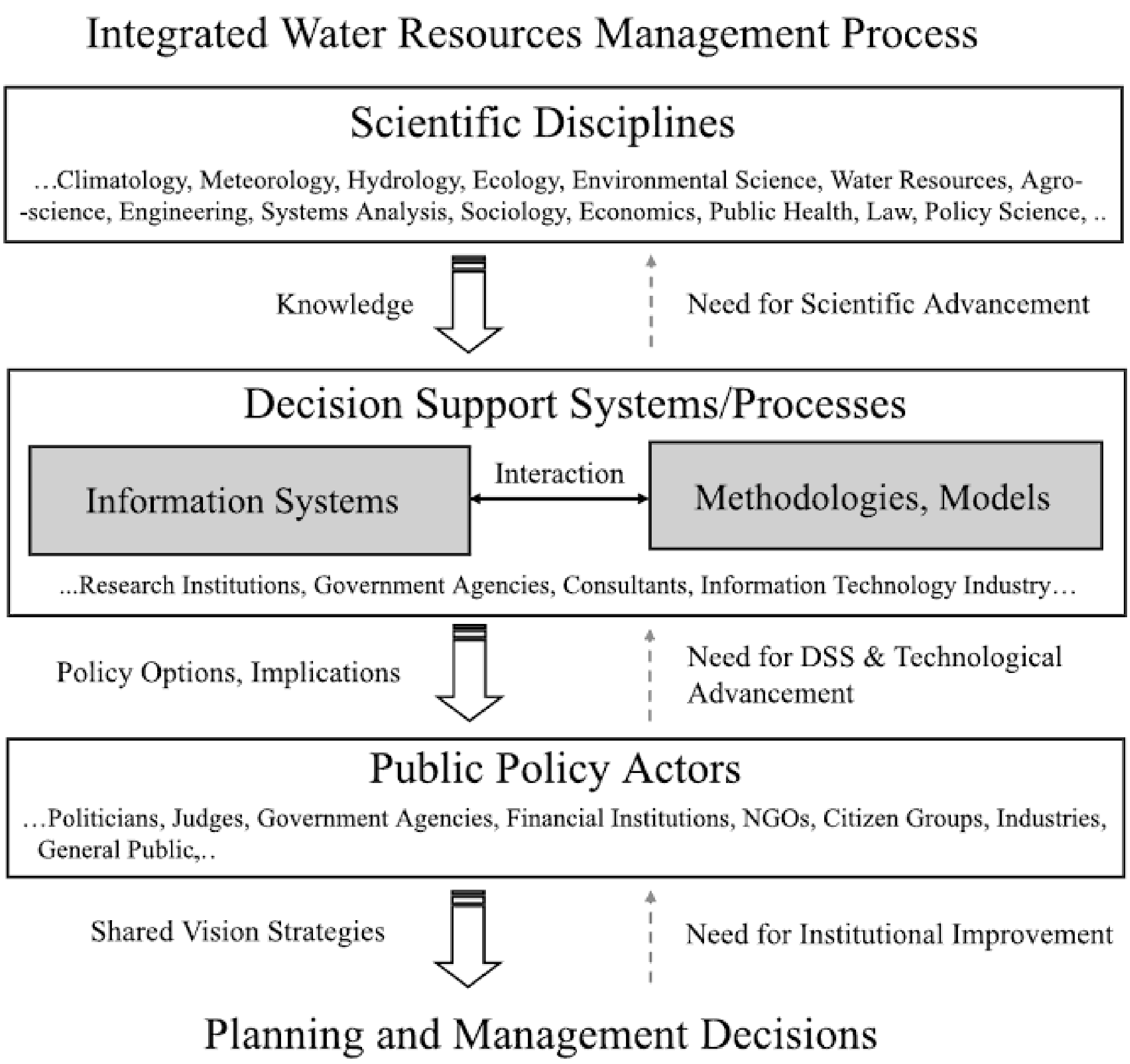



**Figure 2.6:** Decision support system in the planning and decision-making on IWRM (Georgakakos, 2007).

Figure 2.6 demonstrates the scientific disciplines which are possible information to put into the DSS for IWRM. However, the author did not mention the importance of involving farmers in the decision-making process, as well as their feedbacks to improve the DSS. The knowledge of local researchers, farmers and other residents is very crucial to make the DSS and IWRM more practical to solve problems in a real situation. IWRM is largely determined by the nature and extent of emerging conflicts and how they are solved and also upon the interactions between water users and stakeholders. The public/community involvement is crucial for a successful and sustainable water resource management. It has been emphasized that natural resources management related policies including water requires the use of knowledge, experience and opinions of local communities who are the key stakeholders in resource conservation (Dungumaro and Madulu, 2003). Discussions on potential ways forward on IWRM application should be based on better understanding of key stakeholders' perceptions of IWRM, and how cross-sectoral coordination and IWRM can provide added value to those currently in charge of decision making (Suhardiman et al., 2015).

Currently there are many DSS models with economic assessments (Wenkel et al., 2013; West and Turner, 2014; Pedro-Monzonís et al., 2016) that focusing on single topic (e.g. climate change, land use, agriculture, water account), and many socio-economic models (Flörke et al., 2013; Herrero et al., 2014; Visconti et al, 2015) without simulation of hydrological processes. Few models are capable of integrating meteorological, geographical, ecological, social and economic factors, which is based on the simulation of hydrological models, such as MODFLOW-OWHM (Hanson et. al, 2015) and FREEWAT (Rossetto et. al, 2015). Little research has been done to show the interactions of so many cross-disciplinary research on IWRM, to understand Ecosystem Services (ESS) and integrate them into land and water management. Due to model complexity issues, many DSS models have to consider less issues within a specific research frame (McCown, 2002; Basso and Ritchie, 2015). However, to increase model accuracy on the comprehensive analysis in IWRM, the model complexity of DSS is worth the effort (Chenoweth et al., 2004; Power et al., 2015). A particular model was developed in a Middle East water project by Fisher et al. (2001), to optimize water management and resolve water conflicts. They found actual water markets often do not allocate water resources optimally, largely because of the perceived social value of water. However, it is possible to build optimizing models to substitute for actual markets. Such models can assist the formation of water policies, taking into account user-supplied values and constraints. So a new model was developed for cost-benefit analysis of infrastructure, but this model did not deal with crop growing stages and the calculations of water demand and supplies.

It is a commonly used approach that the DSS is based on other platforms or models. Yue et al (2014) developed a decision-making system based on GIS and knowledge. The system was constructed to analyze agricultural distribution of counties, which combines the quantitative analysis of agricultural economic monitoring subsystem with the qualitative analysis of knowledge subsystem. The system utilizes C#.NET as the development platform, and GIS was used in the design of the DSS, which provides decision support for agricultural management. The system can be improved by including ecosystem and the consideration of water cycle. Assessments of climate change and socio-economic impact has been published in recent years. Arnell and Lloyd-Hughes (2014) conducted an assessment of the global and regional scale impacts of climate change on exposure to water scarcity and changes in the frequency of river flooding, using the new matrix methodology. It estimates impacts in 2050 and 2080, under different combinations of rate of climate forcing (RCPs) and socio-economic futures, using a climate model to characterize uncertainty in the geographical and seasonal pattern of climate change. Their research result indicated the difference in impact between RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Compared to impacts under the RCP8.5, exposure to increased water scarcity would be reduced in 2050 by 22-24 % under RCP2.6, and exposure to increased flood frequency would be reduced by around 16 %. Their research was conducted on a global-scale. In the Tarim River Basin, where socio-economic factors are largely dependent on the glacier and snowmelt water, the impacts of climate change would be in a very different situation.

A DSS can be an indicator based tool that enables stakeholders and decision-makers to evaluate the consequences of their actions. Among selected scenarios of future climate and socio-economic development, the impact of planned management measures can be determined by quantitative and semi-quantitative methods. All the indicators and methods can be created by expert knowledge and experience from stakeholders. The involvement of stakeholders are very crucial for the design, development, modification and implementation of the DSS. To bridge the gap between science and practice, the DSS must be understood, accepted and used by stakeholders and decision makers. Therefore, the graphical user interface should be intuitive to use (Disse, 2016). To improve the water resource management of the inland river basins of northwestern China, another DSS was developed by Ge et al. (2013) to provide an operative computer platform for decision makers. The DSS was designed according to actual water resource management problems and was seamlessly integrated into a user-friendly interface. The model estimated crop water demand and water allocation for different levels of water use units. The objective of this study is to aid in the decision-making process related to water allocation scheme planning and implementation and to aid real-time responses to changes in water supply, allowing a new water allocation scheme to be developed based on the actual relationship between the supply and demand for water. The research provides valuable experience for the DSS in water management issues, but it was conducted in Heihe River Basin, and socio-economic factors were not considered.

Many Chinese scientists have conducted researches on the DSS in the Tarim River Basin. Wei developed a DSS which focus on water resources unified regulation system (Wei et al., 2009). Zhang developed a DSS for conversion of farmland and forest protection (Zhang et al., 2008). Researchers from Chinese Academy of Sciences and other Chinese institutions have made large amount of work to provide scientific basis for decision-makings. Hao et al. (2008) analyzed the impacts of human activities and climate change on annual runoff change along the mainstream of Tarim River, and provided scientific reasons to restrict farmland expansion and reduce water consumption in future years. Chen et al. (2011) suggested several possible countermeasures and ideas for mitigating the desiccation tendency in the Tarim River, to provide decision-making references for water resource management and sustainable development in the basin. Peng et al. (2014) conducted field investigations to analyze the driving forces behind forest change from the perspectives of anthropogenic activities and natural forces, to assist decision-making on ecological water conveyance project in the lower reaches. Leiwen (Leiwen et al., 2005) carried out a study on the interactions between population growth and changes in water and land resources, crossing the boundaries of the different reaches in the Tarim River Basin over the past 50 years. Huang (Huang et al. 2012) developed an integrated optimization model for supporting irrigation water management, but socio-economic factors were not considered. Liu (Liu et al., 2015) presented a conceptual socio-hydrological model for the study of the co-evolution of humans and water, but the research was conducted mainly on model framework, rather than in management practices. Huang et al. (2010) developed an integrated modeling system for water resources management of the Tarim River Basin. The system coupled remote sensing (RS)/geography information system (GIS) technique with distributed hydrological model to simulate the rainfall runoff, snow melting, and evapotranspiration process of the hydrological cycle. It is a good approach of RS/GIS technique for effectively accessing, processing, and managing spatial data, which enable them to conduct research on land use, vegetative cover, soil, topography, precipitation, and evapotranspiration, but the socio-economic factors were not considered in the system. Due to limited expert knowledge in interdisciplinary research topics, it is difficult for most researches to integrate the simulation on hydrological processes with socio-economic factors. In general, there is lack of studies on the decision-making processes with comprehensive management on water, farmland, ecosystem, economy and human activities.

# 3 Lumped MIKE HYDRO model

A large-scale hydrological model (MIKE HYDRO) was established for the purpose of sustainable agricultural water management in the mainstream Tarim River. In this arid region, agricultural water consumption issues are crucial to address the conflicts among irrigation water users from upstream to downstream. Calibration data and future predictions based on large amount of data was acquired. The results of model calibration indicated a close correlation between simulated and observed values. Scenarios with the change on irrigation strategies and land use distributions were investigated. Irrigation scenarios revealed that the available irrigation water has significant and varying effects on the yields of different crops. Irrigation water saving could reach up to 40% in the water-saving irrigation scenario. Land use scenarios illustrated that an increase of farmland area in the lower reach gravely aggravated the water deficit, while a decrease of farmland in the upper reaches resulted in considerable benefits for all sub-catchments. A substitution of crops was also investigated, which demonstrated the potential for saving considerable amounts of irrigation water in upper and middle reaches. Overall, the results of this study provide a scientific basis for decision-making on the water consumption and allocation strategies in this arid region.

### 3.1 Data collection and pre-modeling

Data was collected and shared within SuMaRiO research group. Climate data was collected from Xinjiang meteorological stations. Hydrological data was acquired from gauging stations along the Tarim River. Socio-economic data was collected from local county administrations. Particularly, a lot of additionally research data was provided by the research partners from Chinese Academy of Sciences.

The pre-modeling stage includes data sorting, study on the model, as well as Digital Elevation Model (DEM) processed in ArcGIS. The digitizing of Tarim River (Figure 3.1) starts from Alar until Qiala reservoir. River course has changed dramatically from the upper reaches to lower reaches. Downstream of Qiala reservoir, river interception occurred most of the year and river course becomes quite unstable even in flood season. The catchment of mainstream Tarim River has a total area of $1.76 \times 10^4$ km$^2$.

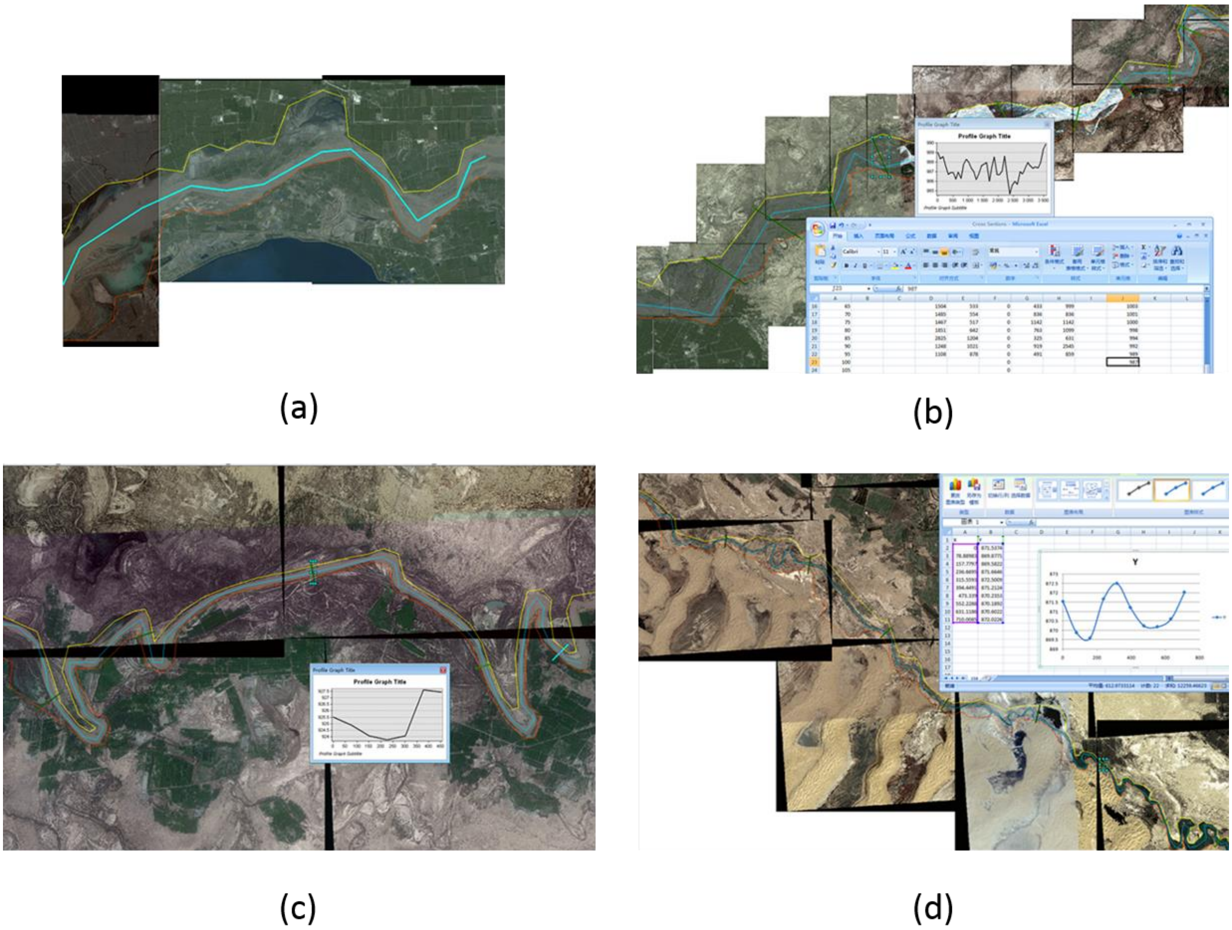



**Figure 3.1:** ArcGIS analysis and cross sections from Google Earth images in the (a) starting point of Alar, (b) upper reaches, (c) middle reaches, and (d) lower reaches.

The satellite images used for the digitizing of the Tarim River was acquired by Google Earth photos, with 30 × 30 m resolution. The changes of land use and river widths are obvious from the upper reaches to lower reaches.

The upper reaches starts from Alar (some researchers prefer to choose Xiaojiake as the starting point, where located 48 km upstream of Alar hydrological station and the tributaries of Tarim River begin to converge) to Yingbaza. The River has no bifurcation in this segment. River width is mostly between 500 to 1000 m in the upper reaches, with smooth and straight river course. In the middle reaches between Yangbaza and Qiala, river width is usually between 100 to 500 m. Water flows slowly with a meandering river course. Water transport dikes and ecological water valves in this segment have been well constructed. The middle reaches of Tarim River is a large water consumptive area in the whole basin and its water abstraction system is very complicated. Irrigation channels for the farmlands, flooding valves for natural vegetation, and ecological outlets for *Populus euphratica* all abstract water from the Tarim River. From the field investigations, natural vegetation nearby the flooding gates have better growing conditions and density than those far distance from the flooding gates.

From the satellite images of upper reaches, middle reaches, to the lower reaches of the Tarim River, we can notice the differences of the land use changes. Upper reaches are occupied by plenty of large farmland areas, and middle reaches are full of forest and grassland, while lower reaches have clear evidence of land desertification. The green belt is very narrow along the river in the lower reaches. The DEM was generated after the digitizing in ArcGIS, and cross sections were analyzed in Alar, Yingbaza and Qiala gauging stations (Figure 3.2).

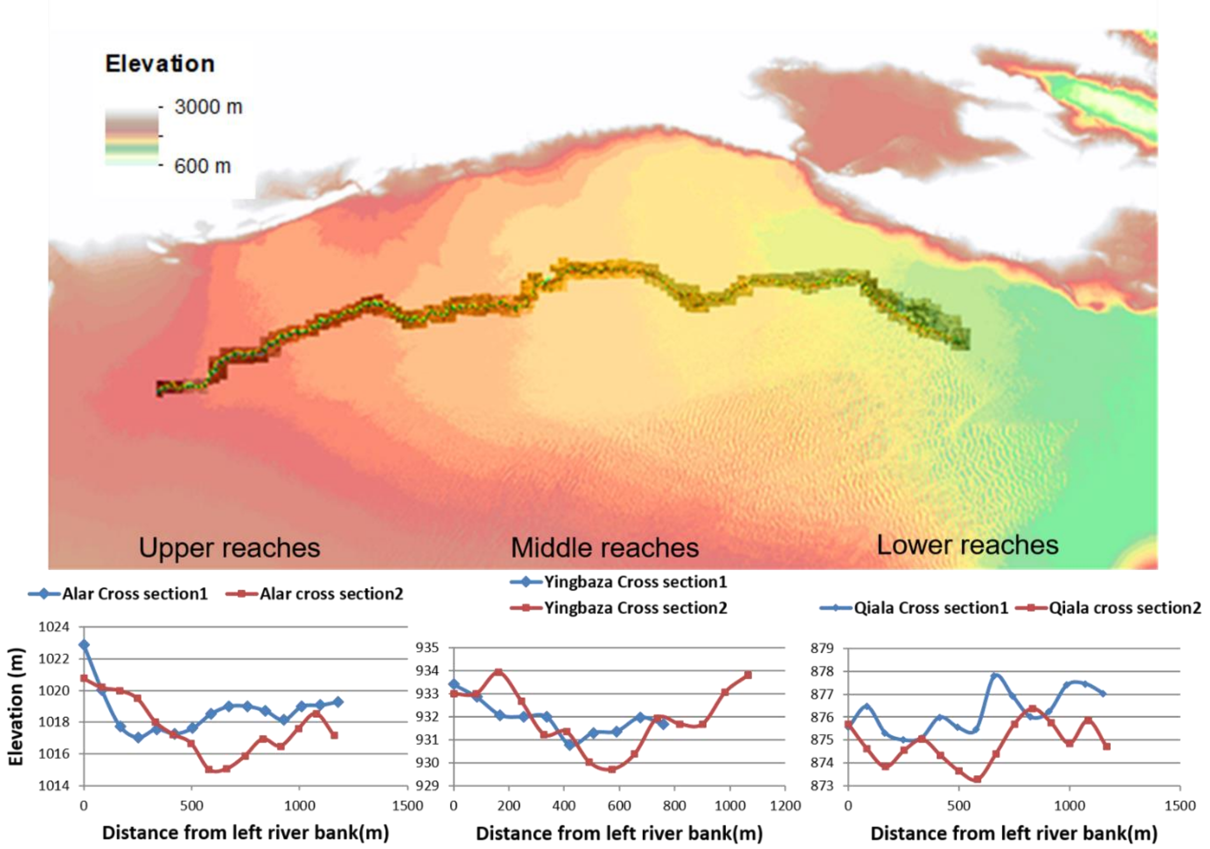



**Figure 3.2:** Digital Elevation Model (DEM) and cross sections in upper, middle and lower reaches.

The digitizing of Tarim River and the DEM model provided river width, slope, distance of the river nodes, and elevation of the river and reservoirs, which are very necessary in the following research for the setup of hydrological models.

## 3.2 Model introduction and background

MIKE HYDRO is an integrated, multipurpose, map-based decision support tool developed by the Danish Hydraulic Institute (DHI). The Basin model type is the MIKE HYDRO module used for a variety of model applications, covering integrated water resources management, water resources assessment, water allocation, reservoir operation and other types of analysis (DHI, 2014). It provides detailed simulations of water resources and land use in the river catchment areas. The scale of these models may range from the large river basin to a smaller local project.

The overall model settings includes specific definitions for the input features in the water resources model (Figure 3.3). Those features can be defined either at the setup wizard at the starting interface or afterwards from the tree view by changing properties. In this simulation specifications section before a model to be built up in the map view, there are five portions to be defined: modules, simulation description, simulation period, time step control, and computational control parameters. The Modules include Basin modules and global parameters that can be chosen from. Basin modules contain two types of modules: Rainfall-runoff and Basin simulation. Groundwater model, reservoir sedimentation, water quality and global ranking can be included in the model. Two particular cases are available in global parameters: 1) the situation of unlimited groundwater in catchments without groundwater model; and 2) the case to subtract area of irrigation users and reservoirs from catchment area to calculate runoff. Runoff from catchments to river nodes can either be included from input time series or from the calculation of precipitation and catchment characteristics.

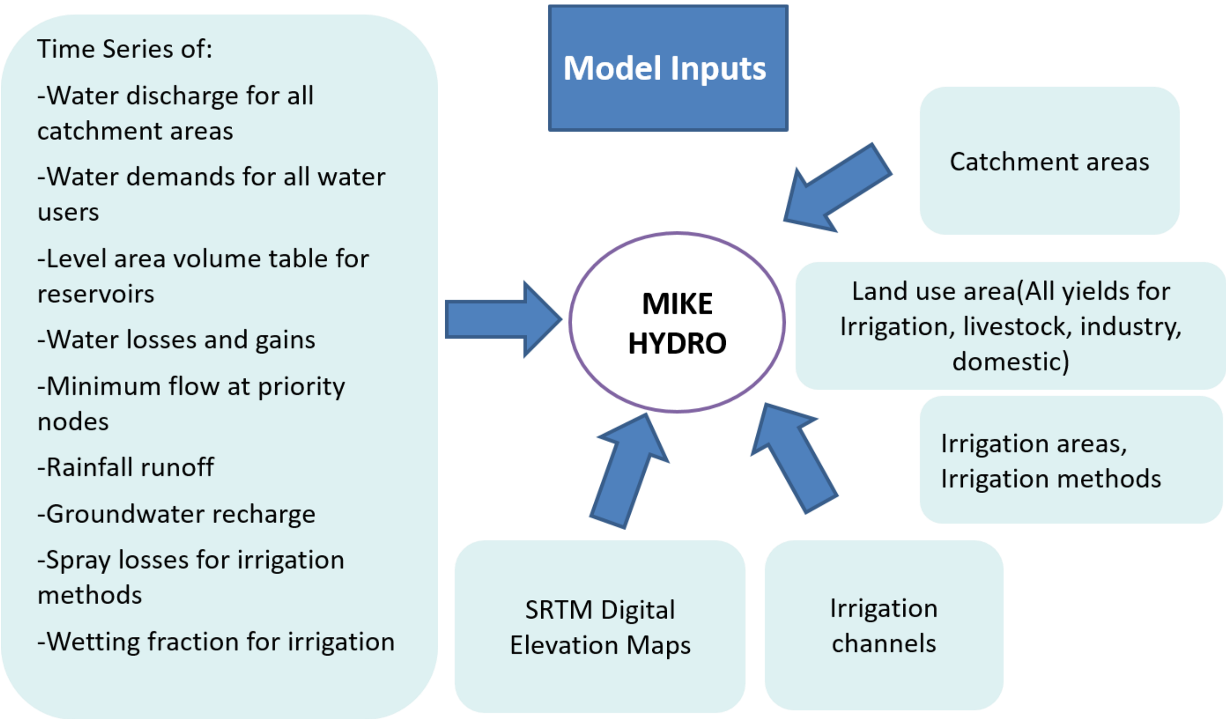



**Figure 3.3:** MIKE HYDRO model inputs.

In the coordinate system, the map view coordinate system have three different choices: no projection, map projection and Sphere Mercator required for Google map. In a realistic project, a visible background map shall always be considered useful. Under the usage of a DEM (Digital Elevation Model) file, a river network and the according catchments could be generated automatically. The DEM file could either be created by the user or acquired online. In the Time step control page, time step length can be chosen from seconds, minutes, hours, days, months and years. Stochastic analysis is offered if the simulation is to be reset to initial conditions yearly. Frequency update for the reservoir surface storage curve is specified by the number of time steps between updates. After including the input parameters and time series, sub-catchments can be established in the model map view (Figure 3.4).

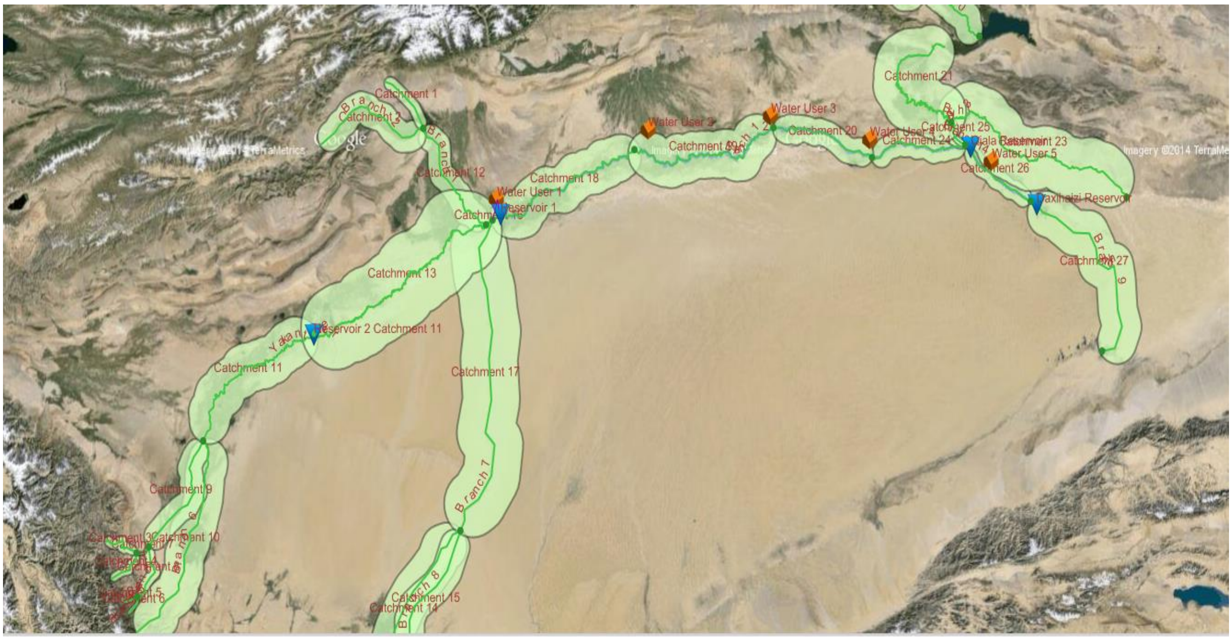



**Figure 3.4:** Sub-catchments in the entire Tarim River Basin in MIKE HYDRO.

Typical MIKE HYDRO Basin applications include: 1) integrated water resources management model; 2) solve multi-sector water allocation problems; 3) improve reservoir and hydropower operations; 4) conduct transparent water resources assessments; and 5) evaluate irrigation scheme performance and crop yield.

It is possible to import river branches from shape files, but digitizing the river branch is indispensable. A river has to be digitized from upstream to downstream. The exact positions of the river branches are not important, as it cannot affect the simulation, nor the properties of the model. To define the properties of a branch or a river node, the interface should be changed from map view to properties view. In the general definitions, the branch name, start chainage and flow direction need to be specified. In the properties page of river nodes, it is optional to add flow loss time series, flow capacity time series, bifurcation time series and bifurcation table into the model. The river nodes has been divided into two types: the regular type, and the catchment type (DHI, 2014).

The study area of mainstream Tarim River starts from Alar and ends at Taitema Lake. The area is characterized by an extremely arid desert climate with low precipitation and high evapotranspiration. The average annual temperature ranges from 10.6°C to 11.5°C and precipitation from 17.4 to 42.0 mm. The monthly mean temperature ranges from 20°C to 30°C in July (Chen et al., 2009). In this arid region, the annual reference evapotranspiration may reach 3,000 mm and is relatively high in July and August. Because of the region's dryness, no overland flow is produced at the alluvial plains of the mainstream. Peak flows, caused by melting glacier water in the upper mountain areas of the Tarim River Basin, occur in July, August and September. River discharge data is collected from four gauging stations (Alar, Xinqiman, Yingbaza and Qiala) and are shown in Figure 3.5.

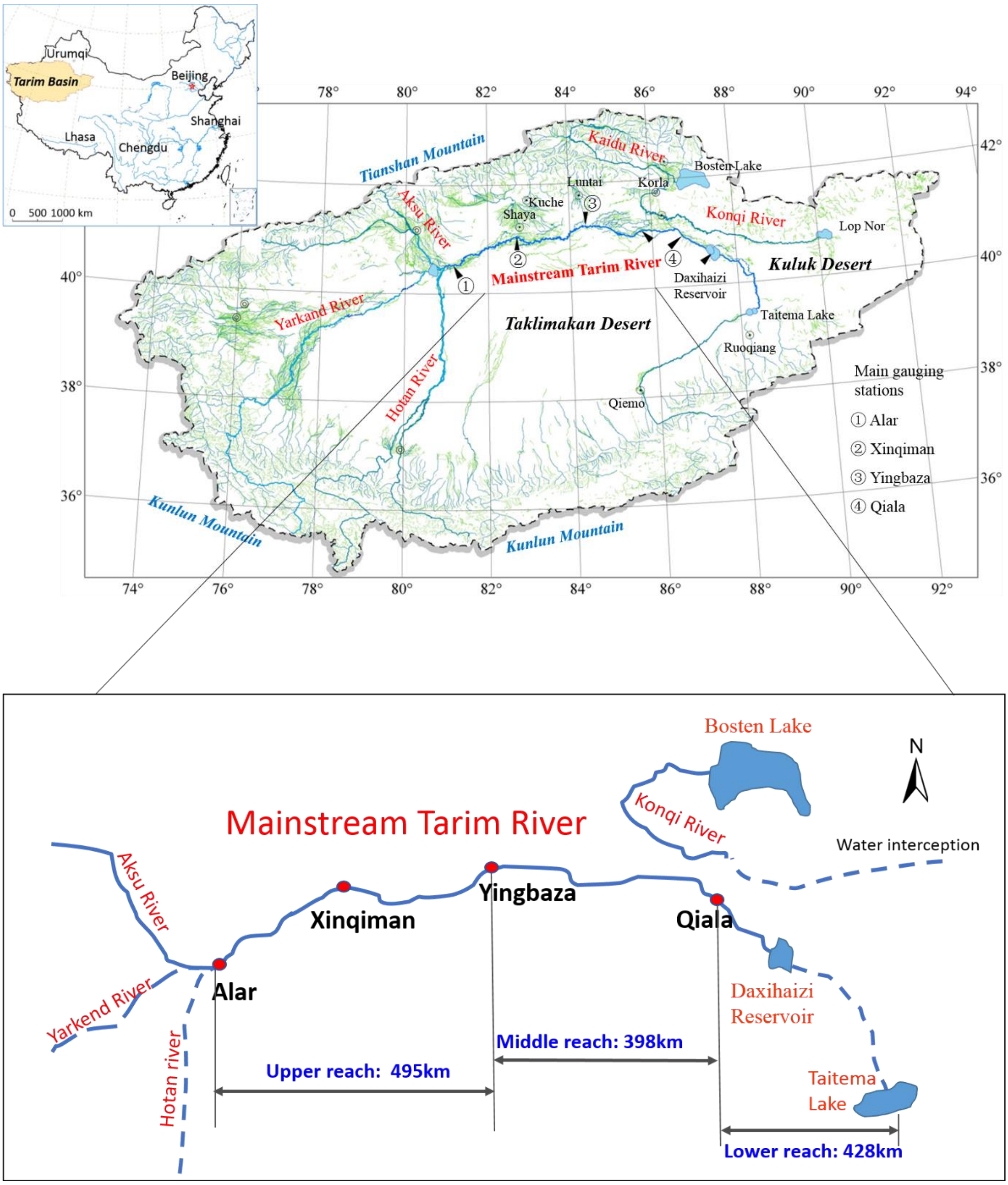



**Figure 3.5:** Tarim River Basin and mainstream gauging stations.

Discharge in the lower reaches has a significant drop from the 1970s, due to overexploitation of water resources in the upper and middle reaches of the river basin. However, since the Tarim River Basin comprehensive management project funded by the Chinese central government was initiated, this decline has reversed during the past decade. The increasing availability of water has had a positive effect on the recovery of the "Green Corridor" in the lower reaches (Xu et al., 2008). However, water scarcity still remains a critical problem in this arid region.

## 3.3 Model setup

This section describes the development of the large-scale hydrological model for the mainstream of the Tarim River, including definition of the four sub-catchments, routing method, calibration of monthly data from three gauging stations, and seven crop modules established in MIKE HYDRO as the basis for irrigation scenarios.

### 3.3.1 Sub-catchments and key modules in MIKE HYDRO model

The basin was divided into four sub-catchments (Figure 3.6), namely Alar-Xinqiman (A), Xinqiman-Yingbaza (B), Yingbaza-Qiala (C), and Qiala-Taitema Lake (D). The sub-catchments were separated by the gauging stations in Figure 1. In each sub-catchment, the parameters were aggregated in an effort to simplify the overall analysis. In the mainstream Tarim River, the upper, middle and lower reaches extend from Alar to Yingbaza, Yingbaza to Qiala and Qiala to Taitema Lake, respectively.

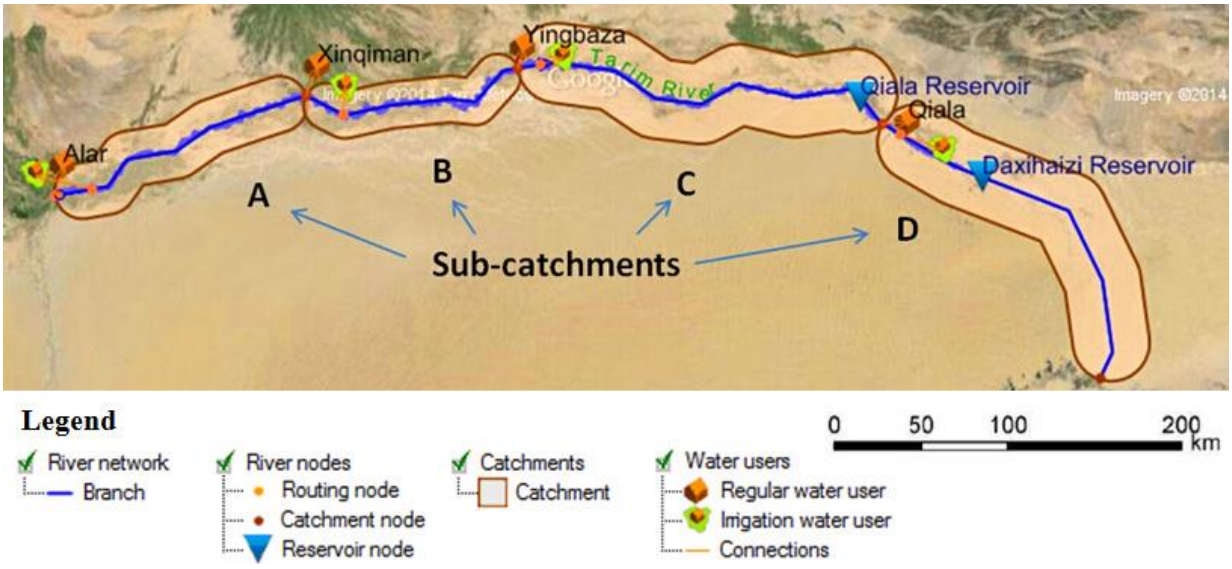



**Figure 3.6:** Sub-catchments in the mainstream of Tarim River in MIKE HYDRO.

River nodes, branches, catchments, reservoirs, water users and their connections were all specified in a network model. MIKE HYDRO contains modules for climate, soil, crop irrigation, overland and channel flow (Table 3.1), and exchange between aquifer and rivers ( river leakage and groundwater pumping). To simulate the conjunctive use of surface and ground water, a commonly used three-dimensional groundwater model MODFLOW was established to provide initial conditions and variance of groundwater movements. Simulation results of MODFLOW provide initial water level and groundwater recharge to the MIKE HYDRO model. Afterwards, the consumption and interaction from surface water and groundwater were simulated in MIKE HYDRO groundwater module. Groundwater interacts with the surface water via groundwater recharge, groundwater discharge and seepage from river, reservoirs, irrigation fields and channels. When the water table of the shallow aquifer reaches the land surface, it starts to spill directly into the river. Additionally, groundwater from the deep aquifer can be pumped by water users. The reason for the outsourcing of groundwater level and recharge is because it can largely reduce model complexity and computational time while keeping the same level of simulation accuracy.

**Table 3.1:** Key modules in MIKE HYDRO model.

| Modules | Why included in the model | Descriptions |
|---|---|---|
| GW module | GW supply for riparian forest and irrigation water use, keep water balance | Simplified one-layer GW model, initial water level and GW recharge input from MODFLOW |
| Surface routing | Determine downstream surface flow | Muskingum routing, Manning's method for water lever calculation |
| Water users | Illustrate water consumption, keep water balance | Irrigation water users and regular water users |
| Crop module | Large farmland areas, considerable differences of water consumption among different crops | FAO dual crop coefficient model |
| Soil module | Crop growth dependent on soil moisture, soil properties effect evapotranspiration and deep percolation | FAO 56 soil model, 9 soil types including sandy loam as the largest share |
| Climate model on the field | Influence on crop water demand and water balance | FAO 56 climate model, Penman-Monteith for evapotranspiration |
| Reservoir | Influence on flow hydrograph, irrigation water supply, and water losses | Rule curve reservoirs, level-area-volume table, characteristic levels time series |

Groundwater interacts with the surface water via groundwater recharge, groundwater discharge and seepage from the river, reservoirs and connections (Figure 3.7). Muskingum routing is applied in the surface routing method, with a delay parameter K and a shape parameter X specified in the calibration period. Manning's method is an approximation approach for calculating water level under the assumption of steady-state flow. With low precipitation in the study area, water level would not usually be changed rapidly, and thus the method is supposed to be able to provide reasonable estimations.

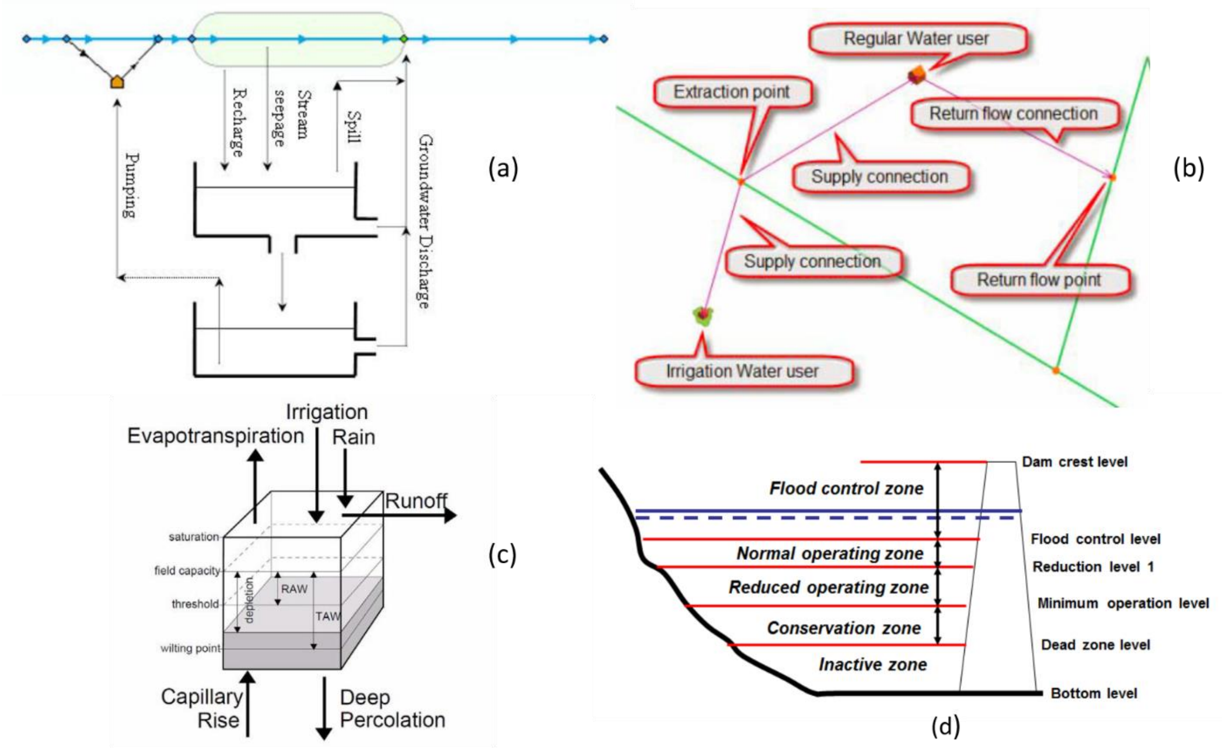



**Figure 3.7:** Key modules (DHI, 2014) (a) Conceptual structure of the groundwater component (b) Illustration of water users connected to the river network through supply connections and return flow connections (c) Soil conditions under soil moisture stress (d) Operation zones in a rule curve reservoir.

Two types of water users are considered by the model: (i) irrigation water users (e.g. cotton, wheat and tomatoes), in which crop, soil and climate modules are specified, (ii) regular water users, in which water consumptions from domestic, industrial, livestock and riparian forest are counted. Each irrigation water user was assigned with one irrigation field wherein different irrigation methods, crop modules and soil types were specified.

The FAO 56 dual crop coefficient model calculates the soil evaporation and crop transpiration separately, and thus allows for a more accurate quantification of the consequences of using different irrigation technologies (DHI, 2014). TAW (total available water) is defined as the volume of water contained in the root zone at field capacity. RAW (readily available water) is the volume of water that can be transpired without exposing the crop to soil water stress.

In a rule curve reservoir, all water users are drawing water from the single physical storage. Dam crest level is the highest water level in the reservoir before spill occurs, and dead zone level is the minimum level from which water can be utilized. Below dead zone level, water can only be lost due to evaporation and bottom infiltration. Reservoirs simulate the performance of different operating policies using associated operating rule curves, which play an important role in reducing peak flow and increasing low flow in the calibration period.

