ZENTRUM FÜR ENTWICKLUNGSFORSCHUNG -

RHEINISCHE FRIEDRICH-WILHELMS-UNIVERSITÄT BONN

Efficient Water Allocation and Water Conservation Policy Modeling in the Aral Sea Basin

Inaugural-Dissertation

zur
Erlangung des Grades

Doktor der Agrarwissenschaften
(Dr.agr.)

der
Landwirtschaftlichen Fakultät
der
Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt am 31.10.2013
von
Maksud Bahodirovich Bekchanov
aus
Khorezm (Usbekistan)

Referent: Prof. Dr. Joachim von Braun

Korreferent: Prof. Dr. Thomas Heckelei

Tag der mündlichen Prüfung: 26.03.2014

Erscheinungsjahr: 2014

EFFICIENT WATER ALLOCATION AND WATER CONSERVATION POLICY MODELING IN THE ARAL SEA BASIN

ABSTRACT

Increasing water demand challenges policy makers to implement in-time and effective water management measures to mitigate both the on-going and upcoming water crisis in the Aral Sea basin (ASB) of Central Asia. The shrinkage of the Aral Sea due to the rapid expansion of irrigated agriculture along the two main rivers of the basin – the Amu Darya and Syr Darya – which accompanied by water overuse is at the core of the all water related problems. Various hypothetical "solutions", including massive inter-basin water transfers, have been considered to ease the water challenge. Yet, given the enormous conveyance and water application losses in the irrigation system combined with ineffective coordination of the basin resources among the riparian countries in both the Amu and Syr Darya basins, increasing the efficiency of using internal water resources is more technically and financially feasible option. Furthermore, water management measures must address the root causes of water scarcity and ecological deterioration rather than attempting to deal with the consequences of the problem only. This study examines therefore three important options for addressing the core reasons of aggravated water (ab)use in the ASB. In the first option, sectoral transformations (e.g., economic restructuring) are considered by prioritizing economic activities with relatively high economic growth impacts and low water consumption requirements. In the second option, it is assessed to replace the current administrative water management institutions with more effective market-based water allocation institutions to encourage cooperation among regional water users for attaining optimal basin-wide benefits. In the third option, technological and infrastructural improvements are evaluated following an increased efficiency of the irrigation systems and building reservoirs in the upper reaches of the rivers to regulate river flow.

Economic restructuring was analyzed by ranking all economic sectors based on their sustainable economic growth potentials using an environmentally extended input-output model. The forward and backward linkages and the total (direct and indirect) water requirements of the different economic activities were estimated and compared as well. The results indicated that water demand in the ASB can be reduced substantially by decreasing the production of the water intensive sectors such as agriculture in favor of the development of less water demanding, non-agricultural sectors. Within the agriculture sector, crop diversifications are recommendable, e.g. by partially replacing rice cultivation and cotton production, which have the highest total (direct and indirect) water use contents of 36 m^3/USD and 18.4 m^3/USD respectively, with high water productive crops such as fruits/vegetables with total water use of 9.1 m^3/USD.

Potential effects of replacing the traditional administrative water allocation system with market-based water allocation approaches were examined through an aggregated hydro-economic model. Substantial basin-wide economic gains is appeared feasible when the trade of water rights among all irrigation zones is allowed in each river basin (the Amu Darya or Syr Darya). Total benefits under restricted water rights trading by permitting a trade only among the regions located within each upstream, midstream, and downstream sub-basins (catchments) is lower than the total economic gains of unrestricted water rights trading but is still higher than total benefits of the option without trading. Depending on water availability, the amount of additional annual gains ranged between $373 and 476 million USD under an inter-catchment (unrestricted) water rights trading system whereas additional annual gains of $259–339 million USD were predicted under intra-catchment (restricted) water rights trading. Benefits from water rights trading increase with growing water scarcity. When purchase of water use rights is considered to enhance environmental flow into the Aral Sea while compensating reduced water withdrawals of agricultural producers, basin-wide economic gains are expected to be higher if water rights trading among irrigation zones are allowed rather than prohibited. Moreover, the cost of purchasing water use rights for environmental needs is less expensive compared to an interbasin water transfer. Since the establishment and operation of market-based water allocation institutions comes with costs, the transaction costs of introducing tradable water use rights were considered in assessing the effectiveness of such institutional changes. An inverse relationship were found between the benefits of water rights trading and its transaction costs. Results showed furthermore that transaction costs of more than \$0.05 USD per m^3 of water use rights eliminate the potential benefits of a water trading option.

Technical improvements to raise the efficiency of water use and water coordination were analyzed through a disaggregated hydro-economic model. Substantial benefits can be expected from improving irrigation (conveyance and water application) efficiencies in the ASB. Total basin-wide benefits can increase by 20% to 40% depending on basin-wide water availability when irrigation system efficiencies are optimized across the basin. The findings showed also that a construction of upstream reservoirs as intensely debated at present by up- and downstream countries in Central Asia does not considerably influence on the irrigation water availability if these reservoirs are operated with the objective of providing optimal basin-wide benefits. In constrast, constructing additional dams can boost hydropower production. Particulalry, additional hydropower produciton benefits are expected to be considerably higher from the construction of the Kambarata reservoir than those from the construction of the Rogun dam because of higher investment costs of the latter. Thus, the construction of dams upstream can increase national and regional energy security due to 65-67% increase in hydropower production levels. Yet, the risks of flooding related to natural and political calamities and reduced downstream water availability during the period of filling the reservoirs should be evaluated further for a more comprehensive assessment of such infrastructural developments. High risks of using upstream reservoirs as a tool of geopolitical influence and consequent damage on downstream irrigation and environmental systems should not be forgotten as well. Establishing effective relationships among the riparian countries, ensuring the rule of law, empowering water users for decision making, raising their awareness on ecological sustainability and market-based management approaches, and maintaining human and technological capacities are also essential for finding a compromise in sharing common basin resources in the ASB.

Keywords: Water rights trading, Transaction costs, Environmental flow, Hydro-economic model, irrigation technology, infrastructural development, Rogun dam, Kambarata reservoir, Sectoral transformation, Virtual water, Input-output analysis

MODELLIERUNG VON STRATEGIEN ZUR EFFIZIENTEN ALLOKATION UND SCHONUNG VON WASSERRESSOURCEN IM EINZUGSGEBIET DES ARALSEES

ZUSAMMENFASSUNG

Im Einzugsgebiet des Aralsees (ASB) stellt der steigende Wasserbedarf eine Herausforderung an die Entscheidungsträger dar, zeitnah Maßnahmen für eine effiziente Wasserbewirtschaftung einzuführen, um die derzeitige und zukünftige Wasserkrise in der Region zu entschärfen. Die schnelle Ausdehnung der bewässerten Landwirtschaft in Verbindung mit einer Über-Nutzung der Wasserressourcen führte zum Schrumpfen des Aralsees; zur Lösung dieses Problems wurden zahlreiche hypothetische Ansätze vorgeschlagen, die auch den massiven Wassertransfer aus anderen Einzugsgebieten einbezogen. Bedenkt man allerdings die enormen Transport- und Wasseraufleitungsverluste in den Bewässerungssystemen und die ineffektive Koordination in der Bewirtschaftung von Ressourcen aufgrund unzureichender Zusammenarbeit zwischen den Staaten in den Einzugsgebieten der Flüsse Amu Darya und Syr Darya, erscheint die Erhöhung der internen Effizienz bei der Nutzung der Wasserressourcen ein in technischer und finanzieller Hinsicht eher Erfolg versprechender Ansatz. Darüber hinaus sollten diese Maßnahmen der Wasserbewirtschaftung auch und vor allem die wesentlichen Ursachen des Wassermangels und der ökologischen Probleme angehen, anstatt lediglich deren Folgen zu behandeln.

Diese Studie untersucht drei wichtige Ansätze, um die grundlegenden Ursachen der sich verschärfenden Wasserbewirtschaftungsprobleme im ASB zu bearbeiten. Die erste Option ist die sektorale Transformation (ökonomische Neuordnung), bei der man wirtschaftliche Aktivitäten mit hoher Priorität versieht, die einen relativ hohen Impuls auf das Wirtschaftswachstum ausüben und einen niedrigen Wasserverbrauch erfordern. Die zweite Option besteht darin, die bürokratischen Wassermanagement-Institutionen durch effektivere Markt-basierte Wasserallokations-Institutionen zu ersetzen, die die Zusammenarbeit zwischen regionalen Wassernutzern fördern, um in Bezug auf das gesamte Einzugsgebiet Vorteile zu erzielen. Die dritte Option beinhaltet die Verbesserung der Effizienz der Bewässerungssysteme und den Bau von Speichern zur Regulierung des Abflusses an den Oberläufen der Flüsse.

Die Möglichkeit der ökonomischen Restrukturierung wurde mit Hilfe eines auf die Umweltfaktoren ausgeweiteten Input-Output Modells analysiert, so dass im Ergebnis alle ökonomischen Sektoren im Hinblick auf ihren potenziellen Beitrag zu einem nachhaltigen Wirtschaftswachstum beurteilt und in eine Rangliste gebracht wurden. Hierfür wurden Vorwärts- und Rückwärtsverknüpfungen und die gesamten (direkten und indirekten) Wasserbedarfswerte der verschiedenen wirtschaftlichen Aktivitäten geschätzt und miteinander verglichen. Die Ergebnisse zeigten, dass der Wasserbedarf im ASB reduziert werden kann, indem die Produktion wasserintensiver Sektoren wie Landwirtschaft verringert wird, während die Entwicklung weniger wasserintensiver Sektoren außerhalb der Landwirtschaft gefördert wird. Innerhalb der Landwirtschaft ist eine Diversifizierung ratsam, die den Anbau von Reis und Baumwolle mit jeweils hohem Gesamtwasserverbrauch (direkt und indirekt) von 36 m^3/USD bzw. 18,4 m^3/USD teilweise ersetzt durch Wasser-produktivere Pflanzen, wie beispielsweise Obst/Gemüse mit einem Gesamtwasserverbrauch von 9,1 m^3/USD.

Mit einem aggregiertem hydro-ökonomischen Modell wurden potenzielle Auswirkungen untersucht, die mit dem Ersetzen des traditionellen administrativen Wasserallokations-System durch Markt-basierte Wasserallokation erzielt werden können. Bedeutende ökonomische Gewinne im gesamten Einzugsgebiet sind erreichbar, wenn der Handel von Wasserrechten zwischen allen Bewässerungszonen in jedem der Einzugsgebiete (Amu Darya oder Syr Darya) erlaubt wurde. Die Begrenzung des Handels von Wasserrechten auf jeweils Untereinheiten der Einzugsgebiete (oberer, mittlerer, unterer Teil) führte zu einem Gesamtgewinn, der zwar geringer ausfiel als im Fall des unbegrenzten Handels aber höher war als bei der Option ohne Wasserhandel. Die Ergebnisse zeigen ein Potential von zusätzlichen jährlichen Gewinnen zwischen 373 bis 476 Millionen USD durch den Handel mit Wassernutzungsrechten im gesamten Einzugsgebieten (zwischen den Untereinheiten) in Abhängigkeit von der Wasserverfügbarkeit. Gleichermaßen ergeben sich zusätzliche Erträge von 259 bis 339 Millionen USD durch den Handel innerhalb von Untereinheiten desEinzugsgebietes. Die durch Wasserhandel erzielbaren Gewinne steigen mit zunehmenden Wassermangel. Wenn Wasserhandel zwischen den Bewässerungszonen eingesetzt würde, um den ökologisch motivierten Mindestwasserfluss zum Aralsee zu erhöhen (und gleichzeitig die entsprechend geringere Wasserverfügbarkeit für die Produzenten in der bewässerten Landwirtschaft kompensiert würde), lässt der Wasserhandel größere ökonomische Vorteile auf der Ebene des gesamten Einzugsgebietes erwarten als ohne die Möglichkeit des Wasserhandels . Zudem wären die Kosten für den ökologisch motivierten Wasserkauf kostengünstiger als die Überleitung von Wasser aus anderen Einzugsgebieten. Da der Aufbau und der Betrieb von Markt-basierten Wassermanagement-Institutionen mit Kosten verbunden sind, werden die Transaktionskosten für die Einführung von handelbaren Wasserrechten berücksichtigt, um die Effektivität der institutionellen Veränderungen zu bewerten. Die Ergebnisse weisen auf eine umgekehrt proportionale Beziehung zwischen den Vorzügen des Wasserrechthandels und dessen Transaktionskosten. Die Ergebnisse zeigen, dass Transaktionskosten von über 0.05 USD/m^3 pro Einheit gehandelter Wasserhandelsrechte die potenziellen Vorteile der Wasserhandelsoption eliminieren würden.

Technische Ansätze zur Verbesserungen der Effizienz der Wassernutzung und -koordination wurden mit einem dis-aggregierten hydro-ökonomischen Modell analysiert. Erhebliche Vorteile werden von der Verbesserung der Bewässerungswirkungsgrade (Bewässerungsnetz und Feldebene) im ASB erwartet. Aufgrund der Ergebnisse lässt sich der Gewinn im gesamten Einzugsgebiet um 20 bis 40% steigern (in Abhängigkeit von der Wasserverfügbarkeit), wenn die Bewässerungswirkungsgrade im gesamten Einzugsgebiet optimiert würden. Weiterhin belegen die Ergebnisse, dass die Konstruktion von Speicher an den Oberläufen der Flüsse (wie derzeit intensiv zwischen Ober- sowie Unterliegerstaaten in Zentralasien diskutiert) die Verfügbarkeit von Bewässerungswasser in der Region nicht erheblich beeinträchtigt, wenn diese Speicher unter der Zielvorgabe optimaler Einzugsgebiets-weiter Vorteile betrieben werden. Der Bau des Kambarata-Speichers lässt erhebliche Gewinne durch Stromerzeugung erwarten, wohingegen dies beim Rogun-Speicher aufgrund der hohen Investitionskosten nicht der Fall sein wird. Dennoch verstärkt die Konstruktion von Dämmen an den Oberläufen die nationale und regionale Energiesicherheit durch eine Zunahme der Energiegewinnung aus Wasserkraft um 65-67%. Jedoch sollten mögliche Überflutungsrisiken durch Erdbeben und politische Instabilitäten sowie die verringerte Wasserverfügbarkeit flussabwärts während der Periode der Füllung der Speicher weiterführend untersucht werden, um eine fundierte Bewertung dieser Infrastrukturmaßnahmen zu ermöglichen. Es sollte nicht vernachlaessigt werden, dass die hohen Risiken von Speichern in oberen Bereichen der Einzugsgebiete durch die Nutzung als Instrumente geopolitischer Einflussnahne und aufgrund von Folgen fuer unterliegende Bewaesserungsgebiete sowie Oekoststeme die Vorteile der Speicher bei der infratsrukturellen Entwicklung eliminieren koennen. Wirksame Beziehungen zwischen den Anrainerstaaten, die Sicherung der Rechtstaatlichkeit, die Stärkung der Mitwirkungsmöglichkeiten der Wassernutzer an Entscheidungen undihres Bewusstseins für ökologische Nachhaltigkeit sowie Markt-basierte Managementansätze und die Aufrechterhaltung von menschlichen und technischen Fähigkeiten sind ebenfalls wichtig, um einen Kompromiss zu finden bei der Aufteilung gemeinsamer Ressourcen im Einzugsgebiet im ASB.

Schlüsselwörter: Wasserhandel, Transaktionskosten, Ökologischer Mindestabfluß, Hydro-ökonomisches Modell, Bewässerungstechnologie, Infrastrukturelle Entwicklung, Rogun Damm, Kambarata Speicher, Sektor-Transformation, Virtuelles Wasser, Input-Output Analyse

ACKNOWLEDGEMENTS

Many similarities exist between the structure of water and knowledge networks. Like water moves from mountains to forests, fields, and lakes, giving a life to the living beings, knowledge is also spread from the science centers, enlightening minds and improving the lives of millions. Like one must travel long along the waterways to reach the spring—the source of pure water—one must trace the flows of knowledge long to taste the real flavor of knowledge. My tracing water started long ago to bring water to our garden and thus learn the sources that water comes from. However, I did not imagine that this tracing would continue in parallel to my journey in the world of knowledge and gradually lead me to get acquainted with local/global water issues and study the complex water systems, and coming to Bonn. I am very thankful for the Almighty for creating this chance and his help and guidance throughout my studies. Indeed, I am indebted to many people—my supervisors, tutors, colleagues, and friends—who helped a lot during the period of tracing water and provided priceless recommendations for successful accomplishment of this work.

I would like to express my deep gratitude to my academic supervisor Prof. Joachim von Braun for his encouragement to study the role of market-based water management instruments for efficient water use at basin scale and for his invaluable guidance and advice throughout this study. He also inspired me to grasp philosophical, institutional, political, and practical aspects of economics. Due to the broad scale of the study region, this study was also interesting and invaluable exercise to study cultural, historical, and political backgrounds of the Central Asian countries. I also wish to thank my second supervisor Prof. Thomas Heckelei for agreeing to provide co-supervision for this study. Heartful thanks to my tutor Dr. Anik Bhaduri who was always welcome to share his knowledge on complex water management and governance systems and provided invaluable support throughout the study. I am very grateful to Dr. Claudia Ringler who contributed a lot to the preparation and improvement of the thesis in all stages by providing expert advice, invaluable comments and guidance. I am also thankful to Prof. Dr. Manfred Lenzen for his close collaboration and expert advice in input-output modeling analysis. I wish to express my sincere thanks to Dr. Arnim Kuhn and Dr. Bernhard Tischbein for their careful review of my papers and different chapters of the thesis and for the provision of very constructive and useful comments that helped me a lot to understand the purpose of the research. I would like to thank to Dr. Zhu Tingju, Prof. Ximing Cai, and Dr. Daniel Tsegai for their comments and important recommendations.

I owe special thanks to Dr. John Lamers for his invaluable support to pursue my PhD studies and delightful discussions throughout the study. He was always supportive with wonderful solutions and recommendations to any kind of research problem. Sincere thanks also goes to Dr. Christopher Martius who was very welcome to discuss my research and provided constructive comments. I am grateful to Dr. Marc Müller for sparing his time to share his knowledge and experiences on modeling.

I am thankful also ZEF doctoral program administration, particularly Dr. Gunther Manske, Jishoy Vithayathil, and Maike Retat-Amin, for their help during my stay in Germany. Special thanks to Mrs. Rosemarie Zabel who supported a lot and did not allow our batch to feel homesick in Bonn. I am also grateful to Mr. Volker Merx for his help to find the important books and papers.

This study would not be possible without financial support by the scholarship program of International Postgraduate Studies in Water Technologies (IPSWAT) of the German Ministry for Education and Research (BMBF) and financial aid by Global Water Systems Project (GWSP). I am also very thankful to fiat panis foundation for supporting several conference participations.

I would like to thank to Dr. Iskandar Abdullaev, Dr. Michael Khorst, Dr. Akmal Karimov, Dr. Murat Yakubov, Prof. Khusnia Muradova for their invaluable advice and recommendations on water use and economic conditions in the study area. I am thankful to Prof. Sanatbek Salaev, Jasur Ataev, Murad Satimov, and Maksud Gulmanov of the Urgench State University for their support and encouragement. I am very grateful to Zahid Rahimov for his strong encouragement to continue

my modeling studies and pursue a PhD program. Special thanks goes to Kudrat Nurmetov for his close friendship and invaluable help in important moments.

I am also thankful to the researchers and members of the ZEF/UNESCO Project in Urgench and Bonn for their support and friendship. Dr. Ihtiyor Bobojonov, Dr. Inna Rudenko, Dr. Tina Shieder, Dr. Mehmood-ul Hassan, Dr. Anna Katherine-Hornidge, Dr. Nodir Djanibekov, Dr. Christopher Conrad, Dr. Ahmad Manschadi, Dr. Ruzimboy Eshchanov, Prof. Dr. Nazar Ibragimov, Lilliana Sin, Natalia Shermetova, Guzal Matniyazova, Eva Oeliger, Sandra Staudenrausch, Dr. Irina Forkutsa, Dr. Akmal Akramkhanov, Oksana Forkutsa, Elena Kan, Dr. Dela Jumaeva, Prof. Dr. Asia Khamzina, Dr. Kirsten Kinzler, Dr. Yulduz Jumaniyozova, Dr. Aziz Karimov, Dr. Bahtiyor Eshchanov, Hilola Masharipova, Vivi Moll, Utkur Djanibekov, Anisiya Kudryavtseva, Bashorat Ismoilova, Farida Abdullaeva, Murod Sultonov, Bekjon Matchonov, Oybek Qalandarov, Mansur Sultonov, and Ilkhom Yuldoshev were among these people who contributed with valuable advice and support during my study.

I wish thanks to my friends Yessengali Oskenbaev, Beatrice Muriithi, Susanna Lin, Saltanat Sabitova, Olena Dubovik, Tania Osejo, Holm Voigt, Nadezhda Kim, Sarah Shülte, Sarah Dusend, Zulfiya Karimova, Grace Villamor, Ying Huang, Maruf Abdumalik, Begzod Jalilov, Bongsong Kim, Ruslan Nazarov, Ikrom Aralov, Mansur Ruzmetov, Shihnazar Ruzmetov, and Muzaffar Yuldashev for their close friendship and support. Sincere thanks also goes to my coursemates and officemates at ZEF for their good companionship.