On each irrigated field, a crop sequence was characterized by a crop, sowing date and reference to the irrigation method used to irrigate the crop. A crop sequence lasted until the end of the previous growth stage. For each regular water user, a water demand time series was specified to represent the total amount of water required to fulfil domestic and ecological water demand in each sub-catchment. If it is allowed to have a water use deficits to be fulfilled in the next time step, then the demand carry-over fraction should be considered. In this case, some water demand in the current time step is going to have a compensation in the next time step. Furthermore, if groundwater is included in the model, then several rules should be specified containing groundwater options, supply catchment, groundwater fraction use time series and groundwater absolute use time series. The initial water table determines the magnitude of the groundwater discharge and the available water for pumping in the initial period of simulation. The groundwater outlet depth determines the storage capacity of the shallow aquifer and the storage capacity available for baseflow generation in the deep aquifer. For shallow aquifers the water table can vary between the outlet depth and ground surface (DHI, 2014).

In this hype-arid environment, crops need to resist high water stress and soil salinization problems. Particularly, cotton is reasonably tolerant of drought and soil salinity. The soil type is mainly aeolian sand soil in most regions of the Tarim River Basin. In the middle and lower reaches, the Qiala and Daxihaizi reservoirs were included to simulate the performance of operating policies using operating rule curves. Since both reservoirs had significant surface areas, evaporation and infiltration of reservoirs were factors important to water balance calculations. Data for parameterization in the reservoirs were acquired and sorted by Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS).

### 3.3.2 Muskingum routing

The Muskingum method is a commonly used hydrologic routing method in situations requiring a variable storage-discharge relationship (Chow et al., 1988). The Muskingum method models the storage volume of flooding in a river channel using a combination of wedge and prism storage. The key parameters in Muskingum routing are K (travel time) and X (weighting coefficient). The value of X depends on the shape of the wedge storage, and ranges from 0 for reservoir-type storage to 0.5 for a full wedge.

The Muskingum method assumes that water surface in the reach is a uniform continuous surface profile between upstream and downstream ends of the section. It also assumes that K and X are constant through the range of flows (Veissman and Lewis, 2003). The Muskingum parameters K and X are best derived from streamflow measurements. In natural rivers, X has a value between 0 and 0.3 with a mean value of 0.2. Greater accuracy in determining X may not be necessary because the results are relatively insensitive to the value of this parameter. In this MIKE HYDRO model of the Tarim River, X was chosen to be 0.2. The measured K values are shown in Table 3.2.

**Table 3.2:** Muskingum routing parameter K for sub-catchments.

| Mainstream | Upper reach | | Middle reach | Lower reach |
|---|---|---|---|---|
| Sub-catchments | A | B | C | D |
| River length (km) | 189 | 258 | 398 | 428 |
| K (hour) | 51 | 86 | 158 | 198 |

### 3.3.3 Crop Factors and growth stages

The FAO56 Dual Crop Coefficient method (in which crop transpiration and soil evaporation are separately calculated to achieve more precise predictions of crop evapotranspiration than the single crop coefficient approach) applied in the model concerns the parameters to be assigned to each crop. Those parameters included the share of the total irrigated area devoted to crops, number of sowing days for each crop, root depth (RD), maximum height (MH), basal crop coefficient ($K_{cb}$) and length (days) of the growing stage for each crop (Figure 3.8). Growing stages were categorized as follows: initial stage (INI), development stage (DEV), mid-season (MID) and late season (LAT).

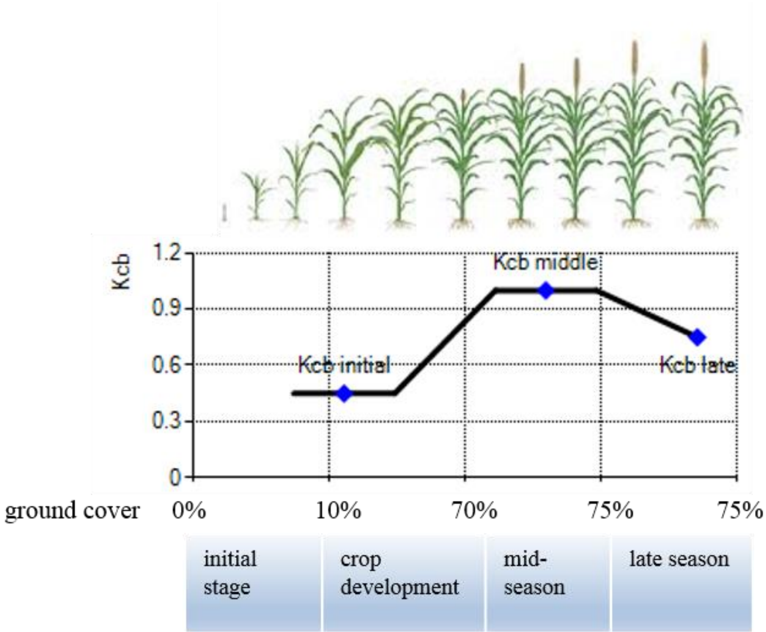



**Figure 3.8:** Crop growth stages in MIKE HYDRO model.

The initial stage is the period from sowing or transplanting until the crop covers about 10% of the ground. The crop development stage starts at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70-80%); it does not necessarily mean that the crop is at its maximum height. The third crop growth stage is mid-season stage. This period starts at the end of the crop development stage and lasts until maturity, which includes flowering and grain-setting. The late season stage starts at the end of the mid-season stage and lasts until the last day of the harvest (FAO, 1986).

Seven crop modules were established in MIKE HYDRO based on field surveys and statistical data (Table 3.3).

**Table 3.3:** Crop factors in study area. RD (mm), MH (m), and $K_{cb}$ values were based on a FAO publication written by Allen et Al. (Allen et al., 1998), with little adjustment based on field surveys of the study area.

| Crops | RD (mm) | MH (m) | $K_{cb}$ INI | $K_{cb}$ MID | $K_{cb}$ LAT |
|---|---|---|---|---|---|
| Wheat | 1500 | 1 | 0.4 | 1.2 | 0.5 |
| Maize | 1700 | 2 | 0.4 | 1.2 | 0.7 |
| Sugarbeet | 1200 | 0.5 | 0.5 | 1.2 | 0.8 |
| Bean | 700 | 0.4 | 0.4 | 1.1 | 0.9 |
| Melon | 1500 | 0.4 | 0.5 | 1 | 0.8 |
| Cotton | 1700 | 1.5 | 0.5 | 1.2 | 0.8 |
| Tomato | 1500 | 0.6 | 0.5 | 1.2 | 0.8 |

Parameterization was based on the average values of the irrigated fields in the sub-catchments. $K_{cb}$ was defined as the ratio of crop evapotranspiration over the reference evapotranspiration when soil surface is dry. $K_e$ was defined as the ratio of soil evaporation. In the initial MID and LAT stage, $K_{cb}$ was assumed to be constant and follow a linear variation between INI and MID. The relationship of reference evapotranspiration ($ET_o$), crop evapotranspiration ($ET_c$) and actual evapotranspiration ($ET_a$) is given in Equation (3.10) and Equation (3.11) as follows.

$$ET_c = (K_{cb} + K_e) \times ET_0 \tag{3.10}$$

$$ET_a = K_s \times ET_c \tag{3.11}$$

where $K_S$ is the water stress coefficient that describes the effect of water stress on crop transpiration and was determined in MIKE HYDRO by considering soil water availability in the irrigated field (Allen et al., 1998). There are a number of models to compute reference evapotranspiration, such as Hargreaves and Samani model, Jensen Haise model, Trajkovic model, Priestley-Taylor model. Due to the higher performance of the FAO-56 Penman-Monteith method, $ET_o$ was computed from meteorological data by Penman-Monteith model. $ET_c$ was calculated from the crop module, which was influenced by the determination of crop factors. $ET_a$ was generated from MIKE HYDRO, which identified the actual rate of crop evapotranspiration under the effects of soil water stress. Due to the rising temperature in recent years, $ET_o$ would be increased by climate change. $ET_c$ is influenced by different crop growth. $ET_a$ is determined by considering water stress. In the hyper-arid region, reliable crop production based on rainfall is not possible, and irrigation is thus essential to reduce water stress in the soil. Crop shares and sowing days in 2006 (Table 3.4) were collected from Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS).

**Table 3.4:** Crop growth stages in study area. Data on the share (%) and sowing day were collected from the CAS.

| Crops | Share (%) | Sowing day | Length (days) | | | |
|---|---|---|---|---|---|---|
| | | | INI | DEV | MID | LAT |
| Wheat | 2.7 | 03.21 | 15 | 25 | 40 | 20 |
| Maize | 1.6 | 04.16 | 20 | 25 | 60 | 15 |
| Sugarbeet | 5.1 | 03.26 | 25 | 35 | 60 | 45 |
| Bean | 1.7 | 04.21 | 20 | 30 | 30 | 10 |
| Melon | 2.1 | 04.01 | 25 | 35 | 40 | 20 |
| Cotton | 82.6 | 04.21 | 25 | 45 | 50 | 40 |
| Tomato | 2.1 | 04.11 | 35 | 40 | 50 | 25 |

The sowing days for the crops differs each year due to weather conditions in the study area. Wheat refers to spring wheat in the crop module. Watermelon and muskmelon were considered in the same category as melons. Cotton is the dominant crop in the sub-catchments, representing 82.6% of the total irrigated area. Maximum RD of cotton depend largely on soil temperature and moisture condition. Soil salinity affects crop development, crop transpiration and, hence, biomass production and harvestable yield. Water in the root zone becomes less available for root extraction when salts build up in the soil profile (Steduto et al., 2012). However, due to data scarcity, soil salinity was not simulated in the model. In some cases, the cotton root of cotton may reach a depth of 2.2 m to obtain water. After a few tests in the MIKE HYDRO model, the simulation results were not sensitive to the variance of RD around the average level, and thus it was regarded as a reliable method for determining average values in the module. Furthermore, Chinese jujube is also widely cultivated in the study area. However, it does not fit into a standard crop module because fruit trees usually need multiyear growth and their water demand is largely different from most crops. Therefore, in the model, jujube was considered to be a regular water user rather than an irrigation water user. A number of other fruits were also taken as regular water users in the model, water consumptions were monthly values in each water user module.

### 3.4 Discharge and calibration

The MIKE HYDRO model for the main stem Tarim River was calibrated manually for stream flow using monthly data from 2006 to 2008. The aim of the calibration was to input discharge data to investigate water allocation scenarios, rather than input climate data to investigate river discharge. Therefore, rainfall-runoff model was not essential in the calibration scheme and there were no future predictions. Calibration was mainly conducted on water losses. Evaporation, seepage losses and soil porosity are optimized values in the model calibration. All these three parameters did not possess very large influence on the stream flow. Evaporation data was computed from meteorological data by FAO-56 Penman-Monteith method. Since the climate data was only acquired from Alar meteorological station, the evaporation data along the main stem Tarim River was given a range of 95%–105% for calibration. The calibrated values of evaporation varied slightly different from year to year, and from sub-catchment to sub-catchment. Based on the information collected from the study area, seepage losses were within a range from 0.0007 to 0.0011 by the fraction of seepage losses from stream flow. The fractions of seepage losses were acquired from hydraulic engineering projects in the 21$^{st}$ century, to increase water transport efficiency by a set of repair and reinforcement projects on river courses, banks, canals and reservoirs. The calibration results were 0.0007 for all the sub-catchments. Soil porosity was another modified parameter during the calibration. Different types of soil (sand, loam, clay, etc.) possessed different ranges of porosities, and the calibrated values varied slightly in different sub-catchments.

The simulation period was not enough to cover the extreme climate situations. Because river discharges of the mainstream were around the annual average level in 2006–2008 (Figure 3.9), the simulation results did not take into account the extreme arid years (e.g., in 2009, discharge in the main stem was less than half of the annual average discharge). Since the simulation results were not mainly dependent on climate conditions, as long as it was not an extremely dry year, the study would be suitable for applications in other cases. Since the aim of this lumped MIKE HYDRO model is to simulate water balance and management scenarios along the mainstream of Tarim River, so the accuracy of the model is essential. For this reason, discharge in Alar was directly used as input discharge into the model. Water balance was calculated from upstream to downstream of the river.

The observed data from Xinqiman, Yingbaza and Qiala stations were applied for model calibration.

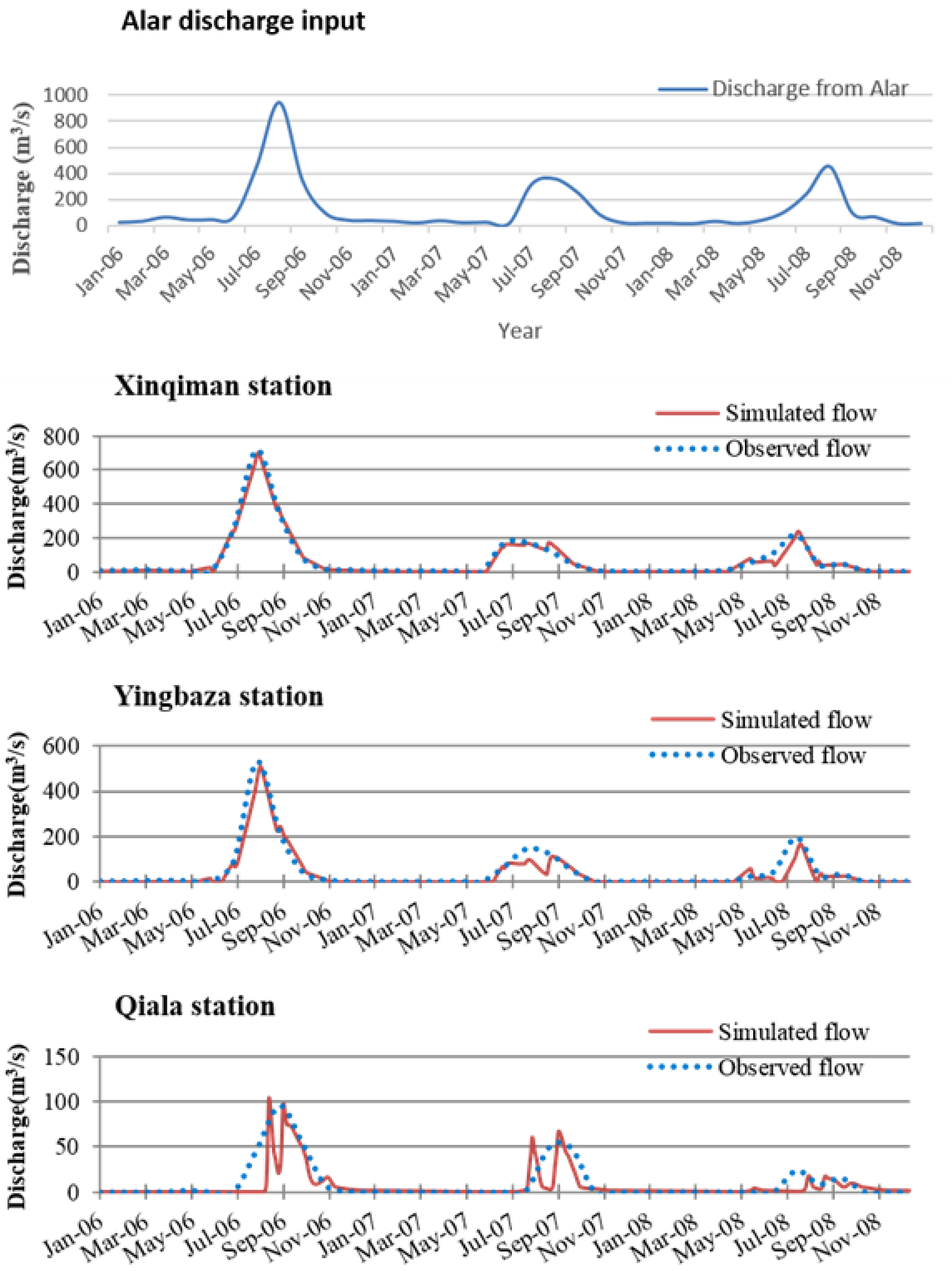



**Figure 3.9:** Input discharge from Alar and calibrated discharges from three gauging stations: 2006–2008.

The model adequately reproduced the patterns of observed discharges and their magnitudes, although the simulated flow was underestimated. The reason of this underestimation likely resulted from the absence of groundwater in the lumped MIKE HYDRO model, which will be improved in the distributed MIKE HYDRO model in the next chapter. Groundwater is pumped for irrigation in the study area. Since the 1980s, the water table has annually declined at a rate of 20 cm, attributable to increases in water resources development and utilization (Feng et al., 2001). In the model, groundwater use was not considered and irrigation was supplied entirely by the surface water. Consequently, the curve for simulated flows would experience an obvious reduction during the crop-growing season compared with that for the observed flow. The simulated peak flow at the Qiala station was lower than the observed flow. Presumably, it was caused by the pumping water from Boston Lake, which increases flows in the lower reach. The influence of this water transfer was evaluated by Xu et al., who concluded that the conveyance of water to the lower reach of the Tarim River has a positive effect on local agricultural development and the river ecosystem (Xu et al. 2008).

NAM automatic calibration was also conducted in the model (Table 3.5), but due to high evapotranspiration and low precipitation, it was assumed to have no effect on the stream flow.

**Table 3.5:** Important parameters for NAM automatic calibration.

| NAM Parameters | Parameter Descriptions | Units | Value Ranges | Calibrated Values |
|---|---|---|---|---|
| Umax | Maximum water content in surface storage | mm | 10–20 | 17.79 |
| Lmax | Maximum water content in root zone storage | mm | 100–300 | 166.25 |
| CQOF | Overland flow runoff coefficient | - | 0.1–1 | 0.51 |
| CKIF | Time constant for routing interflow | h | 200–1000 | 533.28 |
| CK1 | Time constant 1 for routing overland flow | h | 10–50 | 22.98 |
| CK2 | Time constant 2 for routing overland flow | h | 10–50 | 10 |
| TOF | Root zone threshold value for overland flow | - | 0–0.99 | 0.56 |
| TIF | Root zone threshold value for interflow | - | 0–0.99 | 0.53 |
| TG | Root zone threshold value for groundwater recharge | - | 0–0.99 | 0.03 |
| CKBF | Time constant for routing base flow | h | 1000–4000 | 2179.01 |
| CQLOW | Lower base flow, recharge to lower reservoir | percentage | 0–100 | 0 |
| CKLOW | Time constant for routing lower base flow | h | 1000–30,000 | 10,000 |

To examine the hypothesis on the rainfall-runoff and the sensitivity of NAM parameters, the inflows into Qiala Reservoir were tested in the model (Figure 3.10). The first trial was conducted with NAM parameters on the left bound (minimum values), and the comparison trial was simulated by the calibrated NAM parameter values. Results indicated that there were almost no difference between the inflows, which means the

NAM parameters are not sensitive at all to the surface runoff. This phenomenon corroborated the theory that because of the region's aridity, no overland flow was generated from rainfall in the study area.

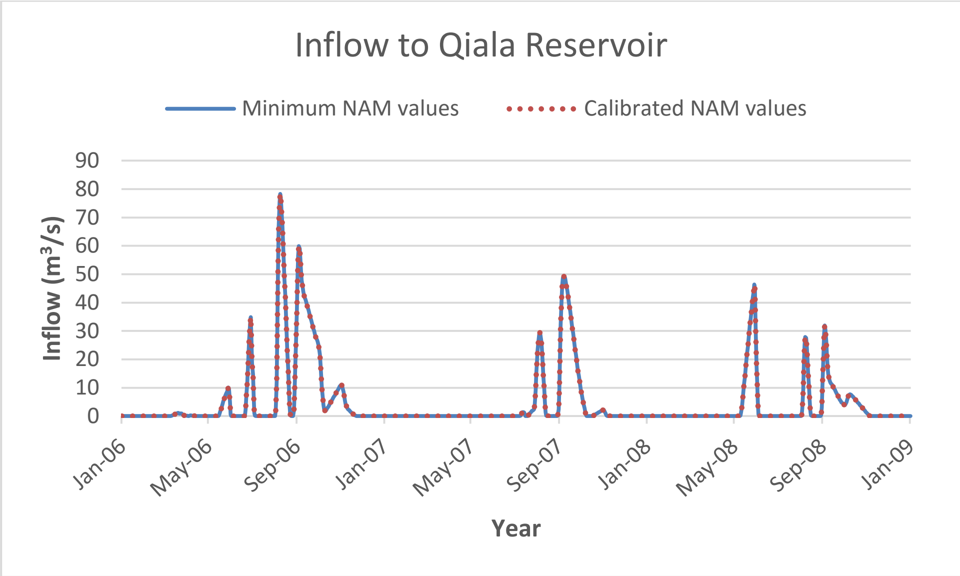



**Figure 3.10:** Inflows into Qiala Reservoir with minimum and calibrated NAM values. A testify of negligible rainfall influence on the runoff in the research area.

To quantitatively evaluate the performance of the model calibration, four error indices were considered: (a) the Nash-Sutcliffe efficiency (NSE); (b) the root mean square error (RMSE); (c) the RMSE-observations standard deviation ratio (RSR); and (d) the % Bias. NSE is defined in Equation (3.12) and compares the relative magnitude of squared residuals to the variance of the observed flow (Nash and Sutcliffe, 1970). RMSE in Equation (3.13) is used to examine the square root of the mean squared difference between the observed and simulated flows. RSR standardizes RMSE using the standard deviation in the observations (Legates and McCabe, 1999) in Equation (3.14). The % Bias is given in Equation (3.15) to assess the values of residuals to the observed flow from the gauging stations.

$$NSE = 1 - \frac{\sum_{t=1}^{t=n}[(Q_{\text{sim}})_t - (Q_{\text{obs}})_t]^2}{\sum_{t=1}^{t=n}\left[(Q_{\text{obs}})_t - \overline{Q_{\text{obs}}}\right]^2} \tag{3.12}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{t=n}[(Q_{\text{sim}})_t - (Q_{\text{obs}})_t]^2} \tag{3.13}$$

$$RSR = \frac{RMSE}{\sqrt{\frac{1}{n}\sum_{t=1}^{t=n}\left[(Q_{\text{obs}})_t - \overline{Q_{\text{obs}}}\right]^2}} \tag{3.14}$$

$$\% \, Bias = \frac{\sum_{t=1}^{t=n}[(Q_{\text{sim}})_t - (Q_{\text{obs}})_t]}{\sum_{t=1}^{t=n}(Q_{\text{obs}})_t} \times 100 \tag{3.15}$$

where $Q_{\text{sim}}$ is the simulated discharge ($m^3/s$), $Q_{\text{obs}}$ is the observed discharge ($m^3/s$), $\overline{Q_{\text{obs}}}$ is the mean observed discharge ($m^3/s$) and n is the number of observations, with time intervals t.

The statistical performances from Table 3.6 could be considered satisfactory compared to the model evaluation guidelines by Moriasi et al. (Moriasi et al., 2007). The simulated discharges were very similar to the observed discharges from the gauging stations, especially the Xinqiman and Yingbaza stations in the upper and middle reaches. Because the efficiency coefficient was sensitive to extreme values, the high values of the NSE (0.88, 0.86 and 0.92) indicated a good match of simulated and observed discharges during flood seasons. RMSE values at the Xinqiman and Yingbaza stations were acceptable in light of the high discharges at both stations. RSR standardizes RMSE by including the standard deviation of the observations, and both values represented good ratings. The increasing tendency of the % Bias from upstream to downstream could be attributed to the absence of groundwater discharge and the pumping of water near the Qiala station. If daily values rather than monthly values are used, it is likely that the calibration would have a lower performance. However, daily time series for the calibration of river flows are not available.

**Table 3.6:** Evaluation of calibration performance for three gauging stations: 2006–2008.

| Gauging Stations | NSE | RMSE ($m^3/s$) | RSR | % Bias |
|---|---|---|---|---|
| Xinqiman | 0.88 | 14.7 | 0.11 | −2.41 |
| Yingbaza | 0.86 | 11.53 | 0.12 | −3.42 |
| Qiala | 0.92 | 3.58 | 0.10 | −8.24 |

The model was lacking of validation mainly because of data limitation. This problem would have influence on the accuracy of the model, especially on the river discharge, evaporation and seepage losses. Consequently, the model could not provide reliable quantitative time series data on water losses, but as long as the qualitative effects and the mutual influences of the four sub-catchments were still valid, simulation results on the water consumption and allocation would be reliable. Furthermore, since river discharge data in the model was not generated from rainfall-runoff model, and no future predictions were made by the MIKE HYDRO model, the accuracy of the simulation results would not be largely affected by the absence of validation. Other authors have also experienced similar difficulties when monitoring data were limited (Girolamo and Porto, 2012; Molina-Navarro et al., 2014). The validated model will be presented in Chapter 4, with daily discharge input, distributed farmlands and water abstractions.

## 3.5 Model scenarios

In the research area, water-saving and farmland reduction are hot topics of water and land management in recent years. Based on recent trends in agricultural practices, different scenarios were developed. The proposed scenarios were designed to provide stakeholders and decision makers with improved insight into water scarcity and solutions for agricultural water allocation.

### 3.5.1 Total Available Water (TAW) scenarios

When calculating the soil-water balance, the amount of water stored in the root zone can be expressed as an equivalent water depth (Wr) or as root zone depletion (Dr). TAW is the amount of water that a crop can extract from its root zone. Its magnitude depends on the soil type and rooting depth. The water content above field capacity cannot be held against the forces of gravity and will drain out because the water content below the wilting point cannot be extracted by plant roots. Accordingly, TAW in the root zone is the difference between the water content at field capacity and the wilting point. At field capacity, Dr is zero and at the permanent wilting point Dr is equal to TAW (Allen et al., 1998).

The design of the TAW scenarios assumed that irrigation starts when soil moisture content reaches the specified fraction of TAW. From TAW = 0.7 to TAW = 0.1, seven scenarios were investigated to show the yield performance by different crops. As crop yield declined with the decrease of TAW, the primary purpose of the scenarios was to find the suitable fraction of TAW for each crop at which less water is consumed while maintaining a relatively high crop yield.

Irrigation is essential for stabilizing and increasing crop yields. Stewart (Stewart et al., 1977) derived the relationship between the decrease in relative yield and the relative evapotranspiration deficit. The water use-yield relationship was determined using Equation (3.16).

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\ (1-\frac{ET_a}{ET_c}) \tag{3.16}$$

where $Y_a$ is the actual harvest yield (t/ha), $Y_m$ is the maximum harvest yield (t/ha) and $K_y$ is the yield response factor representing the effect of reduction in evapotranspiration on lost yield. $K_y$ values were obtained from FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979).

### 3.5.2 Water-saving irrigation scenarios

Water-saving irrigation (Figure 3.9) is a watering strategy that can be applied by different types of irrigation application methods. The correct application of water-saving irrigation requires thorough understanding of the yield response to water (crop sensitivity to drought stress) and of the economic impact of reductions in harvest (English, 1990). In regions where water resources are restrictive it can be more profitable for a farmer to maximize crop water productivity instead of maximizing the harvest per unit land (Fereres and Soriano, 2007). Plastic (ecological) mulch is also commonly used for saving water. The saved water can be used for ecological water or other purposes.

**Figure 3.11:** Water-saving with drip irrigation under mulch.

In the study area, the implementation of water-saving irrigation is developing rapidly by the method of drip irrigation under mulch (DIUM). By applying DIUM method in the irrigation fields, spray loss (SL) and wetting fraction (WF) will be significantly reduced compared with sprinkler irrigation. SL corresponds to the fraction of irrigation water that is evaporated before reaching the soil surface. WF determines the fraction of field surface being wetted during irrigation. SL and WF values are calculated from Equations (3.17) and (3.18):

$$SL = SL_{\mathrm{S}} \times \%SL_{\mathrm{S}} + SL_{\mathrm{D}} \times \%SL_{\mathrm{D}} \tag{3.17}$$

$$WF = WF_{\mathrm{S}} \times \%WF_{\mathrm{S}} + WF_{\mathrm{D}} \times \%WF_{\mathrm{D}} \tag{3.18}$$

where $SL_S$ is the SL for sprinkler irrigation, $SL_D$ is the SL for DIUM, $WF_S$ is the WF for sprinkler irrigation, $WF_D$ is the WF for DIUM. Each of these parameters is multiplied by its percentage applied in the irrigated fields. Only the sprinkler irrigation and DIUM methods were considered in this scenario. Consequently, the sum of $\%SL_S$ and $\%SL_D$ as well as the sum of $\%WF_S$ and $\%WF_D$ were set to be 1 (Figure 3.12).

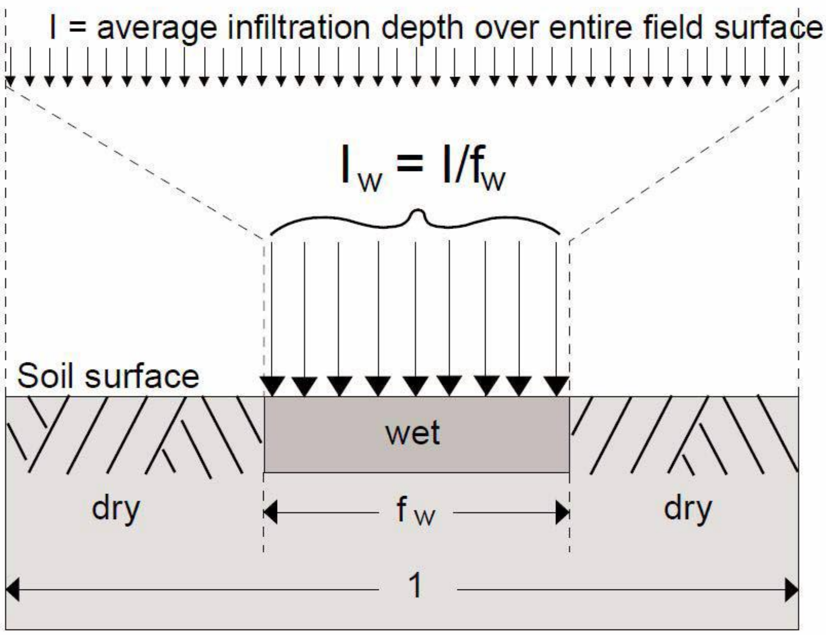



**Figure 3.12:** Illustration of the wetting fraction, where I and $I_w$ are the irrigation depth for the field and the irrigation depth for the part of the wetted surface, respectively, and $f_w$ is the fraction of the surface wetted by irrigation in the soil (DHI, 2014).

DIUM is mainly applied in the cotton fields where the ground surface was approximately 80% covered with transparent polythene film as mulch (Zia-Khan et al., 2014). SL is set to be 0.5 for sprinkler irrigation and 0.1 for DIUM in the model. WF is close to 1 in sprinkler irrigation and reduced to 0.1 for DIUM in MIKE HYDRO irrigation module (DHI, 2014).

Five water-saving scenarios were designed based on the percentage of DIUM applied in the total irrigated area, 10%, 30%, 50%, 70% and 100%, respectively. The primary goal of these scenarios was to investigate how much water could be saved by applying DIUM to the irrigated fields.

### 3.5.3 Land use scenarios

Three land-use scenarios were designed based on the information collected from farmers, surveys, interviews with decision makers in the region, and the Tarim River Basin water resources management ordinance in Xinjiang Uygur Autonomous Region. The ordinance was created by the local government for the sustainable management of water resources.

The impetus for these scenarios included eco-system protection, high prices of agricultural products and government regulations restricting agricultural water use in the Tarim River Basin. In each sub-catchment the hydrological features were lumped together, so the spatial distribution of land use within each sub-catchment was not considered.

The land use scenarios were considered among the sub-catchments. The three scenarios included the agricultural land use decrease scenario (LUD scenario), the land use increase scenario (LUI scenario) and crop type change scenario (CTC scenario). These scenarios were considered independently based on practical situations and local policies.

The LUD scenario reflects the government policy to restrict agricultural water use in the upstream, thus increasing free-flowing water for downstream areas. Under this scenario, approximately 20% of the agricultural land would be abandoned in sub-catchments A and B.

The LUI scenario assumes more available water in downstream areas resulting from new water conveyance projects in the lower reach (Xu et al., 2008). Under this scenario, the amount of new agricultural farmland in sub-catchment D would be increased by 20%.

The CTC scenario reflects the proposal for using less irrigation water by substituting different types of crops. Apocynum grows in the arid climate of Central Asia and provides an income for local people. It withstands higher levels of soil salinity and consumes less water than cotton (Thevs et al., 2012). Apocynum is used as a medicinal plant and a fiber crop. The leaves provide raw material for tea and the stems provide raw material for the textile and paper industries. The CTC scenario assumed that 20% of the cotton would be replaced by Apocynum in all the sub-catchments. Since cotton growth consumes a large amount of irrigation water, this CTC from cotton fields to Apocynum scenario is anticipated to be a water-saving approach.

## 3.6 Results and discussion

### 3.6.1 $ET_a$ and Deep Percolation (DP)

While $ET_a$ refers to the upward loss of water by the vegetated surface, deep percolation (DP) is defined as the downward movement of water through the soil profile beyond the root zone. The results of simulations for $ET_a$ and DP in the four sub-catchments are shown in Figure 3.13. $ET_a$ primarily occurs from June to September, while DP primarily appears in a shorter period from July to August. Compared with $ET_a$, the shorter period of DP may be due to low soil moisture, which restricts crop growth in this arid region (Ma et al., 2011). The rapid increase and decrease of DP at the beginning and end period indicates that DP mainly occurs when soil moisture reach a certain content. $ET_a$ conformed to DP in a slowly increasing trend from sub-catchment A to B and from B to

C. In sub-catchment D, both factors showed a dramatic drop, reflecting the water shortage in this lower reach (Thevs, 2011). The total $ET_a$ for 2006 in sub-catchments A–D was 666, 709, 864 and 190 mm, respectively. This reflected high water stress in the lower reach of sub-catchment D. The highest levels of $ET_a$ and DP both occurred in sub-catchment C during July. Irrigation water consumption was relatively high in this district. In the non-growing season, there was no $ET_a$ or DP. This finding was consistent with Yuan et al. (Yuan et al., 2014), who found that in the early and late stage of the dormancy period of vegetation, $ET_a$ was approximately zero, whereas the level of $ET_c$ was still large. Simulation results of $ET_a$ and DP reflect the yearly patterns of water losses in the fields.

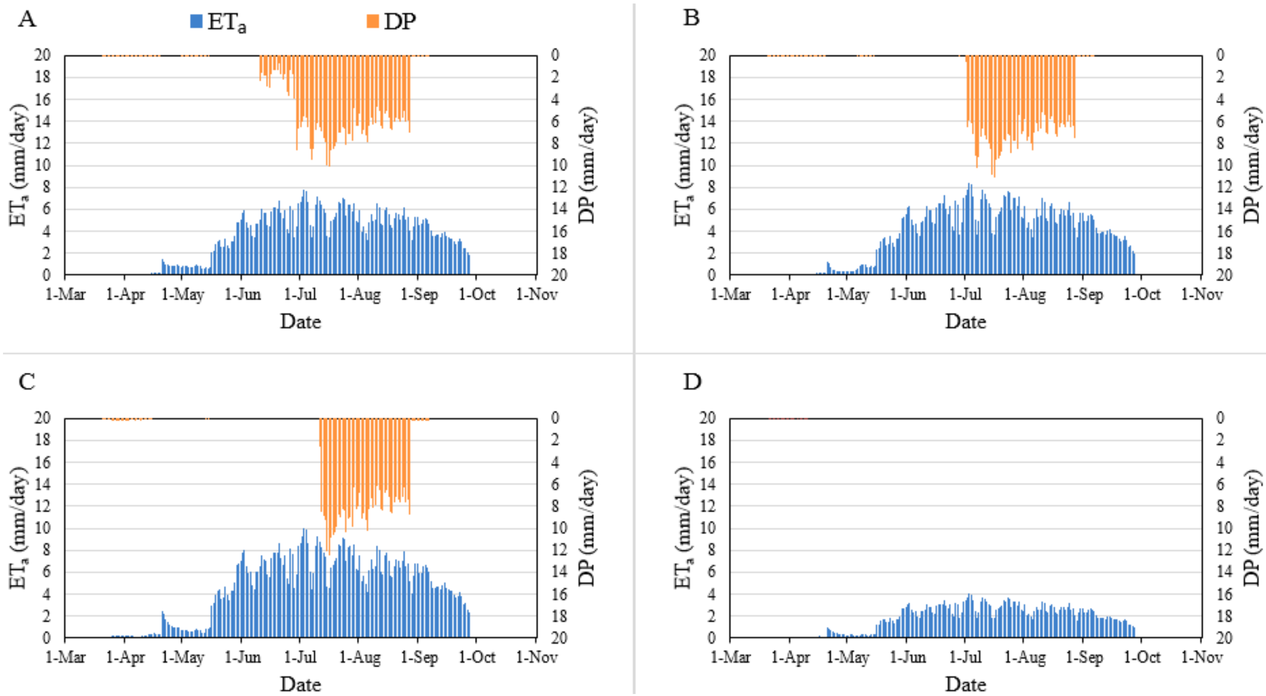



**Figure 3.13:** Actual crop evapotranspiration ($ET_a$) and deep percolation (DP) in sub-catchments A–D during the crop-growing season.

### 3.6.2 Results of scenarios

#### 3.6.2.1 Total Available Water (TAW) scenarios

Optimal crop production depends greatly on available soil water (Stričevič and Čaki, 1997). Analyzing crop yields for every crop type under the same conditions of water scarcity represents a sensitivity analysis. It shows the highly differing susceptibility of crop types to water stress.

Figure 3.14 demonstrates robustness in the performance of cotton yield with reductions in the fraction of TAW. The yield of ginned cotton dropped 6%, from TAW of 0.7 to TAW of 0.4. The yields of wheat and bean also showed robust performances when irrigation water was decreased. Crop yields in response to TAW were investigated beginning at 0.7, where none of the crops suffered a reduction in yield. At a TAW of 0.6, most crops maintained a relatively high yield without a rapid decrease, except for tomatoes. Nearly half of the tomato production was stopped due to lack of water at TAW of 0.4. This demonstrated that tomatoes should be considered only in areas where the supply of irrigation water is ensured. At the same level of TAW, the yield of maize, sugarbeet and melon suffered a significant decline. However, because cotton was the most important crop in the Tarim River Basin (Liu and Chen, 2006), its cultivation should be prioritized in areas where optimum conditions can be maintained. To maintain cotton production at relatively high levels, irrigation at a TAW level of 0.4 is recommended.

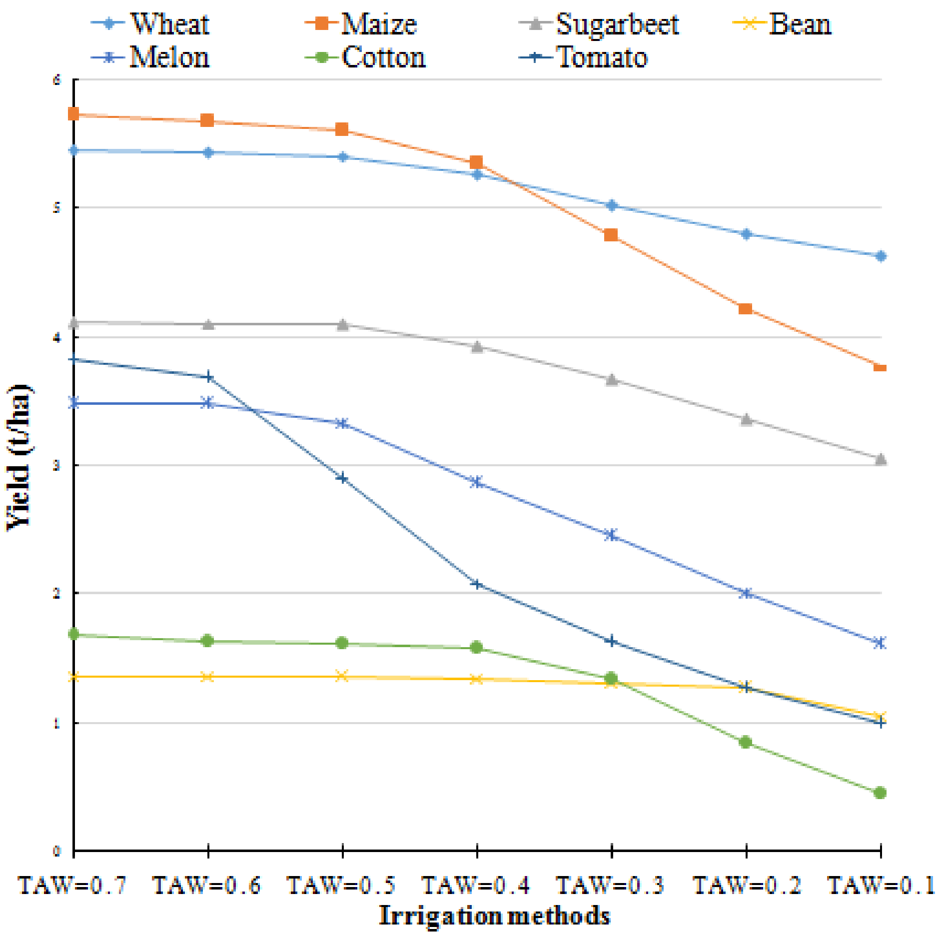



**Figure 3.14:** Irrigation scenarios based on fraction of Total Available Water (TAW). Average yield performance of crops showing in the whole irrigation field within three-year simulation period.

With the decrease of TAW fractions, irrigation period will be longer and irrigation frequency will be reduced. The longer the irrigation period is, the dryer the soil would be. It means total water demand would be less each year, and a possible reduction on crop yield. In the arid region, where water losses are intensive on the fields, the reduction of irrigation frequency can effectively save more irrigation water. For instance, large amount of irrigation water would be saved by reducing irrigation frequency from 5 times per month to 3 times per month. As long as crop production maintains a relatively high level, water use efficiency would be improved by reducing TAW fractions.

3.6.2.2 Water-saving irrigation scenarios

Spray loss (SL) and wetting fraction (WF) showed marked reductions with an increase in the percentage of DIUM applied in irrigated fields (Table 3.7), whereas water saving (WS) and reduction of water demand deficit (RWDD) showed positive effects. WS was only 6% and RWDD was only 5% when DIUM represented 10% of total irrigation. However, WS and RWDD increased to 40% and 30%, respectively, when the level of DIUM applied to all irrigated fields was 100%. This indicates the potential value of DIUM for saving water and reducing water deficits. Even when DIUM is at 50%, WS and RWDD reflected notable changes at 25% and 16%, respectively. When DIUM increased from 10% to 100%, SL decreased from 46% to 10% and WF reduced from 91% to 10%. This reflects the substantial benefits to water savings resulting from the application of these technologies. With increased application of DIUM on the farmlands, more irrigation water can be reduced. The saved water can be used to the ecological water and increase biodiversity for the ecosystem.

**Table 3.7:** Summary of five DIUM scenarios.

| % DIUM | % SL | % WF | % WS | % RWDD |
|---|---|---|---|---|
| 10 | 46 | 91 | 6 | 5 |
| 30 | 38 | 73 | 17 | 12 |
| 50 | 30 | 55 | 25 | 16 |
| 70 | 22 | 37 | 32 | 22 |
| 100 | 10 | 10 | 40 | 30 |

Results of modeling reveal that a considerable amount of water could be saved in with the introduction of water-saving irrigation. Considering the effort of applying DIUM on the irrigated fields, it was an arduous task to immediately raise the DIUM to 100%. However, even at DIUM of 70%, significant potential for saving water and reducing the water demand deficit exists. RWDD was slightly less affected than WS by the increase of DIUM. However, this abatement could result in a crucial change in water scarcity, with the highest value of 30% on the irrigated fields. Similar results were reported by Hu et al. (Hu et al., 2001), who concluded that water-saving economical irrigation can greatly increase water use efficiency. In the study area, soil salinization is a large problem on the fields. Based on the experience from local farmers and researchers, DIUM would require more water in winter irrigation to wash down the salt on the surface soil, which would decrease the water-saving effects by DIUM. Further researches and investigations are needed for more detailed information and data.

#### 3.6.2.3 Land use scenarios

The effects of the scenarios on irrigation water demand and water deficits at the sub-catchment level are shown in Figure 3.15.

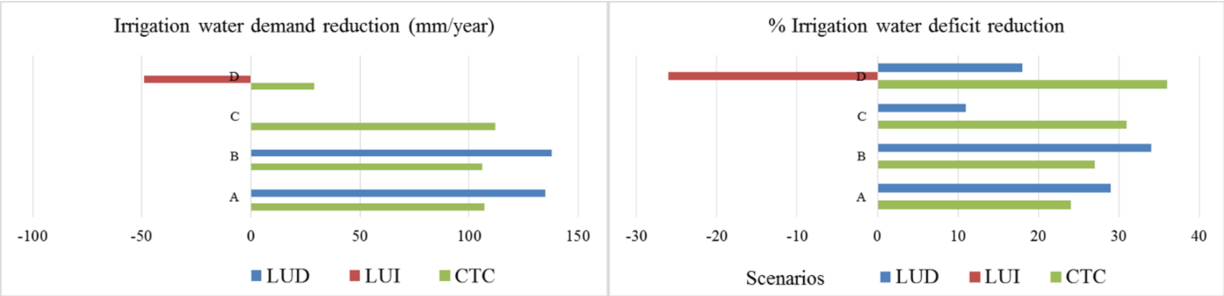



**Figure 3.15:** Effects of land use scenarios LUD (land use decrease), LUI (land use increase) and CTC (crop type change), with irrigation water demand reduction and % irrigation water deficit reduction as indicators in sub-catchments A–D.

In the LUD scenario, the reduction of farmland in sub-catchments A and B indicates a positive effect on the reduction of irrigation water demand. A substantial decline of 100 mm irrigation water demand could be achieved in the upper reaches. Moreover, LUD possessed a broader potential benefit on % irrigation water deficit reduction. All the sub-catchments showed notable decrease on water deficit. A similar land use investigation on the headwater tributary of Tarim River was conducted by Huang et al. (Huang et al., 2015), who found that the expansion of irrigation area ultimately leads to the increase in water consumption and reduces water availability.

In the LUI scenario, irrigation water demand was raised by nearly 50 mm with the increase of farmland in the lower reach. % irrigation water deficit was also increased by over 25% in the region. Since the increase of farmland in the upper and middle reaches had already been strictly restricted by the local government policies, the increase of farmland in the lower reach was also found to be harmful to the water saving purpose, and therefore should not be recommended.

In the CTC scenario, both irrigation water demand and % irrigation water deficit were largely reduced in all sub-catchments. Irrigation water demand dropped over 100 mm in the upper and middle reaches. Especially in the middle reaches, water demand has the largest reduction in all the sub-catchments. In the lower reaches, irrigation water reduction is less obvious. However, because farmland area in the lower reaches is much smaller than the upper and middle reaches, the water reduction is still noticeable and helpful to alleviate water deficit. % Irrigation water deficits were also significantly decreased, with a maximum reduction of 36% in the lower reach. With the crop type change, all the sub-catchments have the reduction on water deficit over 20%. Rotation of crop types can be an effective approach to reduce irrigation water demand and deficit. Therefore, scenario CTC is recommended for future land use developments.

### 3.7 Conclusion

The work of this chapter was supported by German-Sino bilateral collaboration research project SuMaRiO funded by the German Federal Ministry of Education and Research. Our partners from the Chinese Academy of Sciences (CAS) helped with our field work and provided the basic data and information.

The MIKE HYDRO model adequately represented the river discharge and irrigation water allocation at a large catchment scale in the mainstream of Tarim River. By adapting the $K_{cb}$ values, the actual evapotranspiration could also be reliably simulated. In general, the model performed satisfactorily.

In 2006, the total $ET_a$ in sub-catchments A, B, C D was 666, 709, 864 and 190 mm, respectively, which illustrates the condition of high water stress for crops in the lower reaches of sub-catchment D. Meanwhile, the highest $ET_a$ and DP both occurred in sub-catchment C. Irrigation water consumption was relatively high in this district.

Optimal crop production depends greatly on available soil water. Cotton demonstrates a robust yield performance with a reduction in the percentage of TAW. Cotton yield dropped a mere 6% from TAW at 0.7 to TAW at 0.4. To maintain cotton production at a relatively high level, a TAW of 0.4 is recommended. Wheat, maize, sugar beets, beans, melons and cotton all reflected a higher compatibility with water stress compared with tomatoes. Tomatoes should be grown only in areas where the supply of irrigation water is ensured.

WS and RWDD increased up to 40% and 30%, respectively, with DIUM at 100% in all irrigated fields. This indicates the potential value of DIUM in saving water and reducing water deficits. DIUM could largely ameliorate the water balance in the lower reaches, where the natural Tugai vegetation is functioning as an important ecosystem function by restraining dust. This water-saving technique should be applied whenever possible.

A considerable reduction in the demand for irrigation water and water deficits can be achieved in the land use scenarios. Over 100 mm of irrigation water demand was saved by reducing the amount of farmland in sub-catchments A and B. In both sub-catchments, irrigation water deficit decreased by more than 25%. Reduced areas of farmland in the upper reaches could have considerable benefits for all the sub-catchments. The substitution of Apocynum for cotton could be an effective approach in reducing irrigation water demand and water deficit. Therefore, scenario CTC is recommended for future land use developments in the region.

The most important feature of the MIKE HYDRO model is the clarification of the mutual interference of the sub-catchments along the mainstream Tarim River. Issues of agricultural water consumption and allocation cannot be effectively managed in separate regions. Clear evidence was presented to provide stakeholders and decision makers with relevant information about the anticipated effects of each scenario. Because the hydrological model has already been established in the study area, future simulations of water availability and allocation can be undertaken. Groundwater and the spatial distribution of water users in the sub-catchments will be addressed in the next phase of our research. The results of MIKE HYDRO simulations should also contribute to the decision support system (DSS) for sustainable management of water and land use in the Tarim River Basin.

# 4 Distributed MIKE HYDRO model

The lumped MIKE HYDRO model in the last chapter did not combine the land use map, and thus cannot deal with distributed water allocation issues. This chapter presents a distributed MIKE HYDRO model in the mainstream of Tarim River, to find agricultural water allocation strategies on a hydrological modeling basis.

## 4.1 Introduction

Efficient reallocation of existing water supply is gaining importance as demand grows and competitions among users intensify. In extremely arid regions, where deficit irrigation needs to be applied, management decisions on agricultural water allocation are often onerous tasks due to the confliction among water users. This chapter presents a hydrological modeling approach to assist decision-makers and stakeholders to resolve potential water-sharing conflicts among water users. We combine the land use map with water distribution methods to solve the water allocation problems in a large basin scale.

The model is tested and applied in three steps: (1) calibration and validation of water supply and demand along the Tarim River with a combined hydrological and groundwater model, (2) developing climate change scenarios, (3) optimizing agricultural water allocation for the entire Tarim River Basin for these scenarios and deriving of conclusions. The comprehensive management of farmland areas and water distribution strategies are investigated in the model scenarios. The results of these assessments provide opportunities for substantial improvement on water allocation and water right. The access of a user to use the water efficiently should be guaranteed, especially in the lower reaches of the river in the arid land. In practice, the hydrological model assists on decision-making for water resource management in a large river basin, and incentive to utilize water use in an efficient manner.

In a large river basin scale, any form of abstraction, transfer, storage or water losses has effects on the entire downstream river system. The water authority must carry out a comprehensive management on the entire river basin. Through the discussions with decision-makers in Xinjiang Tarim River Basin Management Bureau, two questions are needed to be solved urgently: (i) how much farmland area shall be irrigated each year, and (ii) how to distribute the water in the entire basin.

MIKE HYDRO is a comprehensive deterministic and physically-based modeling tool for the simulation of water flow, water supply/demand, soil moisture and crop growing. It has an integrated modular structure with basic computational modules for hydrology and hydrodynamics. A map layer coordinates the parallel running of the process components. In the distributed MIKE HYDRO model, rivers and sub-catchments are depicted in the map layer (Figure 4.1).

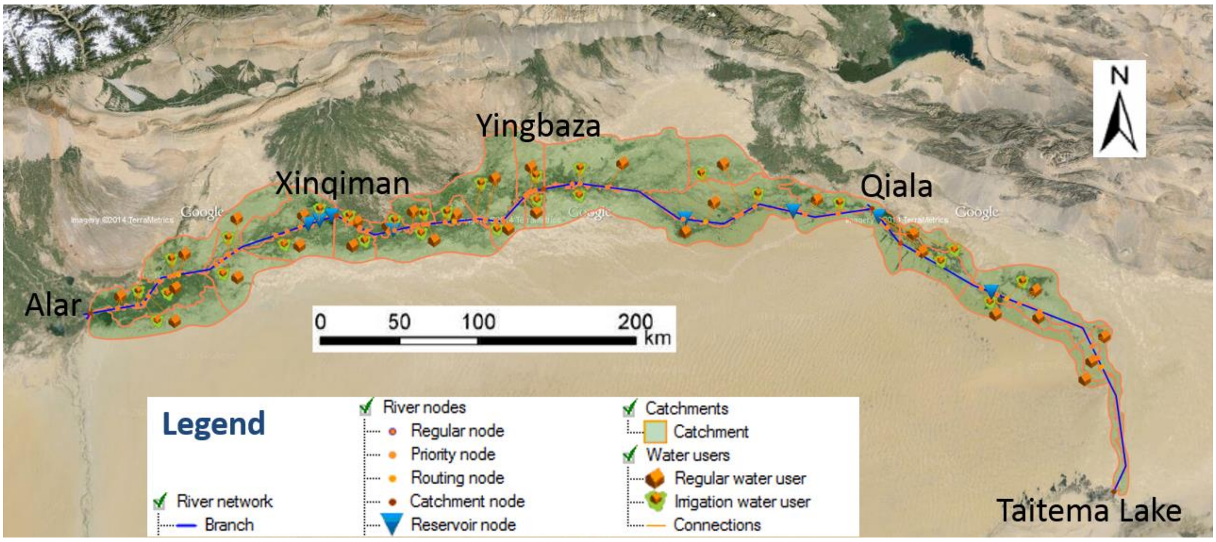



**Figure 4.1:** Distributed MIKE HYDRO model map view.

To simulate the conjunctive use of surface and ground water, a commonly used three-dimensional groundwater model MODFLOW was established to provide initial groundwater conditions. MODFLOW can simulate groundwater movements in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivity or transmissivity for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block (Harbaugh, 2005).

The MODFLOW model has 500 × 500 m cells in the basin, with the same sub-catchments and boundaries. In MODFLOW, an aquifer system is replaced by a discretized domain consisting of an array, so the first step of developing the model was to create numerical grid. After assigning model parameters and boundary conditions to the grid, some model predictions were made according to the limited groundwater data. Only one layer is included in the current model. There was no dynamic relationship between MIKE HYDRO and MODFLOW. MODFLOW provided initial water level and groundwater recharge time series as inputs to MIKE HYDRO (Figure 4.2), while groundwater recharge, groundwater discharge, seepage and conjunctive use of surface water and groundwater were simulated in MIKE HYDRO.

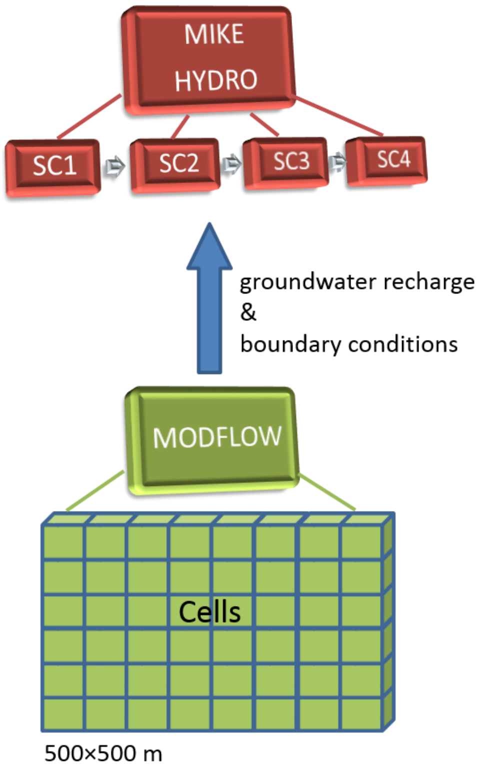



**Figure 4.2:** MODFLOW provides initial water level and groundwater recharge to MIKE HYDRO model.

The sub-catchments are: SC1 (sub-catchment 1) from Alar to Xinqiman, with an area of 5218 $km^2$; SC2 (sub-catchment 2) from Xinqiman to Yingbaza, with an area of 4272 $km^2$; SC3 (sub-catchment 3) from Yingbaza to Qiala, with an area of 5402 $km^2$; and SC4 (sub-catchment 4) from Qiala to Taitema Lake, with an area of 2707 $km^2$. Based on statistical data, the total available groundwater for exploitation is 1.2 billion $m^3$ in the mainstream Tarim River in 2007. Groundwater are widely distributed (Xiao et al., 2014) and usually accessible in all SCs, but it is very crucial for the growing of riparian forest and maintaining ecosystem balance. Therefore, groundwater extractions are regulated by the Xinjiang Tarim River Basin Management Bureau. Digging wells are strictly prohibited without permission from the Bureau. Additionally, due to high salinity problems (Xu et al., 2014), groundwater resources are not largely extracted by the farmers. During crop harvest period, while usually with abundant water in the Tarim River, farmers prefer to extract water from the river over groundwater resources. The initial water head and groundwater depth in irrigation period of MODFLOW model were provided by Philipp Huttner from TUM and shown in Figure 4.3.

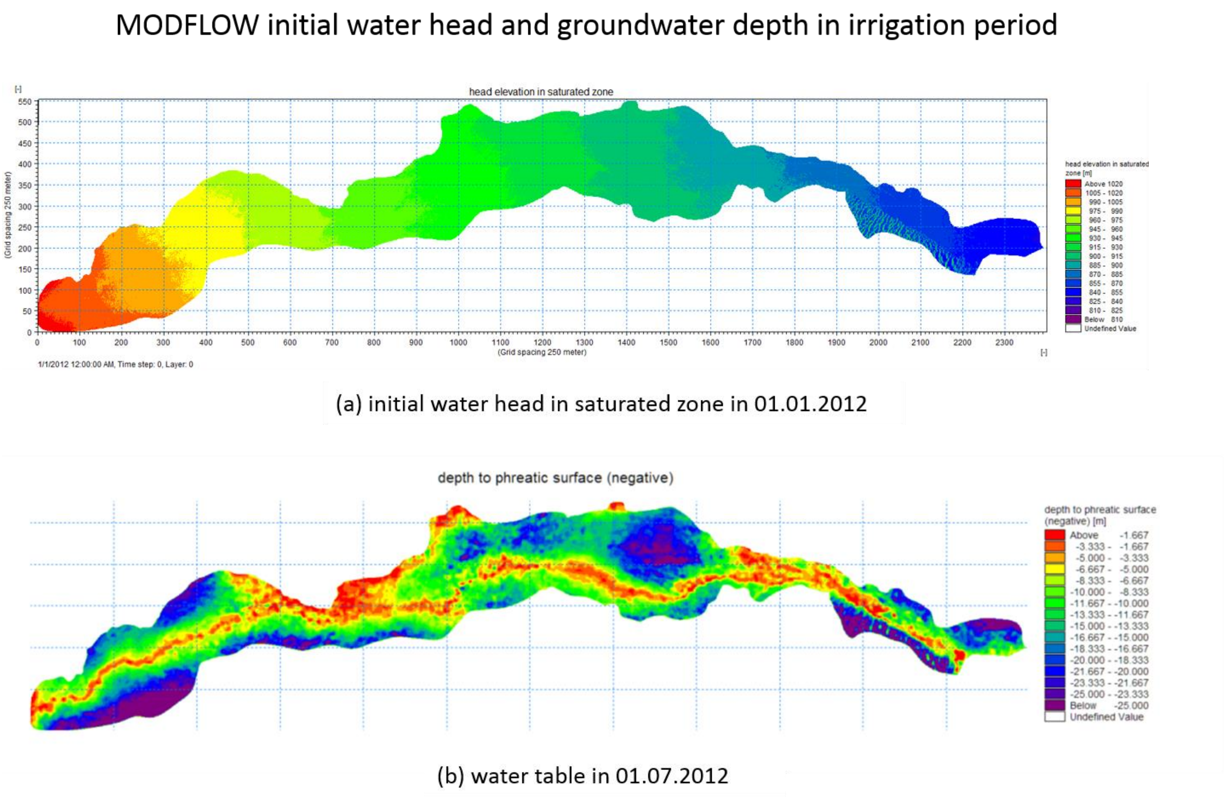



**Figure 4.3:** MODFLOW water table. Cell size is 500 × 500 m, with daily time step (Source: provided by Philipp Huttner from TUM, 2015).

Near the river and irrigation fields, groundwater depths are relatively higher during the irrigation period. In this hyper-arid region, river leakage provides the major source for the generation of groundwater resources. Groundwater recharge in the MODFLOW is comprised with river leakage, irrigation water seepage, infiltration during flood season and ecological water percolation in the lower reaches. In the upper and middle reaches, due to large farmland areas, deep percolation on the irrigation fields is a large water source for the groundwater recharge. During the flood season, infiltration also occurs in natural vegetation areas. In the lower reaches, the water seepage of the ecological water from Bosten Lake should not be neglected. Groundwater recharge data is aggregated in the sub-catchments and provides as input data in MIKE HYDRO.

## 4.2 Land use and hotspots

The land use map (Figure 4.4) was originally based on MODIS data with 250 m resolution. Farmland areas were modified with Landsat data (30 m resolution), and low density riparian areas were adjusted with high-resolution aerial images in Google Earth.

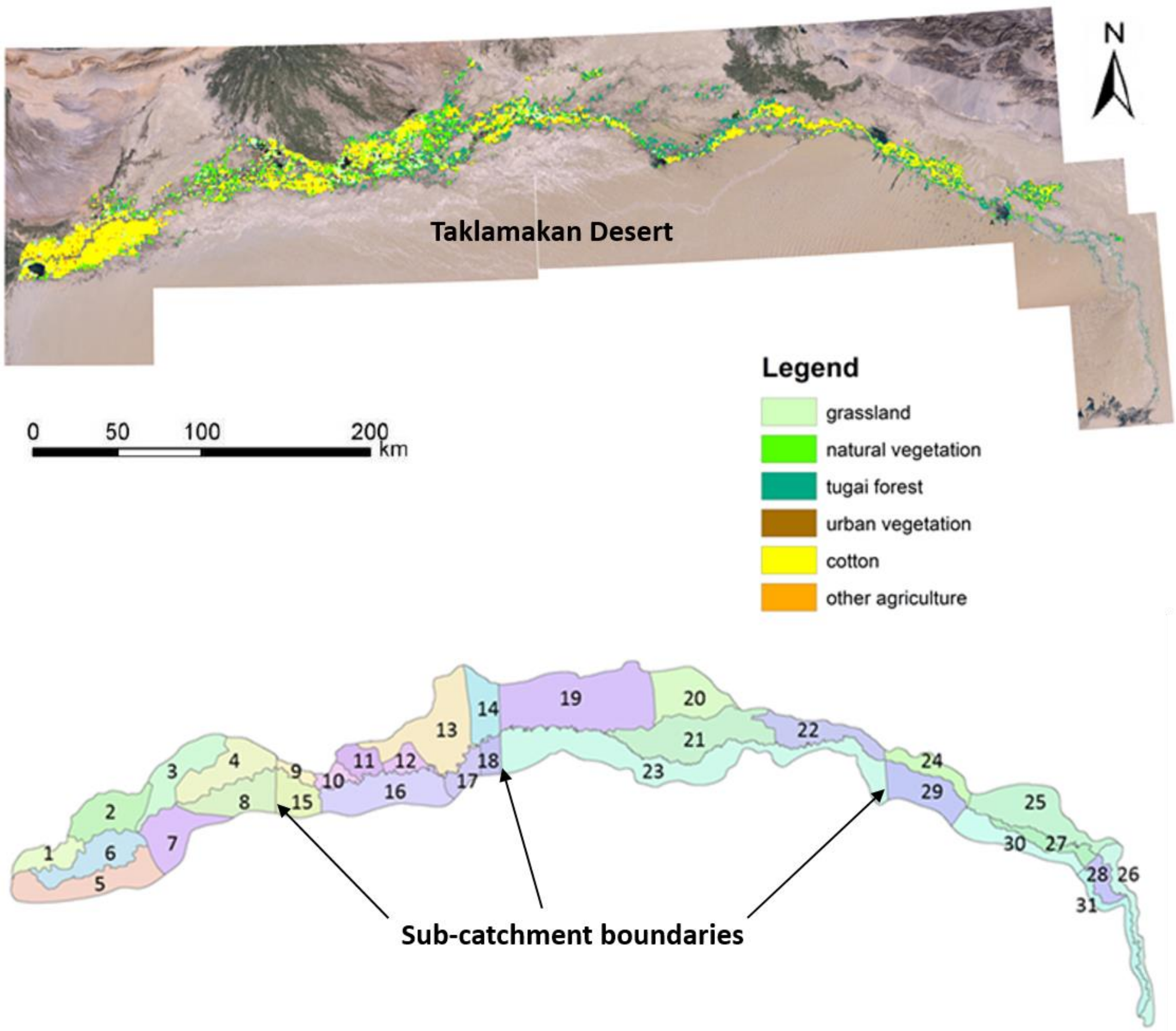



**Figure 4.4:** Land use map and hotspots.

The boundaries of hotspots (Figure 4.4) were defined by county boundaries, sub-catchment boundaries, the Tarim River, and different land use types. The sub-catchment boundaries were set through the hydrological gauging stations and vertical to the river. County boundaries are considered for local decision-making purpose. The Tarim River Basin is endorheic with no overland flow connections with other water body. The delimitation work of the sub-catchments was conducted by a former research group lead by Chinese Academy of Sciences. In this arid region, the land type difference between natural vegetation and desert is clearly visible in the summer, and thus bought some convenience to the delimitation work in most regions.

The locations, areas, counties, and land use types in the hotspots are summarized in Table 4.1. Tugai forests are the riparian forests along the Tarim River (Thevs et al., 2008), which are mainly consist of *Populus euphratica* (Hao et al., 2010). *Populus euphratica* is an ancient tree species in the central Asia. The trees have high tolerance to drought, gusty winds and saline soils. *Populus* trees have an irreplaceable ecological significance in the region due to its windproof and dune-fixing abilities. Because of water scarcity and soil salinization, not all the arable farmlands are cultivated each year. Fallow lands are quite common on the irrigation fields.

**Table 4.1:** Hotspots and land use types in the catchment.

| Hotspots | Location | Area ($km^2$) | Grassland | Natural vegetation | Tugai forest | Arable farmland | Cotton | Unused land |
|---|---|---|---|---|---|---|---|---|
| **SC 1** | 40.34°~41.21° N, 80.92°~82.72° E | **7070.8** | **291.1** | **444.3** | **90.2** | **1505.1** | **1331.2** | **4740.1** |
| HS_1 | 40.47°~40.70° N, 80.93°~81.42° E | 469 | 27.2 | 14.9 | 0.0 | 356.6 | 310.7 | 70.3 |
| HS_2 | 40.65°~40.96° N, 81.31°~81.88° E | 894.9 | 53.7 | 67.2 | 18.6 | 81.1 | 60.7 | 674.3 |
| HS_3 | 40.71°~41.21° N, 81.76°~82.40° E | 905.8 | 9.2 | 13.2 | 2.1 | 10.8 | 10.6 | 870.5 |
| HS_4 | 40.85°~41.19° N, 82.03°~82.72° E | 997.7 | 80.9 | 132.1 | 34.4 | 60.1 | 46.5 | 690.2 |
| HS_5 | 40.34°~40.64° N, 80.92°~81.95° E | 1178.6 | 31.0 | 44.3 | 0.7 | 47.8 | 36.4 | 1054.7 |
| HS_6 | 40.42°~40.73° N, 81.04°~81.84° E | 880.8 | 34.9 | 29.8 | 0.9 | 739.5 | 688.7 | 75.6 |
| HS_7 | 40.49°~40.86° N, 81.77°~82.42° E | 892.9 | 11.7 | 21.0 | 4.7 | 71.4 | 53.4 | 784.1 |
| HS_8 | 40.77°~41.04° N, 82.03°~82.72° E | 851.3 | 42.3 | 121.7 | 28.8 | 137.9 | 124.3 | 520.6 |
| **SC 2** | 40.76°~41.53° N, 82.70°~84.24° E | **5705.1** | **372.2** | **602.7** | **360.2** | **923.3** | **796.1** | **3446.8** |
| HS_9 | 40.92°~41.09° N, 82.71°~82.99° E | 140.7 | 18.8 | 18.2 | 0.0 | 64.0 | 57.8 | 39.6 |
| HS_10 | 40.91°~41.05° N, 82.96°~83.28° E | 200.9 | 41.6 | 40.4 | 3.6 | 41.6 | 34.4 | 73.7 |
| HS_11 | 40.94°~41.15° N, 83.11°~83.44° E | 369.3 | 44.1 | 48.3 | 10.6 | 157.2 | 142.3 | 109.2 |
| HS_12 | 40.97°~41.14° N, 83.42°~83.83° E | 278.3 | 43.6 | 50.9 | 27.9 | 36.3 | 30.6 | 119.5 |
| HS_13 | 40.95°~41.53° N, 83.26°~84.07° E | 1657.1 | 67.7 | 251.1 | 185.1 | 241.3 | 202.4 | 911.9 |
| HS_14 | 41.11°~41.53° N, 83.99°~84.24° E | 632 | 13.5 | 21.4 | 29.0 | 84.3 | 68.1 | 483.8 |
| HS_15 | 40.76°~41.03° N, 82.70°~83.01° E | 531.1 | 34.2 | 29.9 | 6.4 | 175.5 | 160.7 | 285.2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| HS_16 | 40.77°~41.02° N, 82.99°~83.91° E | 1333.4 | 98.5 | 120.7 | 76.3 | 62.1 | 55.5 | 975.9 |
| HS_17 | 40.84°~41.12° N, 83.83°~84.1° E | 321.3 | 2.4 | 12.1 | 5.4 | 15.7 | 11.9 | 285.7 |
| HS_18 | 40.96°~41.16° N, 84.07°~84.24° E | 241.2 | 8.0 | 9.6 | 15.9 | 45.3 | 32.6 | 162.3 |
| **SC 3** | 40.70°~41.52° N, 84.23°~86.82° E | **9264.9** | **181.3** | **222.4** | **510.6** | **600.8** | **454.9** | **7749.7** |
| HS_19 | 41.14°~41.52° N, 84.23°~85.29° E | 2730 | 82.1 | 80.1 | 124.4 | 100.7 | 66.9 | 2342.7 |
| HS_20 | 41.17°~41.47° N, 85.26°~85.86° E | 1017.3 | 0.0 | 7.8 | 29.2 | 0.0 | 0.0 | 980.2 |
| HS_21 | 40.96°~41.26° N, 84.96°~86.09° E | 1693.2 | 37.9 | 54.1 | 169.6 | 71.4 | 54.3 | 1360.1 |
| HS_22 | 40.93°~41.23° N, 85.93°~86.82° E | 807.2 | 17.1 | 16.9 | 65.9 | 235.2 | 182.0 | 472.2 |
| HS_23 | 40.70°~41.22° N, 84.23°~86.82° E | 3017.2 | 44.4 | 63.6 | 121.5 | 193.7 | 151.7 | 2594.0 |
| **SC 4** | 39.47°~40.99° N, 86.81°~88.48° E | **4946.3** | **33.3** | **78.9** | **452.0** | **362.3** | **273.1** | **4019.8** |
| HS_24 | 40.66°~40.99° N, 86.81°~87.38° E | 451.8 | 10.0 | 8.5 | 42.9 | 85.6 | 61.2 | 304.8 |
| HS_25 | 40.37°~40.77° N, 87.34°~88.33° E | 1351.8 | 7.7 | 19.7 | 166.7 | 114.3 | 82.3 | 1043.4 |
| HS_26 | 39.47°~40.43° N, 88.18°~88.48° E | 514.5 | 0.0 | 4.8 | 25.7 | 0.0 | 0.0 | 484.0 |
| HS_27 | 40.31°~40.61° N, 87.48°~88.19° E | 360.2 | 0.2 | 11.7 | 38.1 | 0.0 | 0.0 | 310.2 |
| HS_28 | 40.11°~40.37° N, 88.09°~88.36° E | 274.3 | 0.0 | 0.0 | 13.4 | 0.0 | 0.0 | 260.9 |
| HS_29 | 40.57°~40.94° N, 86.81°~87.34° E | 840.9 | 14.5 | 26.5 | 121.6 | 162.3 | 129.6 | 515.8 |
| HS_30 | 40.28°~40.66° N, 87.23°~88.1° E | 709.8 | 0.8 | 7.6 | 32.2 | 0.0 | 0.0 | 669.2 |
| HS_31 | 39.53°~40.31° N, 88.04°~88.45° E | 443.1 | 0.0 | 0.0 | 11.6 | 0.0 | 0.0 | 431.5 |

*Note: SC: Sub-catchment. HS: Hotspot. The unused land is mainly comprised by the Gobi Desert. Due to water scarcity, not all farmlands are cultivated each year. Crop rotation and land fallow are very common during our field investigations. How much farmland area should be cultivated next year has become a key question for the Xinjiang Tarim River Basin Management Bureau.

In the model, eight big reservoirs have been established in the distributed MIKE HYDRO model. The information of the reservoirs are given in Table 4.2, with the orders from upstream to downstream of the river. The total storage volume of all the eight reservoirs is 10 billion $m^3$, which is over 2 times larger than the average discharge of the Tarim River (4.5 billion $m^3$). The total water area at dam crest level is 577 $km^2$. Water area and volume will be increase with the rise of water level in the Level-Area-Volume (LAV) table in the model. If evaporation is 3000 mm in a year, then the maximum evaporation of all the reservoirs would reach up to 17 billion $m^3$. However, due to water scarcity, water volumes in the reservoirs are usually below flood control level. Water in the reservoirs is often stored for several months after summer floods, to guarantee water resource in autumn harvest and winter uses. In the spring, water levels in the reservoirs are mostly in dead zone. Operations on the reservoirs were quite dynamic based on water scarcities and necessities in the past decades, according to the reservoir managers, and the flooding gates will be open whenever a release order from upper administrations arrives. To avoid large water evaporation losses, reservoirs are often controlled to have high storage after summer floods and low storage in most months. So far water levels in the reservoirs have not been calibrated due to lacking of data. Because the operations of reservoirs are controlled by humans, it will bring some uncertainties to the calculations in water balance.

**Table 4.2:** Eight large reservoirs from upstream to downstream in the model.

| Numerical orders | Names of the reservoirs | Bottom level (m) | Dead storage level (m) | Dam crest level (m) | Water area at dam crest level ($km^2$) | Water volume at dam crest level ($10^6$ $m^3$) |
|---|---|---|---|---|---|---|
| 1 | Jieranlike | 970 | 971 | 975 | 82 | 134 |
| 2 | Dareyi | 970 | 971 | 975 | 145 | 124 |
| 3 | Dazhai | 968 | 969 | 972 | 48 | 84 |
| 4 | Paman | 955 | 956 | 960 | 28 | 46 |
| 5 | Kaerquga | 908 | 909 | 915 | 89 | 186 |
| 6 | Talimu | 887 | 888 | 892 | 60 | 120 |
| 7 | Qiala | 870 | 871 | 884 | 57 | 161 |
| 8 | Daxihaizi | 858 | 859 | 865 | 68 | 168 |

## 4.3 Soil water balance and key modules

Snow melt and water from the mountains are the main drivers of water supply to the discharge. Rainfall runoff module has hardly any influence in the model, because aggregated rainfall is a negligible amount in this extremely arid region. Water quality and sediment transport are also excluded due to their insignificant impact on the water balance.

The FAO 56 soil model is applied to track the water flow and water content in the soil profile. The soil module affects the water balance on two aspects: (i) overall water balance of the catchment. This may be affected mainly by evapotranspiration, deep percolation and groundwater recharge in irrigated areas, (ii) the distribution of catchment runoff amongst different runoff components (overland flow, interflow, baseflow). This may be influenced by infiltration and the abstraction of irrigation water from groundwater or surface runoff.

Soil water content in the effective root zone is estimated by using the water balance equation:

$$\mathrm{WC}\ (\mathrm{t}) = \mathrm{WC}\ (\mathrm{t}-1) + IRR + P - ET_a - DP \tag{4.1}$$

Where WC (t) is soil water content today, WC (t-1) is soil water content yesterday, IRR is Irrigation depth since yesterday, P is precipitation since yesterday, $ET_a$ is actual evapotranspiration, and DP is deep percolation.

The actual evapotranspiration is calculated under water stress conditions using dual crop coefficient approach:

$$ET_a = (K_s K_{cb} + K_e)\ ET_o \tag{4.2}$$

Where $K_s$ is the water stress coefficient, $K_{cb}$ is the basal crop coefficient in transpiration, $K_e$ is the water evaporation coefficient in soil evaporation, and $ET_o$ is the reference evapotranspiration computed from climate data by Penman Monteith method (Allen, 1998).

The FAO 56 climate model accepts a number of climate inputs, including coordinates, rainfall, humidity, air temperature, wind speed, sunshine hours and other climatic data. The reference evapotranspiration is calculated by Penman-Monteith method (Allen etc., 1998), and provides inputs for the crop fields.

Water balance equations on the irrigation fields are shown as follows.

$$WS = IRR_c + IRR_{GW} + IRR_R + R_{GW} + P - \Delta S \tag{4.3}$$

$$WU = ET_a + DP + WL \quad (4.4)$$

$$WS = WU \quad (4.5)$$

$$WD = ET_c + DP + \text{WL} \quad (4.6)$$

$$WDF = WD - WU \quad (4.7)$$

$$RWD = \frac{WDF}{WD} \quad (4.8)$$

Where $WS$ is the water supply for crops, $IRR_c$ is the irrigation water from the channel, $IRR_{GW}$ is the irrigation water from groundwater pumping, $IRR_R$ is the irrigation water from reservoirs, $R_{GW}$ is the root transpiration water from groundwater, $\Delta S$ is the change of storage water in the soil, $WU$ is water use on the fields, $WL$ is water losses in transport, $WD$ is water demand on the fields, $ET_c$ is crop evapotranspiration under excellent soil water conditions, $WDF$ is water deficit, and $RWD$ is relative water deficit.

Water balance calculations cannot begin until soil water content in the root zone is known. The initial soil water content is measured by gravimetric soil water samples, and the successive days are estimated using the water balance equations.

## 4.4 Model calibration and validation

The calibration period is from 2005 to 2009. There are four steps in the calibration: (i) surface routing parameters are calibrated by the observed discharges in the gauging stations. In the Muskingum routing method, travel time K values are firstly calculated by the distance and flow velocity, then adjusted manually according to the discharges, (ii) seepage losses are calibrated by the observed low flows. Different types of soil (sand, loam, etc.) have different recommended ranges of soil porosities, and the calibrated values vary slightly from catchment to catchment, (iii) reservoir behavior is calibrated by the observed hydrograph. Flood control levels and maximum/minimum releases of the reservoirs are calibrated by their downstream temporal and volumetric release, (iv) NAM auto-calibration is conducted to adjust some other model parameters. NAM is a commonly used conceptual rainfall-runoff model, simulating overland flow, interflow and baseflow components. Most of the parameters are not sensitive due to low precipitation in the study area. The threshold of groundwater recharge and root zone storage are the most sensitive parameters in the model. Four objective functions are chosen: to achieve good overall water balance, overall RMSE, peak flow RMSE and low flow RMSE.

Discharge in Alar hydrological station is used as input discharge to the model. The calibration and validation results of the discharge in the Xinqiman, Yingbaza and Qiala gauging stations are shown in Figure 4.5. From Alar to Qiala, the decrease of discharge scales indicates water consumptions in the sub-catchments.


**Figure 4.5:** Input discharge (daily values) in Alar and calibrated discharges in the Xinqiman, Yingbaza and Qiala hydrological stations.

Compared with the discharges in the lumped MIKE HYDRO model (in chapter 3), the discharges in this distributed model have been largely improved. The time step has been investigated on a daily simulation, so that more detailed hydrograph can be presented. Groundwater pumping has been included in the model, and the water consumption gaps in the irrigation period have been filled up. Moreover, the error indices also indicated better simulated runoff than the lumped model. Good performance of the surface runoff in the model is a guarantee for water consumption and allocation simulations.

It is always easier to make the parameters fit than to make them predictable, but good scenarios require predictable parameter values, which tests the understanding of the model in calibration process. That is the reason why good model performance in the validation period is more valuable to us than it is in the calibration period. Because the daily discharge data is used directly as input into the model, so the water balance model could achieve a good validation performance. Evapotranspiration and infiltration changes are calculated in the model, which makes the land use change the only possible large uncertainty factor in the calibration and validation period. The farmlands are mainly cultivated in the upper reaches where abundant water is supplied each year. Drought-resistant and water-saving plants are growing in the middle and lower reaches, which makes the land use change not a big influence on the river discharge. Good calibration and validation performance is a guarantee for the water allocation strategies and future scenarios.

## 4.5 Model scenarios and results

### 4.5.1 Scenarios

The improving of water allocation rules result in better management alternatives. In the model, the priorities of water supply connections and supply rules were defined by the users. Irrigation water demand and supply were calculated in the crop module. Model scenarios were designed based on practical problems raised by decision-makers in their water management practices.

The discharge of Tarim River is dominated by snow and glacier melt water from mountain area in the upper reaches. These regions are particularly sensitive to climate changes, and the influences of climate changes on river discharges were analyzed by a hydrological model WASA (Duethmann et al., 2016). The model was calibrated thoroughly using multiple criteria based on discharge and glacier mass balances. The climate projections were based on three emission scenarios, nine global climate models (GCMs), and additionally two regional climate models (RCMs). The results indicated a decline in glacier area of −90% to −32% until 2099 (based on the 5–95 percentile range of the ensemble). Glacier melt was anticipated to further increase or stay at a high level during the first decades of the 21st century, but then declined because of decreased glacier extents (Duethmann et al., 2016). With different temperature and precipitation rising projections, simulation results all agreed to a common trend on the headwater of Tarim River: overall discharge was anticipated to be increased in the 2020s because of temperature rising, then decreased in the 2080s due to glacier retreat.

The scenario of near future 2020 assumes the discharge in Alar reaches 7 billion $m^3$, and the scenario of far future 2080 assumes the discharge in Alar drops to 3 billion $m^3$. The impacts of climate change on the Tarim River discharge (Sorg et al., 2012), on evapotranspiration (Liu et al., 2010) and crops (Piao et al., 2010), the change of human activities (Tao et al., 2011), downstream and ecosystem effects from changing water regimes (Xu et al., 2009), are considered in the scenarios. Other model conditions, including infiltration, reservoirs, groundwater recharge, soil profile, crop growing factors, are kept business as usual. The flow patterns of year 2020 and year 2080 were used by the reference discharge in 2010 and 2008, with adjustment (multiply coefficient) of water amount to 7 billion $m^3$ and to 3 billion $m^3$, respectively. The hydrographs are shown in Figure 4.6.

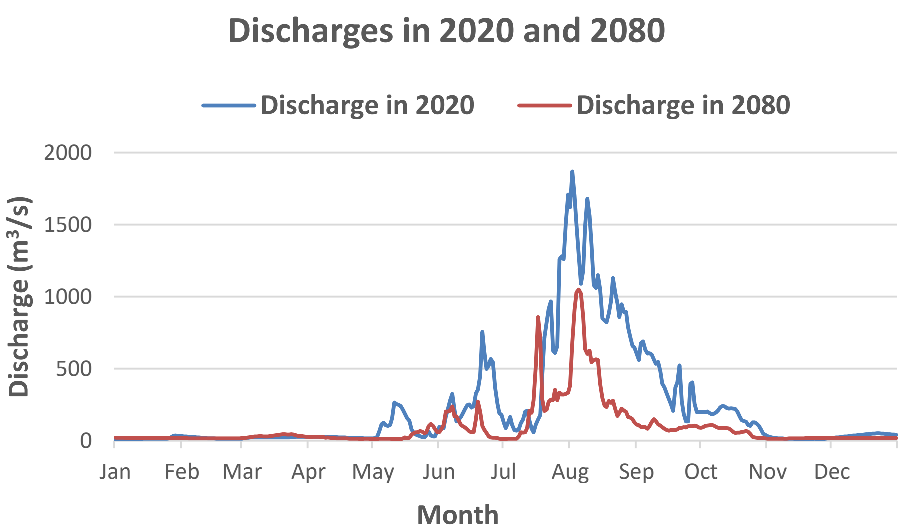



**Figure 4.6:** Input discharges in 2020 (7 billion $m^3$) and 2080 (3 billion $m^3$).

Moreover, the scenarios of assuming discharge from Alar at 4 billion $m^3$ (reference year 2013), 5 billion $m^3$ (reference year 2011) and 6 billion $m^3$ (reference year 2006) are all simulated, to reallocate irrigation water resources in the entire catchment. The strategy of agricultural water allocation regime is to modify farmland areas based on current situation, and optimize water distribution to achieve a relatively low water deficit and high crop production for all the farms.

### 4.5.2 Water deficit

Actual evapotranspiration ($ET_a$) and deep percolation (DP) are not evenly distributed from upstream to downstream sub-catchments (SC). Model simulation results revealed the mean annual $ET_a$ and DP in different hotspots (HS) from 2005 to 2013 in Figure 4.7. More yearly simulation results are demonstrated in the appendix.

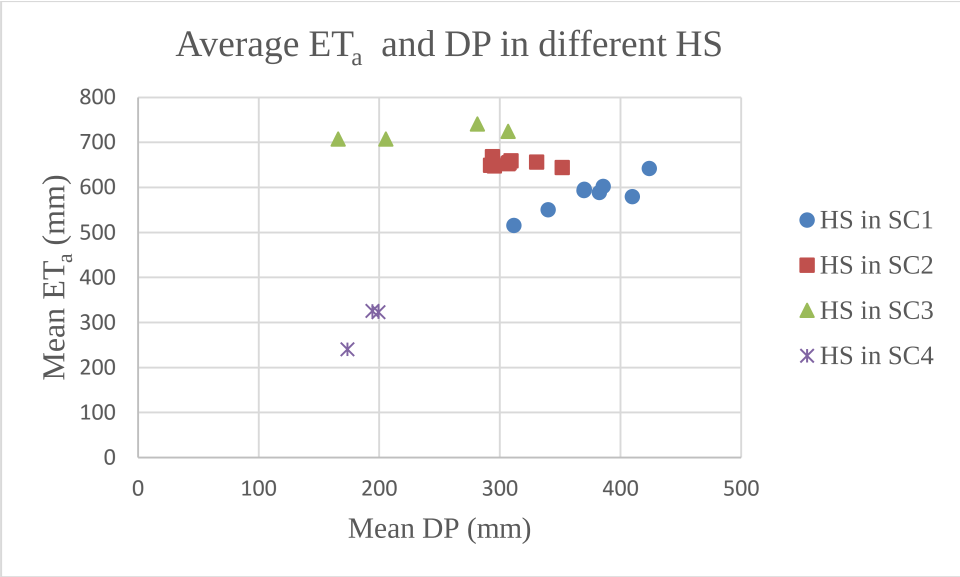



**Figure 4.7:** Mean actual evapotranspiration ($ET_a$) and deep percolation (DP) in different hotspots from 2005 to 2013.

The figure revealed an increasing trend of $ET_a$ and decreasing trend of DP from SC 1 to SC 3, which are caused by the fact that evaporation rate is rising form upper reaches to middle reaches, but the available water for infiltration is getting less. From statistical data, annual temperature is increasing from SC 1 to SC 4, with the sub-catchments further from the mountainous region and closer to the convergence of deserts. Therefore, $ET_a$ has been increased by around 100 mm from SC 1 to SC 3. However, due to lacking of irrigation water, DP has been decreased by over 100 mm from SC 1 to SC 3. In SC 4 (lower reaches), both $ET_a$ and DP are dramatically reduced, which indicated severe water scarcity in the lower reaches. Compared with the results in the lumped MIKE HYDRO model (chapter 3), $ET_a$ and DP are both increase in this distributed model. The phenomenon is caused by adding the ecological water from Bosten Lake to the lower reaches in the distributed model. Additionally, there are one hotspot in SC 3 and five hotspots in SC 4 without farmland areas.