I am very thankful also to my parents, the sister, and the brother for their continuous support and encouragement in all stages of this study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX TABLES

LIST OF BOXES

LIST OF ACRONYMS

AAWTR	Arabian Aral Water Transportation Route
ADB	Asian Development Bank
AHP	Analytical Hierarchical Processes
ASB	Aral Sea basin
ASBOM	Aral Sea Basin Optimization Model
ASBP	Aral Sea Basin Program
ASUB	Automatic Systems of Managing Basins
BEAM	Basin Economic Allocation Model
BLI	Backward Linkage Index
BVO	Basin Water Management Organization
CA	Central Asia
CALVIN	California Value Integrated Network (Economic-Engineering Optimization Model)
CAREWIB	Central Asian Regional Water Information Base
CGE	Computable General Equilibrium Model
EC	European Commission
ECAS	Executive Committee of ICAS
EPIC	Environmental Policies and Institutions for Central Asia (Software)
FAO	Food and Agriculture Organization
FLI	Forward Linkage Index
FWR	Fixed water rights
GAMS	General Algebraic Modeling System
GBAO	Gorno-Badakhshan Autonomous Oblast (in Tajikistan)
GDP	Gross Domestic Product
GIS	Geographic information system
GRP	Gross Regional Product
ICWC	Interstate Commission for Water Management Coordination
HDI	Human Development Index
ICAS	The Interstate Council on the Aral Sea basin
IFAS	International Fund for the Aral Sea Saving
IFPRI	International Food and Policy Research Institute

ILA	International Law Association
IMPACT	International Model for Policy Analysis of Commodities and Trade
INTAS	The International Association for the Promotion of Co-operation with Scientists from the New Independent States (NIS) of the Former Soviet Union
IO	Input-Output
IOT	Input-Output Table
IPCC	International Panel on Climate Change
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
KAZ	Kazakhstan
KazStat	National Statistics Committee of Kazakhstan
KYR	Kyrgyzstan
KyrStat	National Statistics Committee of Kyrgyzstan
MAWR	Ministry of Agriculture and Water Resources of the Republic of Uzbekistan
MCDA	Multi-Criteria Decision Analysis
PODIUMSIM	Policy Dialogue Model Simulation (Model)
RRT	Districts of Republic Subordination (in Tajikistan)
RWT	Restricted water rights trading
SAM	Social Accounting Matrix
SDC	The Sustainable Development Commission
SEM	Socio-Economic Model
SIC-ICWC	Scientific Information Center of Interstate Commission for Water Management Coordination
SU	Soviet Union
TAJ	Tajikistan
TRK	Turkmenistan
TWC	Total water consumption
UAWMS	United Asian Water Management System
UN	United Nations
UNDP	United Nations Development Program
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environmental Program
US	The United States

USA	The United States of America
USAID	The United States Agency for International Development
UWT	Unrestricted water rights trading
UzStat	National Statistics Committee of Uzbekistan
UZB	Uzbekistan
WB	World Bank
WEAP	Water and Environmental Planning System (Software)
WEF	World Economic Forum
WRI	World Resources Institute
WWF	World Water Forum

UNITS

°C	Celsius
ha	Hectare
kg	Kilogram
km	Kilometer
m	Meter
mm	Millimeter

CURRENCIES

Tenge	National currency of Kazakhstan
Som	National currency of Kyrgyzstan
Somoni	National currency of Tajikistan
Manat	National currency of Turkmenistan
UZS or soum	National currency of Uzbekistan
USD	United States Dollar

1 INTRODUCTION

1.1 The importance, availability, and management challenges of water resources

Water is a vital and irreplaceable resource for sustaining life, development and the environment (Dublin Conference 1992). Aside from being a necessary resource for drinking, it is crucial for irrigation, industrial production, hydropower generation, water transportation and ecosystem functioning as well. Moreover, achieving most of the Millennium Development Goals (UN 2000) such as alleviating poverty, eradicating hunger and providing basic sanitation, directly depends on access to a sustainable water supply (von Braun et al. 2003, 2009:23).

Despite the abundant amount of water that exists on Earth, only 3% is usable fresh water and just 0.3% of the entire freshwater resources are readily available to humans as surface water sources such as rivers and lakes (Gleick 1996). Moreover, these surface water resources are not only of varying quality but also very unevenly distributed within and across countries, resulting in limited water supplies in most parts of the world. In contrast to an increasing variations in water supply due to the expected global warming (IPCC 2007), the demand for water resources has been rapidly increasing in recent decades due to population growth, urbanization, dietary changes, industrial development and irrigation expansion (Vörösmarty 2000, Rosegrant et al. 2002, Gleick 2003). Whereas the world population has tripled from 1.6 to 6 billion in the last century, the demand for fresh water resources has increased six-fold (UN WATER 2007). Around one-fifth of the world's population currently lives in water scarce areas, and more than two-thirds will live in areas with physical or economic water scarcity by 2025 (UN WATER 2007). International development organizations frequently underline the possibility of water crisis driven by increasing pressure on water resources due to economic development and aggravating competition for water between the economic sectors (WEF 2008, 2009; WB 1995). Competition over scarce natural resources intensified also as a result of the dramatic rise in global food prices in 2007–08 (von Braun 2009). Natural ecosystems are disproportionately affected by water competition since their value is typically neglected in water sharing decisions, as there are often no representatives to advocate and lobby for environmental water needs (Ringler 2001).

Coping with the increased threats of water scarcity and thus reducing poverty, hunger and malnutrition, require the development and timely implementation of measures for efficient water use (von Braun et al. 2003, von Braun 2008). Since irrigated agriculture consumes more than 70% of the water withdrawn from natural sources (WRI 2005) and average irrigation efficiency is less than 40% at the global level (Pimental et al. 1997), this sector has huge potential for reducing water use. Irrigation water management improvements are particularly essential in developing and transition countries, where more than 80% of the global irrigated croplands are located (FAO 2013) and "*water is the defining line between poverty and prosperity*" (Saleth and Dinar 2004:4).

Although the problems related to water scarcity and the need for a comprehensive approach to water management are common in most of the river basins of the developing and transition world, *"no single recipe for policy reform can be applied universally"* (EC 2000, Ringler 2001, Pujol et al. 2006a). Therefore, prospective water management strategies must consider the characteristics of each region rather than suggesting a universal set of options. The demand of developing improved water resources management strategies is prominent particularly in Central Asia, which during the Soviet period has become, with 8 milion ha (Dukhovny and Shutter 2011), one of the largest irrigated areas and cotton producing zones in the world. However, following independence in 1991, the management strategies promoted by Moscow showed to be insufficient, inadequate and ineffective for a compromising solution for water distribution among individual countries and regions. Yet, the former mindset that guided water management during the SU epoch still prevails.

This study therefore considered the case of the Aral Sea basin (ASB) of Central Asia to investigate the potentials of socio-economic transformations, improved water management institutions, and technological-infrastructural improvements for increasing water use efficiency. The region is representative of areas of the world where the continuation of high water intensive production activities, lack of investments in improvement of the irrigation infrastructure and inefficient water management institutions are accused to be responsible for the recurrently stated unproductive use of resources and reduced environmental flows.

1.2 Water in the Aral Sea basin: issues, research needs and purposes

According to Smith (1995), anthropogenic environmental damages and the potential for conflicts over water needs among irrigated agriculture, energy production, and environmental systems, though not unique, are nowhere in the world more evident than in Central Asia. The tremendous development of irrigation in the ASB to reach the self-sufficiency of cotton production in the former Soviet Union (SU) resulted in economic systems that heavily relied on water resources. Irrigation expansion accompanied by unproductive water uses led to unprecedented environmental problems of which the desiccation of the Aral Sea, once the fourth largest fresh water lake in the world, is only the most prominent and well-known example.

1.2.1 Causes and consequences of the "Aral Sea syndrome": a revisit

Despite increased employment rates in agriculture, typical mindset of considering water as a free good and thus the lack of incentives to efficient use of water was the main reason of unproductive water uses. The dominance of unlined earthen canals and the surface and furrow irrigation techniques have caused extravagant water and energy losses. In the post-independence period, the conflicts over sharing common water resources among the five Central Asian countries - Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (Dukhovny and Schluetter 2011) - also contributed to increased water losses. Regular investments in the operation and maintenance of the irrigation and water regulation infrastructure ceased shortly after independence due to reduced government budgets and disagreements about sharing related infrastructure. Administrative management approach provided insufficient incentives for efficient and sustainable use of water resources and cooperation among the countries of the region. Due to the enormous damage to the environment, social and cultural values, agricultural productivity, as well as the health of people in the circum-Aral region[1] (Micklin 1988), the desiccation of the Aral Sea has been called one of the worst manmade environmental disasters on the planet (The Telegraph 2010, UN 2010). Despite arguments that these environmental damage costs are likely lower than the additional income from irrigation expansion as noted by some (e.g. Morozov n.d.), recent studies emphasized ecological sustainability of water uses and production activities in the region and thus popularized the occurrence and the consequences of the shrinkage as "*the Aral Sea Catastrophe*" (Micklin 1988, Micklin 2010).

Although many studies have addressed the options for the water challenges in the ASB, the solutions offered are highly controversial, with each pitting one set of interests against the other. One ambitious plan forsaw the divertion of up to 60 km^3 of water from other river basins such as the Ob and Irtysh in Siberia (Micklin 2011), or from the Indus and Ganges in Southwest Asia (Khamraev 1996a) not only for refilling the sea but in addition for extending the area of irrigated croplands further. This and other plans exceed the current combined economic potential of the five

---

[1] Territories adjacent to the Aral Sea

Central Asian states to bring to fruition. Alternatively, adopting efficient modern irrigation technologies such as drip irrigation or improving water distribution systems through measures such as lining canals have huge potential for increasing water use efficiency at much lower costs compared to the large-scale diversion of rivers into the ASB. However, according to the former reports of World Bank (1992), even these solutions remain financially infeasible given the economic conditions of the affected countries. Mainguet and Rene (2001) even proposed a return to some sort of nomadic lifestyle as a solution to avoid conflicts over water distribution. In contrast to majority of studies, Varis and Rahaman (2008) argued that there is no physical water scarcity in the ASB because water availability per person (4522 m^3) in the Central Asian countries are much higher than in many countries with similar geomorphologic and climatic conditions. Therefore, these authors concluded that temporal and spatial water scarcity and environmental problems in the region is a consequence of ineffective institutions rather than physical limitedness of water resources. Varis and Rahaman (2008) suggested hence the implementation of an Integrated Water Resources Management (IWRM) approach to deal with water issues in the ASB but without offering concrete measures and action steps. For reducing the influence of the dust-borne winds, the forestation of the dried bed of the Aral Sea was also initiated (UNECE 2011). In contrast, some studies recommended addressing the root causes of the water use and environmental problems in the ASB rather than dealing with the consequences of the problem (Mirzaev and Valiev 2000, Morozov n.d.).

It is sure that the implementation of efficient water management measures is essential to improve the livelihoods in the ASB. Furthermore, the measures should target a balanced use of water resources for both economic and environmental needs concurrently using a holistic approach to water management at country and basin scale. However, given the controversial background of water issues and their potential solutions in the ASB, before proceeding to offer any relevant solutions for the water problems in the ASB, it is necessary to diagnose correctly the actual situation of water use in the basin by investigating the following questions:

1) What is the level of water availability in the ASB?
2) What are the main water consuming sectors of the economy and what are their contributions to national welfare?
3) What are key legal and institutional challenges in the existing water management system?
4) What are the main economic and technical causes and consequences of the decreased water availability and the desiccation of the Aral Sea?
5) What are the known solutions of dealing with water scarcity, improving water use efficiencies and even restoring the Aral Sea?
6) What are the implementation costs of these water management measures?
7) Which non-financial barriers may prevent the realization of water use reduction measures?

Based on the geographic, socio-economic, and institutional background of the water and land use situation in the ASB, developing a consistent map of the relationships between water-land use, production, environment, and institutions, eventually revealing the root causes and consequences of the Aral Sea disaster and water scarcity, is one of the aims of this study.

1.2.2 Options for sustainable economic restructuring

Despite the fact that cotton fiber export is one of the main sources of hard cash revenues for regional governments such as Uzbekistan in Central Asia (Rudenko 2008), excessive water demand and even overuse is inherent to cotton production, preventing the sustainable use of this scarce resource. Governmental intervention in agriculture has been high, as reflected by state control over cotton production and state regulation of cotton prices, particularly in Uzbekistan (Rudenko 2008).

Comparisons of the costs and benefits of cotton production in Uzbekistan showed very low benefits to both farmers and governments, even losses due to low global cotton prices in some years (Müller 2008). Low prices for raw cotton and the obligation to fulfill production mandates without regard to the volume of irrigation water delivered to produce cotton do not provide any incentives for farmers to increase the efficiency of water use. The massive scale of cotton production with its enormous demand for water prevents water flow for environmental needs and intensifies tensions over water use in the basin.

Perhaps the prominence of cotton production in Central Asia was justifiable in consideration of the economic, political, and military realities of the SU in the last century, and that is why it became revered to as "*white gold*" at the level of national policy in the region. However, does a continued production of cotton on such a massive scale really serve the best interests of Central Asian nations in the twenty-first century? Considering the substantial technological and structural changes in the global economic system over the last five-to six decades (Baffes 2007), does it have comparative advantages over other alternative economic activities at the moment? Are not there alternative economic activities with lower water requirements and higher potential for economic benefits? Therefore, another aim of this study is to determine the potential of different economic sectors for sustainable economic growth by comparing their economic growth impacts and total (direct plus indirect) water use requirements.

1.2.3 Market-based water allocation for efficient water use

Competition between upstream and downstream users over water use is also a common problem in Central Asia, often resulting in inefficient water distribution. During water scarce years upstream farmers have access to sufficient water for irrigation needs, whereas downstream farmers do not and consequently face huge economic losses (Abdullaev et al. 2008). However, since the marginal productivity of water is spatially heterogeneous, even if upstream farmers have more productive land than downstream farmers, their combined benefit will be sub-optimal under traditional (administrative) or absolute rights (Harmon rule) based water allocation when water is scarce. This type of problem between upstream and downstream water users does also apply to the water distribution at basin level. Since river basin waters are common resources, selfish behavior unduly decreases the water availability for downstream users and concurrently results in suboptimal basin-wide benefits. Therefore, encouraging the water users to cooperate to additionally gain and equitably share basin-wide economic benefits is of utmost importance for efficient water use and sustainability in the ASB.

Although cooperation among all water users has been postulated as a precondition of attaining environmental sustainability and economic stability (Dukhovny and Schutter 2011), incentives for reaching such cooperation have been rarely investigated. The current practices of water distribution which are based on administrative (command-and-control) management principles inherited from the Soviet Union Era, prevent cooperation incentives and do not allow for a rapid adaptation to environmental and water demand changes. Establishing water markets and allowing water rights trading can be effective measures for enhancing cooperation and efficient water use (Howe et al. 1986, Dinar and Wolf 1994, Rosegrant and Binswanger 1994, Dinar et al. 1998, Ringler 2001), but there are not yet any studies on the feasibility and potential benefits of introducing water markets in the ASB. With respect to this research gap, important questions therefore are:

1) Could the introduction of a water market also enhance efficient water use in the ASB?
2) What are opportunity costs of increased quantities of water being set aside for environmental needs (e.g., flows to the Aral Sea) when water rights trading is allowed?

3) How would transaction costs of establishing water markets influence the benefits from water rights trading?

The third aim of this study therefore is to evaluate cooperation incentives of introducing tradable water use rights in the ASB and relevant economic and environmental benefit changes. Indeed, non-economic and non-environmental barriers (cultural, religious, legal, institutional, etc.) may prevent or at least delay the implementation of the necessary measures of improving water use efficiency. Thus, an attempt is made to analyze also the means of overcoming potential barriers as well as roles of the stakeholders that are the direct beneficiaries of the reforms and the government organizations during and post-reform periods for maintaining the success of these reforms.

1.2.4 The effect of infrastructural improvements in irrigation and hydroelectricity generation

Poor conditions of the irrigation infrastructure and conflicts over regulating these infrastructural resources have been accused of preventing an efficient use of water resources. Very low rates of irrigation and conveyance efficiencies across the ASB (Cai 2003a) contribute to the overall unproductive use of water. Frequent disputes and conflicts between up-stream and down-stream regions over an appropriate regime of the existing water reservoirs complicated the water scarcity challenge. Recent proposals by upstream countries in Central Asia such as Tajikistan and Kyrgyzstan to construct several new dams to store water for hydropower generation were strictly opposed by downstream countries such as Uzbekistan, Turkmenistan, and Kazakhstan (Dukhovny 2011). Downstream countries suspected reduced water supply for their irrigation needs if the upstream regions use the water reservoirs solely for energy production. In contrast, the upstream countries argue that the construction of new reservoirs will increase overall water storage capacities and thus will be beneficial for downstream irrigation during periods of water scarcity. Despite many debates and controversial arguments by both parties over the results of the construction of the dams the impact of these projects on agricultural production and livelihoods in the downstream regions has not been assessed in detail.

Regarding the infrastructural development issues, several questions should be answered to determine the optimal levels of technological improvements and find a compromise between the irrigation, energy sector, and environment. These include:

1) What are the optimal levels of irrigation technology adoption and conveyance efficiency improvement in each irrigation zone throughout the ASB?
2) What is the impact of irrigation technology improvement on agricultural revenues?
3) How does the construction of new reservoirs for regulating river flow in upstream countries affect water availability in downstream?
4) Are there mutually acceptable options that do not make any riparian region worse off if new reservoirs for regulating river flow are built?

Thus, the fourth aim of the study is to determine optimal rates of infrastructural improvement and derive conclusions on comprisable solutions for all parties from the construction of new water regulation facilities in the upper reaches of the ASB rivers.

1.3 Contributions

Given the controversial study results on water availability and relevance and implementability of efficient water management options in the ASB, this study systematizes the causes and consequences of inefficient water management and ecological problems in the region at first.

Moreover, based on the comprehensive analysis and historical overview of water management and economic development issues in the ASB, the root drivers of the potential environmental, economic and social change are identified. Innovative water management approaches from economic, institutional, and technological perspective are offered to enhance water use efficiency that is urgently needed to maneuver the regional economy onto a sustainable development path.

1.4 Hypotheses

The three main hypotheses regarding the three key empirical questions on alternative options to the currently dominant cotton production, potentials of market-based water allocation, and benefits from infrastructural improvements are:

1) There is much room for reduced water demand, through either partially replacing the currently dominant cotton sector with less water intensive crops, or expanding agro-processing industries while reducing high water intensive agriculture, or investing in non-agricultural sectors.
2) Market-based water allocation can provide substantial improvements in basin-wide water use efficiency and considerable increase of irrigation incomes by creating incentives for water users to cooperate in the sharing of common resources if the necessary legal, institutional, and political support for water rights trading is maintained.
3) Improvements in irrigation and conveyance efficiency would allow substantial gains in the ASB. Construction of new reservoirs do not cause worse offs to any riparian region in the basin if the reservoir regulation regimes are set considering optimal basin-wide benefits yet neither the risks of flooding and use of large reservoirs for geopolitical purposes should be forgotten.

1.5 Methodical approaches

The study employs a step-by-step approach to analyze each issue at hand by gradually expanding the scope and details of the research. The “diagnosis of the Aral Sea syndrome” was based on both quantitative and qualitative descriptive analysis. Finding feasible solutions, e.g., the “surgery” of the problem, was based on three analytical tools that are implemented step-by-step while expanding the scope and depth of the research in each step. Either sectoral, or regional, or seasonal aspect of water management is emphasized in any investigation step. Thus, at a first step of the empirical analysis sectoral aspects of water use was addressed by comparing water use requirements and economic importance of the production sectors. This analysis was based on Environmentally Extended Input-Output Model and was completed only for Uzbekistan. Uzbekistan, accounting for more than half of the population and the same amount of the irrigated croplands in the ASB, is representative of the remaining countries in the basin.

At the second step, special attention was paid to regional aspects of water management. Thus, this analysis considered the entire ASB and also administrative regions instead of countries. Since irrigated agriculture requires more than 90% of all water resources in the basin (UNDP 2007), the water use by the remaining sectors was considered as fixed and only options for water allocation among the agricultural demand sites were analyzed. Aggregated irrigation benefit functions by different agricultural demand sites were combined with river node model to develop an aggregated hydro-economic model.

In the third step, a focus was on the analysis of the seasonal aspects of water management and seasonal scarcities. Thus, water use and flows were considered by months instead of ayear while filling the gaps at the previous two steps. The consideration of monthly water uses and flows allows for analyzing seasonal water scarcity and marginal value of water uses by seasons. It is essential since seasonal water scarcity is a serious threat to the yields in addition to annual scarcity, particularly in downstream regions like Khorezm, as was noted earlier (Müller 2008). Moreover, water reservoir regimes, hydropower generation and trade-offs between agricultural and energy sectors can be analyzed only considering monthly water flows in the model. The regional dimension during the third step is the same as the dimension at the second step. The agricultural sector was further disaggregated into detailed crop production activities. Disaggregated hydro-economic model including the components related to water-crop yield relationships, groundwater balance, irrigation technologies, drainage water re-use, reservoir regulation, and electricity production was developed to analyze the impact of the infrastructural improvements on water availability and irrigation revenues.

1.6 The structure of the thesis

The organization of the remainder of the thesis is as follows: Chapter 2 includes a description of the study area, including the main geographic and demographic features and the socio-economic and environmental issues in the ASB (Table 1.1). The role of water and agriculture in regional livelihoods are discussed along with the structure of the economy and water use. Furthermore, the root causes and consequences of the Aral Sea desiccation are clarified, since it is strongly connected to many other water use problems in the basin. Potential solutions that have been suggested for restoring the Aral Sea and their costs are analyzed based on the findings of previous studies. In addition, historical aspects of water management institutions that led to the desiccation of the Aral Sea and prevented the implementation of restorative processes are presented. The main conclusion of Chapter 2 is that there is a great need for the rapid and timely implementation of economic transformation (restructuring) measures, for cooperation to increase the efficiency of the use of basin resources through improved water allocation institutions, and for technological and infrastructural developments in irrigation system. Therefore, a combined analysis of all three options was expected to be an appropriate way of dealing with the root causes of desiccation and enhancing the improvements of water use efficiency and environmental conditions in the ASB.

Chapters 3-5 include the main analytical discussions derived from the need to deal with the root causes of water issues in the ASB. Chapter 3 includes an evaluation of the sustainable economic development potential of different sectors as alternatives to cotton production. Chapter 4 highlights cooperation incentives among the riparian regions to gain additional income and to improve water use efficiency through tradable water use rights. Chapters 3 and 4 begins with a literature review on modeling sectoral transformation and water allocation in the ASB respectively, while pointing out research needs. Chapter 5 is a continuation of Chapter 4, but considers a more detailed analysis of water uses and crop production systems. Therefore, the focus is on opportunities for technical improvement of conveyance and irrigation systems and the effect of the constructing new water regulation facilities in the ASB.

According to the results, agricultural sub-sectors such as the production of melons, other fruits, vegetables, and livestock have higher economic growth impact and lower water use requirements. Agricultural processing industries are even more favorable than other agricultural sub-sectors in terms of economic development impact and water use intensity. In terms of these two criteria, non-agricultural processing industries are even better than processing industries. Additional indicators such as water quality, investment availability, and institutional settings are expected to be part of more comprehensive analysis of determining the key sectors for sustainable growth. In contrast to the general belief that the impediment to necessary economic restructuring is related to the role of cotton in the economy, it is shown that improving human and technological capacity are primary factors for the success of the necessary structural changes.

In addition to the potential benefits from economic restructuring and consequent inter-sectoral water reallocations, inter-regional water reallocations through tradable water use rights can also provide substantial economic gains in the ASB. Cooperation among the regions of the basin through the establishment of tradable water use rights would serve as a key for more efficient and sustainable water use in the ASB. Water markets were analyzed only for the agricultural sector, since this sector consumes approximately 90% of the total water demand in the basin, and because industrial and municipal water use have higher priority than irrigation. It is shown that lower transaction costs of water rights trading should be maintained by improving technical infrastructure, improving the existing legal framework, and establishing productive relationships among the basin countries for effective performance of these institutional changes. Furthermore, the success of institutional changes permitting water rights trading necessitates concurrent changes in the traditional mindsets, which may require time to achieve.

Substantial benefits are also found from increasing irrigation and conveyance efficiencies throughout the ASB. Wide-scale technological developments in the irrigation system can be enhanced by maintaining incentives for producers and securing land use rights. According to the results, the construction of new dams does not have considerable impact on downstream water availability if the regulation of all reservoirs follows the rule of optimizing benefits for all water users in the basin. Benefits of electricity generation largely depend on the investment costs of constructing new reservoirs for regulating river flow. Reservoir constructions most likely lead to substantial improvements of national and regional energy securities when assuming riparian states cooperate to gain the highest basin-wide benefits. However, high risks of dams’ destruction because of their location in highly seismic zones and the possibility of using them as a tool for geopolitical influence eliminate the estimated benefits.

Chapter 6 includes a summary of the study and general conclusions. The major conclusions of this study are that water use efficiency can be substantially improved and that environmental damages from the desiccation of the Aral Sea can be effectively reduced through economic transformation, water rights trading, and technological-infrastructural improvements. However, these changes also require the participation of stakeholders in decision making, governmental involvement in legal and human capacity development, and transparency.

2 GEOGRAPHIC BACKGROUND, SOCIO-ECONOMIC CONDITIONS AND WATER MANAGEMENT PROBLEMS IN THE ARAL SEA BASIN

2.1 Introduction

The ASB is characterized by a diversity of natural landscapes including mountains, valleys, deserts, lakes, and rivers. An arid and continental climate in the lowlands of the basin necessitates irrigation for agricultural production during the growing season. Historically, a nomadic way of life was common in the desert zones of Central Asia, whereas irrigated agriculture and related rural settlements emerged over the centuries on the banks of the Amu Darya (Oxus) and Syr Darya (Yaksart)[1], the two main rivers in the basin. The dominance of rural lifestyles has been culturally retained to the present and the majority of the population lives in rural areas and derives their livelihoods from agricultural activities, primarily producing cotton, wheat, rice, fruit, and vegetables. Agriculture plays a key role in the regional economy with substantial contributions to incomes and employment in the countries of the region.

Because of the heavy dependence of a majority of the population on irrigated agriculture, livelihoods, particularly in downstream areas, are vulnerable to the variability of the water supply at the river nodes (Cai et al. 2003b), which is influenced by climate, geographic location and conditions as well as the socio-institutional environment. Meanwhile increasing demand for water by irrigation, hydroelectric power production, residential use, industry, and environmental needs across the basin fuels the tensions over limited water resources. The tremendous expansion of irrigated agriculture beginning in the 1960s due to the cotton self-sufficiency policies of the Soviet Union is one of the main causes of the severe ecological problems such as the drastic shrinkage of one of the world's biggest lakes, the Aral Sea. Moreover, due to the uneven distribution of water resources across the basin, the emergence of new independent states in the territory of the basin after the collapse of the SU in the 1990s led to intensified interstate water conflicts and worsened economic and environmental conditions.

Following the metaphor by Sachs (2005:74) comparing empirical economic analysis to medical diagnosis and prescription, this chapter includes a diagnosis of "the Aral Sea syndrome." Thus, the chapter provides a detailed description of geographical, climatic and demographic conditions, and the socio-economic and hydro-infrastructural development processes and institutional changes in the ASB, while concurrently overviewing the past, present, and future water management issues in the region and determining the root causes of the Aral Sea desiccation and evaluating the investment costs of potential solutions.

2.2 Geographic outline

2.2.1 Location

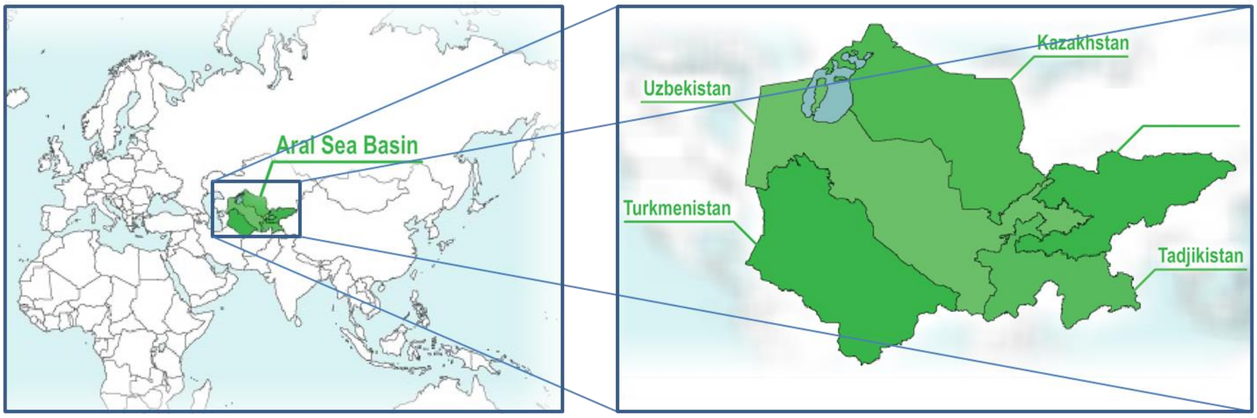
The ASB coincides with most of Central Asia (Figure 2.1). The basin includes the entire territories of Tajikistan and Uzbekistan, the majority of Turkmenistan (excluding the Balkan region), two-thirds of Kyrgyzstan (the Osh, Jalalabad, and Naryn regions), the southern part of Kazakhstan (the South Kazakhstan and Kyzylorda regions), parts of northern Afghanistan and northeastern Iran (Figure 2.2, Table 2.1). The territory of the basin lies between 56^o and 78^o eastern longitude and between 33^o and 52^o northern latitude over an area of 1.55 million km^2.

---

[1] Oxus and Yaksart are ancient names for the Amu Darya and Syr Darya used by the classical Greek geographers (such as Herodotus)

The western and central parts of the basin are desert plains, called Kyzylkum in the north and Karakum in the south; the eastern part of the basin is covered by mountain ranges. Occupying about 20% of the ASB, mountainous zones generate about 90% of the total water supply that flow towards the Aral Sea through the Amu Darya and Syr Darya Rivers (SANIIRI 2004). Irrigated areas and the main population settlements are located along these two rivers (Figure 2.2). Irrigated agriculture has been practiced in the basin since ancient times (Tolstov 2005). Small-scale irrigated agriculture in the western parts of the ASB (in the Kopet-Dag) dates back to 5000 DC and larger irrigation schemes were initiated in different parts of the basin since 2000 DC (Sala 2003; Dukhovny and Schutter 2011:25).

Figure 2.1 Geographic location of the Aral Sea basin



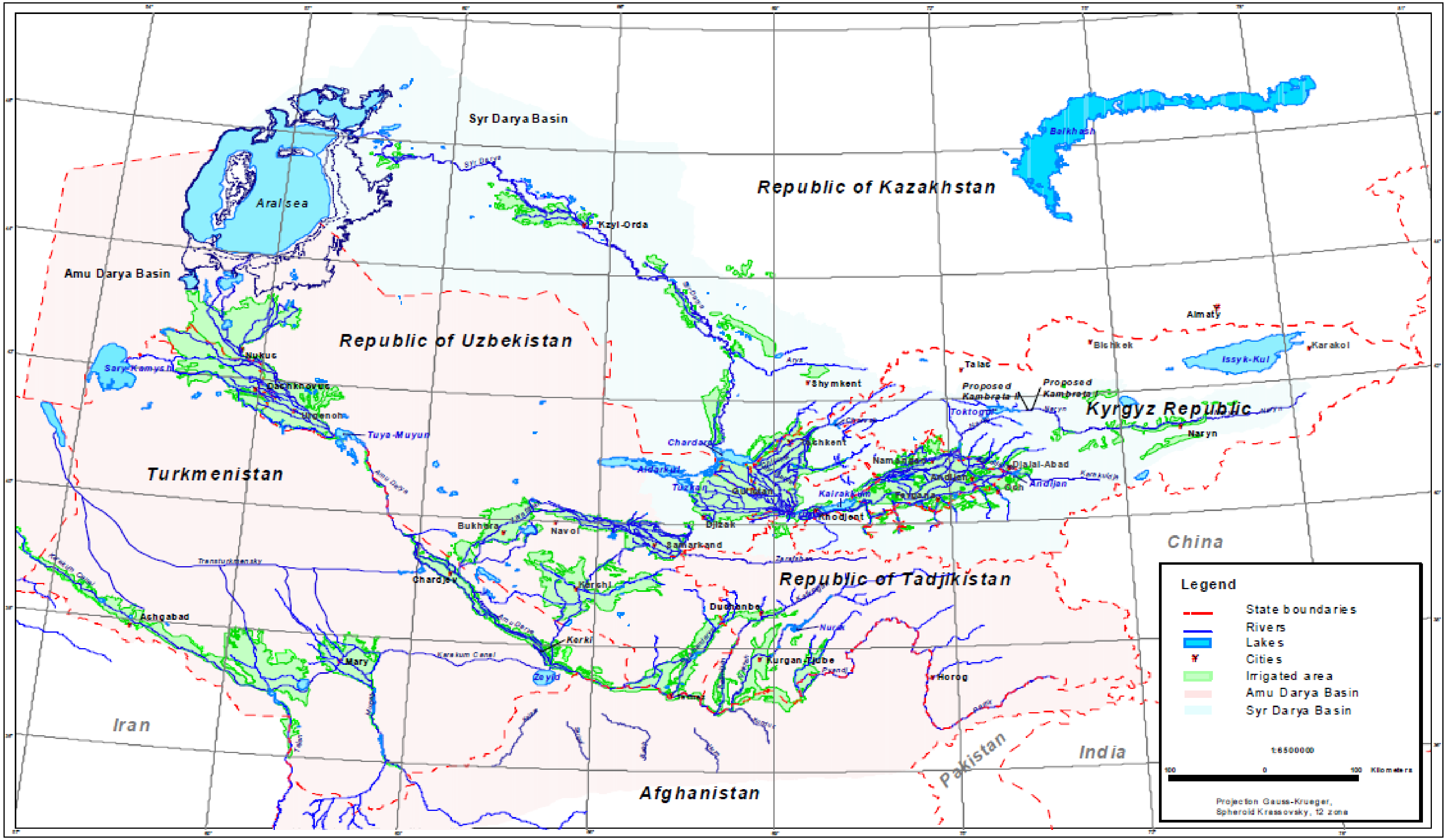
Note: the parts of northern Afghanistan and northeastern Iran are not shown
Source: Based on maps from SIC-ICWC (2012)

Table 2.1 Aral Sea basin area distribution

Country	Area, km^2	Country's share of the total basin area (%)	Basin's share of the total country area (%)	Water supply (km^3)	Country's share of total ASB water supply (%)
Kazakhstan*	344400	22%	13%	2.4	2%
Kyrgyzstan*	124900	8%	62%	29.2	25%
Tajikistan	143100	9%	100%	56.7	49%
Turkmenistan*	348830	31%	71%	1.5	1%
Uzbekistan	448840	28%	100%	11.2	10%
Afghanistan and Iran*	36000	2%	6%	14.5	12%
Total	1585340	100%	34%	116.5	100%

* Only provinces within the Aral Sea basin are included.
Note: since the shares of China and Pakistan in total area of the Aral Sea basin are negligible these areas are not included in the table
Source: Based on Sokolov and Dukhony (2002) and UNEP (2005).

Figure 2.2 Map of the Aral Sea basin



Source: PA Consortium Group and PA Consulting (2002)

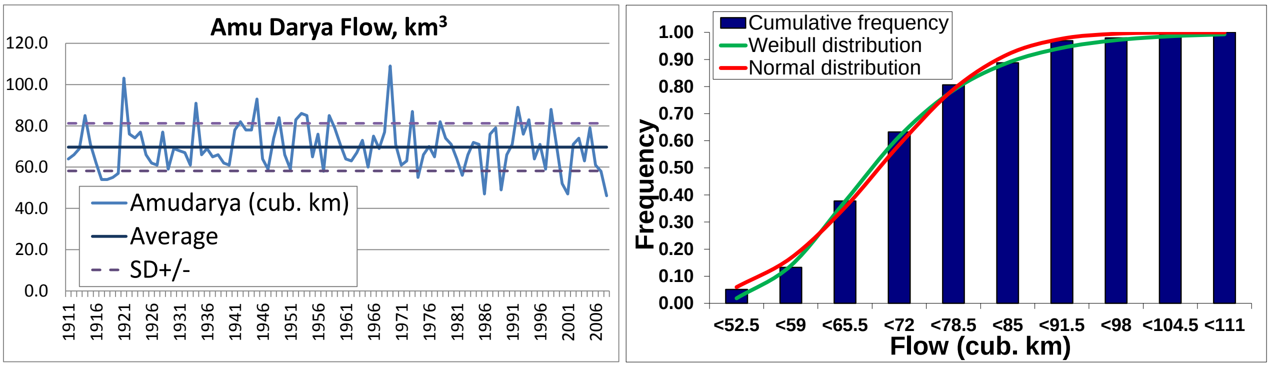
2.2.2 Climate

Owing to the isolated location of Central Asia within the Eurasian continent and its remoteness from the world's oceans, the ASB has a distinctly continental climate (UNEP 2005). Seasonal and daily temperatures in the basin are highly variable, with high solar radiation and relatively low humidity. An average temperature in the basin in July is 26˚C in the north and 30˚C in the south, with a maximum of 45˚to 50˚C (SANIIRI 2004). In January, the average temperature varies between 0˚C in the south and –8˚C in the north with a minimum of –38˚C. Annual precipitation is 1,500–2,500 mm at the glacial belt of Tien Shan and Pamir in eastern parts of the basin, 500–600 mm at the foothills, and 80–200 mm in the lowlands in the west (UNEP 2005:20). Annual precipitation is less than 200 mm in about 40% of Central Asia, 200–300 mm in 30%, and 300–400 mm in almost 20% (de Pauw 2007). Precipitation mainly occurs during winter and spring, outside of the annual growing season. The rate of evapotranspiration is greater than precipitation during the summer in most parts of the basin making crop cultivation possible reliant on irrigation. In contrast to the global significance of rain fed areas, accounting for over 80% of the world's total crop lands and contributing to 60–70% of the annual global food production (Falkenmark and Rockström 2004:67), the share of "green water use" (e.g., direct use of precipitation by crops) in the ASB is low. For instance, the share of "green water use" in cotton and rice production is less than 7% in Tajikistan, less than 4% in Turkmenistan, and less than 6% in Uzbekistan (Aldaya et al. 2010).

2.2.3 Water resources availability and distribution

Two main rivers—the Amu Darya and Syr Darya—are the lifelines of the economies of the ASB countries, where irrigated agriculture plays a pivotal role in providing food security, hard cash revenue, and employment opportunities. The Amu Darya is the largest river in Central Asia with a catchment area of 309,000 km^2. The length of the river is 2,574 km from the headwaters of the Pyanj River on the Afghan-Tajik border to the Aral Sea. The Syr Darya is the second largest river with an overall catchment area of the 219,000 km^2. The river stretches approximately 2,337 km from the Naryn River headwaters in Kyrgyzstan to the Aral Sea, sequentially crossing the Ferghana Valley, the Hunger Steppe and the Kyzylkum desert (SANIIRI 2004). These rivers are mainly fed by snowmelt and glaciers. Therefore, water discharges are maximal in summer and minimal in winter, creating favorable conditions for the use of river flow for irrigation needs. The estimated combined annual flow of the two rivers averages 110 km^3, of which 73 km^3 comes from the Amu Darya and 37 km^3 from the Syr Darya (Figure 2.3 and Figure 2.4).

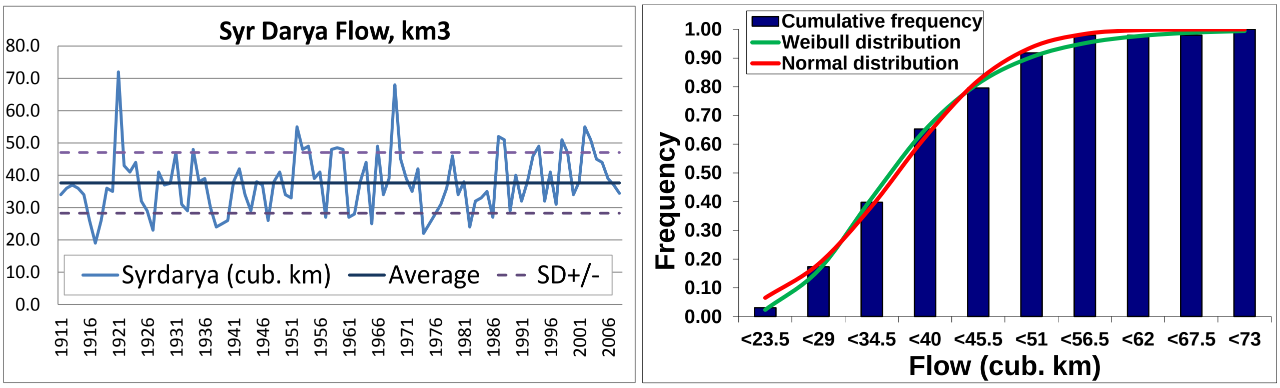
Figure 2.3 Annual amount (a) and distribution function (b) of the Amu Darya flow



(a) (b)

Source: Based on Dukhovny et al. (2008)

Figure 2.4 Annual amount (a) and distribution function (b) of the Syr Darya flow



(a) (b)

Source: Based on Dukhovny et al. (2008)

Annual flow variation is high for both rivers, increasing risks for water intensive irrigated agricultural production, industrial development, and daily drinking water supplies, primarily in downstream regions if the regulation of the rivers is not properly coordinated (Dukhovny and Schutter 2011). Many water reservoirs and dams were constructed[1] in the mountainous zones of upstream countries—Tajikistan and Kyrgyzstan—during the Soviet period in order to distribute water flows more evenly within the ASB over years and seasons, and thus provide stable water supply for irrigating croplands, especially in midstream and downstream areas. However, after independence of the five Central Asian countries reservoir operations have prioritized energy production rather than downstream irrigation needs. Although average annual water resources are generally sufficient to meet the non-environmental needs of ASB countries, uneven distribution of water resources across the basin in space and time has created serious conflicts among the riparian states over common water resources following the dissolution of the SU. Indeed, conflicts over water sharing among the countries of the region existed before 1990s, but the unified coordination and inter-country ‘water use-energy compensation’ schemes restricted their intensification.

Almost 90% of the basin water resources are formed in the mountains within the territories of Kyrgyzstan and Tajikistan, whereas 10% comes from Uzbekistan, and 1% each come from Kazakhstan and Turkmenistan (Figure 2.5). However, the availability of labor and arable land resources, and the favorable soil and climatic conditions in the midstream and downstream river areas have led to the development of irrigated agriculture principally in the downstream territories of Uzbekistan and Turkmenistan (Wegerich 2010). As a result more than 50% of the total water withdrawals in the basin was allocated to Uzbekistan during the Soviet period and more than 20% to Turkmenistan.

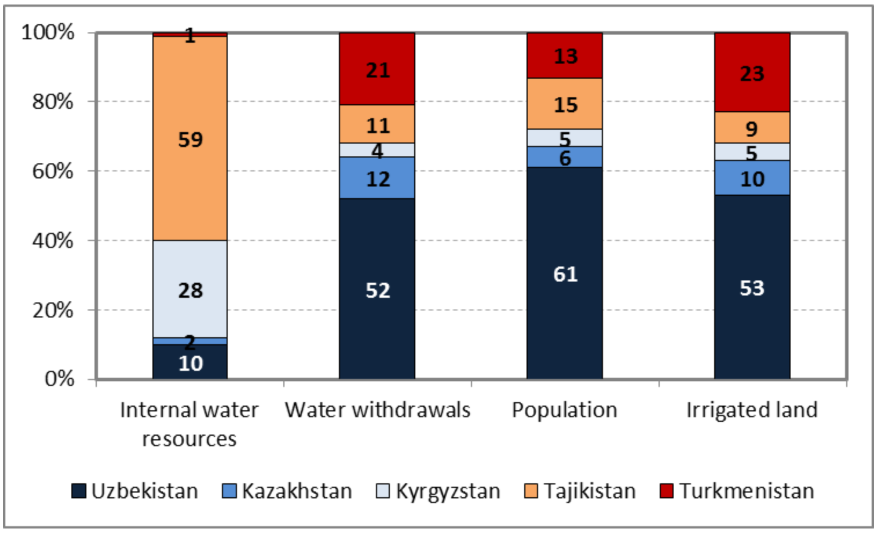
In the aftermath of independence, upstream water-rich countries retained greater water use since vast amounts of water are formed within their territories. In contrast, downstream countries have emphasized the need for water allocation in the basin according to population size or irrigated area (UNEP 2005). Controversial opinions on water sharing were also reflected in the survey of national water experts (Valentini et al. 2004:100). Experts from Kyrgyzstan and Tajikistan have contrasting opinions to their counterparts from the remaining Central Asian countries, believing that historical water distribution schemes should be abandoned and that the countries should have greater rights to freely use water resources that originate in their territory. Concurrently, the majority of the experts

---

[1] Total storage capacity of the reservoirs increased from 4 km^3 to 76 km^3 during the period between 1950 to 1990 with a dramatic shift from 17 km^3 to 56 km^3 in the late 1970s (Dukhovny and Schutter 2011:174)

from Kazakhstan and Uzbekistan have indicated that such an approach is unacceptable (Valentini et al. 2004:100). They claimed that water should be managed as a common resource and distribution decisions should take into account the interests of all riparian states.