If water demand is beyond water supply, water deficit would be formed during the year. On the hotspots with farmlands, the water deficit map is illustrated in Figure 4.8. RWD indicates the level of farm lacking of water, and thus a good indicator for farmland reduction and water transfer in the scenarios. More water deficit maps during the simulation years are shown in the Appendix.

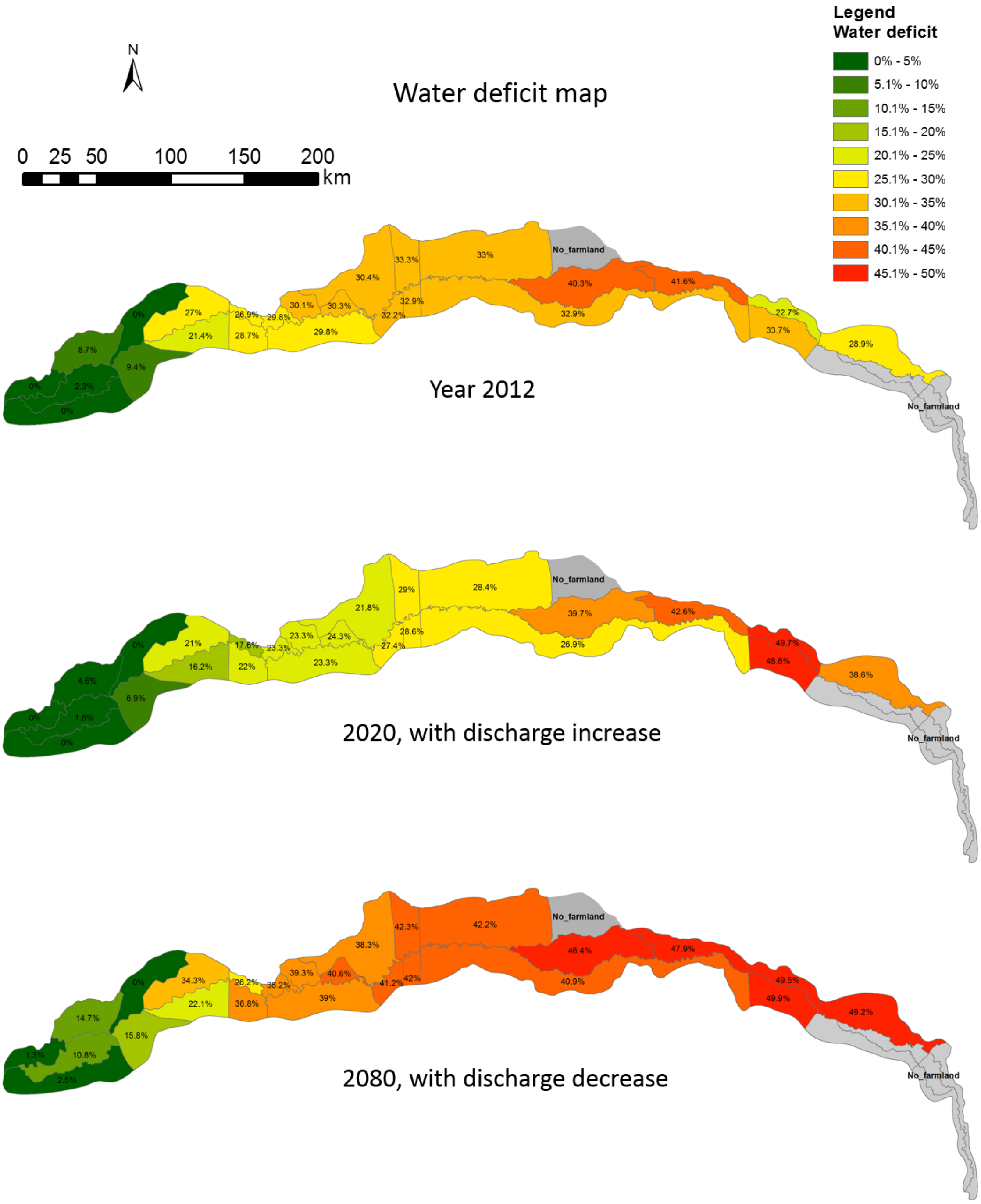



**Figure 4.8:** Relative water deficit map in 2012, 2020 and 2080.

There is an increasing water deficit trend from upstream downwards. The baseline year is 2012, with a discharge (5.4 billion $m^3$) 20% above the average annual discharge for the past 50 years (4.5 billion $m^3$). In 2012, the highest water deficit (41.6%) appears in the midstream SC 3. Meantime, three hotspots in upstream SC 1 have no water deficit. Therefore, the reallocation of water is very important to share the water rights in the whole region and improve the efficiency of water use. In the scenario of 2020, water deficit is mitigated for most hotspots in upper and middle regions compared with 2012. Surprisingly, farmlands in lower reaches suffer a more severe water scarcity. The reason of it turns out to be the water conveyance project to the lower reaches. During dry years, the local government would start delivering ecological water from Boston Lake to the lower reaches. But in wet years, the transported water will be reduced or even halted. Based on the model analysis, we recommend this water conveyance project be carried out each year, without considering a wet or dry year. In the far future 2080, water scarcity would be a grievous blow to the farmlands from upstream to downstream. Immigration of local residents, farmland reduction and water resources reallocation have to be under serious consideration if water use efficiency could not be largely upgraded in this arid region.

If there were water storage in the reservoirs, then water deficit can be alleviated after water release from upstream reservoirs. Water levels in the reservoirs were investigated from the model results in the upper reaches (Figure 4.9). However, the results indicated there were not enough water in the reservoirs to provide downstream water demand.

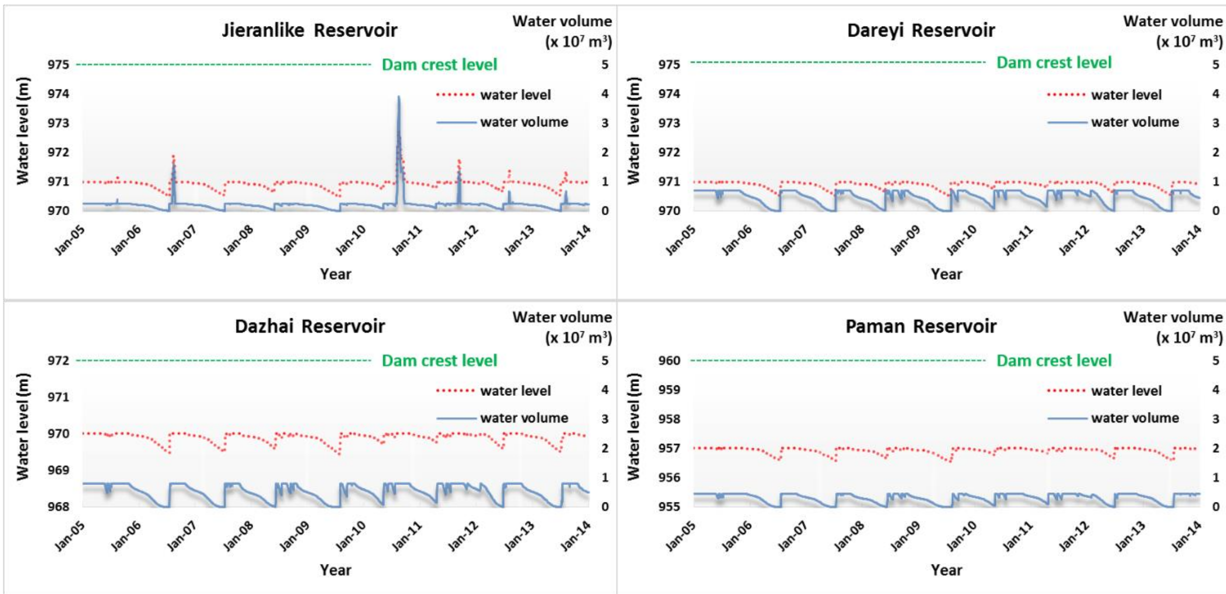



**Figure 4.9:** Water levels of reservoirs in the upper reaches from 2006 to 2013.

Due to the initial water levels of reservoirs, year 2015 was regarded as simulation warm-up period. The results starts from 2006 until the end of 2013. Simulation results indicated water levels in the reservoirs were close to dead storages and far from the dam crest levels, which means water resources are also under shortage in the reservoirs. Since the lower the water level is, the smaller water area in the reservoir would be, water volumes in the reservoirs would be much less than half of the total capacity volumes.

### 4.5.3 Farmland areas

The goal of the scenarios is to keep the RWD below 30% for all the farms, and thus maintain a relative high crop water productivity. Under water deficit, crops demonstrate divergent robust performances due to different crop factors, while cotton maintains a relatively high yield with the decrease of irrigation water (Yu et al., 2015). The concept of deficit irrigation is to maximize crop water productivity instead of maximizing the harvest per unit land (Fereres and Soriano, 2007), so that some valuable water can be saved for riparian forest, grassland, livestock, or domestic use. How much farmland area shall be reduced to and how the corresponding water allocation strategy shall be applied are the main issues in the scenarios.

Two types of supply rules were included in the model. The first supply rule is “call by priority”, which means water is supplied in the order of priority numbers. This type of supply rule was applied in the baseline year, and the priorities of water users were sequenced from upstream to downstream. The second supply rule is “fraction of demand”, which means water supply is designated by the fraction of water demand required from each water user. This supply rule was applied in year 2020 and 2080, and the fractions of water demand were assigned at 70%. Groundwater resources were used to fulfill a fraction water demand which cannot be satisfied by surface water. Because groundwater extractions are strictly regulated in the basin, this fraction was set to be 10% for all the sub-catchments. Moreover, two types of water deficit distribution methods were also employed in the model, namely “by priority” and “equal shortage”.

Because the Tarim River is a seasonal river with water interception problem in the dry seasons, equal water shortage at 30% could not be achieved in a number of hotspots. Many regions had to reduce farmland areas to alleviate water deficit. A series of trials were tested in the simulations for farmland changes in 2020 and 2080. In 2020, due to discharge increase, many hotspots could expend farmland areas slightly (within 30%). In 2080, with discharge decreased dramatically, the reduction of farmland areas had to be found. The algorithm to find the suitable areas is as follows: assuming a farmland area in 2012 is N. The first trial goes to N/2 (integer). If water deficit is higher than 30%, then the next trial would be N/4. Conversely, if water deficit is lower than 30%, then the next trial is 3N/4. The trial continues for half a dozen times until a proper farmland area is acquired. Due to water interception, if a farmland area is reduced to 1 $km^2$ but water deficit is still larger than 30%, then the farmland cannot be maintained in future years. In this case, job change or migration of farmers need to be considered. Table 4.3 provides a volumetric impression of surface water and groundwater supply.

**Table 4.3:** Planned farmland area and water supply in 2020 and 2080. Baseline 2012 (discharge 5.4 billion $m^3$), near future 2020 (discharge 7 billion $m^3$), and far future 2080 (discharge 3 billion $m^3$).

| SC | Hotspots | Year 2012 | | | Year 2020 | | Year 2080 | |
|---|---|---|---|---|---|---|---|---|
| | | Farmland area ($km^2$) | SW supply (million $m^3$) | GW supply (million $m^3$) | Farmland area ($km^2$) | SW supply (million $m^3$) | Farmland area ($km^2$) | SW supply (million $m^3$) |
| **SC1** | HS_1 | 125.39 | 222.03 | 0.02 | 125 | 225.09 | 101 | 199.68 |
| | HS_2 | 20.40 | 25.25 | 0.36 | 22 | 35.97 | 15 | 24.41 |
| | HS_3 | 4.28 | 5.12 | 0.06 | 4 | 7.32 | 4 | 4.92 |
| | HS_4 | 10.02 | 11.33 | 0.32 | 12 | 18.19 | 7 | 8.82 |
| | HS_5 | 14.69 | 28.91 | 0.01 | 15 | 30.12 | 12 | 24.29 |
| | HS_6 | 265.18 | 377.70 | 2.55 | 269 | 470.96 | 183 | 347.37 |
| | HS_7 | 17.68 | 29.81 | 0.13 | 19 | 35.02 | 13 | 26.23 |
| | HS_8 | 30.94 | 37.53 | 0.62 | 35 | 57.06 | 25 | 34.25 |
| **SC2** | HS_9 | 12.45 | 16.92 | 0.03 | 16 | 24.86 | 10 | 14.98 |
| | HS_10 | 6.84 | 8.63 | 0.12 | 8 | 16.38 | 4 | 6.75 |
| | HS_11 | 28.06 | 29.45 | 0.56 | 34 | 57.98 | 17 | 22.86 |
| | HS_12 | 5.99 | 7.27 | 0.16 | 7 | 14.25 | 4 | 4.95 |
| | HS_13 | 39.51 | 44.85 | 0.30 | 50 | 90.23 | 26 | 36.69 |
| | HS_14 | 12.24 | 15.39 | 0.46 | 14 | 31.64 | 8 | 8.04 |
| | HS_15 | 32.98 | 37.77 | 0.36 | 39 | 65.94 | 21 | 31.54 |
| | HS_16 | 11.05 | 12.12 | 0.21 | 13 | 23.15 | 7 | 9.50 |
| | HS_17 | 2.20 | 3.13 | 0.04 | 3 | 6.33 | 1 | 1.84 |
| | HS_18 | 5.92 | 9.10 | 0.17 | 7 | 18.46 | 4 | 4.69 |
| **SC3** | HS_19 | 12.11 | 16.46 | 0.06 | 14 | 38.02 | 7 | 10.06 |
| | HS_20 | _ | _ | _ | _ | _ | _ | _ |
| | HS_21 | 7.81 | 6.29 | 0.15 | 8 | 22.31 | X | X |
| | HS_22 | 25.02 | 18.04 | 1.50 | 24 | 69.91 | X | X |
| | HS_23 | 27.57 | 30.57 | 0.05 | 33 | 68.65 | 18 | 22.73 |
| **SC4** | HS_24 | 14.75 | 41.70 | 0.11 | 6 | 46.25 | X | X |
| | HS_25 | 16.78 | 21.00 | 6.81 | 13 | 52.15 | X | X |
| | HS_26 | _ | _ | _ | _ | _ | _ | _ |
| | HS_27 | _ | _ | _ | _ | _ | _ | _ |
| | HS_28 | _ | _ | _ | _ | _ | _ | _ |
| | HS_29 | 22.99 | 53.66 | 2.43 | 14 | 63.83 | X | X |
| | HS_30 | _ | _ | _ | _ | _ | _ | _ |
| | HS_31 | _ | _ | _ | _ | _ | _ | _ |

*Note: SW: surface water. Symbol “X”: Not possible, indicating the relative water deficit cannot be reduced below 30%. Farmland area should be reduced to 0 and the migration of farmers needs to be considered in this case. Symbol “_”: No farmland.

In the baseline year 2012, water supply was “first come first served”, so upstream areas consumed most of the water and resulted in high water deficit in the lower reaches. In the meantime, riparian forest and natural vegetation were also under severe water scarcity in the middle and lower reaches. Therefore, a better water supply rule would be “fraction of demand”, in which water right in the lower reaches would be improved, and ecosystem balance could be maintained along the entire river oases.

Under the assumption of discharge rising in 2020, several hotspots have to maintain their farmland size, while others can have a slightly extension. The largest farmland lies in HS_6, with an area of 269 $km^2$ and water consumption of 471.36 million $m^3$. However, farmland areas need to be largely reduced in 2080. In the Sub-catchment 3 and 4, five hotspots cannot retain their farmlands anymore. The water deficits are too high to maintain a good crop water productivity. This would lead to a migration wave or career transition for the farmers. The majority of irrigation water is supplied by the channels. Groundwater provides a small proportion in 2012 and tends to decrease in 2020 and 2080 due to groundwater depletion. The model shows groundwater recharge rate is not enough to fulfill the losses.

### 4.5.4 Agricultural water allocation strategies

With the fixed farmland areas, agricultural water allocation strategies can be made in the hotspots. Based on the supply rule, irrigation water is allocated by the fraction of water demand required from each water user. The irrigation water distribution is shown in Figure 4.10 with hotspots which have a farmland area larger than 10 $km^2$. Crop growing season starts from May till end of September in 2012. The figure shows water distribution to the farmland with consideration of water availability in the river.

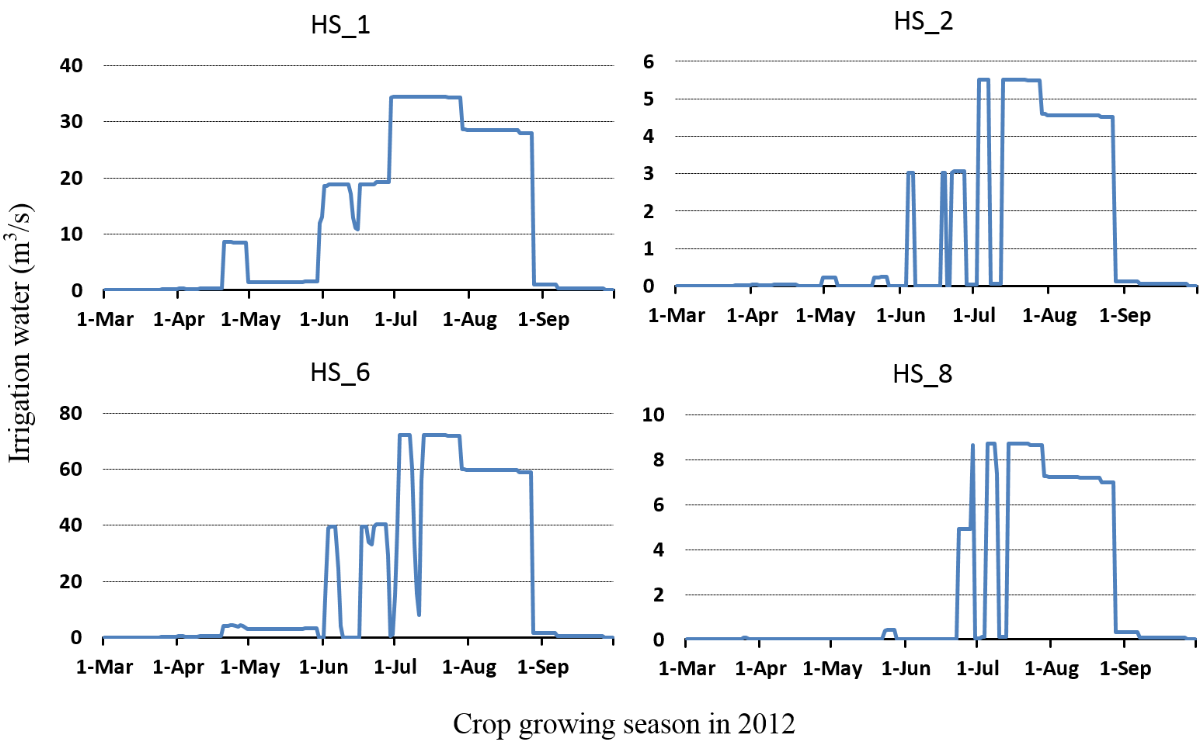



**Figure 4.10:** Agricultural water allocation for large farms in upper reaches in 2012.

From Figure 4.10 we note that the flow peak appears in July and August, and drops sharply after crop harvest date in September. The largest irrigation water flow is 72.21 $m^3/s$, in HS_6 on July. The second largest flow is 34.52 $m^3/s$, in HS_1 on July. The figure illustrated water allocation for relatively large farms in the upper reaches. In the middle and lower reaches, the size of farmland areas are smaller than the farmlands in the upper reaches, and water scarcity is more severe. Therefore, irrigation water consumption will be less in the lower reaches (Figure 4.11).

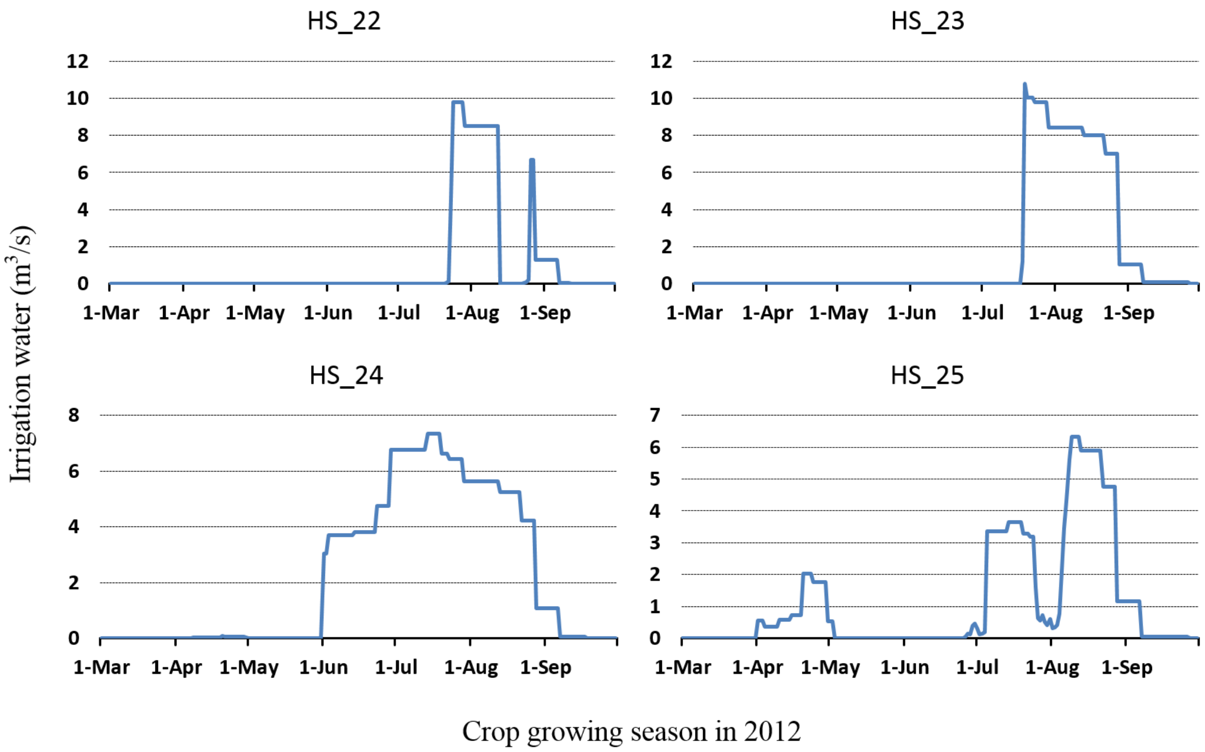



**Figure 4.11:** Agricultural water allocation for large farms in middle and lower reaches in 2012.

Water allocation for relatively large farms in the middle and lower reaches are demonstrated in the figure. Water allocation for other farms can be found in the appendix. Due to water scarcity and river interception, irrigation water cannot be supplied to the most farmlands in the middle and lower reaches during the dry season. Only several hotspots can acquire irrigation water from the channels before June, but there is certain irrigation water demand in the spring sowing time (Jensen et al., 1990; Oweis and Hachum, 2001; Huang et al., 2012). HS_22, HS_23 and HS_24 have hardly any irrigation water supply before June, but the water demand should be there and it can be testified by comparing with HS_25. Because HS_25 is downstream of Qiala reservoir, which has water supply from the Bosten Lake, so there is irrigation water supply in the spring. Water demand cannot be fulfilled in the middle and lower reaches during the dry season. This water demand gap has to be compensated by pumping groundwater due to limited rainfall.

Agricultural water allocation strategies are made for scenarios 2020 and 2080 (Figure 4.12). Maximum flow rates in the irrigation channels are shown to provide the possible capacity for the channels. Average flow rates in the irrigation channels illustrate the spatial distribution of water. Hotspots 20, 26, 27, 28, 30, and 31 have no farmland in the future scenarios, and thus have no irrigation water users in the map view of the figure.

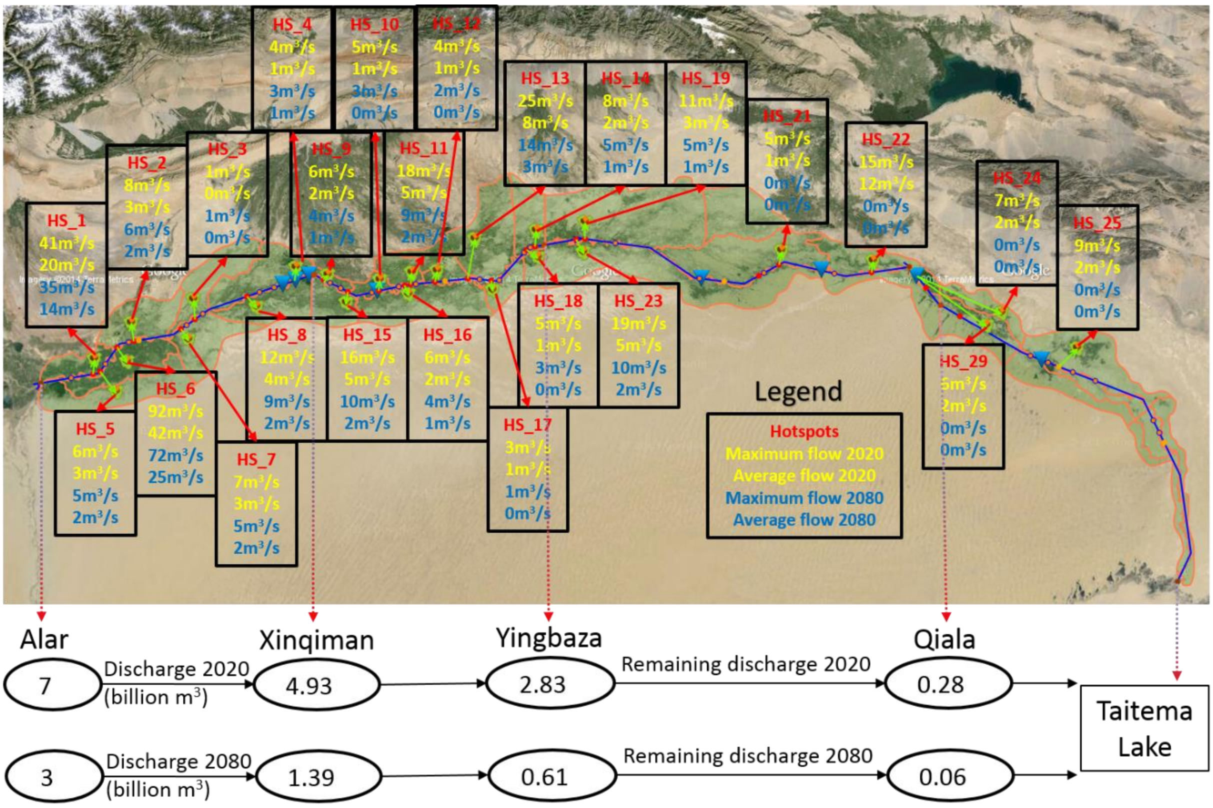



**Figure 4.12:** Agricultural water allocation strategies for scenario 2020 and 2080.

The strategy of agricultural water allocation is made from upstream hotspots downwards. To keep RWD under 30%, reallocation of water resources is imperative. In the middle and lower reaches, water supply of hotspots 21, 22, 24, 25 and 29 cannot be satisfied due to huge water losses in 2080. A test was made with no upstream farmlands, and RWD is still larger than 30% in 2080. These hotspots are all located in Yuli county. Therefore, under the prediction of large discharge reduction in the far future, migrations or career transition of local farmers need to be planned ahead by the county decision-makers.

On the bottom of Figure 4.12, the remaining discharges of sub-catchments are calculated separately in 2020 and 2080. In 2020, water allocation is relatively even in the sub-catchments from Alar to Qiala. However, water resources are more concentrated on the upper reaches to achieve high crop water productivity in 2080. More than 53% of the total discharge is planned to be consumed by the upper reaches. This adjustment is also beneficial for the reduction of water losses during transportation. When discharge is on a relatively low level, water consumption in the lower reaches is very low. It indicates water users in the upper reaches consumes most of the water to maintain their crop production in the dry years. Only initiate water conveyance directly to the lower reaches would alleviate water shortage. In the wet years, more water from the upper reaches would arrive downstream, and water consumption begin to rise in the lower reaches. More irrigation water allocation scenarios are illustrated in the appendix.

Discharge of Alar at 4 billion m$^3$ was considered by reference year 2013. Water allocation strategy is demonstrated by Figure 4.13.

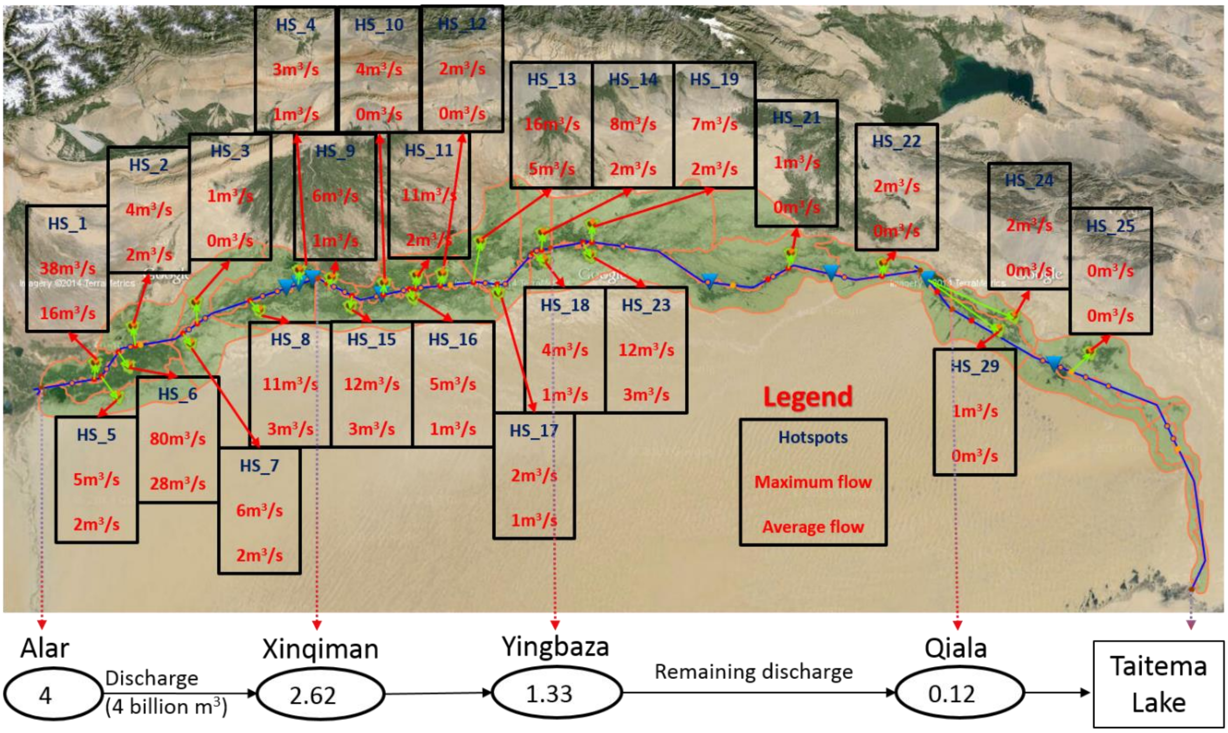



**Figure 4.13:** Agricultural water allocation strategies for discharge at 4 billion m$^3$.

The scenario of Alar discharge at 4 billion m$^3$ is lower than the average annual discharge of Alar for the past five decades, which is 4.5 billion m$^3$. Therefore, although water consumption in the upper reaches have been reduced, there is little water left for the lower reaches, and water deficits would still be very high for the water users.

Discharge of Alar at 5 billion m$^3$ was considered by reference year 2011. Water allocation strategy is demonstrated by Figure 4.14.

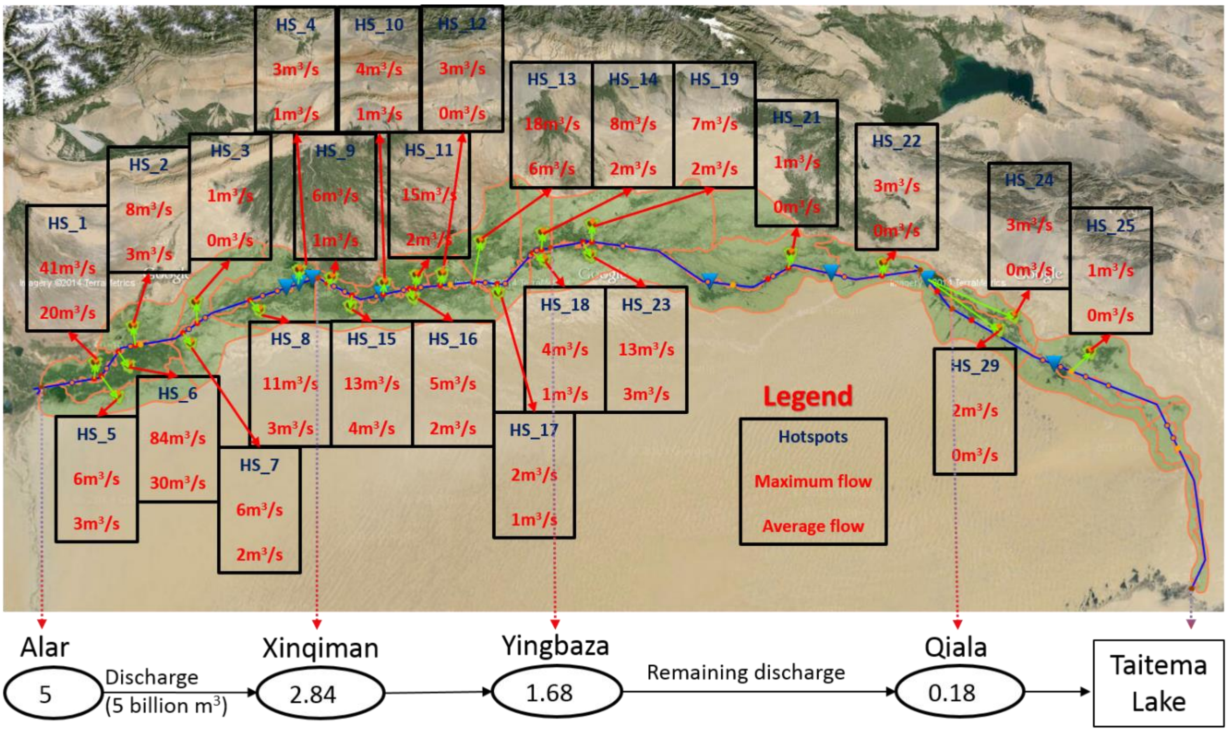



**Figure 4.14:** Agricultural water allocation strategies for discharge at 5 billion m$^3$.

Compared with Figure 4.13, irrigation water users have generally increased their water consumption from upper reaches to lower reaches in Figure 4.14. Because discharge in Alar has been increased over the average annual discharge, water scarcity and water deficits would be improved in this scenario. In several HS (HS_3, HS_4, HS_7 and HS_8) in the upper reaches, water consumption is approximately the same as it is in the Figure 4.13, which indicates water deficits are not severe and water productivity can remain a relatively high level in these regions. In the lower reaches, water consumption is still on a relatively low level, and water scarcity is still severe even the upstream discharge has reached beyond normal years.

Discharge of Alar at 6 billion m$^3$ was considered by reference year 2006. Water allocation strategy is demonstrated by Figure 4.15.

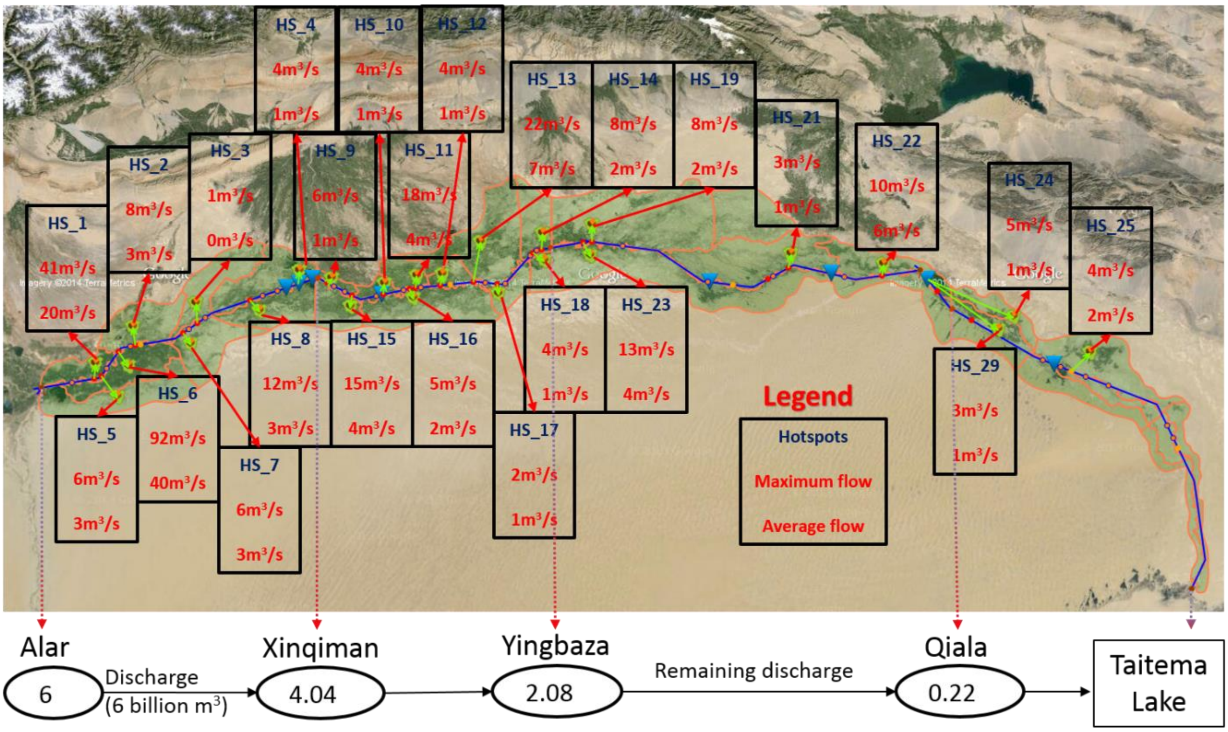



**Figure 4.15:** Agricultural water allocation strategies for discharge at 6 billion $m^3$.

Under the scenario of discharge reaching 6 billion $m^3$, irrigation water consumption in the lower reaches has been largely increased. The improvement of water use in the lower reaches also indicates water deficits have been alleviated and water productivity has reached a relatively high level in the upper and middle reaches.

Based on the water supply rules, water allocation has been largely improved to consider more water rights and equal shortage from upstream to downstream farmlands. Under the rules of maintaining water deficit at 30%, the reallocation of water has only one result. But if the rules are changed, there would be plenty of other possible scenarios and maps. However, there are still some uncertainties in the model. The first problem is the groundwater model has not be calibrated due to lacking of groundwater data. Because digging wells are strictly forbidden along the river oases, further investigation on the groundwater resources have encountered some difficulties, especially for a comprehensive investigation in the entire basin. The second uncertainty comes from the unauthorized water abstraction and farmland extension. Since the river is over 1000 km long, the surveillance of the water consumption is not an easy job, especially in the night. Water stealing has been constantly reported during the past decades, even the punishment is rigorous. Moreover, winter irrigation is not included in the model, so water consumption should be larger than it is in the model. Currently there is no data on how much water would be consumed by winter irrigation, and this process doesn't fit in the present crop module. Based on the experience of farmers in their farming practices, winter irrigation can effectively wash down the salt and improve soil conditions. Further research has to be carried out for a better understanding of winter irrigation and soil salinity conditions from upstream to downstream farmlands.

## 4.6 Concluding remarks

This chapter presents a distributed MIKE HYDRO model which contains land use information. The hydrological model considering both temporal and special variables can adequately reproduce the flow patterns of the Tarim River, and assist decision-makers on the agricultural water allocation issues. To secure and balance the water rights in the whole region, farmland areas should be adjusted according to the discharge in the river, and reallocation of water is imperative.

Water deficit has a rising trend from upper to lower reaches. The comprehensive management of water resources is very necessary from a whole basin point of view, rather than county by county, or farmland by farmland. Lower reaches suffer a severe water scarcity. The water conveyance to the downstream should not be ceased even in wet years.

Based on the scenarios 2020 (with discharge increase due to temperature rise) and 2080 (with discharge decrease due to glacier retreat), the change of farmland area and water allocation strategies are made along the oases of Tarim River. The modification of farmland areas are based on current situation, and optimization of water distribution is to achieve a relatively low water deficit and high crop production for all the farms. The intension of our study is to guarantee water right in the lower reaches, and to save more water for the ecosystem. Currently the economic development in the research area is far behind most regions in China, and there is hardly any industry except for petroleum. Since industry water consumption is negligible in the region, it was not considered in the model. In the model, if agricultural water is saved, then the water would be given to ecosystem. In the real situation, decision-makers should also give priorities to ecological water, rather than industry water. Compared with 2012, farmland area in 2020 can have a slightly extension in several hotspots. The largest farmland lies in HS_6, with an area of 269 $km^2$ and water consumption of 471.36 million $m^3$. But in 2080, farmland areas need to be largely reduced. Five hotspots in middle and lower reaches cannot have any farmland with a relatively high crop production. This would lead to a migration wave or career transition for the farmers in Yuli county.

Scenarios of assuming discharge from Alar at 4 billion $m^3$ (reference year 2013), 5 billion $m^3$ (reference year 2011) and 6 billion $m^3$ (reference year 2006) are all simulated, and irrigation water allocation strategies were made accordingly in the entire catchment. By comparing the water allocation strategies, a regular pattern was found in the scenarios. With the increase of discharge in Alar, HS in the upper and middle reaches would take the extra water to alleviate their water deficit firstly. After discharge beyond 6 billion $m^3$, HS in the lower reaches start to largely increase their water consumption. This phenomenon demonstrates water users in the upper and middle reaches have higher priority to mitigate water deficit than the users in the lower reaches.

To keep RWD under 30% and achieve high crop water productivity, water resources are allocated more concentrate on the upper reaches in 2080. More than 53% of the total discharge is planned to be consumed by the upper reaches. This adjustment is also beneficial for the reduction of water losses during transportation.

The model results indicate one possible water allocation strategy for each scenario. There should be many other strategies based on different conditions and goals. On a project point of view, our intention is to optimize water rights based on current practical situation, and endeavor to achieve the goal with less alternations. Moreover, the distributions of actual evapotranspiration are not even across the basin. It is reasonable to allocate more water to areas with lower $ET_a$. Because $ET_a$ is sensitive to climate change, water scarcity, and crop changes, it can be quite effective to provide guidance for water allocation issues if certain rules can be settled and embedded in the model in future researches.

# 5 Decision Support System (DSS) of SuMaRiO

This chapter presents the development of a Decision Support System (DSS) that links the outputs of hydrological models with real-time decision making on social-economic assessments and land use management. The DSS has four remarkable features: (1) editable land use map to assist decision-making; (2) conjunctive use of surface and subsurface water resources; (3) interactions among water, earth, ecosystem and humans (4) links with hydrological models. Discharge and glacier geometry changes were simulated with hydrological model WASA. Irrigation and ecological water were simulated by a new commercial software MIKE HYDRO. Groundwater was simulated by MODFLOW. The DSS bridges the gap between scientific research and IWRM practice.

## 5.1 Content and structure of the DSS

### 5.1.1 Introduction

The DSS is the main output of SuMaRiO project. The expert knowledge and research outcomes from German and Chinese colleges and institutions are integrated into the DSS. All the outputs of other hydrological models are taken as inputs into the DSS in three types of links: regression equations, stationary data inputs, or dynamic data inputs as the models running parallel in the simulation periods. The DSS integrates the hydrological data, geographic data, social and economic statistical data, and establishes the relationships with equations, conditional statements and fuzzy logics. The programming is realized in C++. The overall goal of the DSS is to combine the outputs of scientific models, knowledge of experts, and perspectives of stakeholders, into a computer-based system, which allows Sustainability Impact Assessment (SIA) within regional planning. This SIA will take into account the perspectives of all relevant actors in the problem field of land and water management, to understand Ecosystem Services (ESS) and integrate them into land and water management. Under scenario assumptions, possible actions and their impacts are estimated in a semi-quantitative way with the help of sustainable indicators, which includes climate indicators, socio-economic Indicators, management Indicators, and ESS Indicators. A user-friendly Graphical User Interface (GUI) was developed to assist the decision-makers and common users with various watershed management practices. The GUI can be opened by Qt Creator, which is a commonly used tool to edit, compile, debug and run GUI applications (Rischpater, 2014).