Figure 2.5 Distribution of runoff, water use, land, and population in the Aral Sea basin



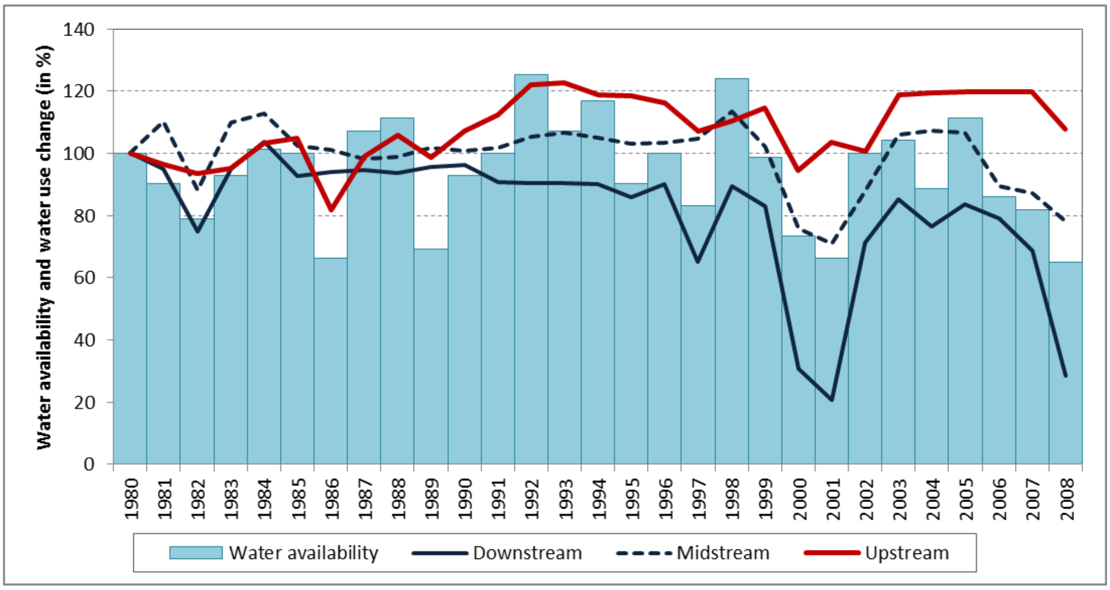
Note: Northern parts of Afghanistan and Iran were not included
Source: Based on McKinney (2004)

Resource-poor but water-rich Kyrgyzstan and Tajikistan attempt to reserve water during the summer time to release it for generating hydroelectric power to meet increased energy demands for heating during the winter (UNDP RBEC 2005). However, water-dependent but resource-rich countries such as Uzbekistan, Kazakhstan, and Turkmenistan have a peak water demand for irrigation during the summer. As a result of water release from the upstream reservoirs during the winters, less water is available for irrigation during summer seasons and flooding is frequent in the winter, eroding irrigated lands and damaging irrigation infrastructure in the downstream areas[1] (Dukhovny and Schutter 2011:290). Moreover, all countries in the region except Kazakhstan have planned to increase the areas of irrigated lands. The “use it or lose it” management approach resulting from the failure to arrive at mutually beneficial coordination over water distribution has caused a “tragedy of commons” situation (Hardin 1968). Upper-reach regions have access to abundant water but not lower-reach regions (Figure 2.6 and Figure 2.7). According to the observations of water consumption between 1980 to 2008, the gap between water use levels in upper-, middle-, and lower reaches of the basin rivers widened. High variation in water use levels among different river zones was more pronounced after 1990, which led to inefficient water allocation. Inefficient water distribution is very common, particularly in the Amu Darya basin during dry years. In 2000, 2001, and 2008, when overall water supply dramatically decreased, upstream regions were only slightly affected, while the downstream regions took the main brunt of the drought. It has been previously reported that water abundance (the ratio of total water withdrawal to the total required water) was 90% in upstream regions of Tajikistan but only 40% and 45% in downstream regions—Dashauz (Turkmenistan) and Karakalpakstan (Uzbekistan)—respectively (Dukhovny and Schutter 2011:277). Thus, there is an indispensable need for improved water management institutions to provide more efficient and equitable water sharing in the basin.

---

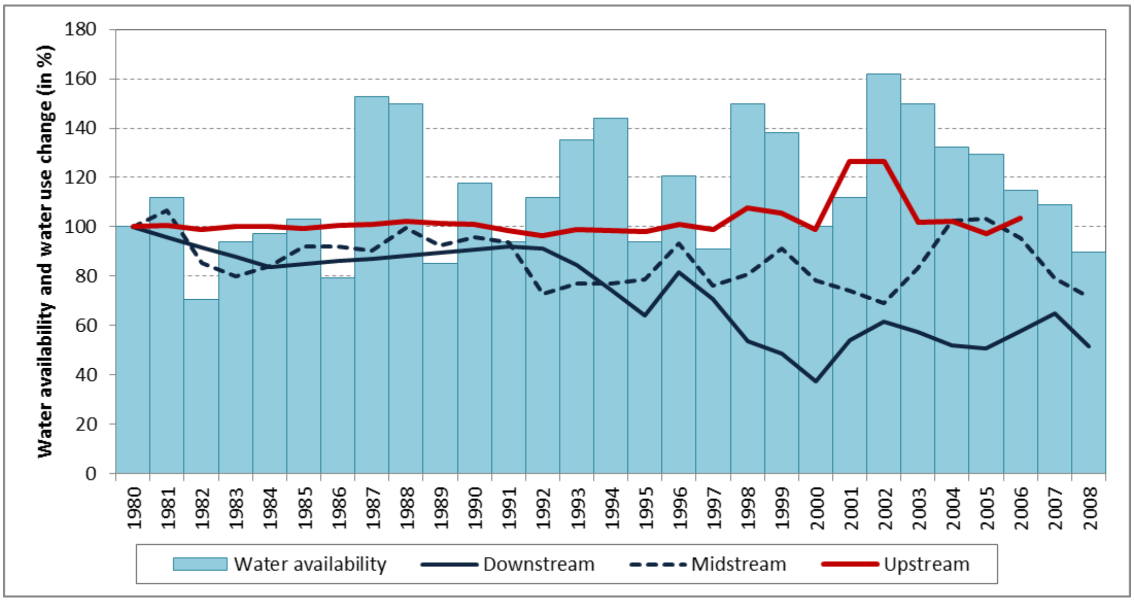
[1] A detailed discussion of this topic is provided in section 2.6.1.

Figure 2.6 Water withdrawals in upstream, midstream, and downstream reaches and water availability during the growing season in the Amu Darya basin, 1980–2008



Source: Data on water availability (river runoff) is from Dukhovny et al. (2008); Water supply (source) for 2008 was extrapolated based on Dukhovny et al. (2008) and water flow observations at Kerki station (UzHydromet 2009); water withdrawals in upstream (the regions of Tajikistan), midstream (Kashkadarya region of Uzbekistan), and downstream (AO Karakalpakstan) are based on SIC-ICWC (2009) and SIC-ICWC (2011)

Figure 2.7 Water withdrawals in upstream, midstream, and downstream reaches and water availability during the growing season in the Syr Darya basin, 1980–2008



Source: Data on water availability (river runoff) is from Dukhovny et al. (2008); Water supply (source) for 2008 was based on Dukhovny et al. (2008) and water flow observations at Kal station (UzHydromet 2009); water withdrawals in upstream (the regions of Kyrgyzstan), midstream (Jizzakh region of Uzbekistan), and downstream (Kyzylorda region of Kazakhstan (1980-1990) Kyzylkum canal (1991-2006) are based on SIC-ICWC (2009) and SIC-ICWC (2011)

2.3 Socio-economic situation

2.3.1 Key socio-economic indicators

As part of the former SU the Central Asian countries were governed under a command-and-control system for more than 70 years before obtaining their independencies in 1991. Currently, a wide range of socio-economic and political reforms is under way with the intention of transforming the regional economies to market-based systems and establish civil society norms. Present socio-economic development levels in Central Asian countries are moderate, as evidenced by the fact that their ranks among 169 countries in terms of the Human Development Index (HDI) vary between 66 (Kazakhstan) to112 (Tajikistan) (Table 2.2). Kazakhstan and Turkmenistan are the richest countries in the region in terms of per capita income, presented here as per capita Gross Domestic Product (GDP). Hard cash revenues from oil and gas exports play a key role in the wealth of these two nations. However, this income is unevenly distributed among their respective populations, as shown by high Gini index values (41) and poverty rates (as of 1998 about 30% of population lives below national poverty line) for Turkmenistan though the conditions in Kazakhstan are better. Analysis based on the survey of more than 7500 households across Kazakhstan also indicated that most of the high-income households are located in two urban centers and areas of resource extraction while poverty is common in the rest of the country (O'Hara and Gentile 2009).

Table 2.2 Main socio-economic development indicators of Central Asian countries

Socio-economic development indicators	**Year**	**Countries**				
		KAZ	**KGZ**	**TAJ**	**TRM**	**UZB**
Human Development Index (HDI)	2010	0.71	0.60	0.58	0.67	0.62
HDI rank among 169 countries of the world	2010	66	109	112	87	102
GDP per capita (USD)	2008	8,513	958	751	3,039	1,023
Consumer price index (%)	2000–2008	8.3	6.1	13.0	8.8[a]	16.1[a]
Life expectancy at birth (years)	2010	65	68	67	65	68
Income Gini coefficient	2000-2010	31	34	34	41	37
Population living below national poverty line (%)	2000–2008	15.4	43.1	53.5	29.9[b]	27.2
Remittance inflows (% of GDP)	2007	0.1[c]	24.4[c]	49.6[c]	3.2[d]	14[e]
Population without access to safe water services (%)	2008	5	10	30	n.a.	13
Population without access to improved sanitation services (%)	2008	3	7	6	2	0
Population affected by natural disasters (per million people)	2000–2009	571	518	100,709	0	2,431
Population living on degraded land (%)	2010	24	10	10	11	27
Employment to population ratio (% of population aged 15–64)	2008	64	58	55	58	58
Adult literacy rate (% of population aged over 15)	2005–2008	99.7	99.3	99.7	99.5	99.3
Decentralization index[f] (1-4)	2008	2.3	2.3	2.3	1.7	1.85

Notes: KAZ- Kazakhstan, KGZ-Kyrgyzstan, TAJ-Tajikistan, TRM-Turkmenistan, UZB-Uzbekistan, AFG-Afghanistan, n.a. – not available.
Sources: UNDP (2012) unless otherwise shown; [a]-IMF (2012); [b] –ADB (2012) as of 1998; [c] –UNDP (2012); [d]-author's estimates based on CER (2010); [e]-CER (2010); [f]-UNDP (2008)

The poorest countries in the basin are Kyrgyzstan and Tajikistan, where the shares of population under poverty are 43.1% and 53.5% respectively (Table 2.2). The incomes of the majority of the population in these two countries are also highly dependent on remittances (equivalent to a quarter of the GDP in the former and a half of the GDP in the latter) from immigrant workers who are usually employed in low-skilled jobs in Russia or Kazakhstan. The poverty of the majority of the population does not allow improved access to water services despite abundant water availability in Tajikistan. Environmental poverty, meaning living in unhealthy environmental conditions is also a serious problem. About 10% of the population was affected by natural disasters in Tajikistan during the period between 2000 and 2009. Due to decreased water quality and soil salinization, about one fourth of populations in Kazakhstan and Uzbekistan must live on degraded lands. Poverty is substantially influenced by low employment opportunities in domestic job markets. Though unemployment rates are very low according to official statistics, the employed share of the population aged 15–64 is only about 60% in Central Asian countries. The poorest country, Tajikistan (53.5% of population lives under poverty), has the lowest employment rates (55%), while the richest country, Kazakhstan (15.5% of population lives under poverty whereas GDP per capita is about $8,500 USD), has the highest employment rates (64%). Despite low employment rates, income inequality, poverty, high reliance on external remittances, and limited capacity to cope with environmental problems, education level is high in all Central Asian countries and more than 99% of population is literate. Considering the abundance of natural resources in the region (ADB 2010), the high literacy rate provides hope for gradual economic development and more equal income distribution through thorough coordination of human, capital, and natural resource allocation. To maintain the success of economic development reforms, the empowerment of ordinary people for decision making is of utmost importance since all spheres of the economy and society is overcentralized as evidenced by low decentralization indexes (UNDP 2008, OECD 2011). Active participation of all members of society in planning, monitoring and evaluating public policy reforms is crucial for steady progress, which is facilitated in a decentralized system (von Braun and Grote 2002).

2.3.2 Population growth and employment

Population growth creating an increasing burden on natural resources is one of the main reasons for increased poverty and intensified conflicts over resources. High rates of population growth during the pre-independence period in all Central Asian countries resulted in an overall population of about 34 million in the ASB in 1990. Uzbekistan had the largest population at 20.4 million at that time, which increased to about 28 million by 2009 (Table 2.3). At present, the overall population living in the basin is over 46 million, of which more than 60% lives in Uzbekistan, and about 16% and 11% in Tajikistan and Turkmenistan respectively. The remaining 12% lives in southern Kazakhstan and Kyrgyzstan. The highest population growth rates were in Tajikistan (1.82% per annum over the last 10 years) and Turkmenistan (an average of 1.76% per annum). The economic crisis during the post-Soviet era increased emigration from Central Asian countries, particularly from Kazakhstan. However, after the recovery of the economy in Kazakhstan due to increased oil production, shifts in global oil prices and increased grain harvests beginning in 2000, population growth rates have stabilized at 1–2%.

Rural lifestyles are common throughout the ASB as evidenced by the fact that about 64% of the population lives in rural areas (Table 2.4). The average domestic shares of rural populations in the ASB regions of Kazakhstan and Kyrgyzstan were about 55% and 73% respectively, with slightly increasing trends during the period between 1990 and 2009. However, since the birth rates in rural areas were higher than in urban areas, substantial shifts in the share of rural populations from 68.3% in 1990 to 78.7% in 2009 occurred in Tajikistan. Similar demographic changes were also observed in Uzbekistan, where the rural share of the population increased from 59.9% in 1990 to

63.3% in 2009. Although urbanization increased as evidenced by reduction in the rural population share in Turkmenistan from 54.9% to 51.4% over the same period, the rural share is still high.

Table 2.3 Population in the Aral Sea basin, 1990–2009 (in millions)

Country	1990	1995	2000	2005	2006	2007	2008	2009	Population share of ASB total	Average growth (1991–2009)
Kazakhstan*	2.5	2.5	2.7	2.8	2.9	2.9	3.0	3.1	**6.7%**	1.05
Kyrgyzstan*	2.0	2.2	2.3	2.4	2.5	2.5	2. 6	2.6	**5.8%**	1.23
Tajikistan	5.3	5.7	6.2	6.9	7.0	7.1	7.3	7.5	**15.6%**	1.82
Turkmenistan	3.7	4.2	4.5	4.8	4.9	5.0	5.0	5.1	**11.1%**	1.76
Uzbekistan	20.4	22.7	24.7	26.2	26.5	26.9	27.3	27.8	**60.7%**	1.64
ASB	33.9	37.4	40.3	43.1	43.8	44.5	45.2	46.0	**100%**	1.62

*Only provinces within the Aral Sea basin are included

Source: Data for Kazakhstan and Kyrgyzstan 1990–2000 is from SIC-ICWC (2011); Data for Tajikistan, Turkmenistan, Uzbekistan 1990–2009 is from ADB (2011); Data for Kazakhstan and Kyrgyzstan 2001–2009 was estimated based on SIC-ICWC (2011) and ADB (2011)

Table 2.4 The rural shares (%s) of national populations in the Aral Sea basin, 1990–2009

Country	1990	1995	2000	2005	2009
Kazakhstan*	54.1	53.3	55.5	55.3	55.5
Kyrgyzstan*	72.4	72.7	73.3	73.2	73.3
Tajikistan	68.3	71.1	73.5	73.6	73.7
Turkmenistan	54.9	54.7	54.2	52.7	51.4
Uzbekistan	59.9	61.6	62.7	63.3	63.3
ASB	61.0	62.4	63.5	63.8	63.7

*Only provinces within the Aral Sea basin are included

Source: Data for Tajikistan, Turkmenistan, and Uzbekistan is from ADB (2011); Data for Kazakhstan and Kyrgyzstan was estimated based on Dukhovny and Sokolov (2000), SANIIRI (2004), and ADB (2011).

Most of the rural population in the ASB is engaged in the agricultural sector (Table 2.5). In 1995, 44% of all labor resources were engaged in agriculture in the ASB, reaching almost 60% in Kyrgyzstan and Tajikistan. Between 1995 and 2008 employment in agriculture rose from 59% to 66% in Tajikistan, from 45% to 53% in Turkmenistan, and from 29% to 40% in southern Kazakhstan. Reduced mechanization of agricultural production may have increased manual labor activities such as cotton and wheat harvesting. Although the share of agricultural employees decreased from 60% to 45% in the ASB provinces of Kyrgyzstan, and from 41% to 24% in Uzbekistan between 1995 and 2008 due to denationalization and privatization policy reforms, these shares are still high considering that engagement in agriculture is typically less than 5% in developed countries (World Bank 2008). Dominance of the rural population and high employment rates in the agricultural sector make livelihoods highly dependent on irrigated agriculture, which is very vulnerable to changes in river flows and prices for energy required for pumping.

Table 2.5 Employment in agriculture in the Aral Sea basin

	1990	1995	2000	2005	2006	2007	2008
	Employment in agriculture (millions)						
Kazakhstan*	0.3	0.3	0.4	0.5	0.5	0.5	0.5
Kyrgyzstan*	0.4	0.5	0.6	0.5	0.5	0.5	0.5
Tajikistan	0.8	1.1	1.1	1.4	1.4	1.4	1.3
Turkmenistan	0.6	0.8	0.9	1.3	1.3	1.3	1.4
Uzbekistan	3.1	3.5	3.1	3.0	2.9	2.7	2.6
Total Aral Sea basin	5.2	6.2	6.2	6.7	6.6	6.6	6.3
	Share of the agricultural sector of total employment (%)						
Kazakhstan*	26	29	41	41	41	42	40
Kyrgyzstan*	44	60	66	52	50	48	45
Tajikistan	46	59	65	67	67	67	66
Turkmenistan	42	45	48	53	53	53	53
Uzbekistan	39	41	34	29	27	25	24
Total Aral Sea basin	40	44	42	40	38	37	35

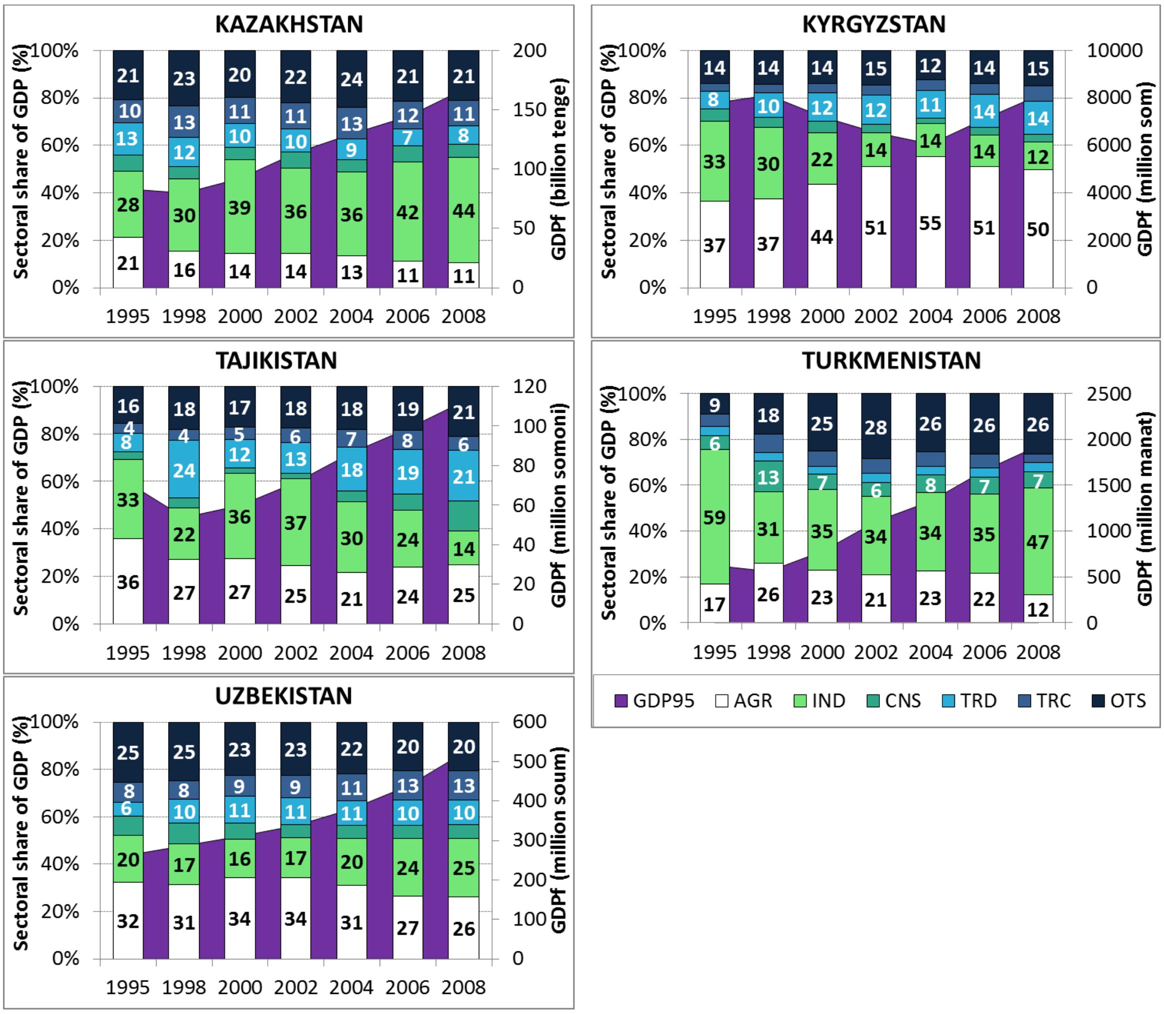
*Only provinces within the Aral Sea basin are included

Source: Most data is from ADB (2011) unless otherwise mentioned. The data from the ASB area of Kazakhstan for 2003–2007 is from KazStat (2011); the data for the other years was estimated using ADB (2011) data at the national level. Kyrgyzstan ASB area data for 1995–1998 is from KyrStat (2011); data from the other years was estimated using ADB (2011) at the national level.

2.3.3 Economic structure and performance

Being a main employer for the majority of population, the contribution of irrigated agriculture to the overall income generation and rural livelihoods is also substantial (Figure 2.8). However, the agricultural share of GDP is decreasing in Kazakhstan, Turkmenistan, and Uzbekistan due to industrialization and privatization processes, and the increasing role of the services sector in the aftermath of independence. For instance, between 1995 and 2008, the agricultural share of the total GDP declined from 21% to 11% in Kazakhstan, from 36% to 25% in Tajikistan, and from 32% to 26% in Uzbekistan. Decreased prices for agricultural commodities in the international market and liberalized prices for industrial commodities in national markets have also reduced the share of the agriculture in GDP (Dukhovny and Schutter 2011:234). In Turkmenistan, the share of agriculture in the GDP decreased from 26% to 22% between 1998 and 2006, and dropped to 12% in 2008. This sudden reduction in agricultural share of GDP and production can be explained by decreased water runoff of the Amu Darya River, which is main supplier of water to most irrigation zones and downstream settlements of Turkmenistan. In contrast, despite Kyrgyzstan's rapid privatization and liberalization reforms, the share of its agricultural sector increased from 37% to 50%, while the share of industry in its GDP decreased from 33% to 12% between 1995 and 2008. The decline in industrial output was caused by decreased capacity in most sectors (except gold mining) due to reduced raw materials supply, increased prices for imported energy commodities, and the shrinkage of consumer's market after the breakdown of the SU (LC 2012).

Figure 2.8 GDP structure and changes in the Aral Sea basin, 1995–2008



Note: GDP95—Gross Domestic Product at factor prices (at fixed prices of 1995), AGR—Agriculture, IND—Industry, CNS—Construction, TRD—Trade, TRC—Transport and communications, OTS—Other services.

Source: Most data is from ADB (2011) unless otherwise mentioned. The Kazakhstan (Kyzyl-Orda and Southern-Kazakhstan provinces) data for 2002–2006 was from KazStat (2008). Data for 1995–2001 and 2007–2008 was estimated using ADB (2011). GRP of Kyrgyz provinces (Jalalabad, Osh, and Naryn provinces) for 2005–2008 came from KyrStat (2011), the sectoral shares for 2000–2008 from UNDP (2010); and other data was estimated based on ADB (2011). The data for Turkmenistan 2008 is from WB (2011).

Although at first sight the dynamic increase in the share of industry within the overall economies of Kazakhstan and Uzbekistan during the last decade seems to be a promising achievement towards economic prosperity, these changes mainly occurred due to increased volumes of oil and gas extraction rather than the development of processing industries with high value added. Exporting non-renewable natural resources is not sustainable in the long-run unless the exporting revenues are invested in technological, infrastructural and social welfare improvements since this activity leaves less resources for the economic development in future (Ostrom et al. 1993, Thomas et al. 2000).

Despite the picture of the economic structure at national level shows rapid industrialization this industrialization took place in the countable number of central cities while vast areas of the Central Asian countries still excessively rely on the irrigated agriculture and thus on irrigation water availability from rivers as reflected in the case of Uzbekistan (Box 2.1). According to the observations in 2009, if the share of agriculture was about 21% in GDP at national level the average share of agriculture in Gross Regional Products was 40% across the districts. Despite industry's share of GDP was 26% at national level average share of industry in Gross Regional Products across the districts was less than 13%. While for the majority of the population agriculture is low income and labor intensive (Box 2.2), the development of the mining industry benefits only a minority of the population employed in this sector, consequently expanding the income gap between the rich and the poor.

As evidenced by the very low industrial output share of private industry-based small businesses, large government-owned enterprises such as cotton gins in rural areas and few metallurgy, mining and machinery factories in urban areas dominate the industrial production of Uzbekistan, fueling the gap between the rich and poor (Box 2.3). Alternatively, development of private industrial small enterprises is an engine for establishing a middle class. Countries with a large middle class are more likely to be well administered and less likely to suffer social conflict[1] (Easterly 2001). Unification of a society by the development of a strong middle class helps create a consensus on equitable economic growth in contrast to social polarization fostered by unequal income distribution, which eliminates incentives for economic growth (Easterly 2001).

Development of industry–based small enterprises would serve for upgrading the agricultural value chains and improving irrigation infrastructure. Industrial modernization would allow increasing capital intensity of production, which is currently highly labor intensive as evidenced by high labor elasticity values for production that varied between 0.54 and 0.96 across Uzbekistan (Box 2.2). Upgrading the agricultural and industrial sectors, particularly agricultural processing industries (including livestock) through maintaining small businesses and entrepreneurship, particularly in rural areas, can reduce dependence on risky water resources and provide more sustainable and equitable development. The success of these development policies is in turn largely dependent on improvements in production and trade infrastructure as well as intensification of cooperation and integration with the global economy (Box 2.3).

Box 2.1 Sectoral structures of the economies at regional level: the case of Uzbekistan[2]

Given priority of industrial sectors at national development policies, the share of the industrial sector in GDP gradually increased while the contribution of agricultural sector decreased in Uzbekistan during the transition period (Figure 2.8). The industry's share of GDP rose up to 26% while the agriculture's share of GDP decreased to 21% coming to 2006 (UzStat 2010). In contrast to the high share of the industrial sector in GDP, the share of the industry in total regional output was less than 20% in most administrative districts indicating additional room for industrial development in vast areas of the country (Figure 2.9). Meantime, agriculture is a dominant sector with a share of more than 40% in total regional output in most of the districts despite its share of GDP hardly reaches 20%.

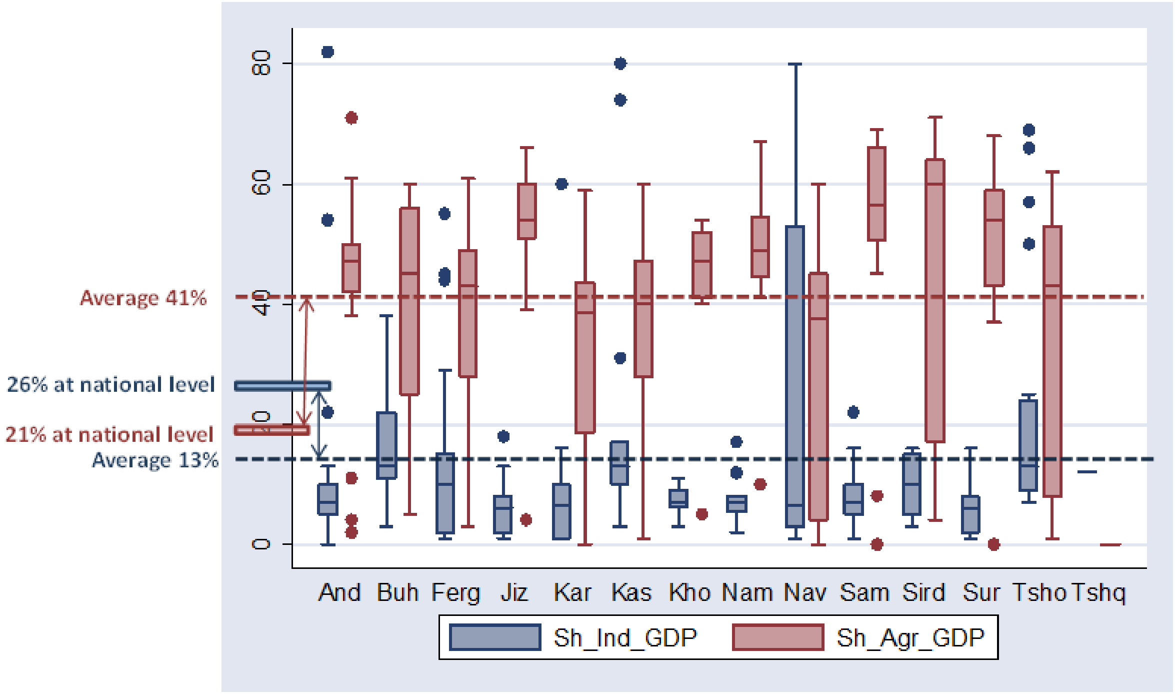
High share of the industrial sector in GDP despite underdevelopment of the industrial sector in most of the districts in Uzbekistan, can be explained by the fact that 10 cities with the highest industrial production provides more than 65% of national industrial output (Table 2.6). Particularly, the capital city-Tashkent specialized in multiple types of industrial activities including food processing, textile, machinery, electro-mechanics, etc., produces one fourth of total industrial output. National center of automotive industry – Asaka contributes one eighth of national industrial output. Muborak where gaz mining is a main industrial activity produces one tenth of total industrial output. Other cities such as Ferghana and Guzar which are specialized in gas and oil mining and extraction as well as cities such as Navoi, Almalik and Bekabad which are specialized in chemical industry and metallurgy are also among the top-ten cities with the highest levels of industrial output.

---

[1] Aristotle (306 B.C.), Politics.

[2] Based on Bekchanov and Bhaduri (2012)

Figure 2.9 Sectoral structure of Gross Regional Products across the districts of Uzbekistan grouped by administrative regions (in 2009)



Notes: Sh_Agr_GDP – agricultural share of GDP; Sh_Ind_GDP – industry's share of GDP; And-Andizhan; Buh-Bukhara; Ferg-Ferghana; Jiz-Dzhizzakh; Kar-Karakalpakstan AO; Kas-Kashkadarya; Kho-Khorezm; Nam-Namangan; Nav-Navoiy; Sam-Samarkand; Sird-Syrdarya; Sur-Surkhandarya; Tsho-Tashkent province; Tshq-Tashkent city
Source: based on UzStat 2010b

Table 2.6 Top 10 cities that produce most of the national industrial output

Rank	City	Industrial output (billion UZS)	Share in total industrial output (%)
1	Tashkent city	4415	19
2	Asaka	2340	10
3	Muborak	1756	8
4	Ferghana	1498	7
5	Guzar	1252	5
6	Almalik	1057	5
7	Navoi	663	3
8	Samarkand	625	3
9	Bekabad	602	3
10	Andizhan	574	3
	Total of 10 top cities	14782	65

Note: According to National Bank of Uzbekistan, average exchange rate in 2009 – 1 USD = 1,500 UZS
Source: based on UzStat 2010b

Box 2.2 Is the national economy labor intensive or capital intensive in Uzbekistan?

The regression results based on a Cobb-Douglass production model (Method is described in Appendix A) showed that capital elasticity estimates were significant for nine out of 13 regions/provinces (Table 2.7). Nevertheless, the average capital elasticity values were below 0.5 for all regions, varying between 0.04 and 0.46 (in parallel, labor elasticity values varied between 0.54 and 0.96 under constant returns of scale). Under the assumptions of the unitary elasticity of substitution between capital and labor, perfect markets, and constant returns of scale, the capital elasticity values below 0.5 or labor elasticity values above 0.5 can be interpreted as labor intensiveness of the national economy in Uzbekistan. Indeed heavy reliance of the economy in the majority of districts of Uzbekistan on agriculture (Box 2.1), which is a very labor intensive sector due in part to rapid technological deterioration in recent years, determined overall labor intensiveness of the entire economy.

Table 2.7 Estimated values for capital elasticity of total production across the regions of Uzbekistan

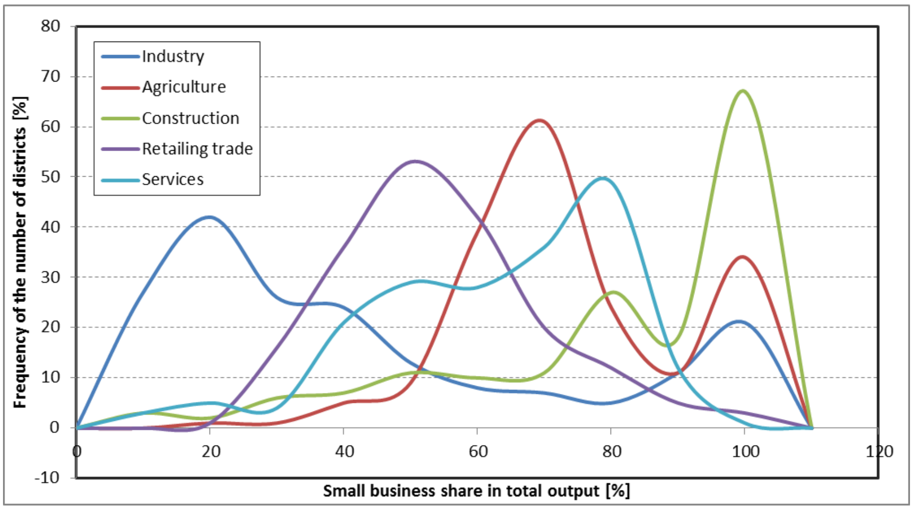
Variable	Coefficient	Standard error	t-Statistics	Probability
D_Andizhan	0.34	0.078	4.33	0.000
D_Bukhara	0.19	0.096	2.00	0.047
D_Jizzakh	0.12	0.185	0.67	0.502
D_Kashkadarya	0.43	0.091	4.67	0.000
D_Navoi	0.04	0.128	0.30	0.765
D_Namangan	0.23	0.106	2.21	0.028
D_Samarkand	0.22	0.091	2.37	0.019
D_Surkhandarya	0.26	0.137	1.92	0.057
D_Syrdarya	0.20	0.128	1.54	0.125
D_Tashkent	0.15	0.101	1.50	0.136
D_Ferghana	0.40	0.074	5.41	0.000
D_Khorezm	0.32	0.111	2.90	0.004
D_Karakalpakstan	0.46	0.078	5.86	0.000
Constant	1.63	0.051	31.93	0.000
Number of observations	188	F-statistic		7.49
R-squared	0.359	Probability (F-statistic)		0.000
Adjusted R-squared	0.311			

Source: Based on UzStat (2010b)

Box 2.3 The role of industry-based small businesses in equitable growth of rural areas

The role of small business enterprises[1] in economic welfare were analyzed by estimating their shares in total sectoral output across the districts and constructing respective kernel density functions (frequencies) for each sector (Figure 2.10). The small businesses' share of total output varied with the smallest value in the industrial sector and the highest value in the construction sector. Because the share of small business in the total industrial output was less than 40% in most of the districts, big enterprises were dominant in the industrial sector. Likewise, in most districts the share of small business in the total sectoral output was between 30% and 70% in the retail sector, between 40% and 90% in the service sector, between 50% and 90% in the agricultural sector, and more than 70% in the construction sector. Thus, the sectors can be ranked according to the concentration of small business in the overall production across the districts as follows: 1. Construction; 2. Agriculture; 3. Services; 4. Retail; 5. Industry.

Figure 2.10 Kernel density functions of small business shares of the total output of all economic sectors across 112 districts of Uzbekistan in 2009



Source: Based on UzStat (2010b)

Despite significant shifts in total production volumes of the industrial sector and maintenance of small business and private entrepreneurship in all spheres of the economy through government policies, in the aftermath of independence the share of small business in the total industrial output has been very low across Uzbekistan. Considering that cotton gins are widespread throughout the districts, it can be concluded that cotton gins dominate industrial production in most administrative districts. Further development of small business and private entrepreneurship in the industry sector would assist the establishment of the middle class and the emergence of competitive markets that are cornerstones for equitable economic growth. Claims on the importance of non-agricultural activities for higher employment, poverty eradication, and consequent economic growth in rural areas of developing countries are also appropriate to the case of transition countries.

---

[1] Small businesses are usually classified based on the number of employees and/or the size of fixed assets. Uzbek legislation on the classification of enterprises according to the size and the type of activity has been changed several times in recent years. Currently companies classified as small business enterprises include: companies with up to 100 employees in light industries, the food industry, metal working, instrument making, wood processing, furniture making, and construction industries. This includes companies with up to 50 employees in machinery, metallurgy, fuel and energy, chemicals, and agricultural processing, and companies with up to 25 employees in science, transportation, information technologies, all other types of services, trade, public catering, and other nonproductive sectors.

2.4 Irrigation expansion and agricultural policies

2.4.1 Irrigated lands expansion and cotton production policies

The reasons for the high dependence on irrigated agriculture in parallel to the underdevelopment of the processing and infrastructural sectors in the ASB need to be viewed from a historical context of the socio-economic and institutional processes that occurred over the past century. Attaining self-sufficiency in cotton production in the Soviet period led to a tremendous expansion of irrigated area in the ASB. Labor intensive cotton production was a massive labor sink that also facilitated social control in the densely populated settlements of the ASB through the complex hierarchical management structure and patronage relationships of the command-and-control system (Weinthal 2002). Thus through expanding cotton production the Soviet leaders at the Kremlin intended to 'hitting two birds with one bullet.' As a result of these policies, irrigated areas almost doubled between 1960 and 2000, increasing employment of the rural population and thus dependence of rural livelihoods on agriculture. Currently the ASB is one of the largest irrigated areas in the world with about 8.5 million hectares of irrigated cropland (Table 2.8). The increase in irrigated areas occurred primarily in the downstream countries of Uzbekistan and Turkmenistan. Irrigated lands stabilized after the 1990s in Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan, but the government of Turkmenistan further expanded irrigated areas by about 40% between 1990 and 2009 (Table 2.8) despite increased conflicts over water in the region after the dissolution of the SU. Being the core regional producer of raw cotton, Uzbekistan contained more than half of all irrigated lands in Central Asia and produced more than 60% of the total cotton output in the SU during the period between 1940 and 1990 (Figure 2.11).

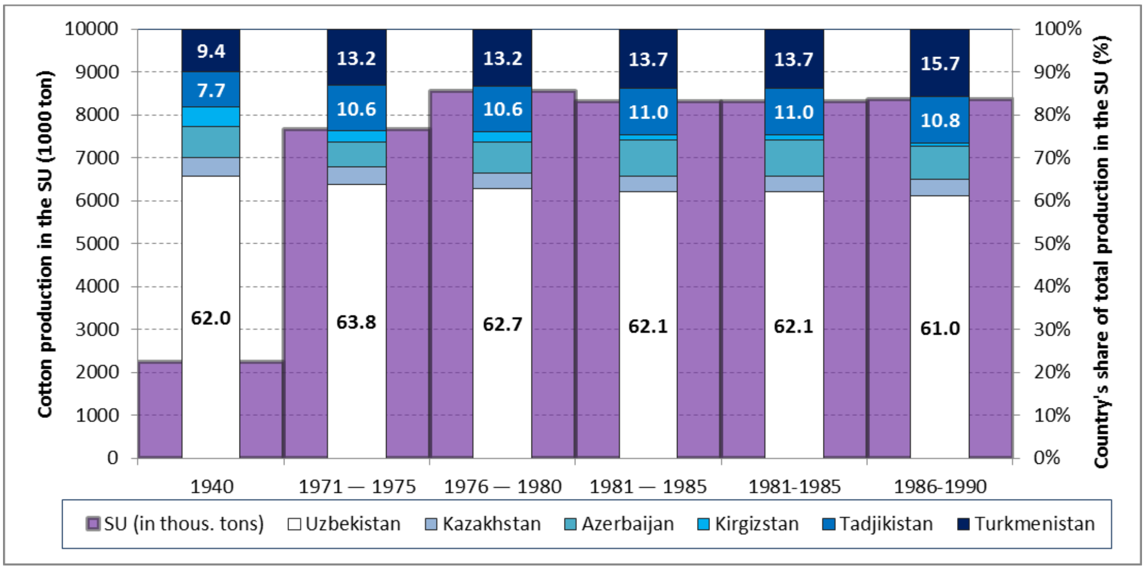
Table 2.8 Irrigated areas in the Aral Sea basin (in 1000s of hectares), 1965–2009

	1965	1970	1975	1980	1985	1990	1995	2000	2005	2009	*FAO 1997* a)
Kazakhstan	493	523	588	696	706	752	758	770	714	745	*786*
Kyrgyzstan	374	383	395	423	425	419	428	429	411	407	*422*
Tajikistan	463	518	567	671	710	751	747	750	763	810	*719*
Turkmenistan	514	643	855	1,080	1,340	1,523	1,967	2,046	2,142	2,188	*1,735*
Uzbekistan	2,787	2,978	3,254	3,688	4,085	4,325	4,466	4,439	4,404	4,346	*4,233*
Aral Sea basin	4,631	5,045	5,659	6,558	7,266	7,770	8,366	8,434	8,434	8,496	*7,895*

Notes: *a)* The data (as of 1994) of this column is from FAOSTAT (1997; cited in Petrov and Ahmedov 2011:11) and is presented here to validate the data from Dukhovny (2010) and extrapolated results.