### 5.1.2 Research contents

The interdisciplinary research challenges are clustered in five interrelated Work Blocks (WB): WB1 has the core task on organization with stakeholders and management issues (Figure 5.1), WB2 on regional climate change and discharge of the Tarim River tributaries, WB3 on sustainable water and land use management, WB4 on Ecosystem Services (ESS) and Ecosystem Functions (ESF), and WB5 on multi-level socio-economic assessment of ecosystem services and implementation tools. DSS will identify realizable management strategies, considering social, economic and ecological criteria.

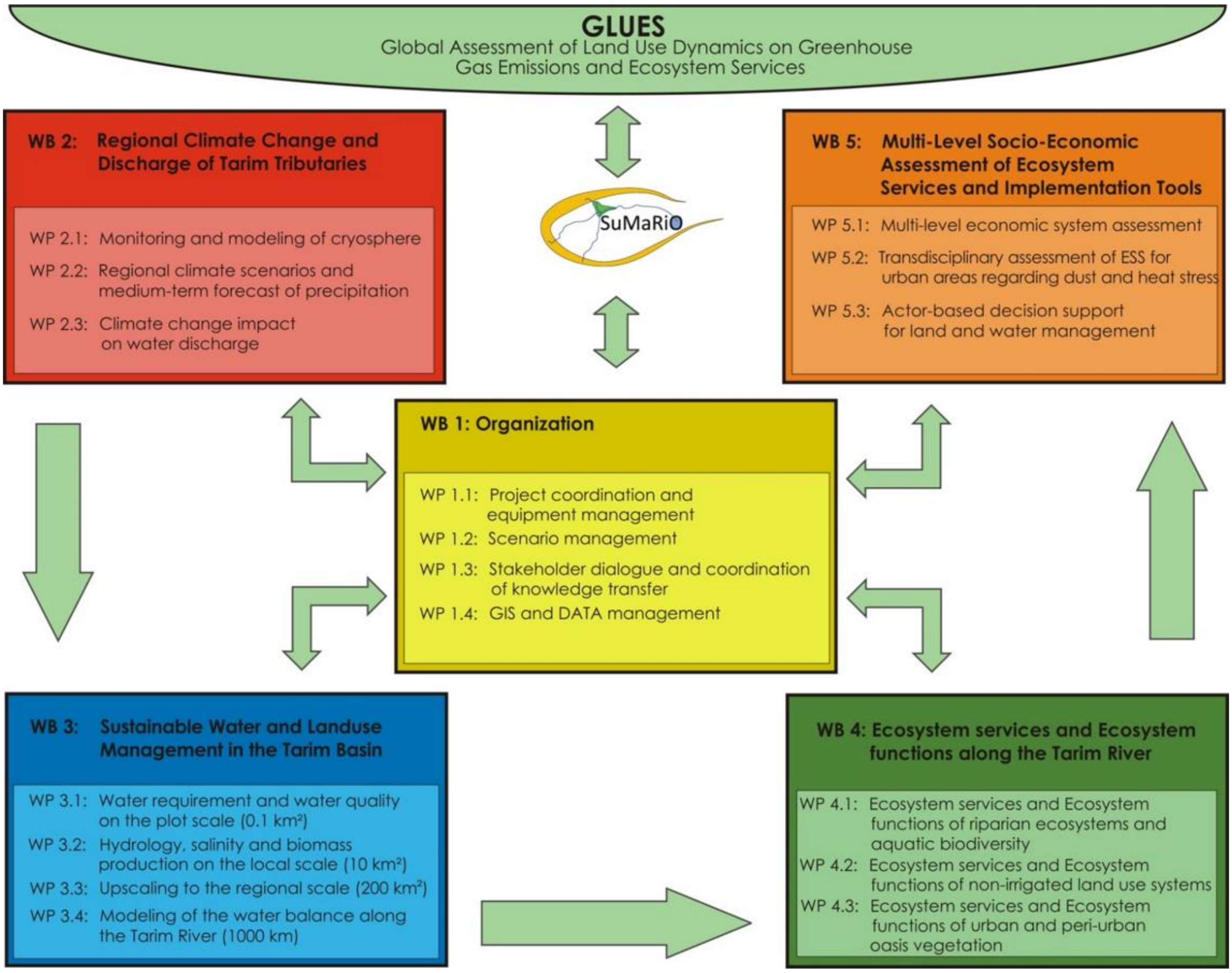



**Figure 5.1:** SuMaRiO work blocks with interdisciplinary research fields (Disse, 2016).

The content of the DSS in detail covers the following aspects in the Tarim River Basin: water resources, climate, biodiversity, demographics, energy consumption and production, poverty and health, economic development, land management, and scenario management (Figure 5.2). A number of theses research fields involve more than one WB, and thus need expert knowledge from interdisciplinary cooperation.

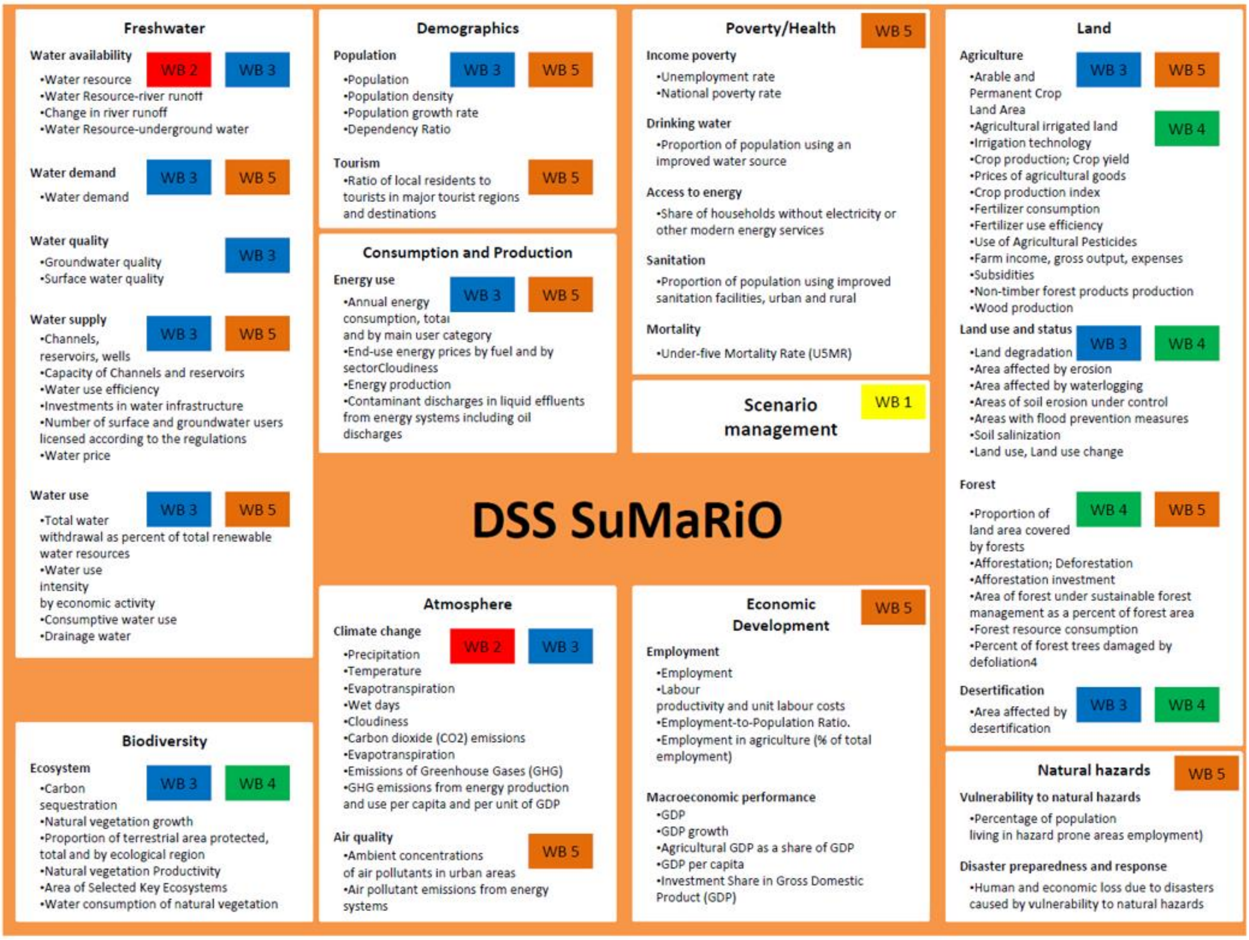



**Figure 5.2:** Research content of DSS in SuMaRiO project (Disse, 2016).

### 5.1.3 Indicators of the DSS

Under scenario assumptions, possible actions and their impacts are estimated in a quantitative way with the help of different indicators. Climate indicators, socio-economic Indicators and management Indicators are input indicators, and ESS Indicators are output indicators (Table 5.1). Input indicators give users opportunities to change the scenario on the baseline or perspective in the planning years, and output indicators demonstrate the simulation results caused by the alternatives.

**Table 5.1:** Input and output indicators of the DSS.

| | | | |
|---|---|---|---|
| **Input Indicators** | **Climate Indicators** | | |
| | Temperature rising [°C] | | |
| | Precipitation increase [%] | | |
| | **Socio-economic Indicators** | | |
| | Cotton production costs [RMB/ha] | | |
| | Average costs for the production of fruits [RMB/ha] | | |
| | Average costs for the production of other crops [RMB/ha] | | |
| | Cotton price [RMB/t] | | |
| | Average price of fruits [RMB/t] | | |
| | Average price of other crops [RMB/t] | | |
| | **Management Indicators** | | |
| | Drip irrigation share in total agricultural irrigation area [%] | | |
| | Subsidy for drip irrigation [RMB/ha] | | |
| | Household and Industry water allocation [%] | | |
| | Flooding of natural vegetation [%] | | |
| **Output Indicator** | **Ecosystem** | **Ecosystem Services** | **ESS Indicators** |
| | Agriculture | PS | Cotton production [million t] |
| | | PS | Fruit production [million t] |
| | | PS | Production of other crops [million t] |
| | | PS | Farmers income [million RMB] |
| | Riparian Forest | PS | Biomass production [million t] |
| | | RS | Drifting dust control by riparian forest [kg] |
| | | RS | Sand mobilization control by riparian forest [million t] |
| | | RS | Wind control [Attenuation in % at 2 m height] |
| | | RS | Carbon storage [million t] |
| | | SS | Mean Species [number] |
| | Grassland | PS | Apocynum production [million t] |
| | | PS | Reed production [t] |
| | | RS | Drifting dust control by grassland [kg] |
| | | RS | Sand mobilization control by grassland [million t] |

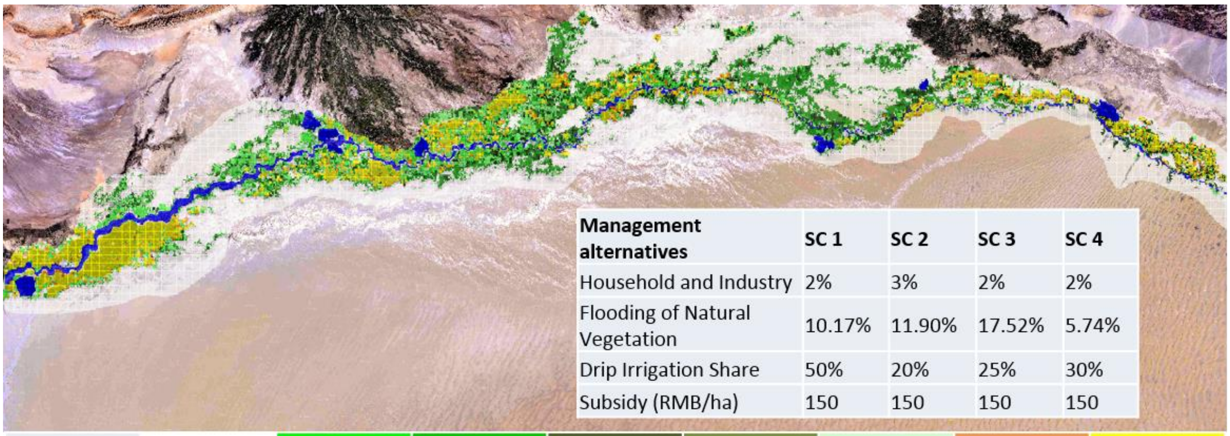
*For Ecosystem Services, PS: Provisioning Services, RS: Regulating Services, SS: Supporting Services.

User can define the inputs of DSS according to the reference values, possible ranges and certain rules. Simulation years can be chosen from 2012 to 2050. Baseline year is 2012. Near future and far future years are 2030 and 2050 respectively, where users can change their perspectives on the input indicators.

Based on different temperature rise and precipitation change projections, four climate scenarios (A1B, RCP2.6, RCP4.5 and RCP8.5) can be selected by users. Yearly temperature rise and precipitation increase are nonlinear. The climate projections are based on nine global climate models (GCMs), two regional climate models (RCMs), and under different emission scenarios (Duethmann et al., 2016).

Socio-economic indicators include costs for running cotton, costs for running fruits, and costs for running other crops, selling price of cotton, selling price of fruits, and selling price of other crops. Reference values are given by the knowledge of experts in SuMaRiO research group. Users can change the values on 2012, 2030 and 2050 based on their own knowledge and perspectives. The yearly values in between these years will be in linear relationships.

Management indicators contain household and industry, flooding of natural vegetation, drip irrigation share, and subsidy for the farmers in the four sub-catchments (Figure 5.3). Users can change the reference values on the management alternatives in the planning years. Reference values of drip irrigation share are 50%, 70% and 90% in 2012, 2030 and 2050 respectively. Any combination of the input values defined by the users should be possible. Seven land use types are depicted in the editable map, with reference land use map generated from MODIS data in 2012.



| Management alternatives | SC 1 | SC 2 | SC 3 | SC 4 |
|---|---|---|---|---|
| Household and Industry | 2% | 3% | 2% | 2% |
| Flooding of Natural Vegetation | 10.17% | 11.90% | 17.52% | 5.74% |
| Drip Irrigation Share | 50% | 20% | 25% | 30% |
| Subsidy (RMB/ha) | 150 | 150 | 150 | 150 |

| Land use | Unused Land | Grassland | Natural Vegetation | Riparian Forest High Density | Riparian Forest Low Density | Urban Vegetation | Other Agriculture | Cotton |
|---|---|---|---|---|---|---|---|---|
| Share | 61.34% | 3.01% | 4.90% | 9.53% | 5.22% | 0.09% | 1.84% | 9.79% |

**Figure 5.3:** Management alternatives. Editable land use map is included to change land use types on the planning years.

Another type of inputs that can be defined are goals and weights. Agriculture can provide provisioning services, including cotton production, fruit production, production of other crops, and farmers' income. Riparian forest has provisioning services (biomass production), regulating services (drifting dust control by riparian forest, sand mobilization control by riparian forest, wind control, and carbon sequestration), and supporting services (tree species). Grassland is considered to have provisioning services

(Apocynum production and reed production) and regulating services (drifting dust control by grassland and sand mobilization control by grassland).

Users can define the goals for these ESS indicators (e.g. make the cotton production goal at 0.2 million ton by the end of simulation period in the first sub-catchment). After the simulation, the results of utility values (range from 0 to 1) would indicate how much the goal can be fulfilled. If the utility value is 1, then it means the goal can be fully achieved. The weights (range from 1 to 5, with 5 means the highest importance) can also effect the final utility values. For instance, the provisioning services of grassland is comprised of Apocynum production and reed production. Apocynum production is considered very important and has a weight of 5, and reed production is regarded not important and has a weight of 1. If Apocynum production goal is fully achieved and reed production goal is accomplished by only a small portion, the final utility value of provisioning services by grassland will be higher than the case they both have a weight of 5.

## 5.2 Logics and links in the DSS

Logics and links provide the relationships of the different parameters and values in the DSS. Editions on these parameters and relationships can be conducted in Qt Creator. The DSS is programmed with C++.

In general, the items in the DSS are firstly calculated cell by cell, then the cell numbers are counted for a specific item (e.g. how many cells is cotton), and finally the aggregated values are presented as outputs.

### 5.2.1 Logics of the DSS

Equations, conditional statements, and fuzzy logic consist the three logical relationships which connects the parameters in DSS.

5.2.1.1 Equations

To build the relationships among the parameters in DSS, equations are formed by expert knowledge, theorem, empirical equations and literature findings. Several examples are given in the following text.

Due to the absence of industry in the region, water consumption from the river is comprised of domestic, flooding of natural vegetation, irrigation water use and water losses. Inflow of the first sub-catchment is given by WASA depending on the climate scenarios. Because no bifurcation exists in the mainstream Tarim River, inflows into the sub-catchments are calculated in a simple way each month by Equation (5.1).

$$Q\,(n+1) = Q\,(n) - Q\,(n) * P\,(\text{domestic}) - Q\,(n) * P\,(\text{flood}) * k - IW * 0.9964 \qquad (5.1)$$

Where $\mathrm{Q}\,(\mathrm{n}+1)$ is inflow into the next sub-catchment ($m^3$), $\mathrm{Q}\,(\mathrm{n})$ is inflow of the current sub-catchment ($m^3$), $\mathrm{P}\,(\mathrm{domestic})$ is interpolated ratio of domestic water use, $\mathrm{P}\,(\mathrm{flood})$ is interpolated ratio of flooding of natural vegetation, $\mathrm{k}$ is flood distribution over the month, and IW is irrigation water demand of current sub-catchment ($m^3$).

Cotton production is calculated cell-by-cell, then aggregated in sum for the DSS output.

$$Y_\mathrm{c} = \left[1 - K_\mathrm{y}\left(1 - \frac{ET_\mathrm{a}}{ET_\mathrm{c}}\right)\right] * Y_\mathrm{m} * \mathrm{m}/100 \tag{5.2}$$

where $Y_\mathrm{c}$ is cotton production in each cell (t), $ET_\mathrm{c}$ is influenced by crop factors and derives Penman-Monteith method, $ET_\mathrm{a}$ is calculated by MIKE HYDRO, which identified the actual rate of crop evapotranspiration under the effects of soil water stress, $Y_\mathrm{m}$ is the maximum harvest yield (kg), m is cotton production distribution over months (%) and $K_\mathrm{y}$ is the yield response factor representing the effect of reduction in evapotranspiration on lost yield. $K_\mathrm{y}$ values were obtained from FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979).

The outputs of the MIKE HYDRO were summarized and integrated into monthly or yearly values in the sub-catchment, then provided as time series data inputs or regression functions in the DSS. If MIKE HYDRO had internal link with the DSS, then the regression functions are not necessary. It is possible that more hydrological models could be coupled with the DSS in future, but currently a number of difficulties still exist. One problem is that MIKE HYDRO and the DSS have different simulation periods. MIKE HYDRO simulates the past years and requires a lot of measured data, but the DSS focus on the future years until 2050. Another problem is on the spatial resolution. The simulation of MIKE HYDRO is on SC level or HS level, while the DSS is simulated on cell level. This difference would require a number of spatial upscaling and downscaling methods, and the computational complexity would be largely increased. Because crop module in the MIKE HYDRO is difficult to be embedded in the DSS, irrigation water demand in the DSS is a linear regression function by the results from MIKE HYDRO model outputs. The regression function is made with the continuous six years from 2008 to 2013, with coefficient of determination at 0.94. However, the uncertainty is large outside of the six-year period.

$$\mathrm{A(WD)} = [182 + 860 * \mathrm{A\,(CA)} - 312 * \mathrm{DIS} + 619 * \mathrm{S(C)} - 716 * \mathrm{S(F)}] * \mathrm{f\,(i)} \tag{5.3}$$

Where A(WD) is aggregated irrigation water demand ($m^3$), A(CA) is aggregated crop area (ha), DIS is drip irrigation share in the farmlands (%), S(C) is cotton share in the farmlands (%), S(F) is fruit share in the farmlands (%), f (i) is the fraction of irrigation water distribution over months (%).

Biomass production is also calculated in the DSS with the following Equation (5.4).

$$\mathrm{BP} = \frac{\left[10^{\log(0{,}0382)+(0{,}8837*\log(\mathrm{DBH}*\mathrm{ht}))} + 10^{\log(0{,}1072)+(0{,}635*\log(\mathrm{DBH}*\mathrm{ht}))}\right] * \mathrm{Nm}}{1000 * \mathrm{Db}} \qquad (5.4)$$

where BP is biomass production of riparian forest of cell (t/ha), DBH is diameter at breast height of the tree (m), ht is tree height of cell (m), Nm is mean number of trees per ha in high density cell (number/ha), Db is distribution of biomass production each year (%).

After the calculations in cells, the items are aggregated together to provide outputs. The aggregated values are normally calculated in the whole basin, with some values calculated in the sub-catchments.

$$\mathrm{A(BP)} = \mathrm{BP} * \mathrm{Nr} * \mathrm{a} \qquad (5.5)$$

where A(BP) is aggregated biomass production by riparian forest (t), Nr is number of riparian forest cells, a is the cell size ($m^2$).

$$\mathrm{Ui} = \min\{(\mathrm{Ri} - \mathrm{Mi})/(\mathrm{Gi} - \mathrm{Mi}), 1\} \qquad (5.6)$$

where Ui is utility value of an indicator, Ri is result value of the indicator after DSS simulation, Mi is minimum value of the indicator, Gi is goal value of the indicator. At the input stage of the DSS, users can define the goals of ESS indicators. After the simulation, utility values represent how much the goals can be achieved each year. Therefore, Ui is an important indicator for the evaluation of ESS performance in the planning years. Farmer's total income is calculated by the aggregated yearly numbers in Equation (5.7).

$$\mathrm{FI} = \mathrm{A(CP)} + \mathrm{A(FP)} + \mathrm{A(OC)} - \mathrm{C(RC)} - \mathrm{C(RF)} - \mathrm{C(RO)} + \mathrm{DI} * \mathrm{S(DI)} \qquad (5.7)$$

where FI is farmers' income (RMB), A(CP) is aggregated cotton income (RMB), A(FP) is aggregated fruit income (RMB), A(OC) is aggregated income of other crops (RMB), C(RC) is aggregated cost of running cotton (RMB), C(RF) is aggregated cost of running fruits, C(RO) is aggregated cost of running other crops (RMB), DI is the aggregated drip irrigation area (ha), S(DI) is the subsidy for drip irrigation (RMB/ha).

The equations have built up the links among the different parameters in the DSS. They play an important role in the logical relationships.

5.2.1.2 Conditional statements

The knowledge of experts are used to formulate the 'if-then' rules to solve modeling problems. Such conditional constructs perform different computations on whether a condition is evaluated to be true or false. Conditional statement is a convenient method if the rules are clear and homogeneous. Three examples are given as follows.

For a grassland cell, if groundwater level is lower than -5 m in 9 months each year and over 7 years, then land use type of the cell will become unused land in the next year.

For a high density riparian forest cell, if groundwater level is lower than -10 m in 9 months a year and over 7 years, then grid cell will become riparian forest with low density in the next year.

For a low density riparian forest cell, if groundwater level is lower than -10 m in 9 months a year and over 7 years, then grid cell will become unused land in the next year.

5.2.1.3 Fuzzy logic

In the DSS, some relationships cannot be precisely expressed as equations or conditional statements, a useful method under such circumstance is called fuzzy logic. Fuzzy logic is a logical approach to deal with uncertainty management (Zadeh, 1983). Elements have degrees of membership in the fuzzy set. Membership functions represent the degrees of truth in vaguely defined sets. Unlike possibilities or conditions, the truth values of variables may be any real number between 0 and 1. Take groundwater level for instance, groundwater level is considered at the low level between -7 and -4 m, medium level between -4.5 to -3.5 m, and high level between -2 to 0 m. There are some overlapping zones in between. From -4.5 to -4 m, groundwater level can either be regarded at low or medium level, but the membership degree of low level is decreasing and the membership degree of medium level is increasing. The final result would be determined by fuzzy rules with the probability of the elements (degree of membership) in the membership function (Figure 5.4).

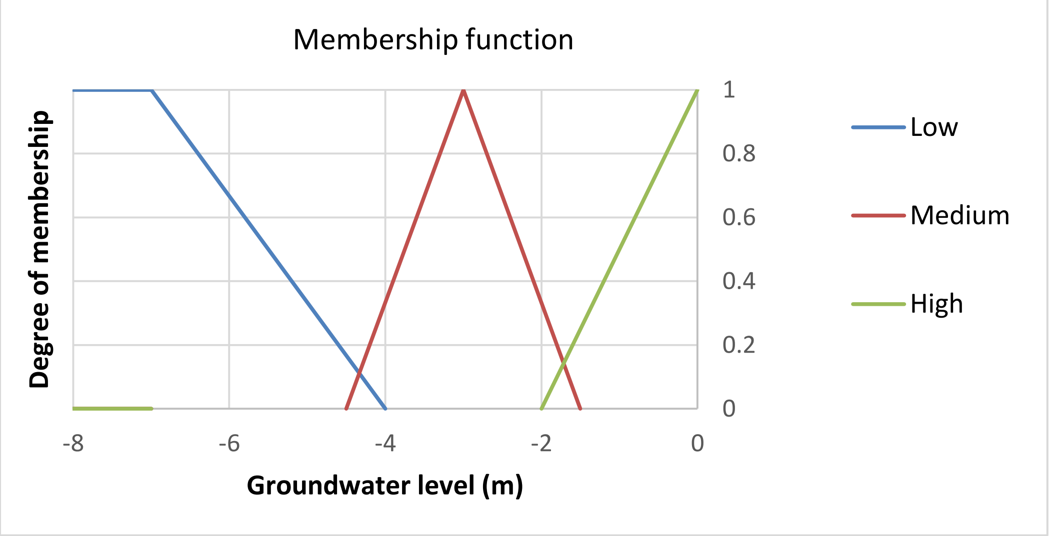



**Figure 5.4:** Membership function of groundwater level.

For the membership function of flooding days, low level is less than 60 days each year. Medium level is within 120 days. So flooding days between 0 and 60 can either be low level and medium. For instance, if flooding is 30 days in a year, it can be regarded as in the middle of low and medium level. Below 30 days, the probability (degree of membership) of low level is higher. Above 30 days, the probability (degree of membership) of medium level is higher. The final result will be decided by the fuzzy rules and probabilities (Figure 5.5). Flooding for more than 120 days each year is regarded as high level of flooding.

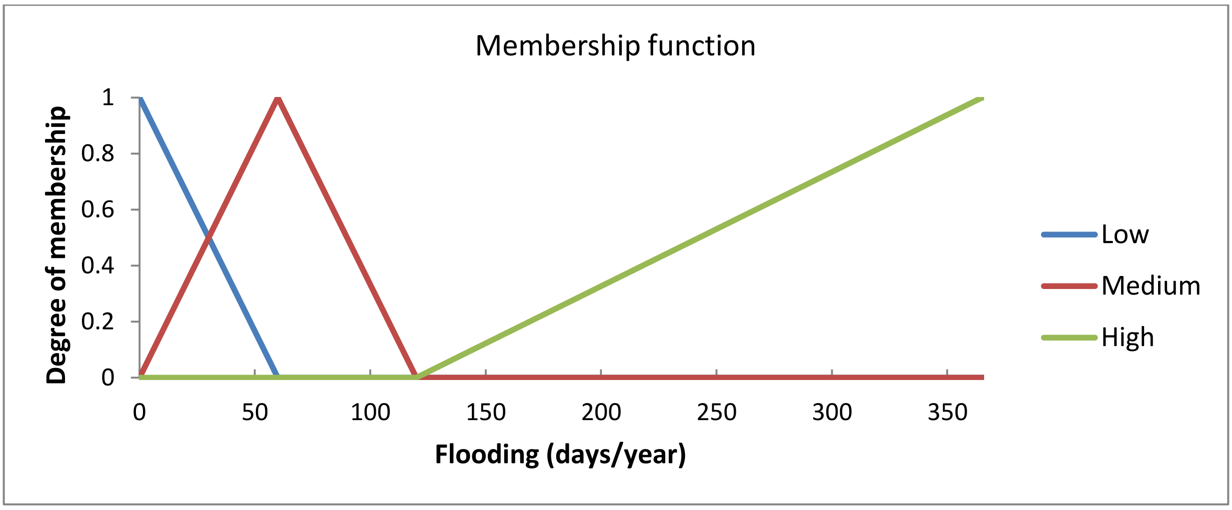



**Figure 5.5:** Membership function of flooding (days/year).

Average tree height is calculated every simulation year in each riparian forest cell. Because tree height is mainly dependent on groundwater level, as long as groundwater level remains stable each year, tree height in each cell would not be largely changed. Fuzzy logic of tree height, which is determined by groundwater level and flooding, is demonstrated in Table 5.2.

**Table 5.2:** Fuzzy logic of tree height.

| | | | | | |
|---|---|---|---|---|---|
| Membership function for tree height (m) | | | | | |
| Status | Left bound | Middle | Right bound | | |
| Low | 3 | | 5 | | |
| Medium | 5 | 7 | 12 | | |
| High | 12 | | 20 | | |
| Fuzzy rules for tree height | | | | | |
| Rules | Groundwater level (m) | | Flooding (days/year) | | Tree height (m) |
| If | High | and | High | then | High |
| If | Low | and | Low | then | Low |
| If | Medium | and | Medium | then | Medium |
| If | High | and | Medium | then | High |
| If | Medium | and | High | then | Medium |
| If | Low | and | High | then | Medium |
| If | High | and | Low | then | Medium |

Because groundwater level is crucial for the growing of the riparian forest, tree height is considered at high level only if the groundwater level is high. Summer flooding also influence the growth of the trees, so if flooding is at low level, tree height will be medium level even groundwater level is high. If groundwater level is low and flooding is also low, then tree height will be decided on the low level. In other cases, tree height will be on the medium level.

Average crown area is calculated every simulation year in each riparian forest cell. Fuzzy logic of crown area, which is determined by groundwater and flooding, is illustrated in Table 5.3.

**Table 5.3:** Fuzzy logic of crown area.

| Membership function for crown area ($m^2$) | | | | | |
|---|---|---|---|---|---|
| Status | Left bound | Middle | Right bound | | |
| Low | 2 | | 6 | | |
| Medium | 5 | 7 | 12 | | |
| High | 10 | | 20 | | |
| Fuzzy rules for crown area ($m^2$) | | | | | |
| Rules | Groundwater level (m) | | Flooding (days/year) | | Crown area ($m^2$) |
| If | High | and | High | then | High |
| If | Low | and | Low | then | Low |
| If | Medium | and | Medium | then | Medium |
| If | High | and | Medium | then | High |
| If | Medium | and | High | then | Medium |
| If | Low | and | High | then | Medium |
| If | High | and | Low | then | Medium |

Similar to tree height, crown area is also dependent on groundwater and flooding. If groundwater is not at low level and flooding is high, then crown area will be on high level. On the contrary, if groundwater and flooding is on low level, then crown area will be at low level. In other cases, crown area will be on the medium level.

Fuzzy logic of drifting dust control by riparian forest, which is determined by crown area and tree height, is illustrated in Table 5.4. The fuzzy rules are different regarding the drifting dust control by high density and low density riparian forest. The fuzzy logic of drifting dust control by high density and low density riparian forest is a function determined by tree height and crown area. For low density forest, no matter the tree height and crown area, the drifting dust control ability is considered on the low level.

**Table 5.4:** Fuzzy logic of drifting dust control by high density and low density riparian forest.

| Membership function for drifting dust control by riparian forest (kg/ha) | | | | | |
|---|---|---|---|---|---|
| Status | Left bound | Middle | Right bound | | |
| Low | 0 | | 0.0000033 | | |
| Medium | 0.0000033 | 0.0000042 | 0.0000058 | | |
| High | 0.0000067 | | 0.0000083 | | |
| Fuzzy rules for drifting dust control by riparian forest high density | | | | | |
| Rules | Crown area ($m^2$) | | Tree height (m) | | Drifting dust control by riparian forest high density (kg/ha) |
| If | High | and | High | then | High |
| If | Low | and | Low | then | Medium |
| If | Medium | and | Medium | then | High |
| If | Low | and | Medium | then | High |
| If | Medium | and | Low | then | High |
| Fuzzy rules for drifting dust control by riparian forest low density | | | | | |
| Rules | Crown area ($m^2$) | | Tree height (m) | | Drifting dust control by riparian forest low density (kg/ha) |
| If | High | and | High | then | Low |
| If | Low | and | Low | then | Low |
| If | Medium | and | Medium | then | Low |
| If | High | and | Medium | then | Low |
| If | Medium | and | High | then | Low |

The fuzzy logic of tree species is dependent on groundwater level and flooding (Table 5.5).

**Table 5.5:** Fuzzy logic of tree species.

| Membership function for tree species (number) | | | | | |
|---|---|---|---|---|---|
| Status | Left bound | Middle | Right bound | | |
| Low | 0 | | 2 | | |
| Medium | 2 | 3 | 5 | | |
| High | 5 | | 14 | | |
| Fuzzy rules for tree species | | | | | |
| Rules | Groundwater level (m) | | Flooding (days/year) | | Species |
| If | Low | and | Low | then | Low |
| If | Medium | and | Medium | then | Medium |
| If | High | and | High | then | High |
| If | High | and | Low | then | High |
| If | Low | and | High | then | Medium |
| If | High | and | Medium | then | High |

If groundwater level is on high level, no matter flooding is high or low, tree species will be on high level. If groundwater level and flooding are both on low level, the tree species will be low. In other cases, tree species will be on medium level.

Groundwater salinity is an important factor for the reed production. Membership function of groundwater salinity is shown in Figure 5.6, with a low level between 1 and 2 g/l, medium level between 0 and 4 g/l, and high level between 2 to 6 g/l.

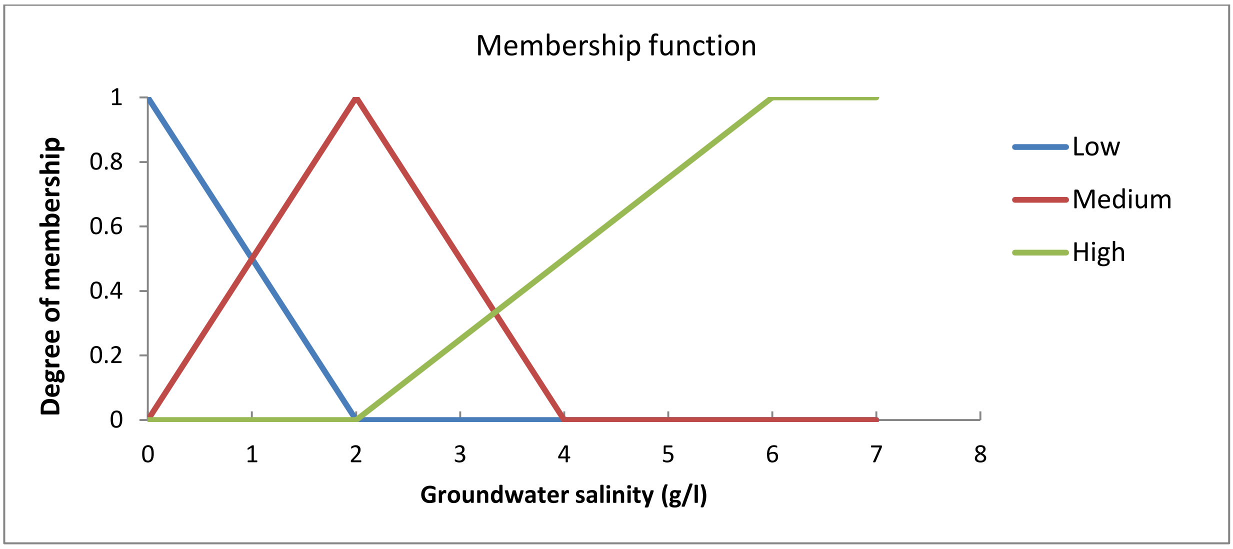



**Figure 5.6:** Membership function of groundwater salinity (g/l).

The fuzzy logic of reed production is dependent on the fraction of yearly growth by reed, groundwater level and groundwater salinity. Since the yearly growth of the reed is quite different, monthly fractions of the growth is considered in the DSS (Figure 5.7).

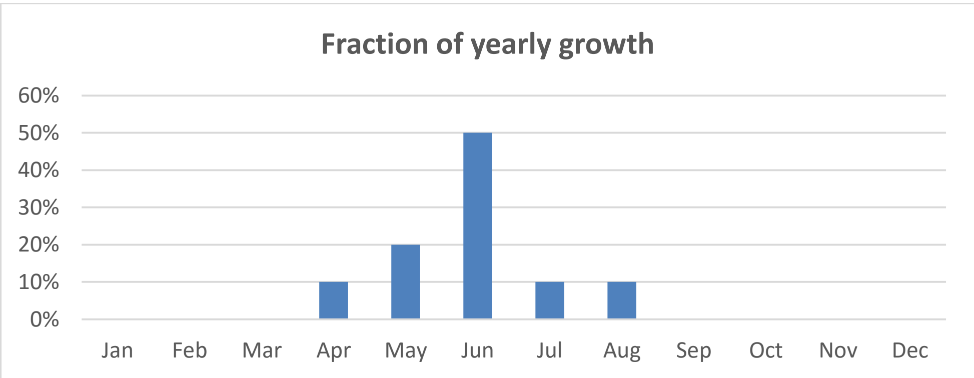



**Figure 5.7:** Fraction of reed yearly growth.

The yearly reed production is determined by fuzzy rules of groundwater level and groundwater salinity (Table 5.6).

**Table 5.6:** Fuzzy logic of reed production dependent on groundwater level and groundwater salinity.

| Membership function for reed production (t/ha) | | | |
|---|---|---|---|
| Status | Left bound | Middle | Right bound |
| Low | 0 | | 2 |
| Medium | 2 | 3,5 | 5 |
| High | 5 | | 10 |

| Rules | Groundwater level (m) | | Groundwater salinity (g/l) | | Reed production (t/ha) |
|---|---|---|---|---|---|
| If | High | and | Low | then | High |
| If | High | and | Medium | then | High |
| If | Medium | and | Low | then | High |
| If | Medium | and | Medium | then | Medium |
| If | Low | or | High | then | Low |
| If | High | and | High | then | Medium |
| If | Medium | and | High | then | Low |
| If | Medium | or | High | then | Low |

Fuzzy logic is an effective measure to build up relationships when precise numbers are not available for some parameters, and the values are within a reasonable range. In the meantime, the fuzzy rules also cause some uncertainties, which will be discussed in chapter 6.

### 5.2.2 Links with other Hydrological models

Discharge and glacier geometry changes were simulated with hydrological model WASA (Güntner and Bronstert 2004). The calibration and evaluation of the model were conducted in the headwater catchments of Tarim River (Duethmann et al., 2015). WASA provides daily discharge input into the DSS. Four types of climate scenarios were included in DSS: CCLM RCP 2.6, CCLM RCP 4.5, CCLM RCP 8.5, and REMO A1B.

For the surface flow, hydrological model MIKE HYDRO (Yu et al., 2015) provides inputs for DSS on a catchment level. The sub-catchments (SC) of DSS and MIKE HYDRO are the same, with Alar-Xinqiman (SC1), Xinqiman-Yingbaza (SC2), Yingbaza-Qiala (SC3), and Qiala-Taitema Lake (SC4). The irrigation water demand was simulated in MIKE HYDRO and a regression function was generated for the DSS calculations. Ecological water for the natural vegetation, seepage losses, fruit production, and crop yields were calculated and summarized as inputs into DSS.

For the groundwater simulation, a MODFLOW model was computed with internal links to DSS on a 500 × 500 m cell level. MODFLOW is running parallel with DSS in the simulation. The daily water head of each cell is simulated in MODFLOW, then updates the cells in DSS. Groundwater recharge is considered via four different sources: river leakage, irrigation water seepage, infiltration during flood season and ecological water percolation in the lower reaches.

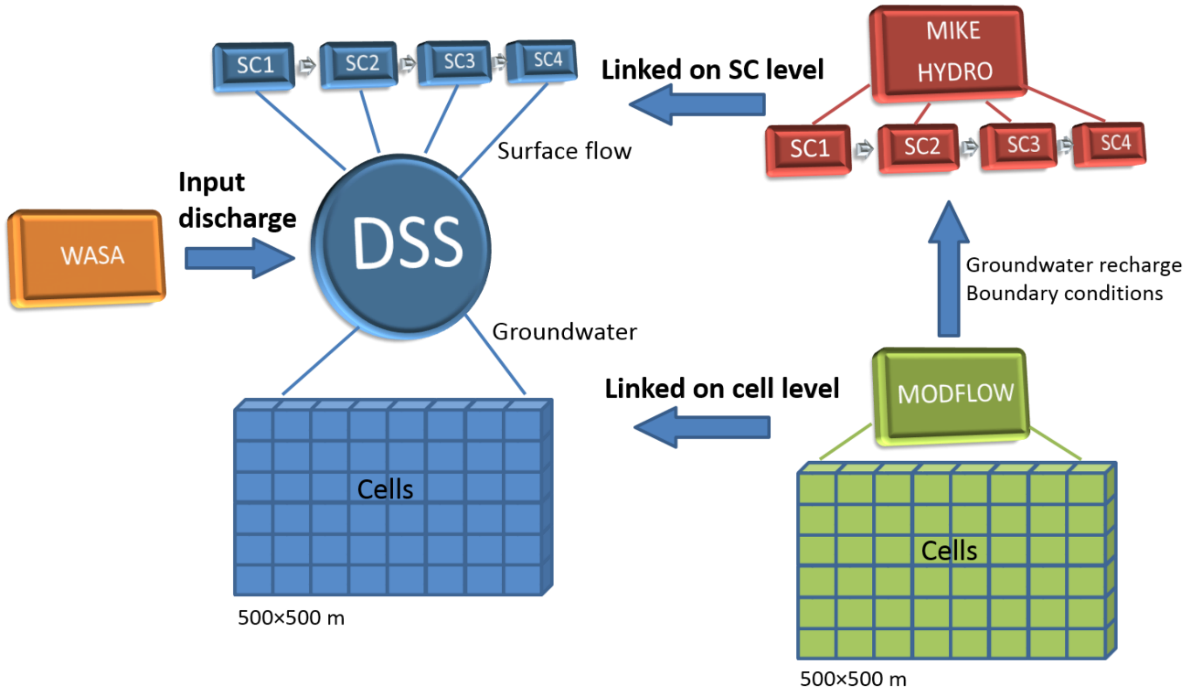



**Figure 5.8:** Hydrological models linked with DSS. WASA provides discharge. MIKE HYDRO provides water consumption and water balance. MODFLOW runs parallel with DSS on groundwater simulations.

It is a challenge to find the links between the DSS and other models. The key issue is that the outputs of different models are not uniform as for the input into the DSS. The parameter sets and their relationships vary largely from model to model. The outputs of different models can either serve as stationary data inputs, regression equations, or dynamic data inputs into DSS as the models running parallel in the simulation periods.

As MIKE HYDRO linked with DSS on the sub-catchment level, data and equations are bridging the two models. MIKE HYDRO provides simulation results of ecological water for the natural vegetation in the upper and middle reaches in the DSS. Crop productions are linked by yield equations calculated from evapotranspiration. Seepage losses were calculated in MIKE HYDRO and aggregated in monthly values into DSS. Irrigation water consumptions were distributed in MIKE HYDRO and integrated on sub-catchment level in the DSS (Figure 5.9).

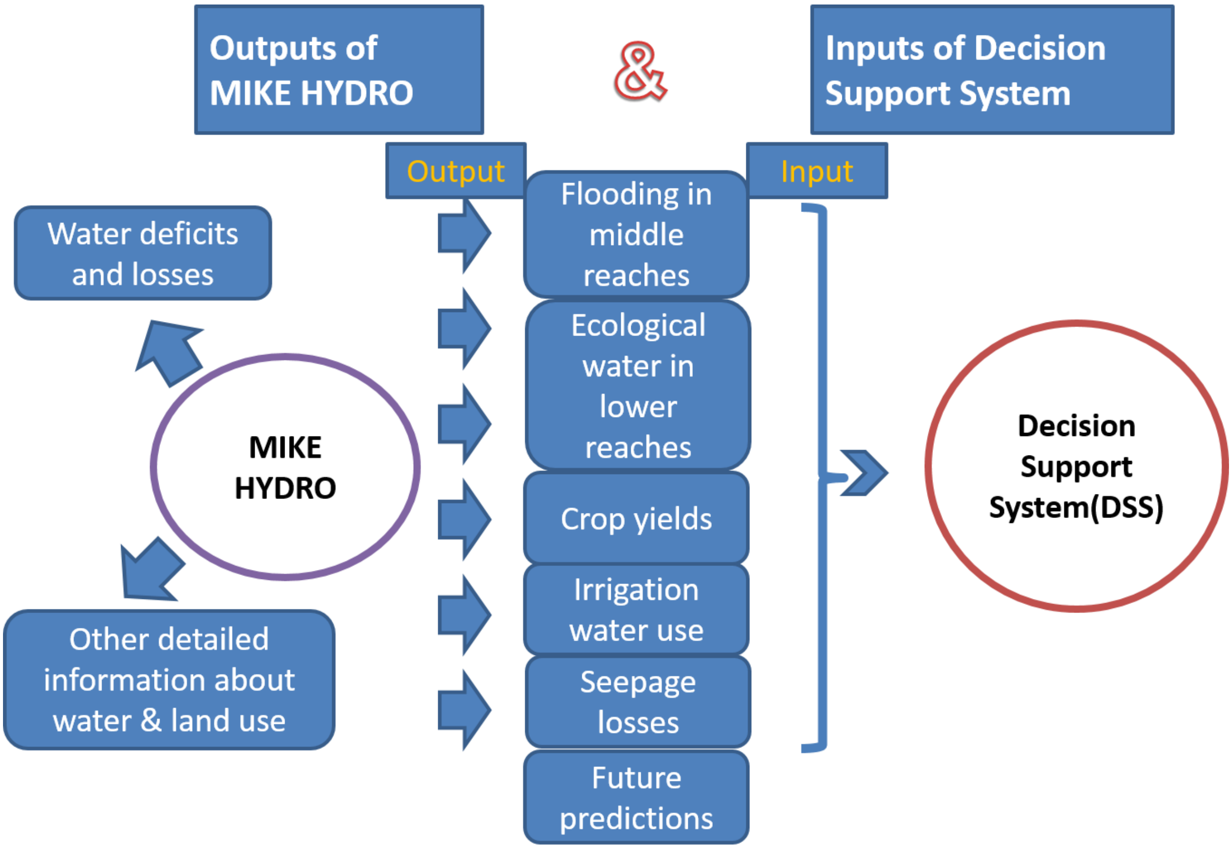



**Figure 5.9:** Links between MIKE HYDRO and the DSS. The irrigation water demand, flooding for the natural vegetation, ecological water in the lower reaches, seepage losses, fruit production, and crop yields were calculated and summarized as inputs into the DSS.

Particularly, MODFLOW has internal links with DSS. AS the same delineation on the cell level, both models are running parallel in the simulation periods. At the beginning of each year, water heads from MODFLOW results are updating the groundwater levels in the DSS. So far it is enough for the MODFLOW to update water heads of the DSS on a yearly basis, because the logics and outputs of the DSS are mainly on yearly values. The calculations would not be largely affected if updating the water heads on monthly values, and computational time would be largely reduced by yearly updates. Groundwater plays a crucial role in the ecosystem, and has large influence on a number of output indicators in the DSS. Groundwater movements and boundary conditions are very important for the water balance.

## 5.3 Graphical User Interface (GUI) of the DSS

A user-friendly Graphical User Interface (GUI) was developed to assist the decision-makers and common users (Figure 5.10), with Chinese and English versions available at the moment. Labels and instructions allow users interact with the DSS more conveniently. The input indicators have default values, acquired from database, literature and expert knowledge. Calculation years start from 2012 to 2050. The land use map is editable as well in the baseline year, to assist decision-making on land use changes. The GUI is designed to be user-friendly so that more stakeholders and scientists could get involved in using and improving the model. The implementation of DSS bridges the gap between research and practice through interviews, workshops, and feedbacks.

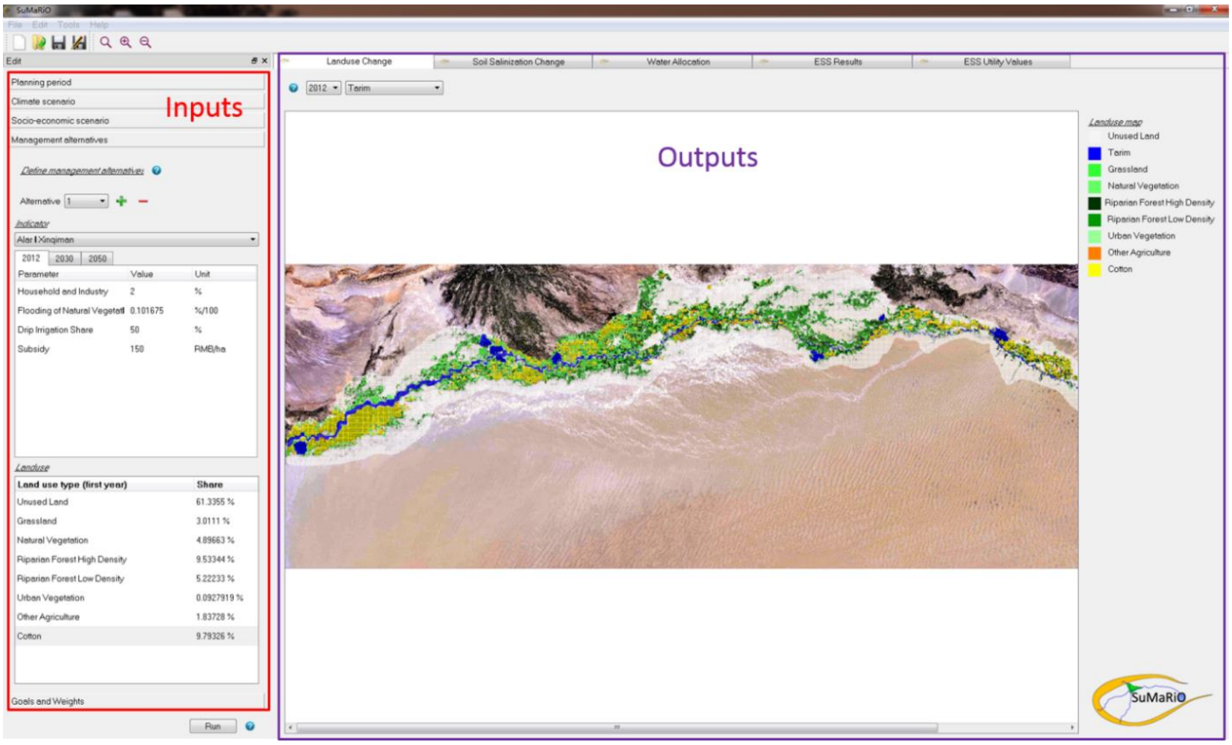



**Figure 5.10:** Graphical User Interface (GUI) of the DSS. User-friendly with labels, instructions, and default values of all the input indicators.

In the GUI, users can freely change the values of input indicators, including planning period (from 2012 to 2050), climate scenarios (A1B, RCP2.6, RCP4.5 and RCP8.5), socio-economic factors, and goals and weights in the management alternatives. In particular, land use changes are editable by clicking cells in the GUI. Because many output indicators are calculated by aggregating the values in the cells, if the land use types are changed in the cells, the outputs would be changed accordingly.

## 5.4 Results and discussions

### 5.4.1 Land use changes

Users can freely change the input land use patterns. For instance, by clicking the cells in the GUI, a new cotton area can be added, or a grassland area can be changed into forest. In this trial, land use types are remained as they were in the default map which acquired from MODIS data. The baseline year is 2012, and all the values of input indicators are kept as default values. Climate scenario is A1B. Year 2030 and 2050 are the planning years, which indicate land use changes in the near and far future (Figure 5.11).

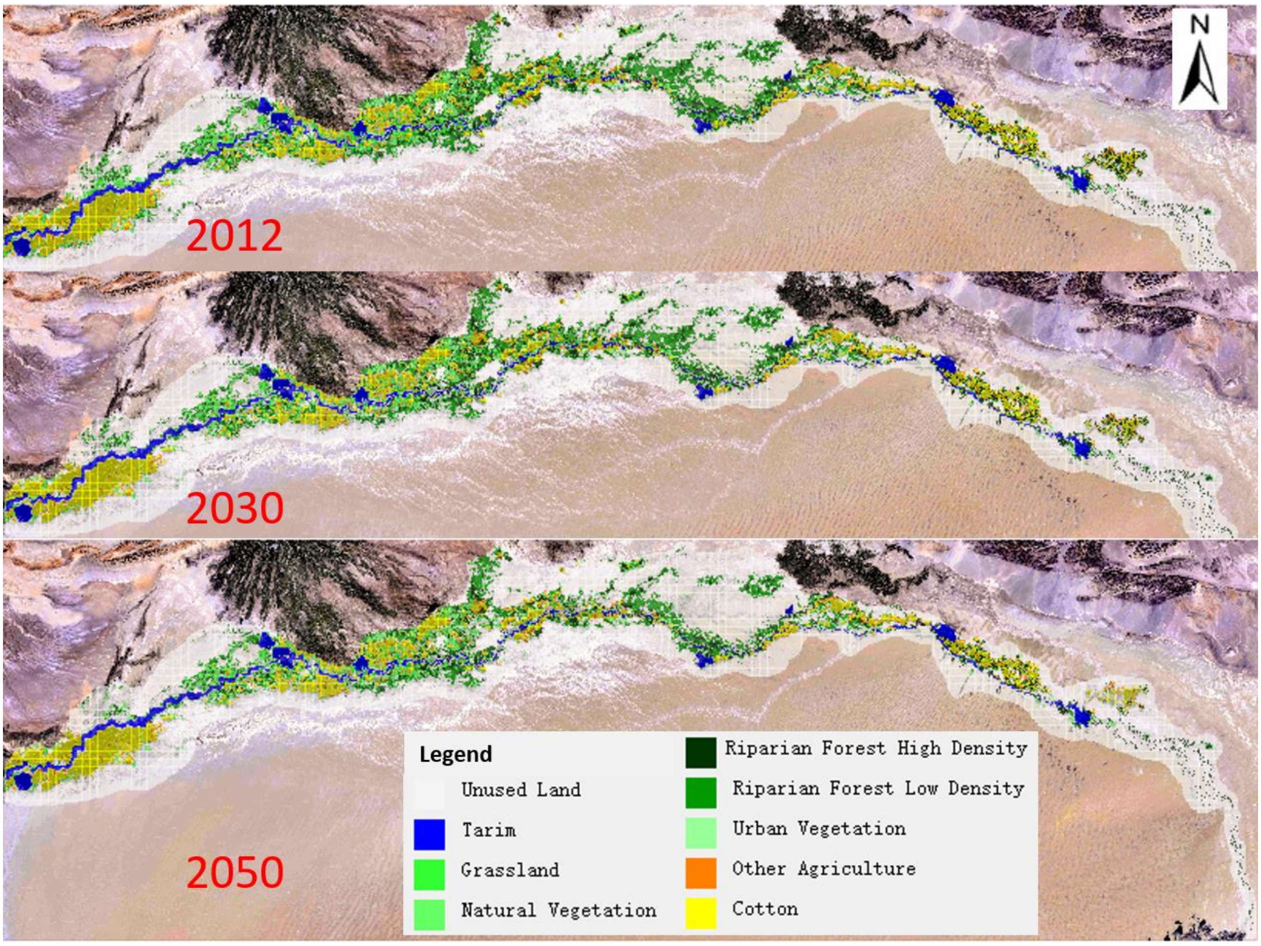



**Figure 5.11:** Land use changes from 2012, 2030 to 2050.

Grassland, natural vegetation and forest will suffer varying degrees of deterioration in the near and far future if the scenario is kept business as usual. In the upper, middle and lower reaches, the decay of green areas are obvious. Similar results were shown by latest findings (Liu et al., 2016; Xiao et al., 2016). Because of the low precipitation and flow rate in the dry season, vegetation are dependent on summer flood and groundwater. Additionally, riparian forests are gradually vanished in some regions by 2050, especially in the middle reaches. Since cotton and other agricultural fields are determined by anthropogenic activities, farmland area remain unchanged throughout the simulation period. However, the consequences of farmland changes can be revealed by output indicators if a user changes the land use types in the first place.

In the middle reaches, where riparian forest (mostly *Populus euphratica*) is mainly growing, forest degradation is severe by 2050 (Figure 5.12). In several hotspots, riparian forest areas have substantially dwindled or even faded away. Theses hotspots are all located on the northern side of the river. Groundwater recession is the reason for forest decay in the model, as deforestation has been prohibited along the river oases. Continuous low groundwater level for more than 7 years is considered fatal to the forest. The correlations between groundwater and *Populus euphratica* were also discussed by Thomas (Thomas et al., 2016), who made further discussions on the threats for these precious trees.

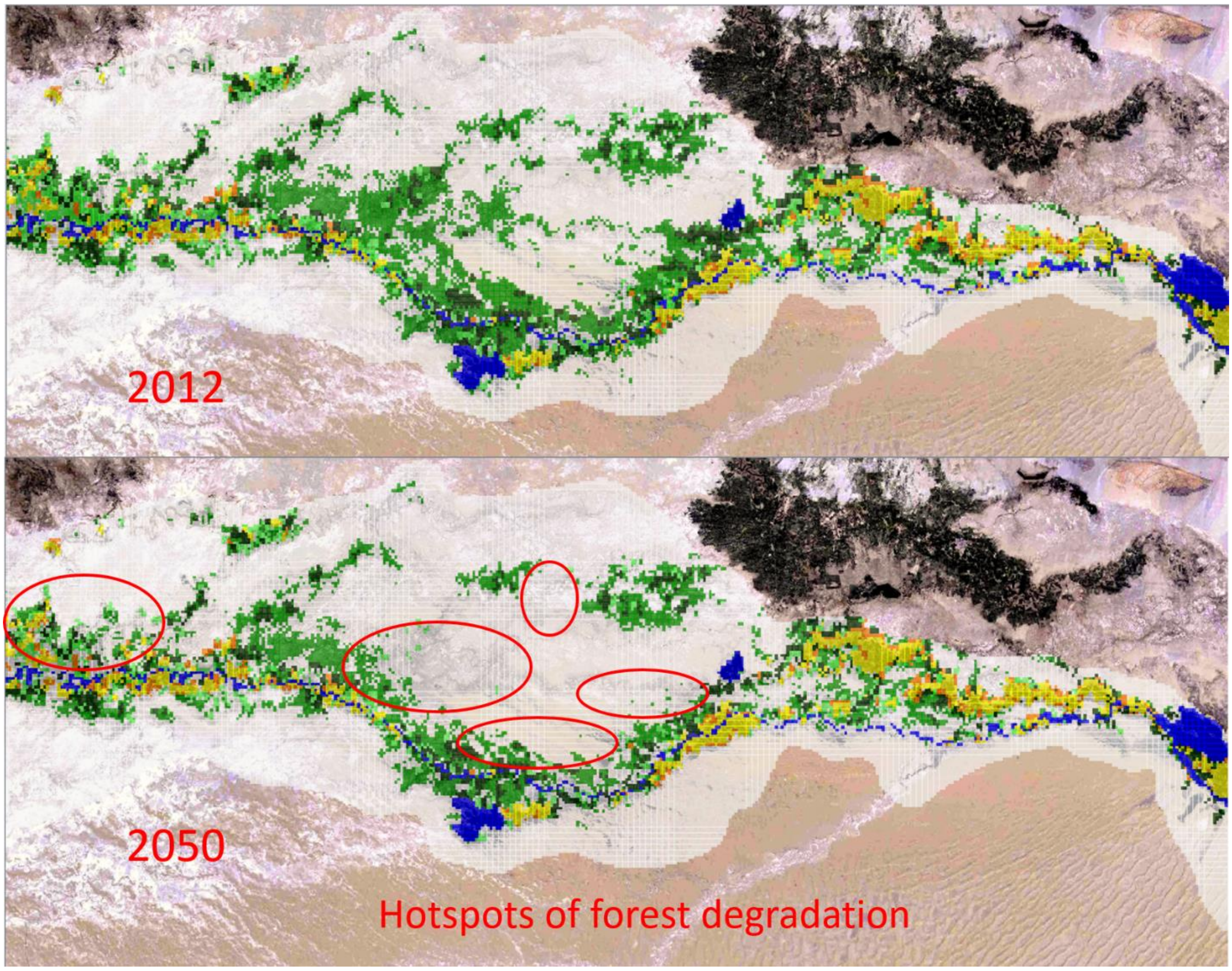



**Figure 5.12:** Forest degradation in the middle reaches (Xinqiman to Qiala).

### 5.4.2 Downstream outflow

The natural terminal of Tarim River is Taitema Lake. However, due to long-term water interception downstream, the outflow of Tarim River is studied at Daxihaizi Reservoir. The reservoir is located 358 km above Taitema Lake, and no farmlands or residents were found downstream the reservoir.

The outflow of Tarim River in future years is dependent on the upstream discharge and water consumption along the oases, which were calculated from the other hydrological models. According to the research of Duethmann et al. (2016), discharge of the Tarim River is anticipated to be increased by 2020, then decreased until 2080. In the test, climate scenario is A1B, all the other input indicators are kept as default values. Simulation results indicate an increasing trend of outflow in 2020, and a decreasing trend in 2030 and 2040 (Figure 5.13). Negative values of outflow indicate the water deficit at Daxihaizi Reservoir.

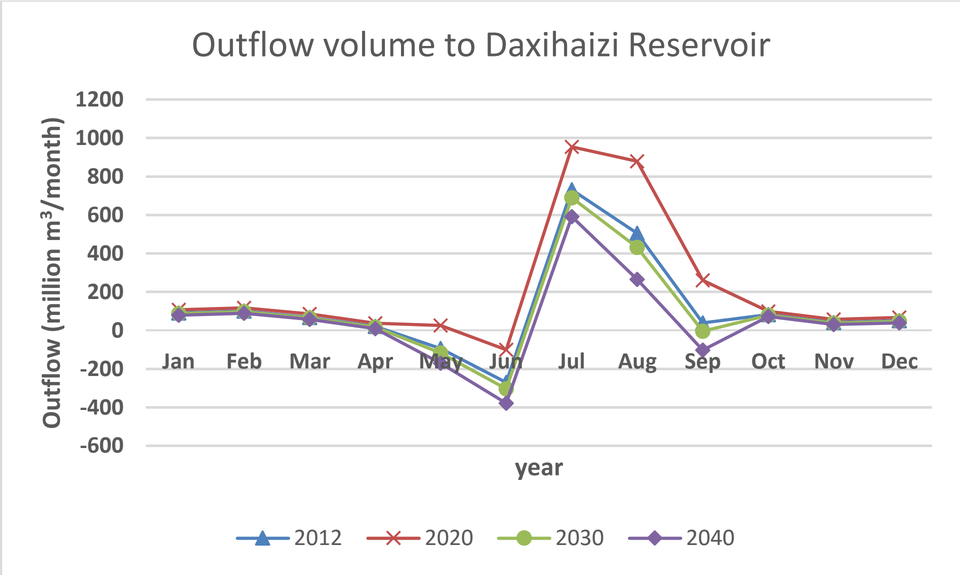



**Figure 5.13:** Downstream outflow in the Daxihaizi Reservoir in 2012, 2020, 2030 and 2040.

Peak volumes of outflow appear in July, with 731.92 million $m^3$ in 2012, 953.84 million $m^3$ in 2020, 689.14 million $m^3$ in 2030, and 591.28 million $m^3$ in 2040. From the figure, summer flood last two months in July and August, and drop dramatically in September. These results agree with the outputs of hydrological model (Yu et al., 2015). Dry season occupies most of the year. In June, water deficits occur in all the simulation years. Particularly, near 400 million $m^3$ of water shortage is predicted in June 2040. A noticeable water deficit also shows up in September 2040, which is the first time that the outflow water is on shortage in September. Upstream reservoirs need to prepare enough storage for the water crisis in future.

The downstream outflow is also influenced by different climate scenarios. In general, the more precipitation is, the more outflow will be. The higher temperature is, the more discharge is, in the meantime the more evaporation is. So there is no obvious positive relationship between temperature and outflow. Downstream outflow in the Daxihaizi Reservoir under four climate scenarios A1B, RCP 2.6, RCP 4.5 and RCP 8.5 were investigated in 2020 (Figure 5.14).

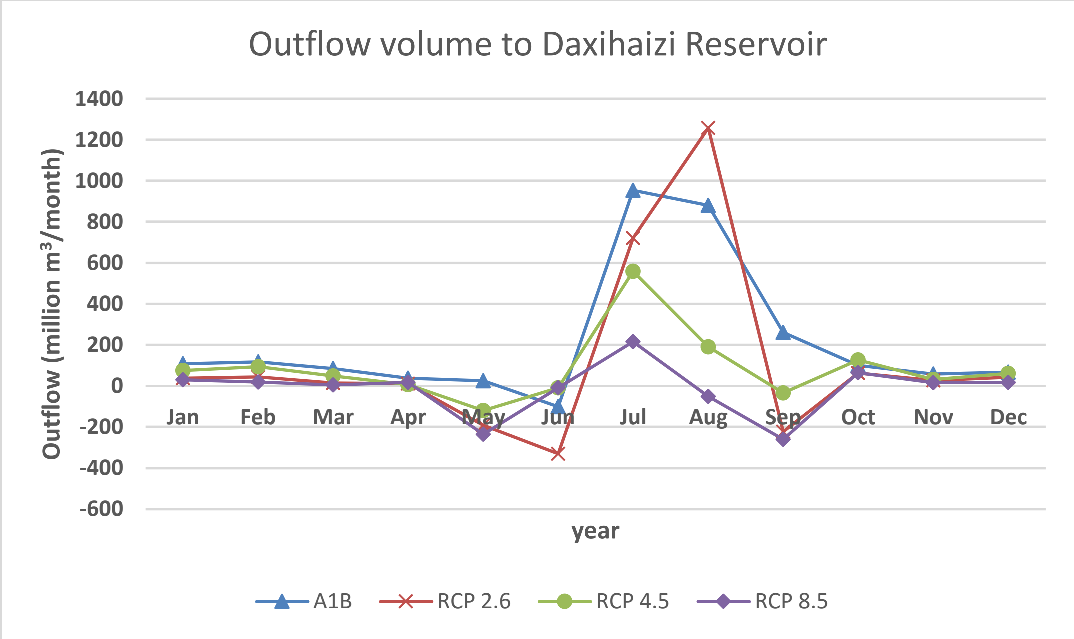



**Figure 5.14:** Downstream outflow in the Daxihaizi Reservoir under climate scenarios A1B, RCP 2.6, RCP 4.5 and RCP 8.5 in 2020.

### 5.4.3 Socio-economic outputs

Cotton production, fruit production, biomass production, mean species of plants, farmers' income, wind control, drifting dust control by riparian forest, drifting dust control by grassland, and sand mobilization control by grassland are shown as examples for the socio-economic assessments (Figure 5.15). These indicators are calculated separately in the four sub-catchments: Alar to Xinqiman, Xinqiman to Yingbazar, Yingbazar to Qiala, and Qiala to Taitema Lake. Climate scenario is A1B. Simulation period is from 2012 to 2050, and all the inputs are kept as default values.

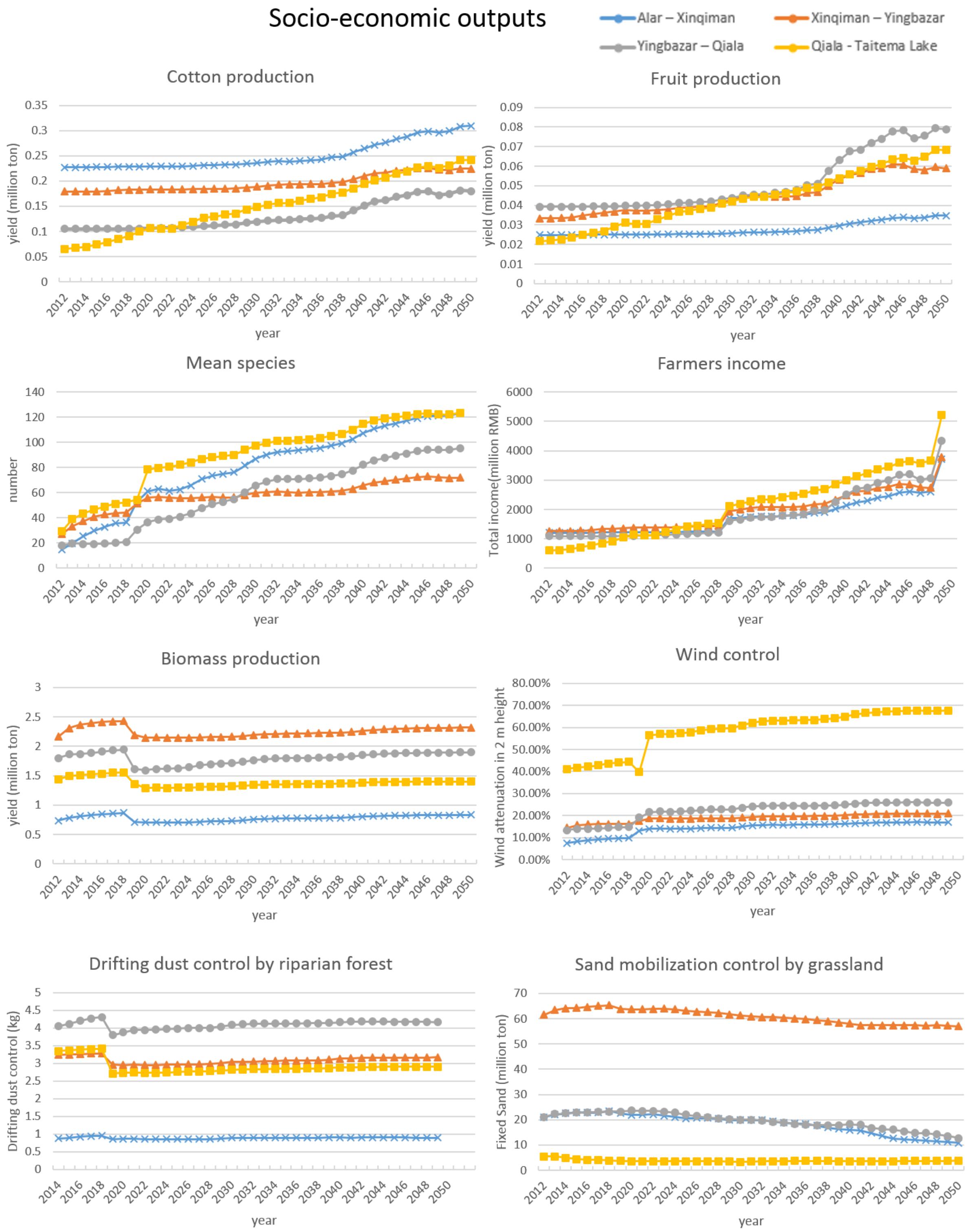



**Figure 5.15:** Socio-economic outputs from 2012 to 2050. Input indicators are kept as default values.

Cotton production has an increasing trend in all the sub-catchments. The largest cotton production region is within Alar to Xinqiman catchment, but the fastest production growth comes from Qiala to Taitema Lake catchment. This result complies with the study of Xu (Xu et al., 2008), who concerns the agricultural development in the lower reaches may cause water scarcity problems for the ecosystem. Fruit production also has a rising trend, and develops rapidly in the lower reaches. On the other hand, biomass production experiences an increasing period till 2018, then drops in 2019 and remains steady afterwards. The reason for this sudden change may because of the rules in DSS are not complex and smooth enough, so that quantitative accumulations lead to a qualitative transformation in 2019.

The number of mean species of plants has a steady growth, similar to farmer's income. Because of the development of economic crops, farmer's income in the lower reaches has the largest growth among all the sub-catchments. Due to lacking of clear policy and data in future years, change of population and migration are not considered in current version of DSS. Wind control and drifting dust control by riparian forest remain stable, even the forest area is shrinking. This is caused by the contribution of growing tree height and crown area. In comparison, drifting dust and sand mobilization control by grassland have declined in varying degrees until 2050.

One scenario was tested as an example for land use management and assessments (Figure 5.16). In the baseline year of 2012, 400 cells ($10^4$ ha) of cotton fields are changed into grassland in the first sub-catchment, to investigate the consequences of this action in future years until 2030.

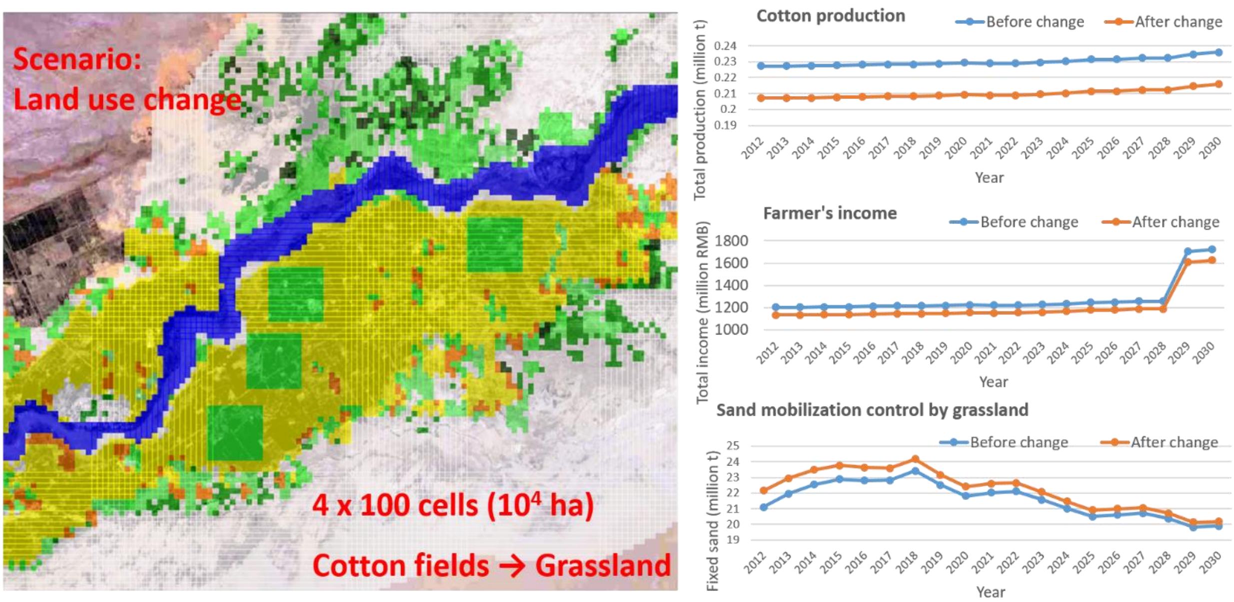



**Figure 5.16:** Editable land use map in the DSS. In the first sub-catchment, 4 × 100 cells ($10^4$) of cotton fields are changed into grassland in 2012. Cotton production, farmer's income and sand mobilization control by grassland are investigated as output indicators of this action.

The simulation results indicate the reduction of cotton production and farmer's income, and increase of sand mobilization control by grassland after land use change. Cotton production provides the main income for local farmers. From a local decision-maker's point of view, if the losses of farmers' income are too large to bear, then this land use change scenario may not be accepted. However, if sand mobilization control is considered more important than the economic losses, the decision-maker may adopt this scenario, and mitigate the farmer's losses in other ways. Additionally, the increased portion of sand control is shrinking in the future years. This phenomenon indicates either groundwater level is too low in the fields, or groundwater salinity is too high for grass to grow.

To increase farmer's income, either increasing crop production or reducing the cost is an effective approach, another way is to acquire more subsidies from drip irrigation. The expansion of farmland area is a direct way to increase crop production, but it will also increase irrigation water use, and this approach is strictly regulated by the Xinjiang Tarim River Bureau. On the contrary, the decrease of farmland area is comply with water policies of the bureau, but it has negative effects on the farmer's income. To achieve a win-win situation, on one hand, farmland area should be strictly controlled to guarantee ecological water for the forest and grassland. On the other hand, farmers' income should be compensated by other measures, such as subsidies from the government and developing other industries (e.g. tourism), as long as the new career for the farmers are environmental-friendly and able to compensate the income losses.

## 5.5 Conclusion

A model based decision support system was developed to assist the stakeholders with decision-making on sustainable land management and socio-economic assessments along the oases of Tarim River. The development and implementation of DSS involves knowledge of experts in interdisciplinary research aspects, as well as the experiences and feedbacks from a large number of local stakeholders. The DSS has notable features in a number of research aspects.

(1) Editable land use map in the GUI was developed to assist stakeholders of decision-making on land use management. The clicking and drawing on the land use map provide stakeholders a catchy approach for examining land management alternatives. If the scenario is kept business as usual in the simulation, then natural vegetation, riparian forest and grassland would suffer varying degrees of deterioration in the near and far future. In the upper, middle and lower reaches, the decay of nature vegetation are obvious.

(2) The conjunctive use of surface and subsurface water resources provide more accuracy on the system. The DSS integrates the hydrological data, geographic data, social and

economic statistical data, and establishes the relationships with equations, conditional statements and fuzzy logics. Under scenario assumptions, possible actions and their impacts are estimated in a semi-quantitative way with the help of climate indicators, socio-economic Indicators, management Indicators, and ESS Indicators. Socio-economic outputs illustrate more crop productions and farmers' income, but weaker sand mobilization and drifting dust control in future. The conjunctive use of surface water and groundwater resources cannot only solve the problem of water shortages, but also improves the water use efficiency and ecosystem rehabilitation.

(3) The integration of expert knowledge on interdisciplinary studies gave specific insights on the interactions among water, earth, ecosystem and humans. The system does not only consider direct impacts, but also side effects among different matters. For instance, increased irrigation water may raise crop production, but it can also cause less water for winter flooding, therefore aggravate salinization on the field, and lead to less yield in the end.

(4) Links with hydrological models help reduce system complexity and increase model accuracy of the DSS. MODFLOW is running parallel in the simulation periods with DSS. WASA provides discharge inputs, and MIKE HYDRO simulates irrigation and ecological water consumptions. All the outputs of theses hydrological models were taken as inputs into the DSS. After the calculations of water balance in the DSS, simulation results indicate an increasing trend of outflow in 2020, and a decreasing trend in 2030 and 2040.

Though a lot of expert knowledge and stakeholder feedbacks were considered in the developing phase, the DSS should not be recognized as an end product. Lots of estimations and uncertainties still remain in the system, which requires further research and development. The DSS is a good decision-making platform for many other associated studies. The GUI was designed to be user-friendly so that more common stakeholders can use and improve the system, and make the further steps in bridging the gap between research and IWRM practice.

# 6 Implementation of the DSS with stakeholders

Research should serve practice, and genuine knowledge comes from practice. The implementation of DSS provides local stakeholders guidance in their management activities, and gathers feedbacks to improve the DSS.

## 6.1 Application of DSS with stakeholders

The Chinese version of the DSS is designed for the convenience of local decision-makers and stakeholders (Figure 6.1). This version has been introduced to the researchers and stakeholders via workshops and visiting trips to the local administrations and research institutions. Because local researchers and stakeholders are familiar with the Tarim River Basin and its environmental conditions, most users found it relatively easy to get to use the DSS. However, it certainly doesn’t mean everyone understood the principles and algorithms of the DSS.

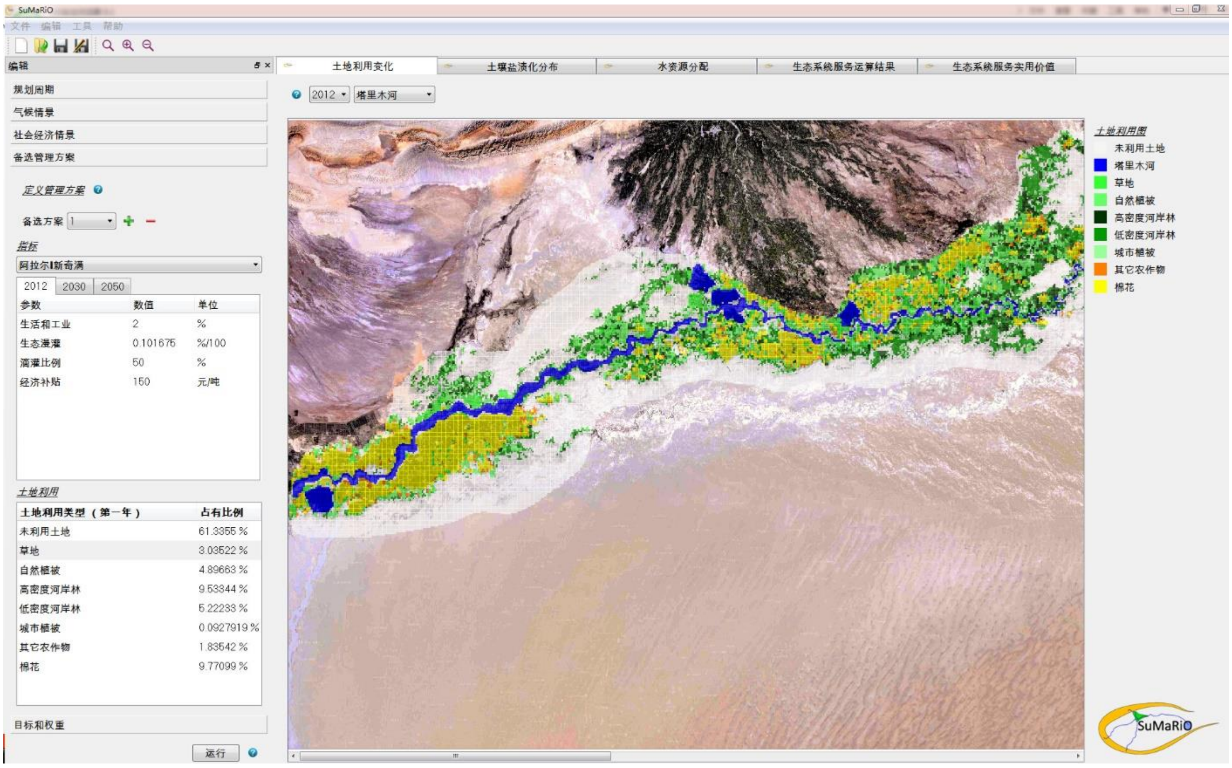



**Figure 6.1:** Chinese version of the DSS.

To demonstrate the research outcomes and introduce the DSS to local stakeholders, the SuMaRiO implementation conference took place in September 2015 in Urumqi (Figure 6.2). The conference marks the beginning of the implementation work of the DSS. Research results and the generated knowledge of the different research fields are being provided to the stakeholders. Moreover, the conference is aiming at an active knowledge exchange between scientists and stakeholders to further expand and improve the DSS beyond the SuMaRiO Project.


**Figure 6.2:** Implementation conference of SuMaRiO-stakeholders meet scientists.

Besides formal meetings and conferences, interview trip to the local areas is another effective approach to acquire more knowledge and information to improve the research work. A number of local policies and customs were obtained this way. SuMaRiO project aims to improve the land and water management strategies, so it is very important to understand the current situation and management strategies. Visiting the local residents provide the opportunities to gather research data and knowledge, as well as implement research outcomes. The DSS is user-friendly for supporting decision-making progress to the stakeholders and decision-makers. Moreover, local stakeholders and residents will benefit in the long term from sustainable management practices. Therefore, getting the stakeholders involved in the research process is very crucial to the project. Due to the relatively poor living conditions in the region, visiting the villages is the only effective way to communicate with local farmers. The farmers have their own experience in agricultural practices and management perspectives. Lots of their opinions have been considered in the research to improve the outcomes.

## 6.2 Feedbacks from stakeholders

The implementation of the DSS has drew great attention from the Xinjiang Tarim River Basin Bureau. In February 2016, the bureau released a document, in which many valuable feedbacks are given to the research work of SuMaRiO. They think the project has made significant achievements, including the establishment of the DSS and research reports. In the document, the bureau also have suggestions on the implementation of the DSS and expect for the trainings on it to assist future decisions.

There are five prefectures of 42 counties, and 4 divisions of 55 agricultural regiments in the river basin. The coordination among different interest groups is a tedious task along the river oases. Most people are minority ethnic groups, and social stability is an important matter in the region. The local government has steadily performed aid-the-poor policy, which provides basic living allowance for local people. This policy benefits for increasing farmers' income and improving living conditions in the local area, and thus makes easier to implement water policies and nature protections.

Water-tight river banks, canals and reservoirs have been constructed along the river to prevent water leakage. Since the year 2000, a number of hydraulic projects were carried out to prevent water losses and increase water use efficiency along the mainstream Tarim River, including the following projects: (1) water-saving transformation project in irrigation areas; (2) water-saving reconstruction project for reservoirs; (3) development and utilization of groundwater project; (4) river bank and canals construction project; (5) ecological water conveyance project in lower reaches; and (6) ecological recovery construction project in middle reaches. These engineering projects will reduce water losses and save water resources for ecosystem balance along the river.

Not all the farmlands are cultivated each year. Due to water scarcity, the land fallow and crop rotation are very common on the fields. To prevent depletion of the soil, some arable lands lay fallow for continual several years, especially on high salinity soil. The land fallow leads to reducing crop production and water consumption. Land fallow and crop rotation are quite flexible in some regions, because they are highly dependent on the local government policies and available water resources. Similar to the farmlands, grazing is also strictly controlled in the river oases. Grassland regions have the rotations for feeding livestock each year. The rotations are flexible and dependent on the grassland growth, drought condition, available water resources, and movements of the shepherds.

Unauthorized human use of water (irrigation, grazing, etc.) remains a problem due to negligent supervision on the river of more than 1000 km. In the lower reaches, the national highway No.218 is the only road for supervision along the river, yet with single lane and maximum speed of 60 km/h. Besides law enforcement and investigation, education is another effective way to raise public awareness of water law and environmental protection. The improvement of farmer's education conditions is catalyzing the diversionary from expanding farmland area into increasing land productivity, and further into water productivity.

Farmland area is larger in practical than it is in statistics, due to overexploitation of lands and false declarations of farmers. Additionally, unauthorized domestic and livestock water use are also increasing the actual water consumption, and thus intensify water scarcity in the real situation. In flood seasons (July to September), flooding over river banks and reservoirs is another cause of losing large amount of water. In the dry seasons like spring, when snow-melting water from the mountains is not coming, groundwater extraction is the major source of water supply for the farmers. But since groundwater is also the main water supply for the riparian forest in dry seasons, the decline of water head becomes more and more troublesome for the ecosystem balance.

Cotton production is the major income for the farmers. A second-round cropping is always necessary to assure a good harvest. In October, the weather changes rapidly and temperature drops sharply. Due to lacking of labor forces, the best harvest timing is often missed on many farmlands. Therefore, the actual cotton production is always lower than expected, and running cost is usually higher. Local farmers are often organized together to develop characteristic agriculture, such as Chinese jujube, Apocynum venetum tea, long-staple cotton. It is a good measure to increase crop production and farmers' income, and reduce waste resources on the other hand.

Drip irrigation is more commonly used in agricultural regiment farms than ordinary farms owned by local farmers. If subsidy of drip irrigation implementation is guaranteed, farmers are willing to perform drip irrigation on the fields. But salinization remains a big problem, which requires large amount of water use in winter to wash down the salt on surface soil. Moreover, the plastic mulch which is used in drip irrigation will entangling the plant root in the following years, and cause the reduction of crop productivity. For land sustainability in the long term, the mulching films on the fields have to be degradable. It means the material of the films cannot be plastic, and thus increase the cost of drip irrigation under mulch.