Source: Dukhovny (2010), FAOSTAT (1997), author‘s estimates using extrapolation method

Figure 2.11 Cotton production in the former Soviet Union

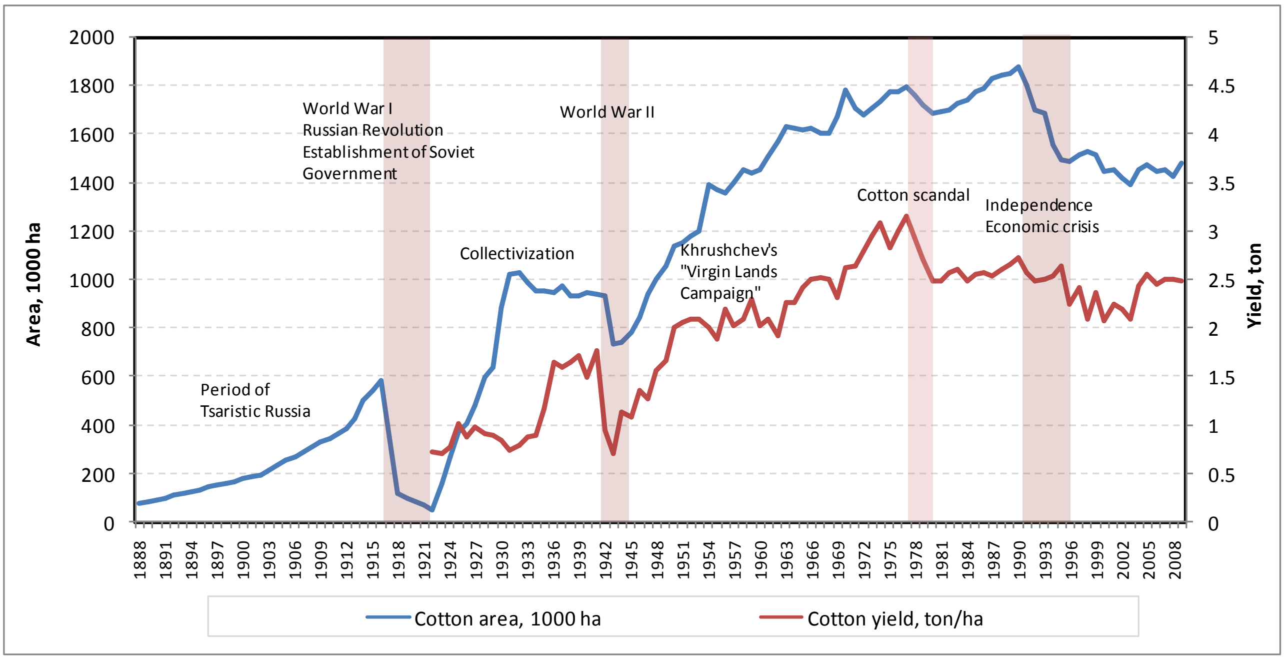


Source: Based on SSU (1990)

Cotton has long been integral to life in Central Asia, particularly in Uzbekistan. Therefore, the dynamics of the cotton industry in Uzbekistan since the 1890s serve as a broader reflection of the history of political events, economic and technological changes, and the agricultural reforms in the region (Figure 2.12). Understanding cotton production policies is also important for understanding the water management legacy and issues (Weinthal 2002:104) that developed around cotton expansion.

The availability of land, water, and cheap labor for cotton production in Central Asia was one of the main motivations behind the invasion of the region by Tsarist Russia. The civil war in the USA in the 1860s and consequent reductions in cotton exports from “the cotton belt” to Russia increased demand for cotton from Central Asia and accelerated expansion of the cultivation of this crop, which became colloquially referred to as “white gold” (Spoor 1993). As a result, Central Asia became a main provider of raw material to textile plants in Russia and the Ukraine (Spoor 1993). The area under cotton production in 1888 was about 74,700 ha, and by 1916 it had increased by about eight times, reaching 580,000 ha. During World War I and the Russian Civil War, the supply of bread and industrial goods from Russia decreased, which increased food prices in the region. The drastic decrease of the food supply and constant prices for raw cotton lead to reduced cotton production areas that in 1918 were only one-fifth of the area under cultivation in 1917. During the period between 1922 and 1928, the Soviet government reverted to the pre-revolutionary policies of expanding cotton cultivation and the areas under cotton increased to the pre-war levels of 1913. By the early 1930s, cotton self-sufficiency of the SU had been virtually reached, with the largest area of cotton cultivation in the pre-World War II period. However, the subsequent collectivization and consequent establishment of production cooperatives (*kolkhozes*) and state farms (*sovkhozes*) in the agricultural sector lead to slight decreases in cotton production.

Figure 2.12 Cotton cultivation area and harvest yields in Uzbekistan, 1888–2009[1]



Note: The cotton cultivation area for 1888, 1902, 1912, 1914 is for Central Asia (Turkestan), but most irrigated lands in that period were located in the territory of current Uzbekistan (Arapov 2011).

Source: Cultivation area and yields from 1922 to 1972 are from MA UzSSR (1973). Data for 1974–1977 are from MA UzSSR (1975–1978). Data for 1980–1994 are from SIC-ICWC (2011). Data for 1995–2009 are from UzStat (1999), UzStat (2003), UzStat (2007), and UzStat (2010a). Data for 1889–1901, 1903–1911, 1913, 1915–1916, 1917–1921, and 1973 were interpolated based on the documented values.

Further expansion of cotton cultivation continued until the 1970s during Khrushchev's "Virgin land campaign," and as a consequence the area under cotton production reached 1.78 million ha by 1970. Although the virgin land campaign mainly concentrated on the expansion of irrigated land in Kazakhstan and western Siberia, Khrushchev also promoted increasing irrigated lands in the ASB. The construction of the Karakum canal in Turkmenistan with a length of more than 1,400 km (a water discharge of 10–12 km^3 per year and the capacity to irrigate more than 800,000 ha of land) and the construction of the Bukhara and Kashkadarya pumping stations in Uzbekistan with discharge rates of 270 m^3/second and 350 m^3/second (at elevations of 57 m and 170 m) respectively reflect the extensive scope of water management projects of that period (Nanni 1996, Wegerich 2010:59).

However, the combination of consistent orders from Moscow to increase cotton production and yields year after year while neglecting soil quality decreases due to over irrigation and over fertilization of the cultivated lands, led Uzbek and other Central Asian country's officials to misreport record improvements in yield and production volumes over the course of the 1970s. Indeed, In the late 1970s, Andropov's "anti-corruption" policy campaign following the Brezhnev era stopped the practice of falsified reporting that caused the so-called "cotton scandals" that coincided with the purges of thousands of cadres in Uzbekistan and other Central Asian countries (Spoor 1993, Micklin 2000). This resulted a decline in reported yields during this period.

---

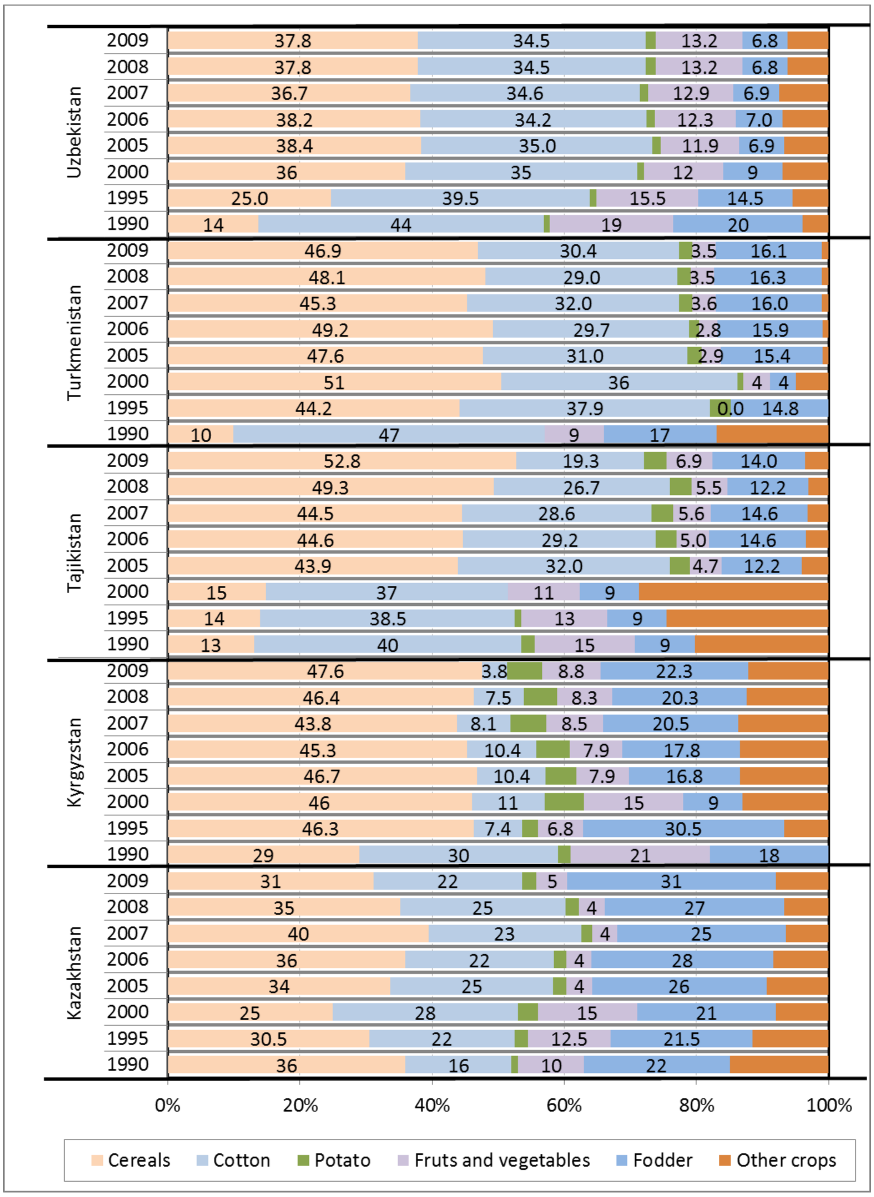
[1] Although Uzbekistan was formally established in 1924, most of the irrigated lands in the ASB were located in the territory of the current borders of Uzbekistan at the beginning of 20th century.

The dissolution of the Soviet system in the early 1990s loosened trade relationships between the economically interdependent commonwealth countries and resulted in sharp decline of the economies in these countries. Wheat supplies from Russia and the Ukraine to Central Asia dramatically decreased during this period. Market channels for cotton exportation to traditional importers such as Russia and the Ukraine were discontinued. Consequently the newly independent countries of Central Asia (with the exception of Kazakhstan), implemented food self-sufficiency policies that led to reductions in the cotton production areas of Uzbekistan from 1.9 million ha in 1990 to 1.5 million ha in 1995. Despite these changes, cotton cultivation continues to be the backbone of the agricultural sector in Uzbekistan and dominates in terms of cultivated area relative to other crops.

2.4.2 Cropland pattern changes and crop specialization across administrative provinces

Cotton is the main cash crop not only in Uzbekistan, but also in the other ASB countries (Figure 2.13). In 1990 cotton occupied about 44% of the cultivated lands in Uzbekistan, and its share in total croplands were 47% and 40% in Turkmenistan and Tajikistan respectively. As previously mentioned, following the post-Soviet food self-sufficiency policies in all ASB countries except Kazakhstan, the cultivation of cereals increased, partially reducing cotton production (Micklin 2007). According to estimates based on official statistics, in 2009 the cereal production share of total croplands was about 38% in Uzbekistan, 47% in Turkmenistan, 53% in Tajikistan, and 47% in Kyrgyzstan. Despite the substantial reductions, the current share of cotton is still high, occupying about 35% of the total cultivated areas of Uzbekistan, 30% in Turkmenistan, and 20% in Tajikistan. In contrast to the major trends, the cotton share of total cultivation area increased from 16% in 1990 to 22% in 2009 in the southern provinces of Kazakhstan. Considering the substantial contribution of cotton fiber exports to hard currency revenues for the ASB countries and the availability of inherited cotton processing infrastructure, the expansion of wheat cultivation was primarily at the expense of fodder crop production in Uzbekistan. On one hand, the changes in crop area patterns as a result of governmental reforms reflect efforts to improve public welfare by achieving grain self-sufficiency. However, these changes also indicate the intentions of these countries to establish closed (autarkic) economies rather than seeking to increase gains through improving cooperation, liberalizing trade, and thus take advantage of the relative strengths of each country in the production of a particular commodity.

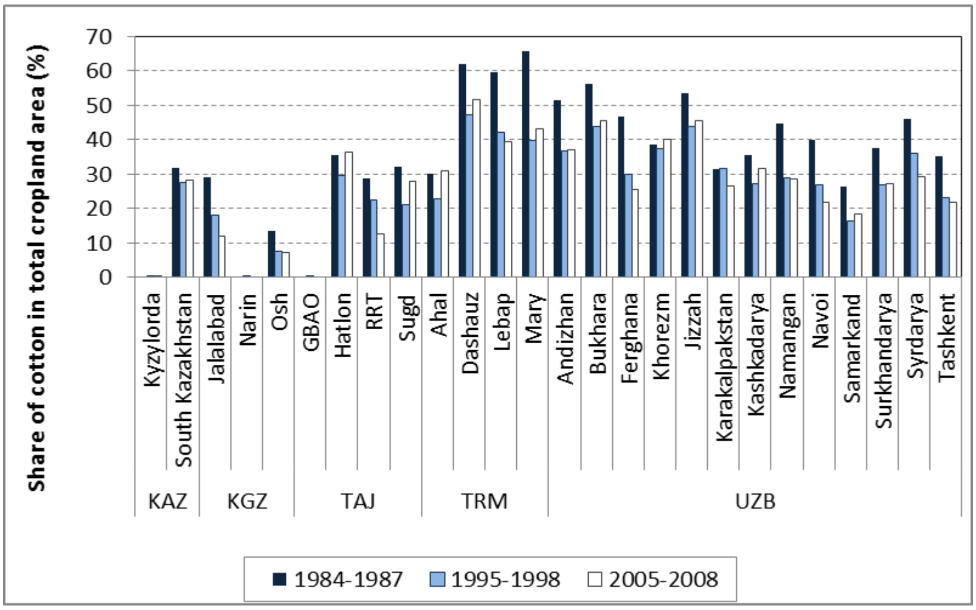
Figure 2.13 Cropland structural patterns by country in the ASB, 1990–2009



Source: Based on data for 1990–2000 from SIC-ICWC (2011); data for 2005-2008 from each country's statistical organization (KazStat (2010), KyrStat (2010), TajStat (2010), TurkmenStat(2012), UzStat (2010a))

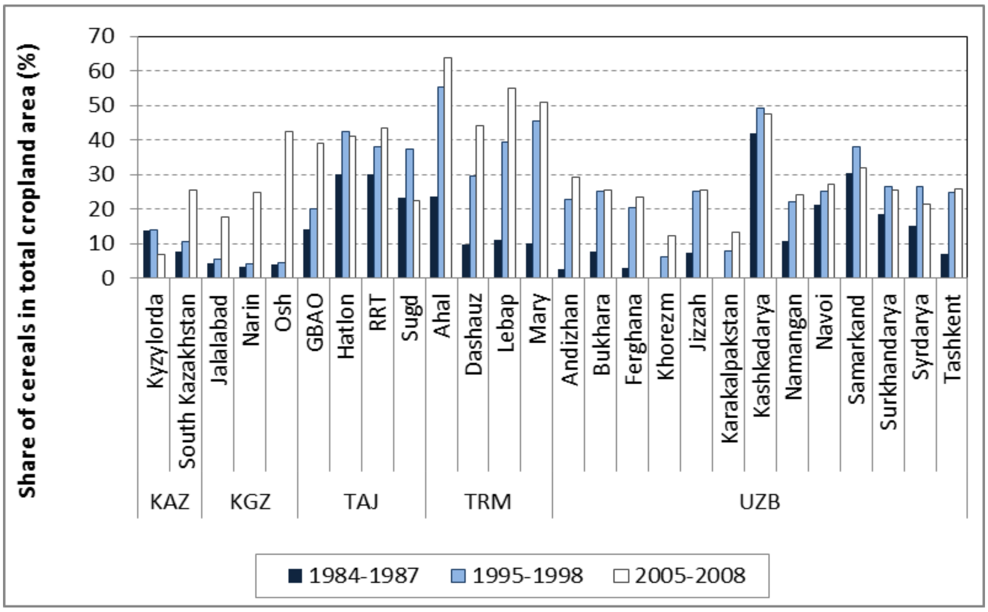
Cotton is not only the dominant crop at the national level, but also at the provincial level in the ASB as illustrated by the shares of cotton in total cropland in the provinces of the ASB countries (Figure 2.14). Comparison of the cropland share of cotton across the 26 administrative regions of the Central Asian countries shows that cotton shares exceeded 30% in most regions, and reaching as high as 60% in regions of Turkmenistan (Dashauz, Lebap, Mary) during the pre-independence period. Cotton's share considerably decreased in most regions but remained high in the aftermath of independence (1995-1998) but did not change much after 2000 (2005-2008). In parallel, the cropland share of cereals increased substantially in the post-independence period and cereals occupied more than 20% of the total cropland area in most regions during the period between 1995 and 1998 (Figure 2.15). Further expansion of the cereals production occurred in all regions of Kyrgyzstan and Turkmenistan, in the Kazakh region of South Kazakhstan, and Tajik region of GBAO. As in the case of cotton, the cropland shares of cereals vary widely across the ASB.

Figure 2.14 Comparison of the share of cotton of total cultivated area by regions (provinces) in the ASB in the periods of 1995–1998, 1981–1984 and 2005-2008



Notes: KAZ-Kazakhstan, KGZ-Kyrgyzstan, TAJ-Tajikistan, TRM-Turkmenistan, UZB-Uzbekistan
Source: Data for all countries for 1980-2000 are from SIC-ICWC (2011); data for 2005-2008 are from each country's statistical organization (KazStat (2010), KyrStat (2010), TajStat (2010), TurkmenStat(2012), UzStat (2010a))

Figure 2.15 Comparison of the cropland share of cereals by regions (provinces) in the ASB in the periods of 1995–1998, 1981–1984 and 2005-2008



Notes: KAZ- Kazakhstan, KGZ-Kyrgyzstan, TAJ-Tajikistan, TRM-Turkmenistan, UZB-Uzbekistan
Source: Data for all countries for 1980-2000 are from SIC-ICWC (2011); data for 2005-2008 are from each country's statistical organization (KazStat (2010), KyrStat (2010), TajStat (2010), TurkmenStat(2012), UzStat (2010a))

Based on the cropland shares of different crops, crop specialization in the region is described in Table 2.9. Kyzyl-Orda, Kazakhtan's downstream region, is highly dependent on rice production, complemented by a substantial share of fodder crops. Cotton is a major crop in South Kazakhstan. Cotton is the dominant crop in the Kyrgyz region of Jalalabad, fodder dominates in Naryn, and crops from household plots dominate in Osh. Tajikistan is mainly dependent on cereal production. In all Turkmen regions cotton and cereals each occupy more than 30% of the total croplands. The predominance of cotton and cereals was observed in most of the regions of Uzbekistan. Khorezm and Karakalpakstan, located in the lower reaches of the Amu Darya, primarily depend on cotton and rice production. Fruits and grapes occupy more than 20% of the total cultivated area in the Ferghana and Namangan regions of the Ferghana Valley, as well as in the regions located in the midstream reaches such as Tashkent, Samarkand, Surkhandarya, Navoi, and Syrdarya.

Table 2.9 Crop specialization by regions (provinces) in the ASB in 2000

Regions	Cotton	Fodder	Fruit & Grapes	Cereals & Maize	Household Plots	Cords	Rice	Potato & Vegetables	Other	Share of total area (%)
Kazakhstan										
Kyzylorda		++		+			+++			1.9
South Kazakhstan	+++	+		+						5.0
Kyrgyzstan										
Jalalabad	++			+	+				++	1.5
Naryn		+++			+			+		0.6
Osh			+	+	++				++	1.8
Tajikistan										
Hatlon	++	+		+++						3.9
Sugd	+	+	+	+++						3.4
RRT	++	+	+	+++						1.1
GBAO		++		++	+	++				0.4
Turkmenistan										
Dashauz	+++			++			+			4.9
Mary	+++			+++						5.6
Lebap	+++			+++						3.4
Ahal	++			+++						5.0
Uzbekistan										
Andizhan	+++			++	+					3.4
Bukhara	+++			++	+					3.5
Jizzah	++			+++						4.8
Kashkadarya	+++			+++						6.6
Navoi	++		++	++						2.0
Namangan	++		++	++	+					4.4
Samarkand	+		++	+++	+					6.9
Surkhandarya	++		++	++	+					5.6
Syrdarya	+++		++	++						4.7
Tashkent	++		++	++						5.9
Ferghana	++		++	++	+					5.5
Khorezm	+++	+			+		+		+	3.3
Karakalpakstan	+++	+			+		+		+	5.0

Note: Crop shares of total cropped area was denoted by y; "+++"if y>30%, "++"if y >20%, "+"if y >10%.
Source: based on SIC-ICWC 2011

The total cropland area and cropland structure are key determinants of total irrigation water demand and in turn on environmental flow availability. Replacing water intensive crops with less water demanding crops would allow substantial reductions in overall irrigation water demand, part of which can be retained for natural ecosystems (Levintanus 1992). However, crop pattern changes in the ASB have mainly been driven by either national food self-sufficiency initiatives or efforts to maximize export revenues, rather than environmental concerns. Despite huge environmental damage (see section 2.6 for details) and relatively low profitability to farmers, Central Asian governments still maintain high levels of cotton production because of the substantial revenues that it generates. It is important to note that rice production, which requires 4–5 times more water than cotton production, dominates the tail reach zones of the ASB where water scarcity is frequent. Though pursuing cotton self-sufficiency was a main factor in determining crop specialization in the region during the Soviet period, rice was promoted as an appropriate crop at the tail reach zones of the ASB due to its ameliorative function in areas with high soil salinity. However, due to its huge water use requirements current rice production in the downstream regions should be carefully reconsidered by both farmers and policy makers under conditions of increased pressure on water resources. Policies should not address only the economic benefits of agricultural choices but also lower resource use intensity and environmental sustainability should be emphasized in order to prevent environmental, social, and political conflicts in the ASB.