Grass-panes are largely use in the lower reaches for sand-fixation and water conservation. Grass-panes don't need any water, and plays an important role to maintain local ecosystem balance. Spots of bushes (*Tamarix*, *Halimodendron halodendron*, *Nitraria tangutorum*) together with *Populus Euphratica* constitute the "Green corridor" in the lower reaches. They stretched out for hundreds of kilometers along the river, and separate the Taklimakan and Kuluk Desert.

## 6.3 Modified DSS version

The DSS is modified based on the feedback information from the stakeholders. In the new version of DSS, five aspects have been revised compared to the old version:

(1) Groundwater boundary conditions have been modified. The mainstream Tarim River catchment is downstream of Aksu River catchment. It is on the border of Tailan River catchment and Kongqi River catchment to the north, and Taklimakan desert to the south. Although no streamflow connects Tailan and Tarim River catchments, the lateral flow of groundwater should not be neglected. The initial water head and groundwater boundary conditions were modified by using groundwater data from Aksu, Tailan and Kongqi River catchments. On the longitudinal section of the Aksu, Tailan, and Kongqi River boundaries, boundary condition can be regarded as fixed water head. Initial water head was generated based on lots of collected groundwater data, but it can still be improved with more comprehensive data. Since digging wells are strictly controlled in the watershed, which brings certain difficulties for researchers to gather information, currently there are not enough validation data for MODFLOW to improve water heads and groundwater movements.

(2) Farmers' income have been improved in the calculation. Farmers usually have more income sources from the subsidies for living to the compensation to reduce the cost. Chinese government has aid-the-poor policy in the study region for many years. Each year, the budgetary funds will be released from the central and local governments for poverty alleviation. The average amount of this money were collected and added into the DSS calculation on farmers' income. Moreover, another type of special funding on agriculture development is also distributed each year to the farmers, which compensate the cost for running cotton and other crops. This agricultural development funding is added in the current version of the DSS (Figure 6.3). The simulation period is from 2012 to 2030, and all the reference values kept business as usual on other input indicators.

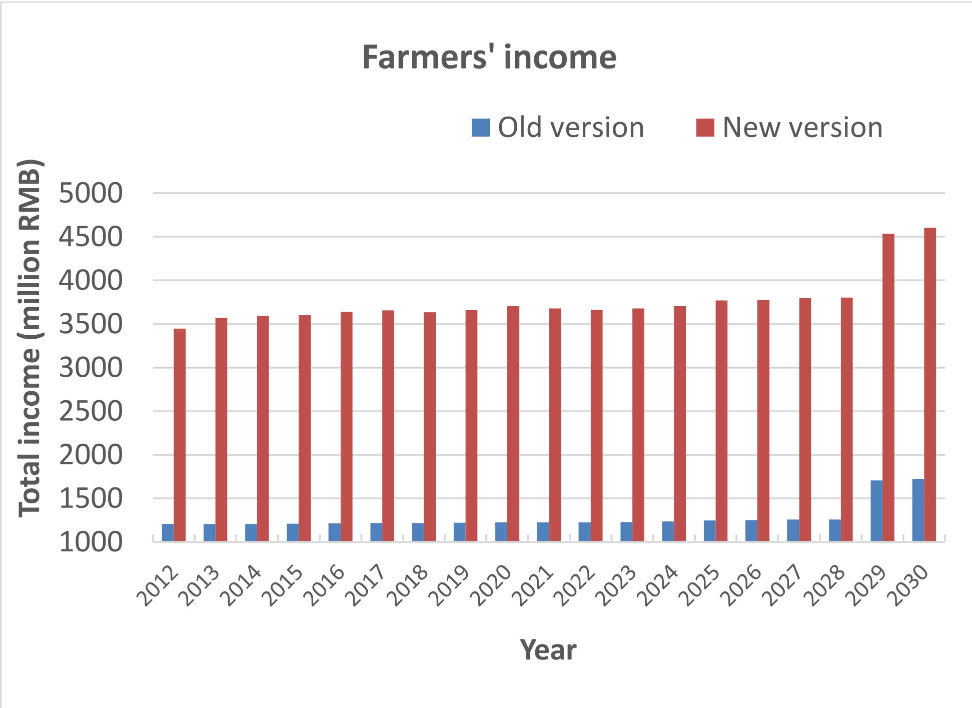


**Figure 6.3:** Comparison of farmers' income between old and new versions of the DSS.

(3) Fuzzy rules regarding low density riparian forest have been reconsidered and verified in the DSS. Low density forest and sparse vegetation were recognized as not important in the old version of DSS, their function on the dust and sand control are underestimated. Based on the feedbacks of stakeholders and investigations from researchers, low density riparian forest is crucial for the maintaining of "Green Corridor" in the lower reaches. The trees can abstract groundwater from 10 m deep and have large root area to fix the sand. They also provide shade for other vegetation. Together with spots of bushes and grass-panes, low density riparian forest is a significant component of the "Green Corridor" in the lower reaches, which is essential for preventing the desert and maintaining ecosystem balance (Figure 6.4).

**Figure 6.4:** Low density riparian forest and grass-panes in the lower reaches.

The drifting dust control ability by low density riparian forest should not be underestimated. Fuzzy rules in the old version of DSS used to keep all the results at the low level, and they have been changed into medium level if either crown area or tree height is on the high level (Table 6.1).

**Table 6.1:** Modified fuzzy logic of drifting dust control by low density riparian forest.

| Rules | Crown area (m$^2$) | | Tree height (m) | | Drifting dust control by riparian forest low density (kg/ha) |
|---|---|---|---|---|---|
| If | High | and | High | then | ***Low (changed into Medium)*** |
| If | Low | and | Low | then | Low |
| If | Medium | and | Medium | then | Low |
| If | High | and | Medium | then | ***Low (changed into Medium)*** |
| If | Medium | and | High | then | ***Low (changed into Medium)*** |

Since the raise of drifting dust control ability of low density riparian forest in the DSS, the comparison of results between the old and new versions of the DSS are shown in Figure 6.5. The baseline year is 2012, and all the values of input indicators are kept as default values.

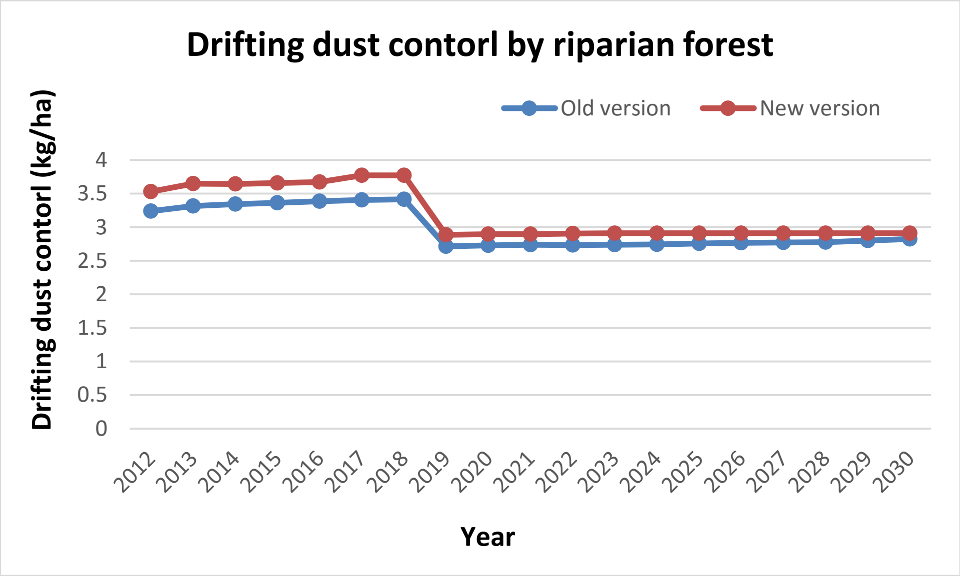



**Figure 6.5:** Comparison of drifting dust control by riparian forest between old and new versions of the DSS.

Similar to the drifting dust control, sand mobilization control by low density riparian forest is also underestimated. Even the forest is sparse within a green corridor, it still plays a key role in preventing the desert, especially in the lower reaches. Without the riparian forest along the river oases, it is hardly possible to control the sand and maintain ecosystem balance. Therefore, if crown area or tree height is on the high level, sand mobilization control by low density riparian forest is changed into medium level (Table 6.2).

**Table 6.2:** Modified fuzzy logic of sand mobilization control by low density riparian forest.

| Rules | Crown area ($m^2$) | | Tree height (m) | | Sand mobilization control by riparian forest low density (t/ha) |
|---|---|---|---|---|---|
| IF | High | and | High | then | ***Low (changed into Medium)*** |
| If | Low | and | Low | then | Low |
| If | Medium | and | Medium | then | Low |
| If | High | and | Medium | then | ***Low (changed into Medium)*** |
| If | Medium | and | High | then | ***Low (changed into Medium)*** |

In the lower reaches, comparison of sand mobilization control by riparian forest between old and new versions of the DSS are shown in Figure 6.6.

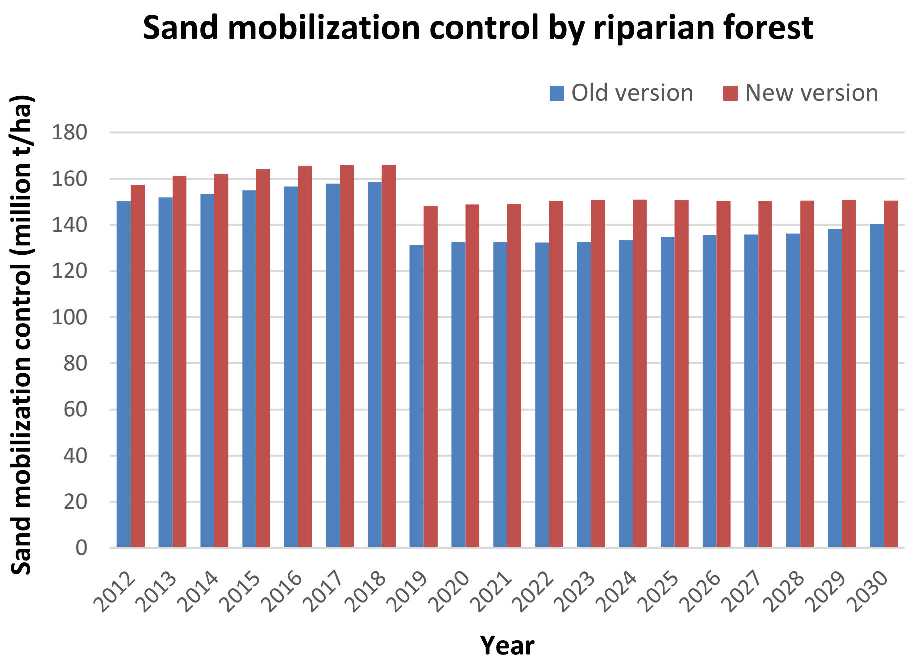



**Figure 6.6:** Comparison of sand mobilization control by riparian forest between old and new versions of the DSS.

(4) Weights of the ESS reference values have been changed to give more priority to grassland and riparian forest, especially in the lower reaches (Figure 6.7). Agriculture is not as important in the lower reaches as it was in the upper reaches, and the ESS weights of agriculture is adjusted to lower values. As the feedbacks of stakeholders suggested, the weights in the weights of grassland and riparian forest need to be raised to match the growing importance of natural vegetation on the ESS functions.

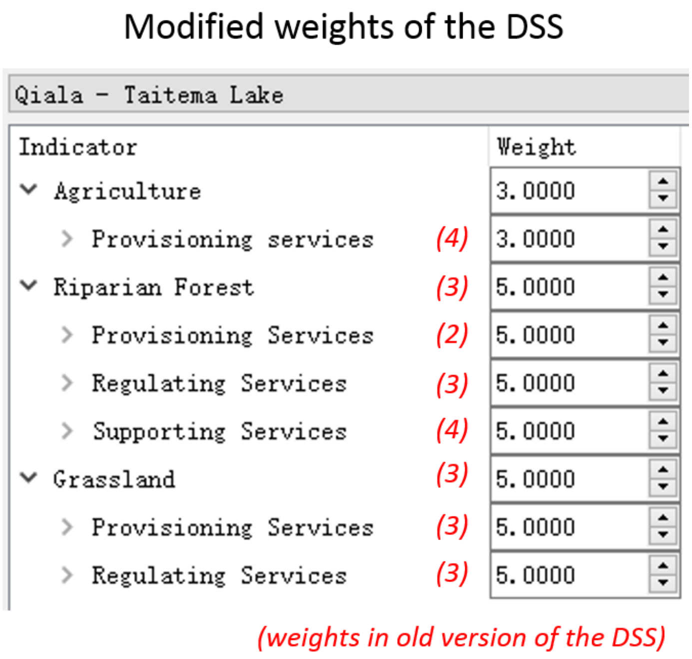



**Figure 6.7:** Modified weights of the DSS, with more priority to grassland and riparian forest, especially in the lower reaches.

To examine the consequences of this modification, a scenario (Figure 6.8) is conducted with planning period from 2012 to 2030. Climate scenario is A1B. The reference values of goals and weights are defined by the researchers and stakeholders in the workshops. If a goal is determined (e.g. cotton production reaches 1 million ton each year), then the output indicator gives a time series of utility values (from 0 to 1), to examine how much the goal can be achieved. In this scenario, the ESS planning goals includes agriculture goals (cotton production 0.1 million ton, fruit production 0.2 million ton, production of other crops 0.1 million ton, and farmers' income 5 million RMB), riparian forest goals (biomass production 0.8 million ton, drifting dust control 1 kg/ha, sand mobilization control 20 million ton/ha, wind control attenuation at 3, carbon sequestration 0.2 million ton, and tree species at 2), and grassland goals (Apocynum production 500 ton, reed production 14000 ton, drifting dust control 5 kg/ha, sand mobilization control 9 million ton/ha). Utility values for agriculture, grassland and riparian forest indicators are calculated separately based on how much the goals have been achieved each year, then the total ESS utility values (defined in Equation 5.6) are calculated by the weights of these indicators.

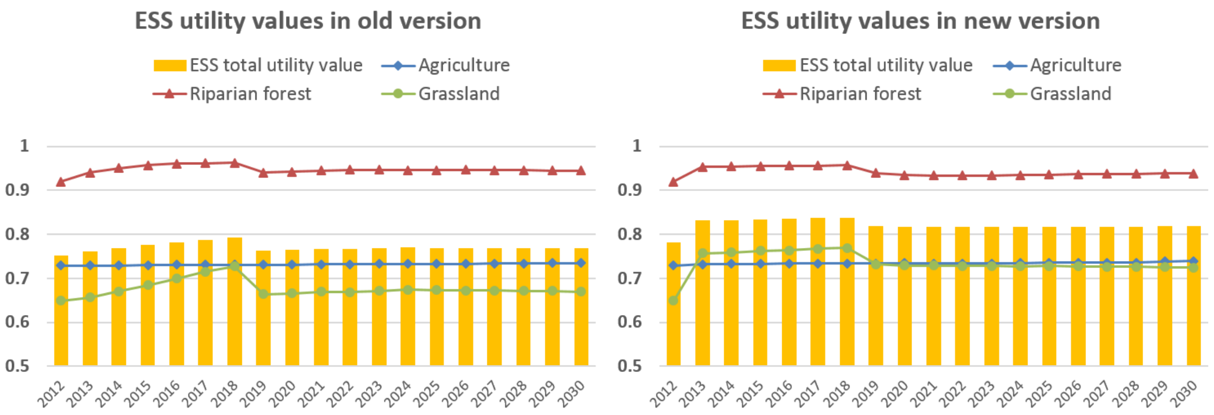



**Figure 6.8:** Comparison of ESS utility values in old and new versions of the DSS.

The results of the utility values indicate that the ESS total utility values have been increased in the new version of the DSS. The ESS utility values in the old version are below 0.8, which means less than 80% of the ESS goal is achieved each year. In the new version, more than 80% of the ESS goal is fulfilled in most years. Utility values of riparian forest remains over 0.9 in both old and new version. Agricultural utility values has a slightly decrease and grassland utility values have a slightly increase in the new version. Overall, the modified weights in the DSS has given more priority to the grassland and riparian forest and less priority to the agriculture, which leads the function of natural vegetation more important in the ESS.

(5) The Chinese version of DSS has been modified during the implementation stage. During the workshops and conferences of the DSS, the Chinese version have been tested many times by the users. In general, most users have found the DSS not difficult to use with the GUI and instructions, but several items were found to be confusing at some extent. Those misleading points and errors had been revised in the current version of the DSS. To modify the algorithm and the GUI, revisions have to be made in the programming, which can be handled in Qt Creator (Rischpater, 2014).

## 6.4 Uncertainties in the DSS

In the DSS, the delineation of regions are relatively homogeneous in multiple criteria, including hydrological, meteorological, geographical, ecological, socio-economical, and political aspects. Therefore, the complexity of the management practices cannot be completely reproduced. A good number of socio-economic and management indicators are sensitive to the change of government policies and water authority regulations, which could cause large uncertainties in future planning years. It is difficult to say which scenario has the most robustness, or one scenario is more preferable than the other. Based on a number of trials and comparisons with real data, most outputs of the DSS were reasonable and comply with the knowledge and perceptions of local stakeholders.

However, there are still a lot of weakness and uncertainties in the DSS which need to be improved in future research.

In the DSS, equations, conditional statement and fuzzy logic all have limitations in the delineation of parameter relationships, and thus cause uncertainties by temporal and spatial changes on specific matters. Equations are mostly generated from literature or linear regression functions, they may not be suitable for the application in the entire catchment or in the whole simulation period. For instance, the irrigation water demand origins from the output of MIKE HYDRO. To create relationship in future years, a linear regression function was made based on the simulation results of MIKE HYDRO. Although the function matched very well in the six years, the large temporal and spatial uncertainty in the future years also exist. Conditional statements are normally based on the expert knowledge, but the knowledge among different experts may differ from each other, and it is doubtful whether the statements represent the real cases. Fuzzy logic includes possibility and uncertainty in the logic itself. For the elements which are not easily quantified for a single value, fuzzy logic would be applied to give a certain range for the parameter, and thus create the uncertainty from the foundation of the logic.

Groundwater is very important in the logics with many ecological aspects in the DSS. Due to lacking of groundwater data in the entire river basin, only several observation wells were used for the establishment of MODFLOW model. Compared with the large research area and groundwater movement in this arid river basin, groundwater data is so scarce that cause a lot of uncertainty in the DSS. Although the hydrological models were calibrated and validated to increase the possibility of more reliable results, the DSS has not been calibrated so far. However, this work is very important that requires the feedback from local stakeholders, more statistical data, and a better understanding of the DSS itself for a comprehensive model calibration. Since DSS involves knowledge on varying aspects, no individual developer is able to master all the criteria. Interdisciplinary cooperation is as important in the implementation and optimization phases as it was in the system developing phase.

Climate change in future years is a large uncertainty in the DSS. Although there are four climate scenarios in the model, the conditions are all under assumptions with future temperature and precipitation increase. Climate scenario projections are made until 2050, with so many factors could affect future climate. For instance, it is difficult to say that the temperature in 2030 will be hotter than it is in 2029, and it is hard to tell which year would have more precipitation between 2041 and 2042. The climate scenarios are based on a general trend of temperature and precipitation increase, and even this general trend would be based on lots of assumptions and predictions. Therefore, the purpose of climate scenarios are made for the preparation of different management alternatives according to climate change, rather than for climate predictions.

Soil salinization changes are not sensitive in the model. Soil salinity is represented by soil electrical conductivity ECe, which is dependent on capillary rise and influenced by groundwater level and soil type. The research on the salinization is an important issue for this arid region. Ideally, soil salinity change would also be associated with irrigation process. However, currently no crop growing module is embedded in the DSS, so soil salinity has no effect on crop yields in the DSS so far. Farm process could be added in the DSS in future if more internal links were established with other hydrological models, such as MODFLOW-OWHM and FREEWAT. Furthermore, because winter irrigation uses extra water to washes down the salt, salinization on the surface soil should be changed obviously in winter. The process of winter irrigation is not included in the simulation at the moment, and can be considered as a typical point to increase system reliability in future improvements.

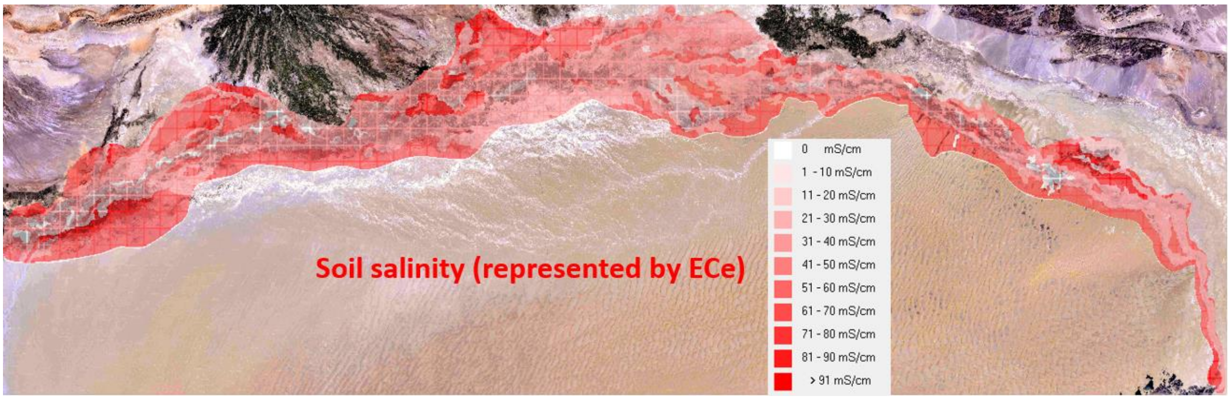



**Figure 6.9:** Distribution of the salt concentration in the soil by ECe (mS/cm) (Source: provided by Philipp Huttner from TUM, 2016).

Reservoirs are not simulated in the DSS. Reservoirs play an important role in water storage during flooding period and water release in the dry season. The evaporation and leakage losses in the reservoirs are also not negligible. Therefore, the absence of reservoirs in the DSS could have large potential difference on the water balance over the simulation years. In the distributed MIKE HYDRO model, eight large reservoirs were included. The reservoirs could be included in the future research for a better simulation of water balance in the entire catchment, but this will certainly increase model complexity and processing time.

In general, to better simulate overland flow, the internal interface/dynamic interaction with hydrological models (e.g. MIKE HYDRO) is very necessary. Because the elements and logics in the DSS are defined on the current expert knowledge and outputs from hydrological models, uncertainties in the far future would be larger than the near future.

After all, anthropogenic activities possess the largest influence on the water consumption, land use change, and socio-economic factors in the DSS. The change of water and social policies would be essential to the sustainable management of the river oases in future years.

## 6.5 Conclusion

The DSS is an open source research outcome. It is the outcome of the interdisciplinary cooperation research among 11 German universities and 9 Chinese research institutions within SuMaRiO. The implementation and further development of the DSS are needed to summarize and receive plentiful research fruits. Due to the limitation of knowledge and article content, a number of research aspects and outcomes in the DSS were not thoroughly discussed. However, the DSS should be the basis of a good start, rather than the end of research cooperation. Many further researches and projects can learn experience from the algorithm and methodologies of the DSS, which is totally applicable to other regions. The DSS is free available on request. Comments and further discussions are welcome.

The implementation of the DSS brings together the researchers and stakeholders. Both Chinese scientists and stakeholders appreciated the interdisciplinary research and the integrative dialogues within SuMaRiO and agreed that increased application of this research mode would support a sustainable land and water management in Xinjiang. Research cooperation among hydrologists, ecosystem ecologists, foresters, engineers, soil scientists, agronomists and remote-sensing specialists is strengthened to intensify the development of the DSS. Sustainability-oriented projects are evaluated with respect to both scientific excellence and quality of implementation strategies.

The involvement of stakeholders in the research phase is crucial to the development of the DSS, as well as to the project. In the implementation stage, it is very important for the stakeholders to understand the basic principles of the DSS, and use the model in their management practice. The feedbacks from the stakeholders are helpful to the modification of the DSS, and provide new ideas to improve the DSS in future research. Groundwater boundary conditions were modified in the new version of the DSS. Farmers' income have been improved in the calculation by adding subsidies and other income sources for the farmers. Fuzzy rules regarding low density riparian forest have been reconsidered and modified, to increase the influence of low density riparian forest in the lower reaches. Weights of the ESS values have been raised to give more priority to grassland and riparian forest, to emphasize their functions in maintain the ecosystem sustainability. The Chinese version of the DSS had also been modified during the implementation of the DSS in Xinjiang.

Although the interdisciplinary expert knowledge were included in the DSS, the uncertainty is still large in many aspects. The DSS should be recognized as a platform for new research possibilities, rather than a final ending product. Linear regression equation, conditional statement and fuzzy logic all have limitations in the definitions, and cause temporal and spatial uncertainties in the water consumption, land use change, soil salinization, and socio-economic factors in future scenarios. More stakeholders should be involved and more expert knowledge should be collected to improve the DSS in future. The basic principles and algorithm have been tested and highly appraised by the local stakeholders in the Tarim River Basin. With more information shared and data collected in future research, the DSS would be able to provide more convincible and reliable results to assist decision-making process.

# 7 Conclusion and outlook

This is the final chapter of the dissertation, which includes summary of the work and research outlook.

## 7.1 Summary of the work

To provide scientific basis for sustainable water and land management along the Tarim River Basin, hydrological models and a DSS were developed to assist decision-making process with stakeholders. The whole research work includes data collection, field investigation, hydrological modeling, calibration and validation, joint development of the DSS, the DSS implementation, and modification of the DSS in the Tarim River Basin. The interdisciplinary research in the SuMaRiO is highly appraised by the Chinese partners and stakeholders. The research work is considered valuable and successful by the Xinjiang Tarim River Bureau, and the implementation of the DSS has received many positive responses from the stakeholders, which has established solid foundation for management practices and future cooperation researches.

A lumped and a distributed MIKE HYDRO model were separately established in the basin. MIKE HYDRO was used for the simulation of water flow, water supply/demand, soil moisture and crop growing. The integrated modular structures were included with basic computational modules for hydrology and hydrodynamics, with groundwater inputs from MODFLOW. Both the lumped and the distributed model achieved good agreements during model calibration processes. In this arid basin, agricultural water consumption issues are crucial to address the conflicts among irrigation water users from upstream to downstream. The lumped model focus on the irrigation water consumption. Irrigation scenarios revealed that the available irrigation water has significant and varying effects on the yields of different crops. Irrigation water saving could reach up to 40% in the water-saving irrigation scenario. Land use scenarios illustrated that an increase of farmland area in the lower reach gravely aggravated the water deficit, while a decrease of farmland in the upper reaches resulted in considerable benefits for all sub-catchments. A substitution of crops was also investigated, which demonstrated the potential for saving considerable amounts of irrigation water in upper and middle reaches. Irrigation water use can be reduced by several effective methods, the saved water can be used to the ecosystem and increase biodiversity in the basin.

The lumped MIKE HYDRO model did not combine the land use map, and thus cannot deal with distributed water allocation issues. Therefore, the distributed MIKE HYDRO model was established in the mainstream of Tarim River, to find agricultural water allocation strategies along the river oases. The model presents a hydrological modeling approach to assist decision-makers and stakeholders to resolve potential water-sharing conflicts among water users. The land use map was combined with water distribution methods to solve the water allocation problems in a large basin scale. The model is tested and applied in three steps: 1) calibration and validation of water supply and demand along the Tarim River with a combined hydrological and groundwater model, with inputs from

MODFLOW; 2) developing climate change scenarios; 3) optimizing agricultural water allocation for the entire Tarim River Basin for the land use degradation scenarios and deriving of conclusions. The comprehensive management of farmland areas and water distribution strategies are investigated in the model scenarios. The results of these assessments provide scientific basis for substantial improvement on water allocation and water right. The access of a user to use the water efficiently should be guaranteed, especially in the lower reaches of the river. To secure and balance the water rights in the whole region, farmland areas should be adjusted according to the discharge in the river Water deficit has a rising trend from upper to lower reaches. The comprehensive management of water resources is very necessary from a whole basin point of view, rather than county by county, or farmland by farmland. Lower reaches suffer a severe water scarcity. The water conveyance to the downstream should not be ceased even in wet years.

Water allocation strategies were made to save extra irrigation water in the upper and middle reaches, and to maintain a relatively high water productivity in the entire catchments. Based on model scenarios, farmland areas need to be largely reduced in most hotspots by 2080. In five hotspots, water deficits are too large to maintain high crop water productivity. Reallocation of water resources is imperative in many hotspots due to huge water losses. To keep water deficit under 30%, migration or career transition of the farmers need to be planned ahead in many hotspots, especially for the decision-makers in Yuli county. In practice, the hydrological model assists on decision-making for water resource management in a large river basin, and incentive to utilize water use in an efficient manner. Scenarios of assuming discharge from Alar at 3 billion $m^3$, 4 billion $m^3$, 5 billion $m^3$, 6 billion $m^3$, and 7 billion $m^3$ were simulated, and irrigation water allocation strategies were made accordingly in the entire catchment. With the increase of discharge in Alar, hotspots in the upper and middle reaches would firstly take the extra water to alleviate their water deficit. After discharge beyond 6 billion $m^3$, HS in the lower reaches start to largely increase their water consumption. This phenomenon demonstrates water users in the upper and middle reaches still have higher priority to mitigate water deficit than the users in the lower reaches. Water supply rules have already been improved from “first come first serve” to “fraction of demand” in the MIKE HYDRO model, to improve water right in the lower reaches, and it can still be improved in future researches and models.

The development of the DSS links the outputs of hydrological models with real-time decision making on social-economic assessments and land use management. The DSS integrates the hydrological data, geographic data, social and economic statistical data, and establishes the relationships with equations, conditional statements and fuzzy logics. All the equations and expert knowledge are integrated in the DSS, to form the logics and links among the parameters. The programming is realized in C++. A user-friendly GUI is developed with both English and Chinese version. In the GUI, users can change the values and choose the options in the input indicators from their management alternatives, and the logics in the DSS determine the simulation results in the output indicators. Therefore, the stakeholders can easily evaluate the consequences of their actions in water and land management by using the DSS. The DSS has four remarkable features: 1) editable land use map to assist decision-making; 2) conjunctive use of surface and subsurface water resources; 3) interactions among water, earth, ecosystem and humans 4) links with hydrological models. Discharge and glacier geometry changes were simulated with hydrological model WASA. Irrigation and ecological water were simulated by MIKE HYDRO. Groundwater was simulated by MODFLOW. The DSS combines the outputs of hydrological models, knowledge of experts, and perspectives of stakeholders, into a computer-based system, which allows water and land management within regional planning. Simulation results of land use changes indicated a rising trend of deterioration on the grassland, forest and natural vegetation in 2030 and 2050. Downstream outflow results demonstrated an increasing trend of outflow in 2020, and a decreasing trend in 2030 and 2040. Socio-economic outputs show a rising trend of farmers' income, but a decreasing trend in drifting dust control and sand mobilization control by grassland. The DSS should not be recognized as a final product. Considerable amount of estimations and uncertainties were involved in the system. It can be improved by integrating more experience from the stakeholders and knowledge from researchers.

The DSS bridges the gap between scientific research and IWRM practice. The implementation of the DSS is crucial to the research and to the project. The application of DSS provides local stakeholders guidance in their management activities, and gathers feedbacks to modify the DSS. Knowledge exchange between scientists and stakeholders are very important for the DSS. A number of formal conferences and personal meetings were held to bring together scientists, ecologists, farmers and decision-makers in the Tarim River Basin. Several aspects in the DSS were modified based on the feedbacks from stakeholders. The successful implementation of the DSS provides a good example for other researches in future. The algorithm and methodologies are applicable to other research regions. The DSS is free available on request.

## 7.2 Final remark and future research

Research hypothesis of this Ph.D work have been testified by the research: 1) with the successful establishment of MIKE HYDRO models, water consumption issues were clarified and water allocation strategies were illustrated in the future scenarios; 2) The hydrological models provided guideline for solving practical water and land management problems; 3) the goals and requirements have been fulfilled with the application of water allocation rules in the models; 4) the DSS has been successfully developed by integrating interdisciplinary research topics. Based on the feedbacks from the stakeholders, the results of the DSS complies with their own practical experiences.

With the assist of hydrological models and the DSS, the research problems have been explained and answered in this thesis: 1) from the simulation results of MIKE HYDRO models, water losses were calculated water deficit maps were created along the river oases; 2) water allocation maps were generated based on different discharge scenarios; 3) new farmland areas were suggested on HS level; 4) different water-saving scenarios were tested to guarantee ecological water for nature vegetation; 5) the DSS was developed to assist decision-making processes; 6) hydrological models are linked with the DSS and provide scientific outputs for the DSS; 7) several scenarios were tested in the DSS under different management alternatives; 8) the knowledge of stakeholders were integrated in the DSS and their feedbacks contributed in improving the DSS; 9) the ecological and socio-economic outputs of the DSS provided guideline for making goals and strategies; 10) several examples were given in the thesis, to explain that the DSS can be further developed in various of aspects based on the feedbacks and perspectives from the stakeholders.

Most decision-makers have realized the necessity of protecting ecosystem and performing sustainable management in the Tarim River Basin, and the major problem becomes how to conduct the management practices in future. Hydrological models and the DSS provide scientific guidance on the decision-making process of sustainable water and land management. The involvement of stakeholders is crucial for a more reliable and valuable research. Through the discussions with stakeholders and researchers, three major research topics could be carried out in future research work.

Topic 1: spatial and temporal groundwater distributions in the Tarim River Basin. Groundwater resources are crucial to the growing of riparian forest, natural vegetation, and even for irrigation water abstraction. In the dry season, crop growth is dependent on groundwater abstraction. Though high groundwater salinity is a problem for the farmers, the use of groundwater is very common in the basin whenever necessary. Effective measures have to be seriously considered to prevent groundwater depletion. Before that, further research needs to be carried out for a better understanding of the groundwater conditions. Due to lacking of groundwater and salinity data, currently the MODFLOW model has not been calibrated, and the spatial and temporal soil salinity distribution is not clear. If groundwater and soil salinity map could be established in future researches, then the dilemma which farmers are facing while abstracting groundwater in the dry season could be better understood, and the process of winter irrigation could be simulated in the model. The modification of the current MODFLOW model could be a good start for future groundwater studies, with further research cooperation with Chinese scientists and more information gathered.

Topic 2: hydrological modeling which focus on irrigation and water allocation. In the arid regions of Central Asia, water scarcity and water saving remain hot topics in the IWRM practice. The studies on the runoff, reservoirs and water consumption are very important to understand water balance and to make better water allocation strategies. Currently in the MIKE HYDRO model, water levels in the reservoirs have not been calibrated due to lacking of data. The improvement of water allocation rules have not considered the regional differences and special needs of water (e.g. developing local characteristic agriculture). Irrigation water consumption is simulated on a hotspot level, and a better study would be on farmland scale. This downscaling of research could not be carried out without more detailed knowledge on the irrigation water abstractions. Further researches could also be conducted on the interactions between surface water and groundwater, as well as on methods to improve water use efficiency and maintain ecological water in the river oases. It is important to consider water productivity in water allocation and farmland management scenarios. The application of water-saving irrigation is a general trend in most arid regions in Central Asia. The effectiveness of drip irrigation under mulch should draw more attention in future years. Moreover, the land use type changes and other possible water-saving approaches could be investigated on farmland scale in future studies.

Topic 3: modification of the DSS and application of new DSS in other watersheds. Based on the effectiveness of the DSS in decision-making process and successful experience of project SuMaRiO, further modification of the DSS is valuable and applicable to other arid regions. The modification of the DSS could be conducted on the fuzzy rules, equations, reference values and adding more parameters and logics in the DSS. It is possible to link the DSS with other hydrological models, such as MODFLOW-OWHM and FREEWAT, to include farm process in the simulation. Particularly, the improvement of the DSS could aim on providing scientific support for ensuring sufficient ecological water, curbing the degradation of the desert ecosystem and protecting the ecological security of the oases. The improved DSS should provide guidance for practical solutions on ecological system restoration, which is a hot topic in the development plans by Xinjiang local governments. Besides ecological factors, the DSS could also be modified by revising and adding more socio-economic criteria. Some researchers and decision-makers have started discussions on the marketization of water rights along the Tarim River, to seek economic balance between water supply and water demand. Furthermore, future studies could also be carried out to relate the distributions of wild animals with climate change, land use, water resources and human activities. To gather expert knowledge in various research aspects, the interdisciplinary research cooperation is very necessary. More stakeholders and decision-makers should be involved in the future research to provide more valuable and sufficient information in their management practices. In general, the DSS could be a good platform for many other studies relating to water cycle in arid regions. With further research and improvements, the DSS could be a very practical and useful tool to assist decision-making on sustainable water and land management in large river basins.

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**Appendix I:**

**Photos depicting the landscape of the Tarim River Basin**

**Figure A1:** Upper reaches of the Tarim River.

**Figure A2:** Lower reaches of the Tarim River during flood season.

**Figure A3:** *Populus euphratica* in the middle reaches of the Tarim River Basin.

**Figure A4:** Taitema Lake. The natural ending of the Tarim River (from the north of the lake) and Qarqan River (from the south of the lake).

**Figure A5:** Drip irrigation applied in the orchard.

**Figure A6:** Low bushes near the Taklimakan Desert.

**Figure A7:** Dry canal in the lower reaches.


**Figure A8:** Land deterioration has aroused high attention by the local government and water authority.

**Figure A9:** Discussions with local stakeholders and farmers.

**Figure A10:** Wood of *Populus euphratica* for barbecue. Many old habits which are harmful to the ecosystem still exist in the study area.

**Figure A11:** Water-tight canal in lower reaches. New canals and river banks have been built in recent years to prevent water losses.

**Figure A12:** Unauthorized water abstraction. Water surveillance is a difficult issue along the river of 1321 km.


**Figure A13:** Qiala Reservoir. The largest reservoir in lower reaches.

**Figure A14:** Daxihaizi Reservoir. The outflow of the DSS is calculated here due to long period of river interception downstream.

**Figure A15:** Cotton field. A second-round cropping is always necessary to assure a good harvest.

**Figure A16:** Grass-panes are largely used in lower reaches to prevent the invasion of the deserts.

**Figure A17:** Field trips and data collections.

**Figure A18:** Land use types with possible changes in the Tarim River Basin.

## Appendix II:

### Soil property and MIKE HYDRO model outputs

**Table B1:** The representative soil property values and maximum depletion by evaporation for an evaporation layer of 0.1 m (DHI. 2014).

| Soil type | Field capacity | Wilting point | Difference | Max. depletion by evaporation (mm) |
|---|---|---|---|---|
| Sand | 0.07-0.17 | 0.02-0.07 | 0.05-0.11 | 6-12 |
| Loamy sand | 0.11-0.19 | 0.03-0.10 | 0.06-0.12 | 9-14 |
| Sandy loam | 0.18-0.28 | 0.06-0.16 | 0.11-0.15 | 15-20 |
| Loam | 0.20-0.30 | 0.07-0.17 | 0.13-0.18 | 16-22 |
| Silt loam | 0.22-0.36 | 0.09-0.21 | 0.13-0.19 | 18-25 |
| Silt | 0.28-0.36 | 0.12-0.22 | 0.16-0.20 | 22-26 |
| Silt clay loam | 0.30-0.37 | 0.17-0.24 | 0.13-0.18 | 22-27 |
| Silt clay | 0.30-0.42 | 0.17-0.29 | 0.13-0.19 | 22-28 |
| Clay | 0.32-0.40 | 0.20-0.24 | 0.12-0.20 | 22-29 |

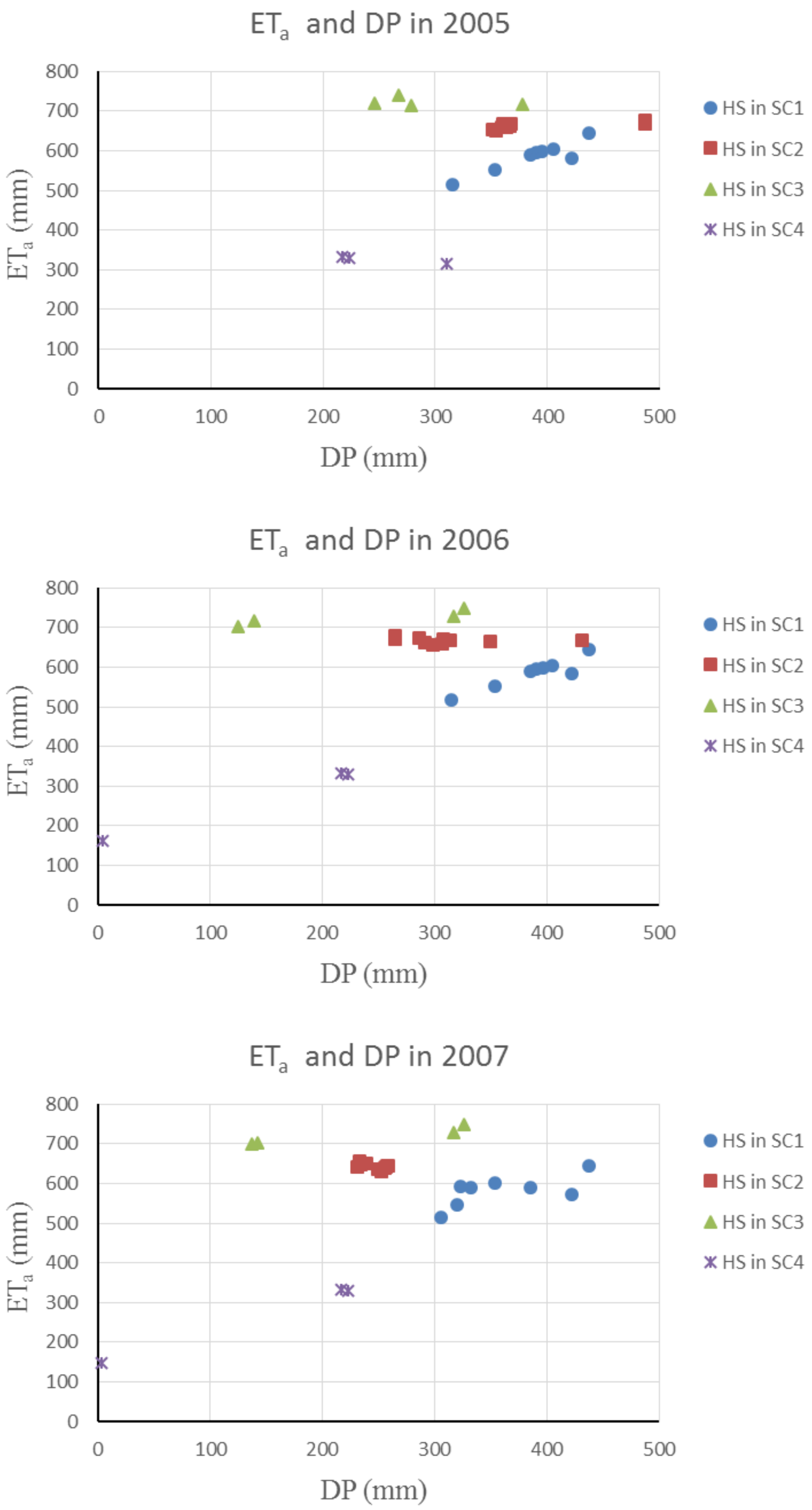


**Figure B1:** Actual evapotranspiration ($ET_a$) and deep percolation (DP) in different hotspots (HS) and sub-catchments (SC) from 2005 to 2007.