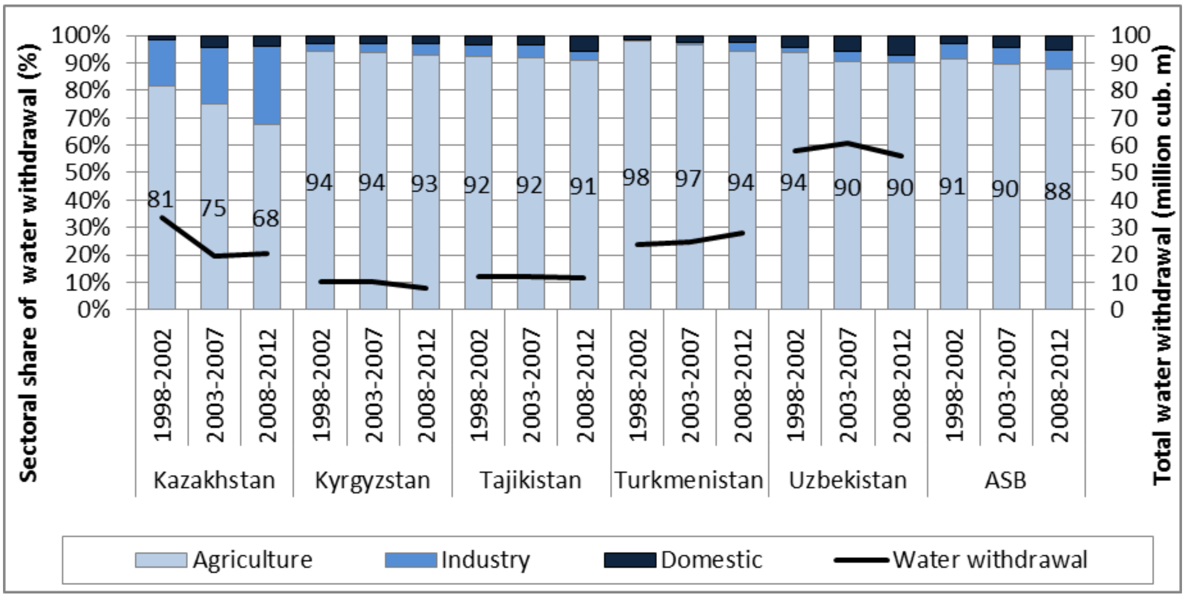
2.5 Water use by sectors

2.5.1 Irrigation

Due to the dominance of water intensive crops such as cotton across the entire territory and rice in downstream regions irrigation demands almost 90% of the total water withdrawals in the ASB (Figure 2.16; SANIIRI 2004). During the period between 2000 and 2010 slight decrease of the share of irrigation in total water withdrawals was observed in Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan but remained about 90% or more. In this period, agriculture’s share of total water withdrawals decreased from 81% to 68% in Kazakhstan. Reduced water withdrawals in Kazakhstan’s regions are due to their downstream location. Using the Tokhtogul reservoir in energy production mode increased artificial water scarcity in growing season that prevented water to reach the downstream regions. Since there was no possibility of building large reservoirs that can provide stable water supply to irrigation in downstream regions water releases from the upstream reservoirs in winter could not be stored in downstream but wastefully released to the Arnasay depression (Mirzaev and Khamraev 2000).

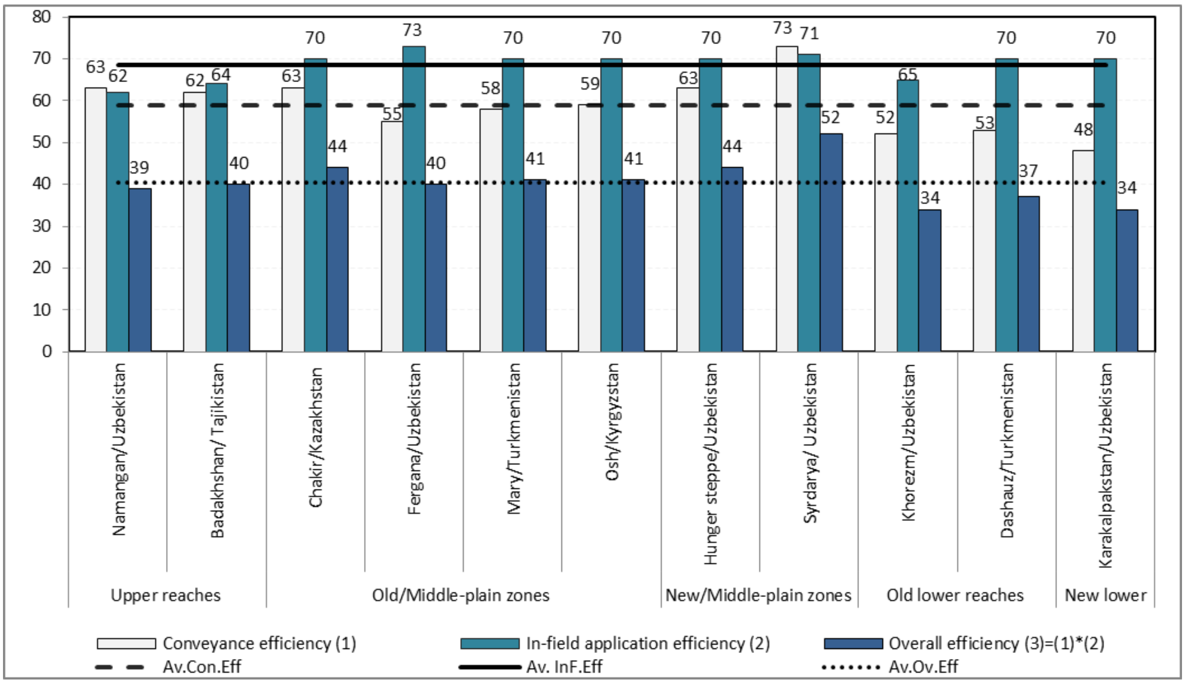
In addition to the massive scope of the irrigation system, excessive water losses in delivering water to the fields and irrigating crops also determine high share of the agricultural sector in total water use. Water losses are enormous because of the poor efficiency of the outdated irrigation and drainage (I&D) network (Kyle and Chabot 1997, Purcell and Currey 2003), which has been in operation without any modernization for more than three decades. Due to the predominance of unlined earthen canals, the average efficiency of water delivery is about 60% (Figure 2.17). Particularly in the downstream regions of the Amu Darya, approximately half of the water diverted from the river for irrigation purposes does not reach to the fields. A small proportion of water is lost through evaporation during conveyance, but most is lost by seepage and percolation along the main inter-farm and on-farm canals. In addition, substantial operational water losses due to overflows from these canals into the drainage system occur regularly. Because conventional irrigation methods are common at the field level, 50% more water than the actually required volume is applied to irrigate crops.

Figure 2.16 Sectoral water withdrawals in the countries of the Aral Sea basin, 1998–2012



Source: FAO (2012)

Figure 2.17 Water use efficiency in the Aral Sea basin

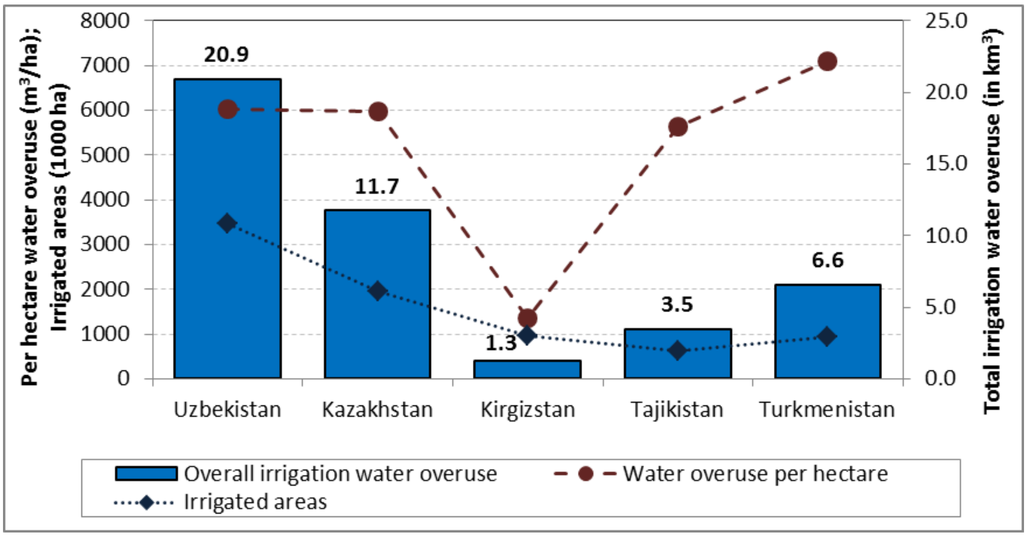


Notes: *Conveyance efficiency is the ratio of the water volume delivered to the field to the volume diverted from the source river. **In-field application efficiency is the ratio of water volume used for crop growth to the volume delivered to the field.

Source: Based on GEF (2003)

Except the delivery of water through unlined earthy canals and using conventional irrigation techniques such as furrow and basin irrigation (Bekchanov et al. 2010), free supply of irrigation water to the fields caused careless use and waste of these precious resources. Night irrigations and irrigation duration longer than the time that the field is irrigated adequately are just some few examples for unwanted unproductive use of water. As a consequence of careless use of water resources, farmers (former agricultural enterprises—*kolkhozes* and *sovkhozes*) were using much more water than the required amounts, consequently wasting about 44 km^3 of water annually in the ASB in the early 1980s (Figure 2.18; Glazovsky 1990). While wasteful use of water was only 1300 m^3/ha in Kyrgyzstan, this amount was more than 5500 m^3/ha in the other ASB countries, reaching up to 7000 m^3/ha in Turkmenistan. Since there were no substantial investments to modernize the irrigation infrastructure over the last three decades water overuse due to inefficient water application practices has been perpetuated to the present. Although recently established Water User Associations (WUAs) are assumed to provide efficient water use through charging fees for its water delivery and canal maintenance services (Bobojonov 2008) in reality these water fees are based on the cropland area rather than water used by the farmers and thus do not give any incentives for careful use of the scarce resources.

Figure 2.18 Irrigation water wastage in the Aral Sea basin, 1980



Source: Based on Glazovsky (1990:76)

2.5.2 Hydro-electricity production

In contrast to the long-term history of irrigation practices in the ASB, hydro-electricity generation has been mainly established at the second half of the last century. Numerous reservoirs were built mainly in mountainous up-stream countries to provide stable water supply for growing irrigation needs (Table 2.10). Nurek and Tokhtogul are the largest reservoirs with energy production capacities of over 3,000 and 1,200 MW respectively. Rogun and Kambarata reservoirs with energy production capacity of 3,600 and 1,900 MW, respectively, are under the way of construction. Numerous other hydropower plant construction projects are planned particularly in the upper reaches of the Amu Darya River.

Table 2.10 Operating, emerging, and planned hydropower stations (HPS) in the Amu and Syr Darya river basins

Hydropower station	Capacity of reservoir (million m^3)		Installed capacity (MW)	Annual power generation (1000 MWh)	Location (River)	Status (O-operating; UC-Under construction; P-Planned)
	Full	Useful				
Chardara	5700	4700	100	516	Syr Darya	O
Farkhad	350	20	126	870	Syr Darya	O
Kairakum	4160	2600	126	691	Syr Darya	O
Charvak	2000	1580	620.5	2000	Chirchik	O
Andijan	1750	1600	140	435	Karadarya	O
Tokhtogul	19500	14000	1200	4400	Naryn	O
Kambarata	4650	3430	1900	4580	Naryn	UC
Other in the SDB (O)	650	87	1955	7028		O
Other in the SDB (UC)	70	8	360	1000		UC
Other in the SDB (P)	816	491	1004	3203		P
Total of the SDB (O)	34110	24587	4268	15940		O
Total of the SDB (UC)	4720	3438	2260	5580		UC
Total of the SDB (P)	816	491	1004	3203		P
Total of the SDB	39646	28515	7532	24723		
Rogun	11800	8500	3600	13300	Vakhsh	UC
Nurek	10500	4500	3000	11200	Vakhsh	O
Rushan	5500	4100	3000	14800	Panj	P
Dashtijum	17600	10200	4000	15600	Panj	P
Upper Amudarya	15200	11400	1000	4400	Amu Darya	P
Tuyamuyun	7300	5100	150	550	Amu Darya	O
Other in the ADB (O)	320	40	885	4700		O
Other in the ADB (UC)	325	17	890	3670		UC
Other in the ADB (P)	16650	3950	12250	59200		P
Total of the ADB (O)	18120	9640	4035	16450		O
Total of the ADB (UC)	12125	8517	4490	16970		UC
Total of the ADB (P)	54950	29650	20250	94000		P
Total of the ADB	85195	47807	28775	127420		
Total of the ASB	124841	76322	36307	152143		

Notes: Amu Darya basin - ADB; Syr Darya basin - SDB; Aral Sea basin - ASB
Source: Based on Jigarev (2008)

Hydropower contributes more than one fourth of total electricity production in the ASB (Table 2.11). In contrast to small share of hydropower production in downstream countries hydroelectricity generation plants provide 82 and 96% of total energy production respectively in upstream countries such as Kyrgyzstan and Tajikistan. These two countries together produce more than two thirds of total hydroelectricity outputs despite they are using only less than 10% of their potential capacity. If the full potential of hydroelectricity production was reached in Central Asia, Tajikistan would produce about 70% of regional hydroelectricity production whereas Kyrgyzstan 22%. Most of the electricity produced are consumed domestically in the Central Asian countries except Kyrgyzstan as evidenced by high ratios of consumption to production. Despite the lowest per capita energy consumption, Kyrgyz government prefers to export most of its electricity outputs.

Table 2.11 Actual and potential levels of hydroelectricity production in the ASB

Description	KAZ	KGZ	TAJ	TRM	UZB	CA
Reservoir storage capacity (million m^3)[a]	6[b]	20	29	3	19	77
HPP installed capacity (MW)	2248	2910	4037	1	1420	10616
Total electricity production (billion kWh) (2010)	82.6	11.4	16.4	16.7	51.7	178.8
The share of hydropower production (HPP) in total electricity production (%)	10	91	97	0	21	25
Actual HPP (billion KWh) (2010)	8	10	16	0	11	45
Potential HPP (billion KWh)	27	99	317	2	15	460
Utilization of HPP potential (%)	30	10	5	0	73	10
The country's share of total hydroelectricity production (%)	18	22	36	0	24	100
The country's share of total regional HPP potential (%)	6	22	69	0	3	100
Energy consumption (billion kWh) (2010)	77	7	14	12	47	158
The ratio of energy consumption on production	0.93	0.66	0.84	0.73	0.91	0.88
Energy consumption per capita (kWh per capita)	4728	1375	1808	2403	1648	2627

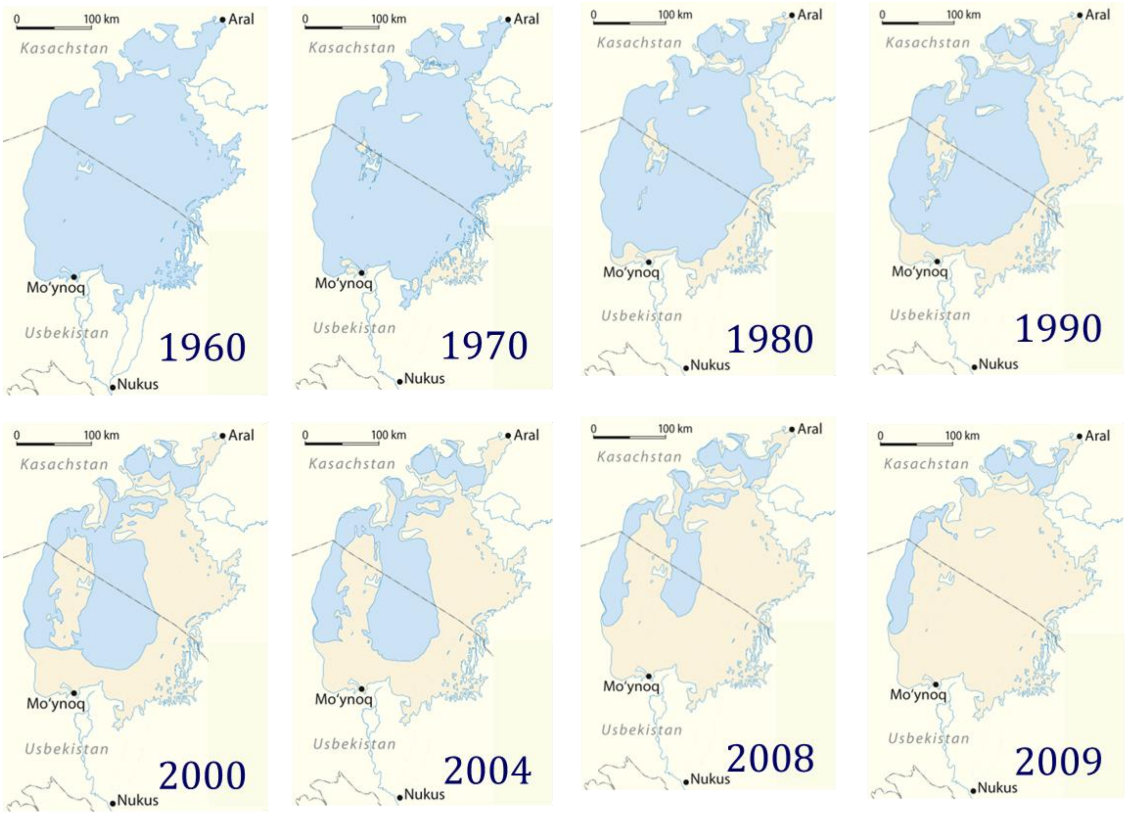
Notes: [a] Including reservoirs without hydropower plants; [b] Only reservoirs in southern parts of Kazakhstan are included; KAZ- Kazakhstan, KGZ-Kyrgyzstan, TAJ-Tajikistan, TRM-Turkmenistan, UZB-Uzbekistan, CA-Central Asia.
S.: Based on World Bank (2013) if not mentioned; reservoir volume for Southern regions of Kazakhstan from Jigarev (2008) and for the other countries from Rakhmatullaev (2010); HPP capacity from EADB (2008).

Although hydro-electricity production does not require considerable water consumption, changed reservoir mode depending on seasonal electricity demand can be in conflict with irrigation water uses in growing season unless there are possibilities to build reservoirs in downstream. Recent trends in the operation mode of the reservoirs located in Kyrgyzstan and Tajikistan indicate that both countries are increasing winter water releases to produce electricity for increased heating and export demands while increasing water storage in summer period and thus decreasing water availability to irrigation (Dukhovny and Schuetter 2012). Considering substantial potential for developing hydropower plants, these countries also attempt to extend their hydroelectricity production capacity by constructing additional reservoirs. Increased electricity output is planned to export to the Russian and South Asian markets (Rizk and Utemuratov 2012). However, since 20-30% of lands is isolated from electricity in cold winter months domestic electricity scarcity should be solved first before planning any exports (Rizk and Utemuratov 2012). Increasing electricity production potential in upstream countries should not neglect the interests of downstream regions as well since water is common resource for the entire region.

2.5.3 *Environmental flows*

Despite improved employment and welfare opportunities for a growing population and elimination of the dependence of the SU on expensive cotton imports, the tremendous development of irrigated agriculture in the ASB reduced water availability for the environmental systems and caused severe ecological problems. As a consequence of excessive diversion of water for irrigation, ever smaller fractions of river water reached the Aral Sea, leading to its gradual desiccation (Figure 2.19 and Figure 2.20). In 1960, the Aral Sea was the fourth largest freshwater lake in the world with a depth of 53 m, a volume of 1,064 km^3, and a surface area of 66,000 km^2 (Mirzaev and Khamraev 2000). Inflows to the sea were about 50 km^3 annually[1]. The sea was vital for regional fisheries and water-based transportation, and integral to maintaining favorable climatic conditions for living and agricultural production in the circum-Aral region. As a result of the reduced inflows and consequent desiccation, the Aral Sea was divided into two parts–the Large Aral Sea in the south and the Small Aral Sea in the north. By 2006, levels had lowered to depths of 30 m in the Large Aral Sea and 40.5 m in the Small Aral Sea, and the combined volume had decreased to 108 km^3 with a reduced surface area of 17,400 km^2. The decreased volume of the lake led to increased salinity levels that reached more than 30 g/l (Micklin 2007).

Figure 2.19 The desiccation of the Aral Sea

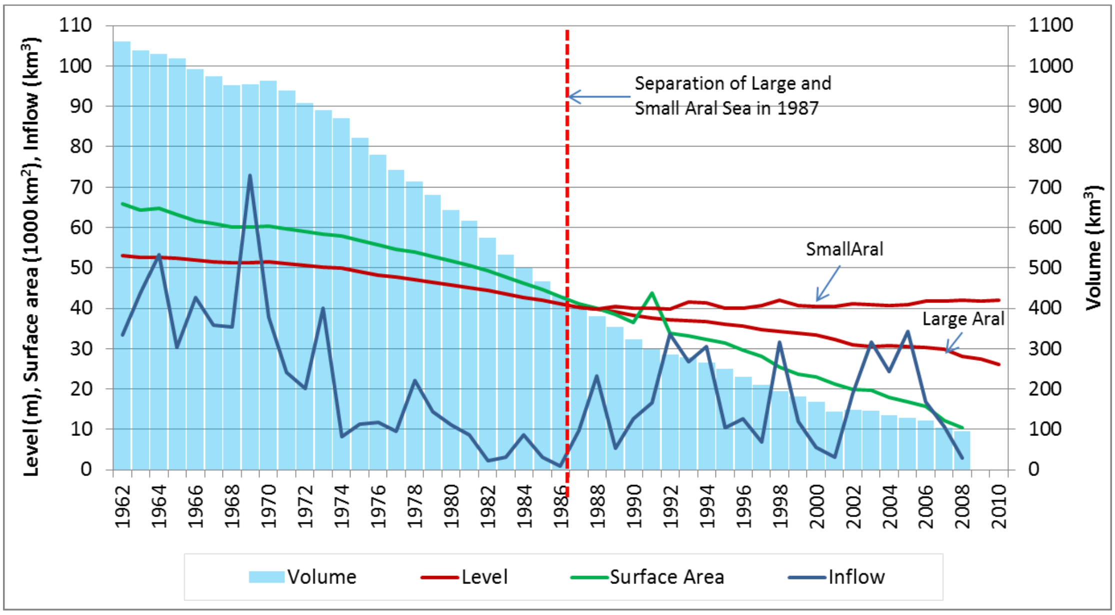


Source: Based on Kartenwerkstatt (2008)
Note: Initial area of the Aral Sea in the 1960s was more than 60,000 km^2, which is equivalent to the approximate area of the territories of the Netherlands and Belgium together.