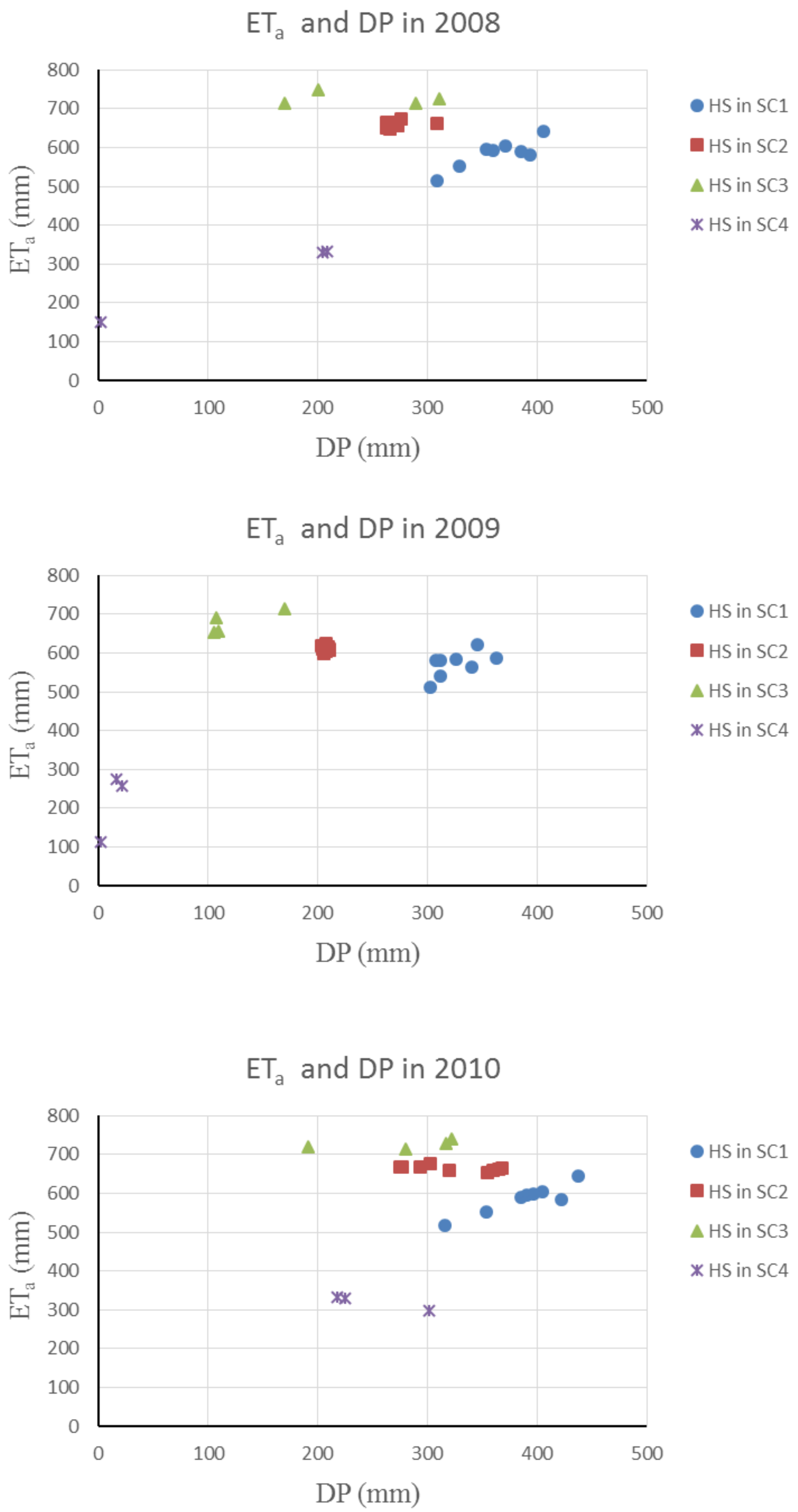


**Figure B2:** $ET_a$ and DP from 2008 to 2010.

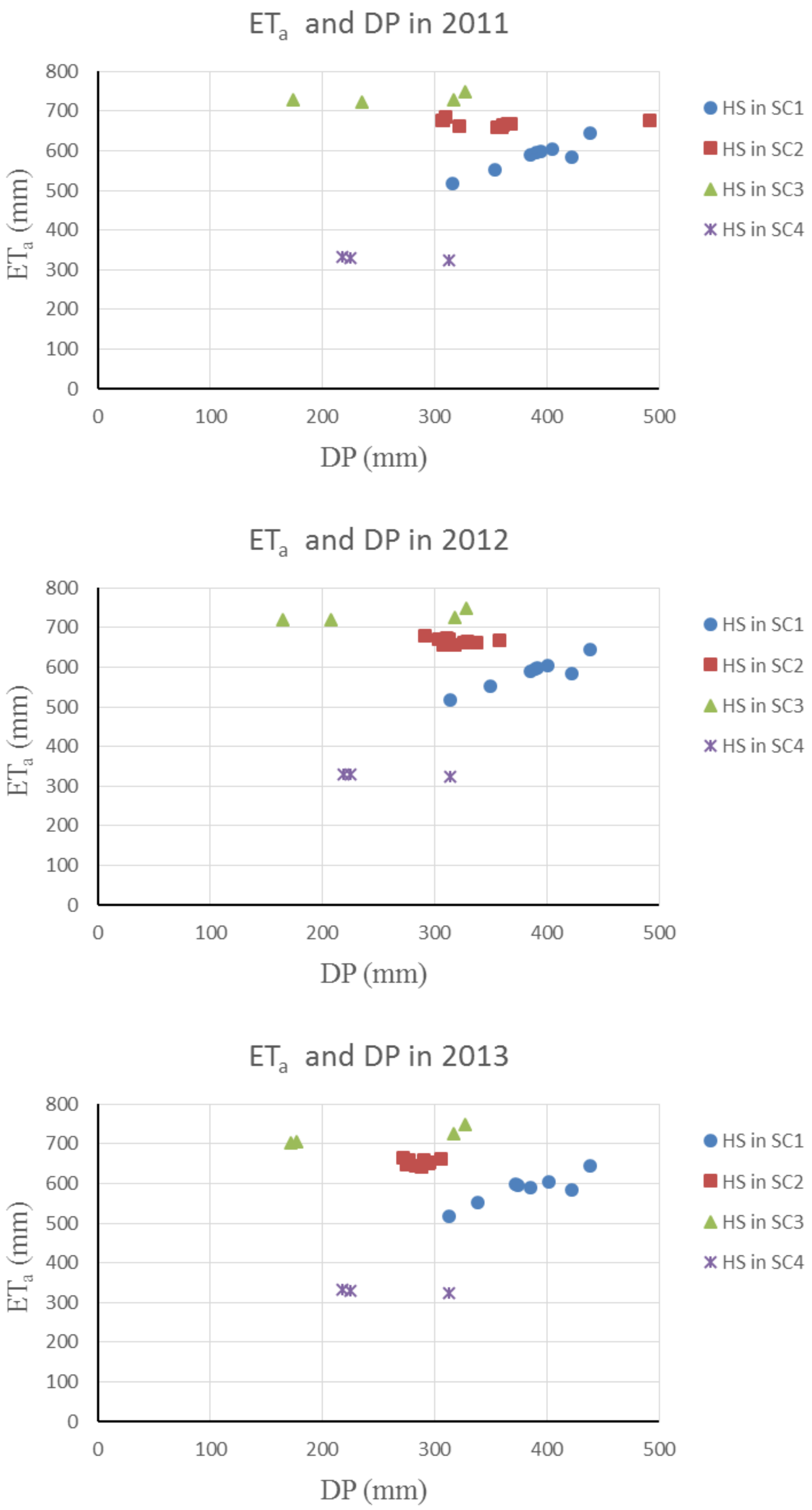


**Figure B3:** $ET_a$ and DP from 2011 to 2013.

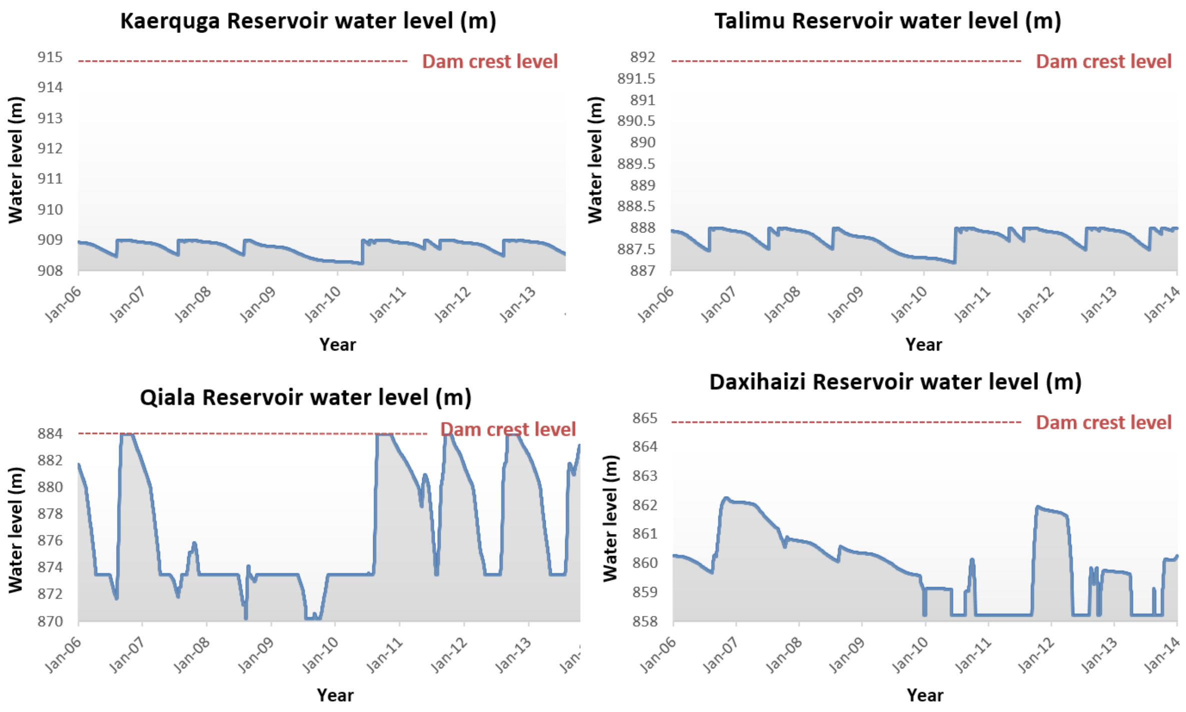


**Figure B4:** Water levels of reservoirs in the middle and lower reaches from 2006 to 2013.

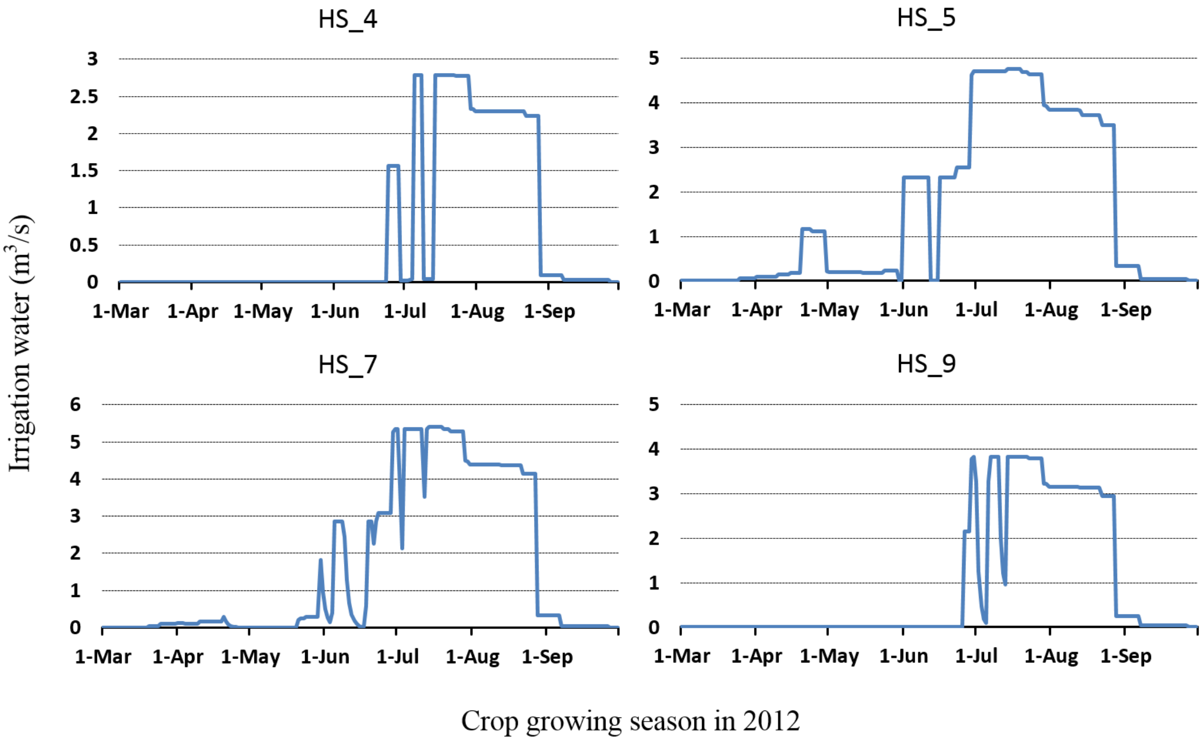


**Figure B5:** Agricultural water allocation for HS_4, HS_5, HS_7 and HS_9 in 2012.

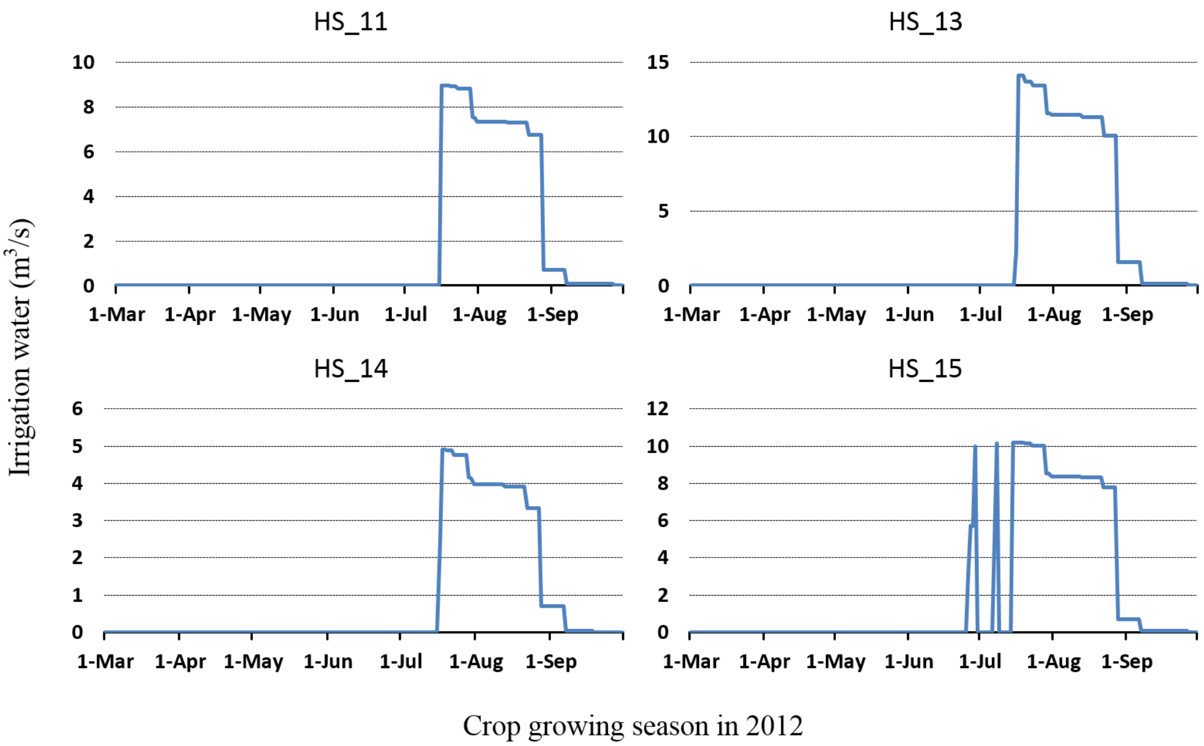


**Figure B6:** Agricultural water allocation for HS_11, HS_13, HS_14 and HS_15 in 2012.

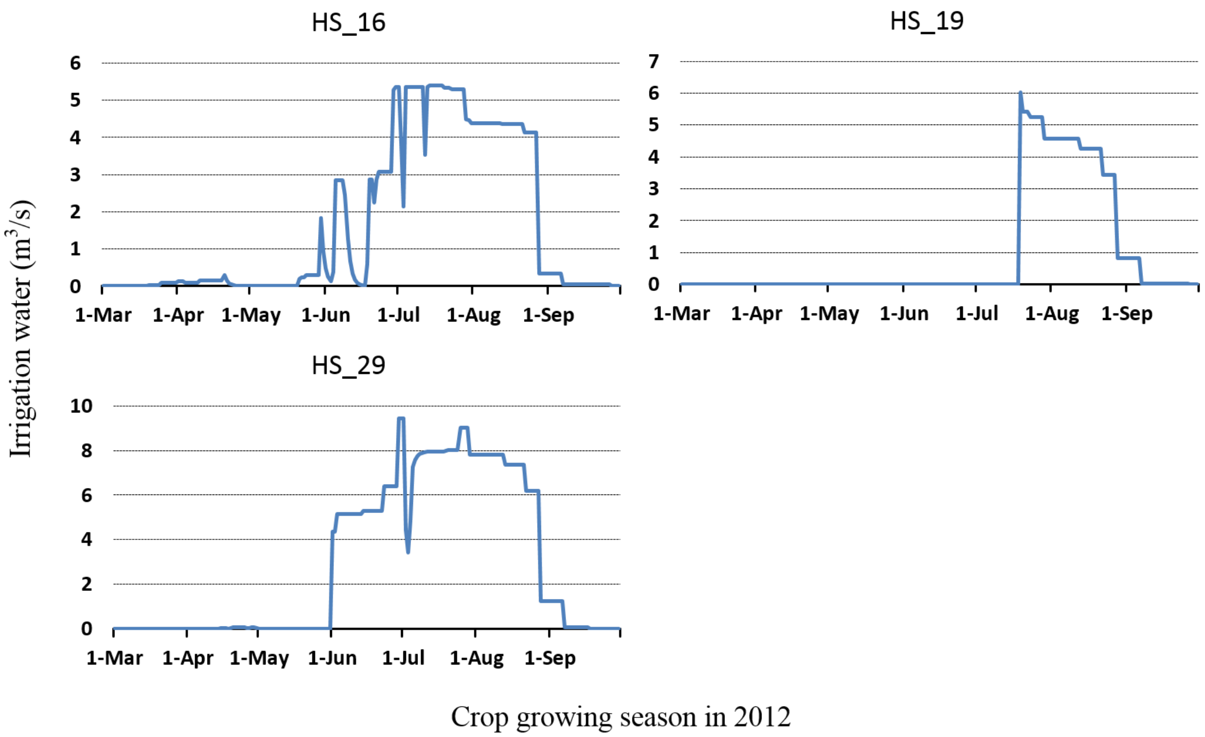


**Figure B7:** Agricultural water allocation for HS_16, HS_19 and HS_29 in 2012.

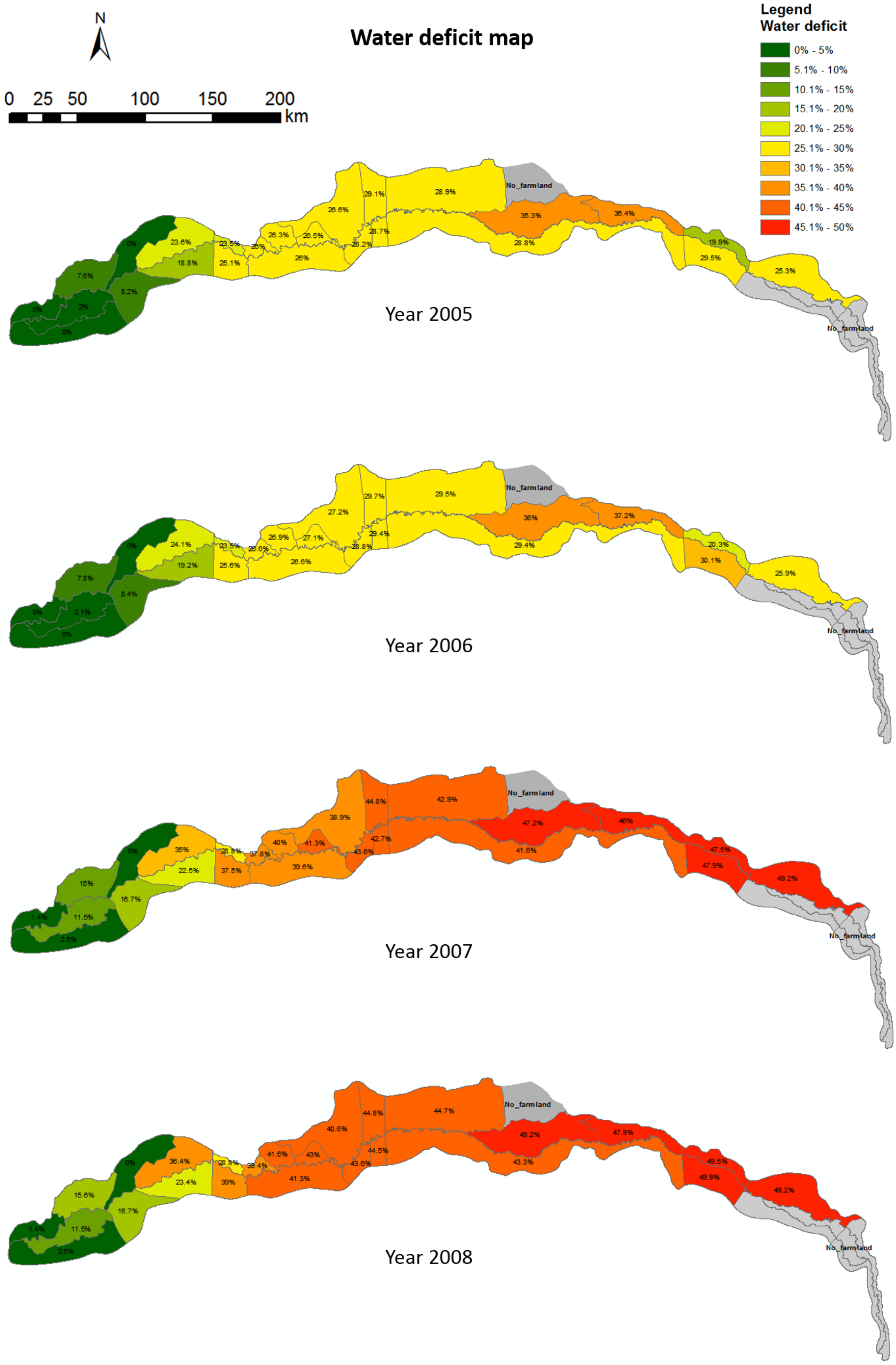


**Figure B8:** Water deficit map from 2005 to 2008.

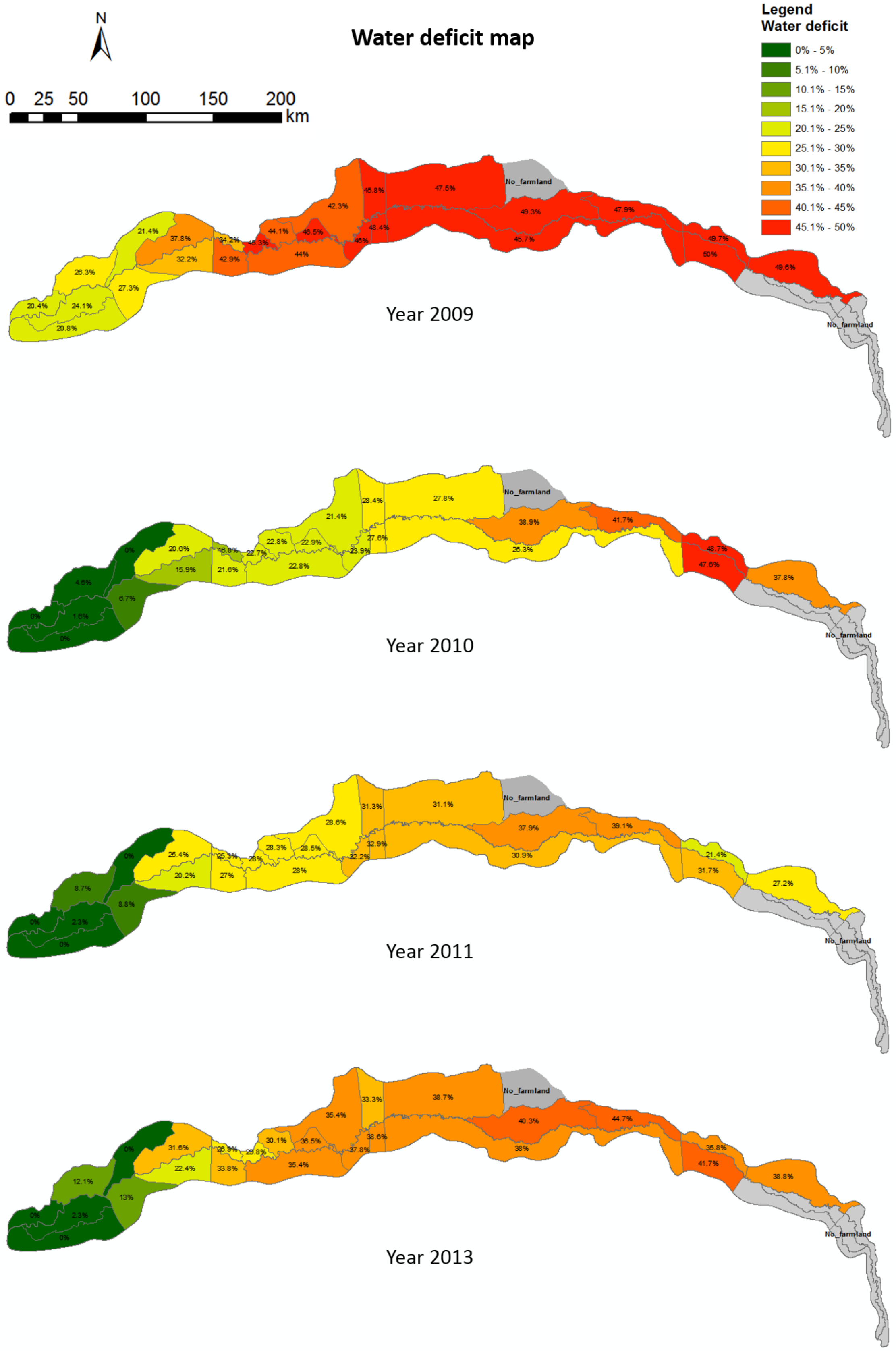


**Figure B9:** Water deficit map in 2009, 2010, 2011 and 2013.

## Appendix III:

## Algorithm: Output calculation of the DSS

- **for** m = 0 **to** n **do** */*for each management alternative defined by the user*/*
    - **for** r = 0 **to** 4 **do** */*for each of the four regions*/*
        - **for** y = start year **to** end year **do** */*for each year from the start year to the end year defined by the user*/*
            - **for** t = 0 **to** 12 **do** */*for each month*/*
                - calculate irrigation water demand
                - calculate inflow into the sub-catchments
                - **for** i = 0 **to** number of grid cells **do** */* for each grid cell with the size of 500m x 500m*/*
                    - calculate groundwater level;
                    - calculate evapotranspiration;
                    - calculate groundwater salinity;
                    - calculate soil salinity; */*main output for [m][r][y]; aggregation over months*/*
                    - calculate d^2 h / dx dy;
                    - **case** landuse in cell == grassland
                        - calculate grassland indicators;
                    - **case** landuse in cell == natural vegetation
                        - calculate natural vegetation indicators;
                    - **case** landuse in cell == riparian forest high density
                        - calculate riparian forest high density indicators;
                    - **case** landuse in cell == riparian forest low density
                        - calculate riparian forest low density indicators;
                    - **case** landuse in cell == cotton
                        - calculate cotton production;
                    - **case** landuse in cell == other agriculture
                        - calculate fruit production;
                        - calculate production of other crops
            - aggregate grassland indicators on sub-catchment level over months;
            - aggregate riparian forest indicators on sub-catchment level over months;
            - aggregate cotton production on sub-catchment level over months;
            - aggregate fruit production on sub-catchment level over months;
            - aggregate production of other crops on sub-catchment level over months;
            - calculate farmers‘ income

(Source: created by Marie Hinnenthal from Universität der Bundeswehr)

**Algorithm: fuzzy rules of drifting dust control in the program**

```
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::High);
rule->add(fl::Rule::And, fl::Rule::High);
rule->result(fl::Rule::Medium);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Low);
rule->add(fl::Rule::And, fl::Rule::Low);
rule->result(fl::Rule::Low);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Medium);
rule->add(fl::Rule::And, fl::Rule::Medium);
rule->result(fl::Rule::Low);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Medium);
rule->add(fl::Rule::And, fl::Rule::High);
rule->result(fl::Rule::Medium);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::High);
rule->add(fl::Rule::And, fl::Rule::Medium);
rule->result(fl::Rule::Medium);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Medium);
rule->add(fl::Rule::And, fl::Rule::Low);
rule->result(fl::Rule::Low);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::High);
rule->add(fl::Rule::And, fl::Rule::Low);
rule->result(fl::Rule::Low);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Low);
rule->add(fl::Rule::And, fl::Rule::Medium);
rule->result(fl::Rule::Low);
rule = driftingDustControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Low);
rule->add(fl::Rule::And, fl::Rule::High);
    rule->result(fl::Rule::Low);

driftingDustControlByRiparianForestLowDensity.output->functions[0].addPoint(0.0000067, 0.0);
driftingDustControlByRiparianForestLowDensity.output->functions[0].addPoint(0.0000083, 1.0);
driftingDustControlByRiparianForestLowDensity.output->functions[1].addPoint(0.0000033, 0.0);
driftingDustControlByRiparianForestLowDensity.output->functions[1].addPoint(0.0000042, 1.0);
driftingDustControlByRiparianForestLowDensity.output->functions[1].addPoint(0.0000058, 0.0);
driftingDustControlByRiparianForestLowDensity.output->functions[2].addPoint(0.0, 1.0);
driftingDustControlByRiparianForestLowDensity.output->functions[2].addPoint(0.0000033, 0.0);
```

(Source: created by Marie Hinnenthal, modified by Yang Yu)

**Algorithm: fuzzy rules of sand mobilization control in the program**

```
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::High);
rule->add(fl::Rule::And, fl::Rule::High);
rule->result(fl::Rule::Medium);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Low);
rule->add(fl::Rule::And, fl::Rule::Low);
rule->result(fl::Rule::Low);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Medium);
rule->add(fl::Rule::And, fl::Rule::Medium);
rule->result(fl::Rule::Low);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::High);
rule->add(fl::Rule::And, fl::Rule::Medium);
rule->result(fl::Rule::Medium);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Medium);
rule->add(fl::Rule::And, fl::Rule::High);
rule->result(fl::Rule::Medium);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::High);
rule->add(fl::Rule::And, fl::Rule::Low);
rule->result(fl::Rule::Low);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Low);
rule->add(fl::Rule::And, fl::Rule::Medium);
rule->result(fl::Rule::Low);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Low);
rule->add(fl::Rule::And, fl::Rule::High);
rule->result(fl::Rule::Low);
rule = sandMobilizationControlByRiparianForestLowDensity.createRule();
rule->add(fl::Rule::None, fl::Rule::Medium);
rule->add(fl::Rule::And, fl::Rule::Low);
    rule->result(fl::Rule::Low);

sandMobilizationControlByRiparianForestLowDensity.output->functions[0].addPoint(250.0, 0.0);
sandMobilizationControlByRiparianForestLowDensity.output->functions[0].addPoint(500.0, 1.0);
sandMobilizationControlByRiparianForestLowDensity.output->functions[1].addPoint(0.83, 0.0);
sandMobilizationControlByRiparianForestLowDensity.output->functions[1].addPoint(166.67, 1.0);
sandMobilizationControlByRiparianForestLowDensity.output->functions[1].addPoint(333.33, 0.0);
sandMobilizationControlByRiparianForestLowDensity.output->functions[2].addPoint(0.0, 1.0);
sandMobilizationControlByRiparianForestLowDensity.output->functions[2].addPoint(0.83, 0.0);
```

(Source: created by Marie Hinnenthal, modified by Yang Yu)

**Algorithm: weights of the ESS indicators in the program**

```
weightApocynumProduction = {0.0, 3.0, 3.0, 3.0, 3.0, 0.0};
weightReedProduction = {0.0, 4.0, 4.0, 5.0, 5.0, 0.0};
weightDriftingDustControlByGrassland = {0.0, 4.0, 4.0, 5.0, 5.0, 0.0};
weightSandMobilizationControlByGrassland = {0.0, 4.0, 4.0, 5.0, 5.0, 0.0};
weightBiomassProduction = {0.0, 2.0, 2.0, 2.0, 2.0, 0.0};
weightDriftingDustControlByRiparianForest = {0.0, 4.0, 5.0, 5.0, 5.0, 0.0};
weightSandMobilizationControlByRiparianForest = {0.0, 4.0, 5.0, 5.0, 5.0, 0.0};
weightWindControlByRiparianForestHighDensity = {0.0, 3.0, 3.0, 3.0, 3.0, 0.0};
weightCarbonStorageByRiparianForestHighDensity = {0.0, 3.0, 3.0, 3.0, 3.0, 0.0};
weightSpecies = {0.0, 3.0, 3.0, 3.0, 3.0, 0.0};
weightCottonProduction = {0.0, 4.0, 4.0, 4.0, 4.0, 0.0};
weightFruitProduction = {0.0, 4.0, 4.0, 4.0, 4.0, 0.0};
weightProductionOfOtherCrops = {0.0, 5.0, 5.0, 4.0, 4.0, 0.0};
weightFarmersIncome = {0.0, 5.0, 5.0, 5.0, 5.0, 0.0};
weightGrasslandProvisioningService = {0.0, 4.0, 4.0, 5.0, 5.0, 0.0};
weightGrasslandRegulatingService = {0.0, 4.0, 4.0, 5.0, 5.0, 0.0};
weightRiparianForestProvisioningService = {0.0, 4.0, 5.0, 5.0, 5.0, 0.0};
weightRiparianForestRegulatingService = {0.0, 4.0, 5.0, 5.0, 5.0, 0.0};
weightRiparianForestSupportingService = {0.0, 4.0, 5.0, 5.0, 5.0, 0.0};
weightAgricultureProvisioningService = {0.0, 4.0, 4.0, 3.0, 3.0, 0.0};
weightGrassland = {0.0, 4.0, 4.0, 4.0, 5.0, 0.0};
weightRiparianForest = {0.0, 4.0, 5.0, 5.0, 5.0, 0.0};
weightAgriculture = {0.0, 4.0, 4.0, 3.0, 3.0, 0.0};
```

(Source: created by Marie Hinnenthal, modified by Yang Yu)

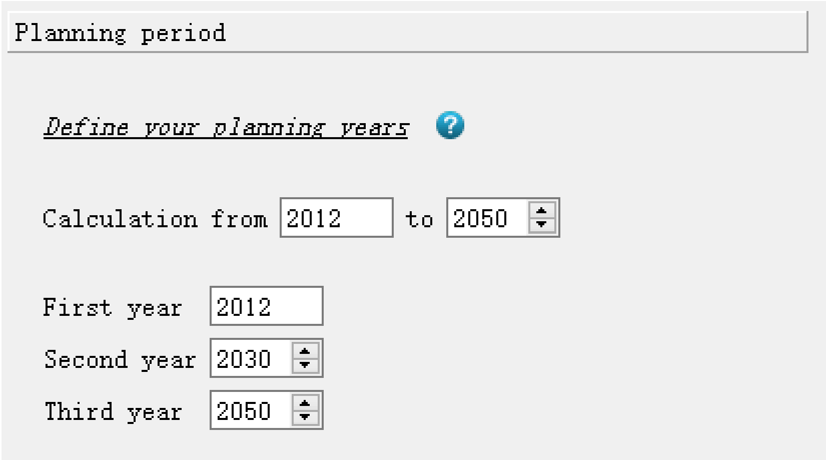


**Figure C1:** Planning period from 2012 to 2050.

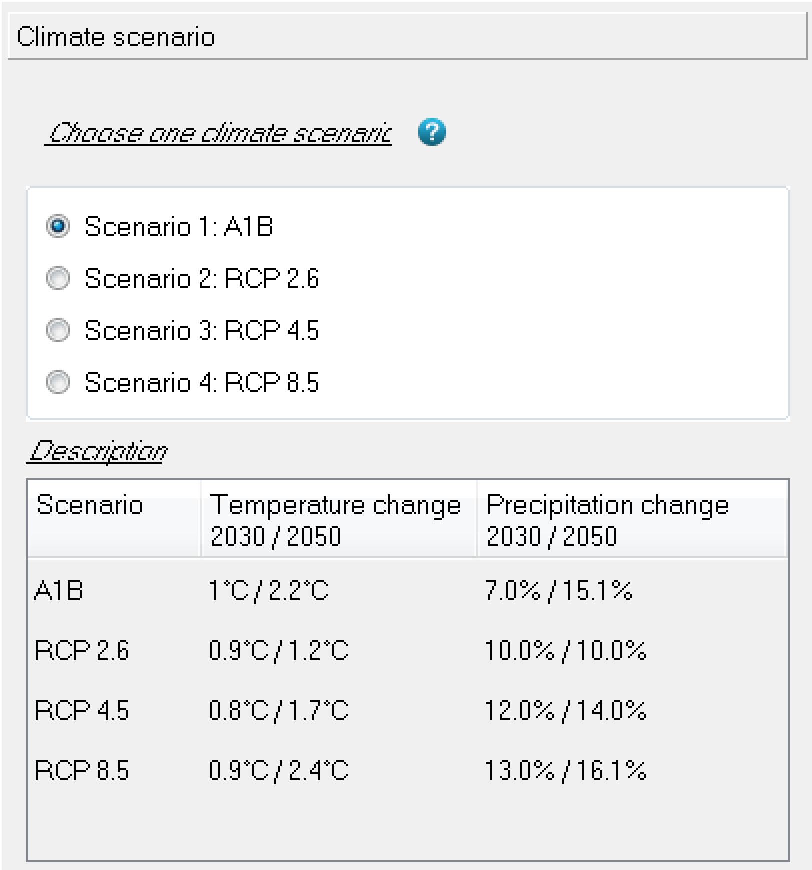


**Figure C2:** Four climate scenarios can be chosen by users under different temperature rise and precipitation increase projections.

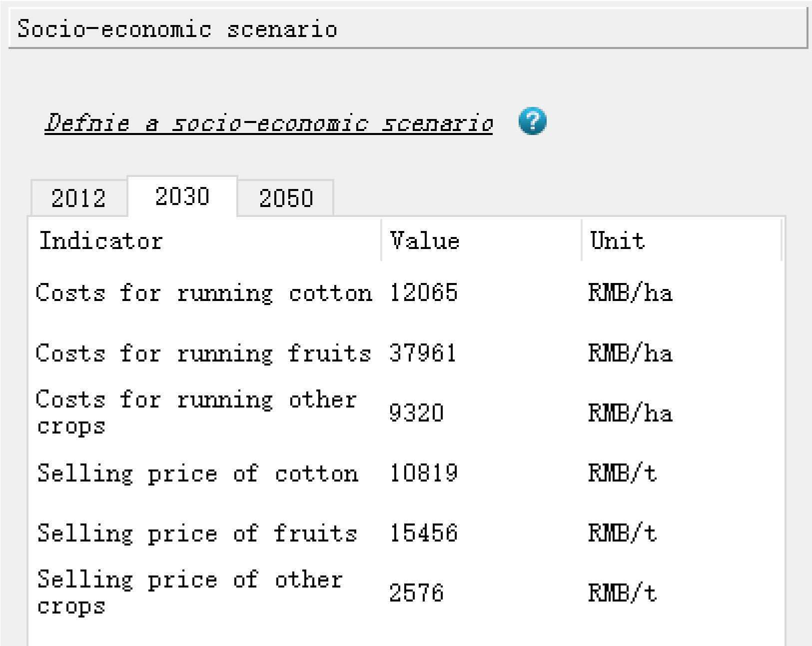


**Figure C3:** Socio-economic scenarios.

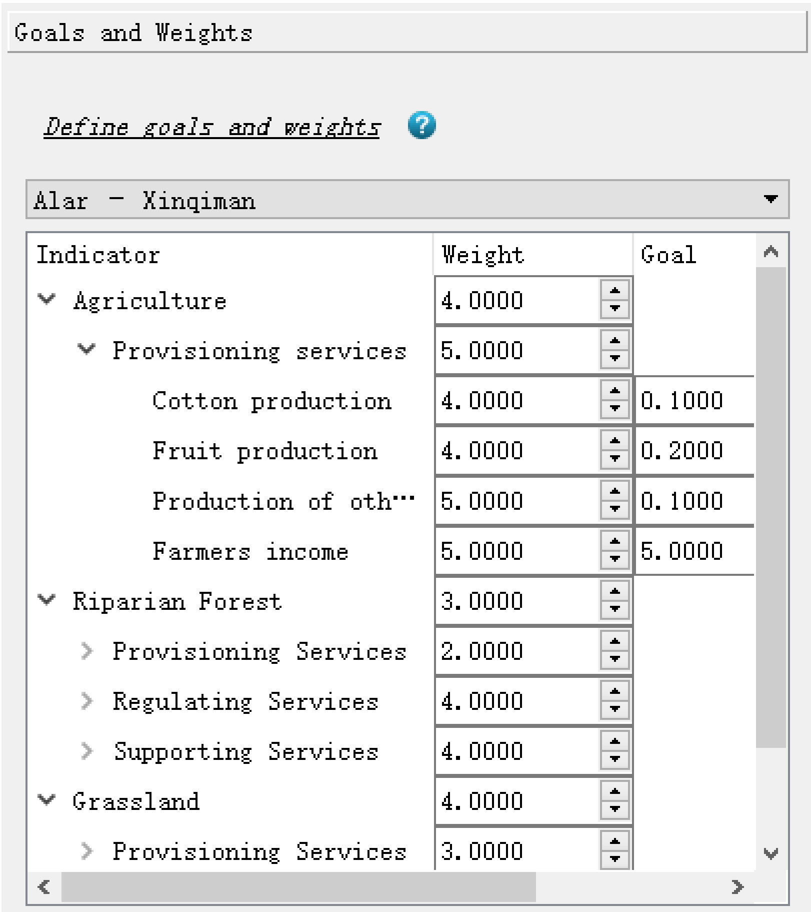


**Figure C4:** Goals and weights for the indicators of ecosystem services.

**Appendix IV:**

شىنجاڭ ئۇيغۇر ئاپتونوم رايونى تارىم دەريا ۋادىسىنى باشقۇرۇش ئىدارىسى

新疆维吾尔自治区塔里木河流域管理局

## Suggestion for SuMaRiO Project Results

Sino-German SuMaRiO project management unit:

From 2011 to 2015, supported by BMBF, organized by Technical University of Munich and Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, research on land and water management in the Tarim basin was successfully done collaboratively by over 100 Germans and Chinese scientists. In September 2015, the project wrap-up session was held in Urumqi, Xinjiang, China, the related department of Xinjiang Tarim River Basin Management Bureau attended the meeting. We believed that during the past five years, the project has made significant achievements. Including establishment of the Decision Support System (DSS) and research reports .We greatly appreciate for your contributions.

As the management administrative department of Tarim River Basin, the following suggestions are from our side:

1. Present the research report and policy advice to Xinjiang Tarim River Basin Bureau, as an important reference for future decisions.

2. Due to the importance of the Decision Support System

**Figure D1:** Documentation from the stakeholders with suggestions on the DSS (a).

(DSS) of the Tarim River Basin, we would be very appreciated if it could be transfer to the management administrative department of Tarim River Basin.

3. Training for using the Decision Support System (DSS) is requested.

4. Sustainability-oriented projects is very important for the developing of DSS.

Again, we highly appraise the valuable and successful research work of the Sino-German SuMaRiO project, for the sustainable management of river oases along the Tarim River. We hope we will have a good cooperation in the future, for the sustainable development of our globe.

Xinjiang Tarim River Basin Bureau,

China

2016-02-29

**Figure D2:** Documentation from the stakeholders with suggestions on the DSS (b).