---

[1] Cai et al. (2003b) erroneously reported that annual inflows to the Aral Sea from the Amu Darya and Syr Darya rivers were 72 and 37 km^3 respectively. These figures indicate total annual volumes of these rivers, but not inflows to the sea.

Figure 2.20 The state of the Aral Sea and annual inflow volumes, 1962–2010



Source: Based on data for 1962–2000 from INTAS (2006), data on the sea level for 2002–2007 from Zonn et al. (2009), data for the Small and Large Aral Sea levels for 1987–2010 from Micklin (2010), data on annual inflows and surface area was extrapolated based on river flow observations at the hydroposts (Farkhad GES in the Syr Darya and Chatli in the Amu Darya)

Although diverting all water resources of the Amu and Syr Darya rivers for irrigating desert lands and increasing cotton production primarily occurred during the Soviet period the idea was already popular during the Tsarist period (Ashirbekov and Zonn 2003*)*. In his report on Russia's rivers, the geographer Voyejkov (1882) wrote that, "*the existence of the Aral Sea in its current boundaries while availability of huge area of drylands suitable to cropping in the lower and middle reaches of the Amu and Syr Darya is a proof of our ignorance and unskillfulness to manage water resources efficiently. In the country which can manage natural resources efficiently, the Aral Sea should serve as a sink only for winter flows and high summer floods*." This plan was supported by Masalsky, the head of the water sector during the tsarist period, and was implemented during the Soviet period without consideration of environmental flow needs.

Although the desiccation of the Aral Sea was intentionally planned by policy makers, its environmental and socio-economic costs were not expected to be enormous. Because of the worsening environmental and health conditions, the circum-Aral Sea region[1] was declared an ecological catastrophe zone in the late 1980s during the late Soviet period by decree of the supreme court of the USSR on October 27, 1989 (Levintanus 1992, Mirzaev and Valiev 2000). Though there was a plan to gradually increase guaranteed annual flows to the sea from 8.7 km^3 in 1990 to 21 km^3 by 2005,[2] these plans were never realized because of the economic and political problems that occurred after the break-up of the SU (Weinthal 2002:111).

---

[1] The circum-Aral region includes the Karakalpakstan republic and the Khorezm region of Uzbekistan, the Dashhauz region of Turkmenistan and the Kyzyl-Orda province of Kazakhstan.

[2] A decree of the communist party on "Measures for the radical improvement in the ecological and sanitary situations in the circum-Aral Sea region and for raising the effectiveness of use and strengthening the protection of water and land resources in the ASB," issued on September 19, 1988.

2.6 Water management institutions in the Aral Sea basin: historical outline

The lingering dominance of cotton production, high reliance on irrigated agriculture, and consequent environmental degradations were the result of the continuity of formal and informal institutions based on a command-and-control management principle. Reducing cotton dominance and improving water productivity and environmental conditions should go hand in hand with more effective institutions that can support economic restructuring. Considering the path dependence of institutional change (North 1990), understanding the historical roots of the current water management institutions in the ASB is important for the consideration of any future institutional improvements. The main changes in the ASB water management institutions occurred in parallel to the governmental regime changes. Four distinct historical periods can be differentiated:

1) Water management institutions during the mid-centuries, which were based on Islamic law and were being practiced before the Russian invasion of Central Asia;
2) Water management institutions under Tsarist Russia, which was characterized by a mix of colonial and traditional management styles;
3) Water management institutions under Soviet rule, when water resources were fully owned by the government and enormous changes in the regulation of water use occurred;
4) Water management institutions in the aftermath of independence under intensified conflicts over water and energy resources use among the five newly emerged CA states.

2.6.1 Water management during the Mid-Centuries

Before the Russian invasion of Central Asia, water management in the region followed rules based on the Koran and Sharia, and water relationships were regulated based on traditions and customs formed over centuries (Mirzaev 2000). A Water Code, *The Book on Ariks*[1], was prepared by Muslim scholars and theologians from Khorasan[2] and Iraq, and served to regulate water distribution and solve water conflicts in Central Asia over centuries (Dukhovny and Schutter 2011:54). Though the original text of the code did not survive, its rules were reflected in the Sharia and daily customs and traditions. The Sharia, a collection of Islamic laws, required adherents to avoid polluting and wasting water resources. According to the Koran, nobody but Allah (God) has the right to own water resources. Water was considered as a sacred gift from Allah given to all people and intended for the general welfare. Rotational methods of distributing water among the users to increase water productivity were established by Sharia centuries ago and continue to be practiced effectively.

In addition to treating water as a common good and recommending rotational water distribution, the Sharia regulations required fair and equal distribution of water resources under water scarcity conditions and obligatory participation of water users in constructing, repairing, and cleaning irrigation canals and facilities (Dukhovny and Schutter 2011:56). Obligatory compensation for the damages incurred due to canal construction through the land of another user were also stated in these religious law collections. *Mirabs* (water managers) elected by local communities were responsible for the proper implementation of the Sharia rules in water use, distribution, and conflicts resolution, while *Imams* (priests in the mosque) were entrusted with general supervision. Despite its long history of practice, Sharia rules do not explicitly clarify legal rights on the distribution of common river basin resources. Particularly, the opinions of Muslim scholars vary regarding the benefit sharing based water allocation through treating water as an economic good (Kadouri et al. 2001).

---

[1] *Arik* means canal in Central Asia

[2] Historical region, the majority of which lies in the current territory of northeastern Iran, parts of Afghanistan and parts of the Central Asain countries: Turkmenistan, Uzbekistan, and Tajikistan

2.6.2 *Water management under Tsarist Russia*

After the invasion of Central Asia (formerly Turkestan[1]) the colonization campaign began to transform the region into the production center of raw cotton supplies for the Russian empire. In consequence, the tremendous expansion of irrigated areas was achieved through massive diversions of water from the rivers. These developments in turn required the construction of large-scale water management infrastructure, the development of massive water management measures, a new legal basis for water distribution, and institutions to manage water resources (Mirzaev 2000). Three main policy documents were adopted during this period: “Temporary rules on the irrigation works in Turkestan” (1878), “Article on governing Turkestan region” (1886), and “The instruction on the rights and obligations of irrigation ranks, district heads, *aryk-aksakals* and *mirabs*[2] responsible for irrigation in the Turkestan region” (1886). These documents legalized government ownership of water resources and established that farmers were to share and use their approved water quotas according to government laws, Sharia, and traditional customs. To take over the overall control of water resources and strengthen the role of government for reallocating water resources towards higher cotton production, the authorities established the Turkestan Administration of Water Works (IRTUR) subordinated to the Central Directorate of Land Management in 1907 (Dukhovny and Schutter 2011:109). This water department was responsible for the control of water management at the level of Turkestan Governor-General as of 1910. Later the colonial government developed the “Legislation system of water resources management in Turkestan,” which became the basis of developing the subsequent “Principles of water law in the former SU.”

2.6.3 *Water management under Soviet rule*

A decree “On the organization of irrigation work in Turkestan” issued by Lenin in May 1918 was the basis for large-scale expansion of irrigation to attain self-sufficiency in cotton production during the Soviet period (Weinthal 2002:72). Since the economy had fallen into a desperate state during the civil war and peasants had abandoned cotton production for grain to reduce the effects of famine,[3] several resolutions were adopted to incentivize producers for increased cotton cultivation through restoring the largely deteriorated irrigation system and offering credits to rebuild irrigation facilities. In contrast to the small-scale farming that existed in the pre-Soviet period where local authorities supervised water withdrawals, maintenance, and the cleaning of irrigation canals, large-scale farming through the establishment of collective farms were promoted during the 1930s. These changes in turn necessitated the centralized coordination of water distribution among multiple users with competing interests and mitigating potential conflicts over water quantity and quality (Weinthal 2002:90).

Although the organizational structure of water management institutions during the Soviet period was slightly different from the Tsarist structure, its scope widened to the entire SU (Mirzaev 2000). The Soviet structure of water distribution and use institutions was established at the end of 1950s along with the Ministry of Melioration and Water Management (*Minvodkhoz*). This institution governed the entire water fund within SU territory and determined the strategies for ameliorative and irrigation construction. Multiple scientific bodies and construction companies belonged to the

---

[1] Turkestan (or Turkestanski Krai in Russian) was the name of the Central Asian territory when governed by Tsarist Russia

[2] *aryk-aksakals* are officials appointed for regulating and monitoring water use along main irrigation canals, *mirabs* are elected by local community to manage water in the canal branches

[3] Dukhovny and Schutter (2011) indicated in the preface to their book that the Central Asian region had never experienced famines; however, famines were actually common due to production collapses as a result of political crises and wars, though land and water resources were always sufficiently abundant to feed the existing population in the region.

ministry, which ordered, developed, established and implemented projects, and distributed water resources on the basis of overall benefits to the entire SU. Regional and sub-regional branches of the ministry operated in each SU country and in their respective provinces. The main responsibilities of the regional branches were restricted to fulfilling orders from the central offices in Moscow.

Two important international agreements over river management between the SU and Afghanistan were signed on 13 June 1946[1] and on 18 January 1958.[2] The 1946 agreement concerned water diversions and runoff, and provided for the establishment of a joint commission (Nanny 1996). Under the 1958 treaty, the two states agreed to carry out joint measures to prevent water pollution, to exchange water level information, and to establish a flood warning system.

During the 1960's the policy treatise "Schemes of integrated use and protection of water resources in the Amu Darya and Syr Darya basins" was prepared, which describes the principles of water distribution among the riparian states and the development of new irrigation zones in Central Asia. Considering its negligible share of overall irrigated area and water diversions in the ASB, Afghanistan was not included in this general water development program despite the country's 20% share of the overall water resources in the Amu Darya basin. The recommendations of this document have been perpetuated until the present. Each country and irrigation zone had a fixed share (quota limit) of the total available water (Table 2.12). According to the water limits distribution, the share of Uzbekistan in total water withdrawals was the highest at about 40% and 50% from the Amu Darya and Syr Darya River basins respectively. These limits were determined based on existing land resources, cropland structure, crop water requirements, and the respective irrigation development plans of each zone (Nanni 1996). The actual volumes of water used were corrected regularly based on actual water availability.

Table 2.12 Water use limits (%) of the Central Asian countries in the Aral Sea Basin

	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Uzbekistan
Amu Darya	-	0.3	15.2	42.3	42.3
Syr Darya	42.0	0.5	7.0	-	50.5

Source: Dukhovny and Schutter (2011: 272–273)

Despite the centralized water management system's success in developing massive irrigation systems and hydrological management infrastructure, considering water needs of the ecosystems and maintaining appropriate environmental water flows were neglected. Instead, the ideology of *"conquering the nature"* was propagated (Sehring and Diebold 2012). As a consequence, environmental disasters such as the Aral Sea desiccation made this conventional development path unsustainable. Additionally, there was poor coordination among the different agencies of the central *MinVodKhoz* that had overlapping tasks. Furthermore, a lack of economic incentives to use water resources efficiently and absence of stakeholder participation, resulted in inconsistencies and

---

[1] Frontier Agreement Between Afghanistan and the Union of Soviet Socialist Republics, June 13, 1946, Afghanistan-USSR.

[2] Treaty Between The Government of the Union of Soviet Socialist Republics and the Royal Government of Afghanistan Concerning the Regime of the Soviet-Afghan State Frontier, January 18, 1958, Afghanistan-U.S.S.R.

water overuse (Sehring and Diebold 2012). Farmers (members of the collective farms-*kolkhozes*) did not have any incentives to use water more efficiently since they were rewarded only for meeting production targets (Weinthal 2002:93). Thus centralized water governance and state ownership of all water resources during the Soviet period was inefficient and unsustainable with respect to water use, leading to water wastage in irrigation systems and water scarcity in environmental water demand sites.

During the last period of the Soviet era in 1986, two river basin management organizations (the Basin Water Management Organizations (BVOs) of the Amu Darya and Syr Darya Rivers) were established to manage water resources within watershed boundaries instead of administrative boundaries and to make integrated decisions for the entire river basins. The establishment of Automatic Systems of Managing Basins (ASUBs) were also initially tasked to the BVOs, but could not be fulfilled. The BVOs were later tasked with organizing the distribution of interstate water resources and coordination of the hydrological management infrastructure (Mirzaev 2000). After the break-up of the SU none of the emerging CA countries favored BVO control of infrastructure located in their territories and only the responsibilities of the BVOs related to the regulation of water distribution in the Amu and Syr Darya basins were assumed by the newly independent states.

2.6.4 Water management institutions following independence

Parallel to the disintegration of the SU and the emergence of new independent states in Central Asia, new issues over water management surfaced that required new institutional settings to solve the problems associated with sharing water resources and the use of related infrastructure. In the beginning the need for cooperation on water management among the five Central Asian states was recognized and they agreed to establish the Interstate Commission for Water Management Coordination (ICWC) with the mandates: to determine and approve annual water withdrawal limits for each state, to approve the reservoir operation regimes, and to regulate rational use and protection of ASB water resources.[1] The two BVOs, Amu Darya and Syr Darya, were made subordinate to the ICWC. Together these organizations were responsible for water allocation plans, water quality control, and environmental protection in the ASB (Vinogradov and Langford 2001).

According to the agreement the rules of water allocation adopted during the Soviet period remained temporarily valid despite the fact that the five new republics had different interests regarding water resource use (Mirzaev 2000). Later some of the newly independent states noted that the historical water distribution rights did not consider their own needs for irrigation development and energy generation fairly, and decided to take greater control over the water resources formed within their respective territories rather than releasing these water resources for the benefit of the other ASB countries. Consequently, a new round of agreements took place between 1993 and 1995, and four other intergovernmental water management organizations were established for maintaining regional cooperation (Vinogradov and Langford 2001):

1) The Interstate Council on the ASB (ICAS), with the task of establishing water management policies and providing intersectoral water use coordination;
2) The Executive Committee of the ICAS (EC-ICAS), with the purpose of implementing the Aral Sea Program financed by the World Bank, the UNDP, and the UNEP;
3) The International Fund for Saving the Aral Sea (IFAS), with the purpose of coordinating financial resources provided by member countries and donors;

---

[1] Agreement on cooperation in joint management, use and protection of interstate sources of water resources, 18 February 1992, five Ministers of Water Resources of Central Asian states (N. Kipshakbayev, M. Zulpuyev, A. Nurov, A. Ilamanov, R. Giniyatullin) signed in Almaty.

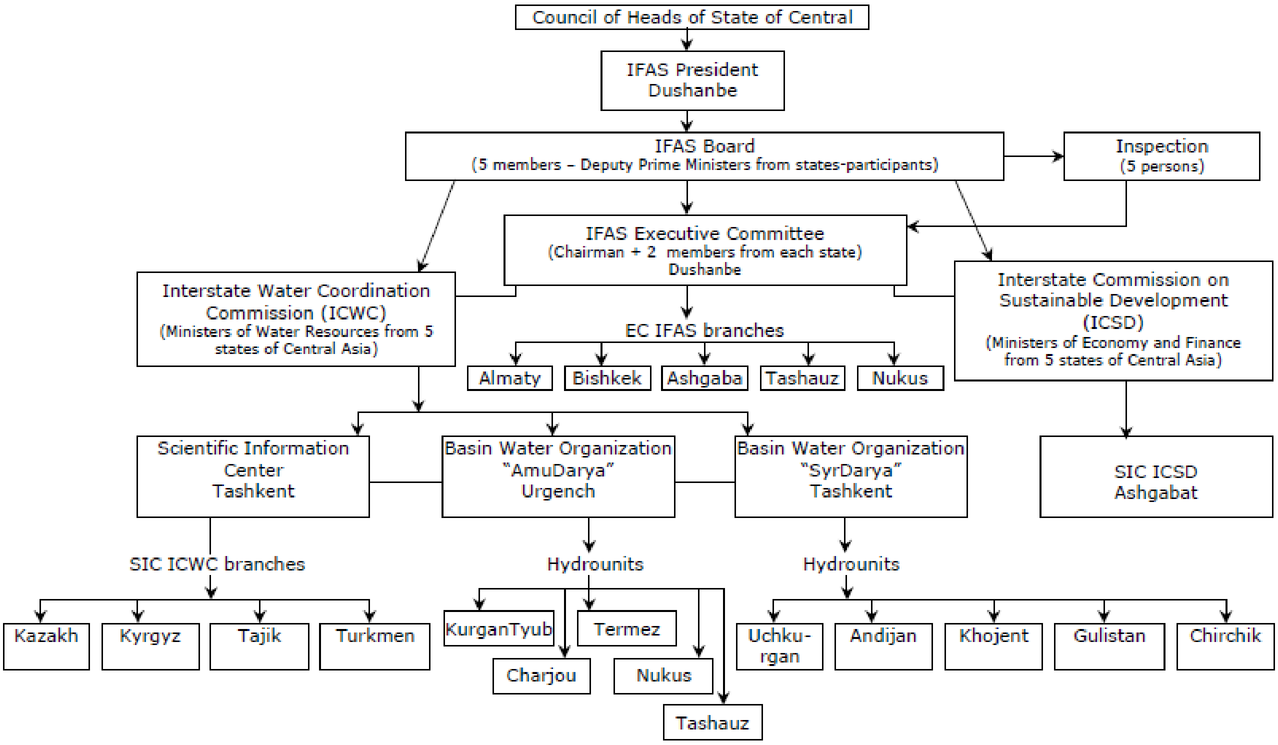
4) The Sustainable Development Commission (SDC), established to ensure equal importance of economic, social, and environmental factors in development decision making.

The “Agreement on Joint Activities for Addressing the Crisis of the Aral Sea and the Zone around the Sea, Improving the Environment and Ensuring the Social and Economic Development of the Aral Sea Region” was signed by representatives of the five Central Asian states on March 26, 1993. This document was adopted to maintain cooperative management of the water resources in the basin and to combine efforts to solve the Aral Sea desiccation crisis. The agreement set rules that established a minimal flow into the Aral Sea and the river deltas, and to prevent the discharge of municipal and industrial wastewater, agricultural return flows, and other pollution sources into the rivers (Nanni 1996).

Later in 1997 the new International Fund for the Aral Sea (IFAS) was established as the successor to the former ICAS and the previous structure of the IFAS (Figure 2.21). The IFAS is the highest political authority that is led by a board composed of five deputy prime ministers from each of the five member states, with portfolios comprising agriculture, industry, and the environment and its decisions are approved by the heads of the states (Vinogradov and Langford 2001). The board makes decisions on policies and proposals recommended by a permanent working body of the fund (Executive Committee of IFAS) in meetings that take place at least three times a year. While IFAS is responsible for policy and financial decisions, the ICWC and its organs function as the implementing agency (Vinogradov and Langford 2001). Specifically, ICWC controls compliance with the interstate agreements on water distribution, distributes annual water quotas (limits) to users and the Aral Sea, and develops measures to maintain water supply and distribution regimes.

One of the main activities of IFAS was to implement the Aral Sea Basin Program (ASBP; 1993–2002) as a joint action plan with the WB, UNDP, and UNEP. This plan proposed to maintain a sustainable environment in the ASB, restore the environmentally devastated zones adjacent to the sea, promote improved water management on the transboundary rivers, and maintain the capacity of the regional and local water management organizations responsible for the implementation of the plan (Sehring and Diebold 2012). In 2003, IFAS prepared a second phase of the ASBP (ASBP-II; 2011–2015). The second phase of the program included several economic development and environmental protection plans, such as: developing comprehensive water management mechanisms in the ASB, rehabilitating hydro-economic and irrigation facilities, improving environmental monitoring and flood management systems, combating desertification, promoting rational use of return flows, and maintaining cooperation among the riparian states to effectively implement the action plan (IFAS 2003). Although cooperation among the states to share common water, environmental, and infrastructural resources was partially reached in some years, failures in finding compromises were more common because of unilateral actions that neglected the interests of the other water users. Moreover, high dependence of IFAS on international funds and the irregularity of payments from the member countries did not allow to this organization to fulfill most of its initially planned tasks concerning improvements of the environmental and economic situations in the circum-Aral Sea region (Weinthal 2002:153). Currently a third phase of the program (ASBP-III; 2011–2015) approved in 2010 is an ongoing process; the primary objectives of the ASBP-III are to implement IWRM principles and develop mutually beneficial agreements on water use among the basin states in order to maintain sustainable socio-economic development in the ASB (Dukhovny and Schutter 2011).

Figure 2.21 Organizational structure of water resource management in the Aral Sea basin



Source: Sokolov and Dukhovny 2002

Considering the issues that arose over the reservoir regime of the Syr Darya basin, several agreements on the rational use of water and energy resources were adopted in late 1990s. The agreements, "On the use of water and energy resources of the Syr Darya basin," "On joint and complex use of water and energy resources of the Naryn Syr Darya cascade reservoirs," and "On cooperation in the area of environmental protection and rational utilization of natural resources," were signed by the governments of the Republic of Kazakhstan, the Kyrgyz Republic, and the Republic of Uzbekistan on 17 March 1998. These agreements provide the legal basis for cooperation of the CA states on water and energy resources in the ASB.

None of these agreements mentioned the maintenance of hydrological management infrastructure, the introduction of innovative water saving technologies, the exchange of information, and the coordination of joint activities in response to extreme events (Vinogradov and Langford 2001). Water problems were viewed from the perspective of water consumption (i.e., each member state attempted to increase its water use share, neglecting efficient water use), which resulted in a "*tragedy of the commons*" situation (UNEP 2005). Incentives for efficient water use under conditions of increasing water scarcity were not considered or discussed. Despite an agreement[1] among all Central Asian governments to consider the Aral Sea as an independent user and to guarantee at least some minimum inflow to the sea, river discharges have not often met stipulated volumes (UNEP 2005). Under conditions of increased drought risk, particularly in downstream reaches, the CA governments are challenged to develop more effective institutions, change the organizational structure of water management, and develop innovative water allocation mechanisms that provide incentives to water users for cooperation with one another for more efficient water use, ecosystem protection, and sustainable economic development.

---

[1] Agreement on joint activities for addressing the Aral Sea crisis and the surrounding zone, improving the environment, and ensuring the social and economic development in the Aral Sea basin, March 26, 1993.

2.7 Socio-economic and technical reasons of water allocation problems in the Aral Sea basin and potential solutions

2.7.1 Causes and consequences of the "Aral Sea syndrome"

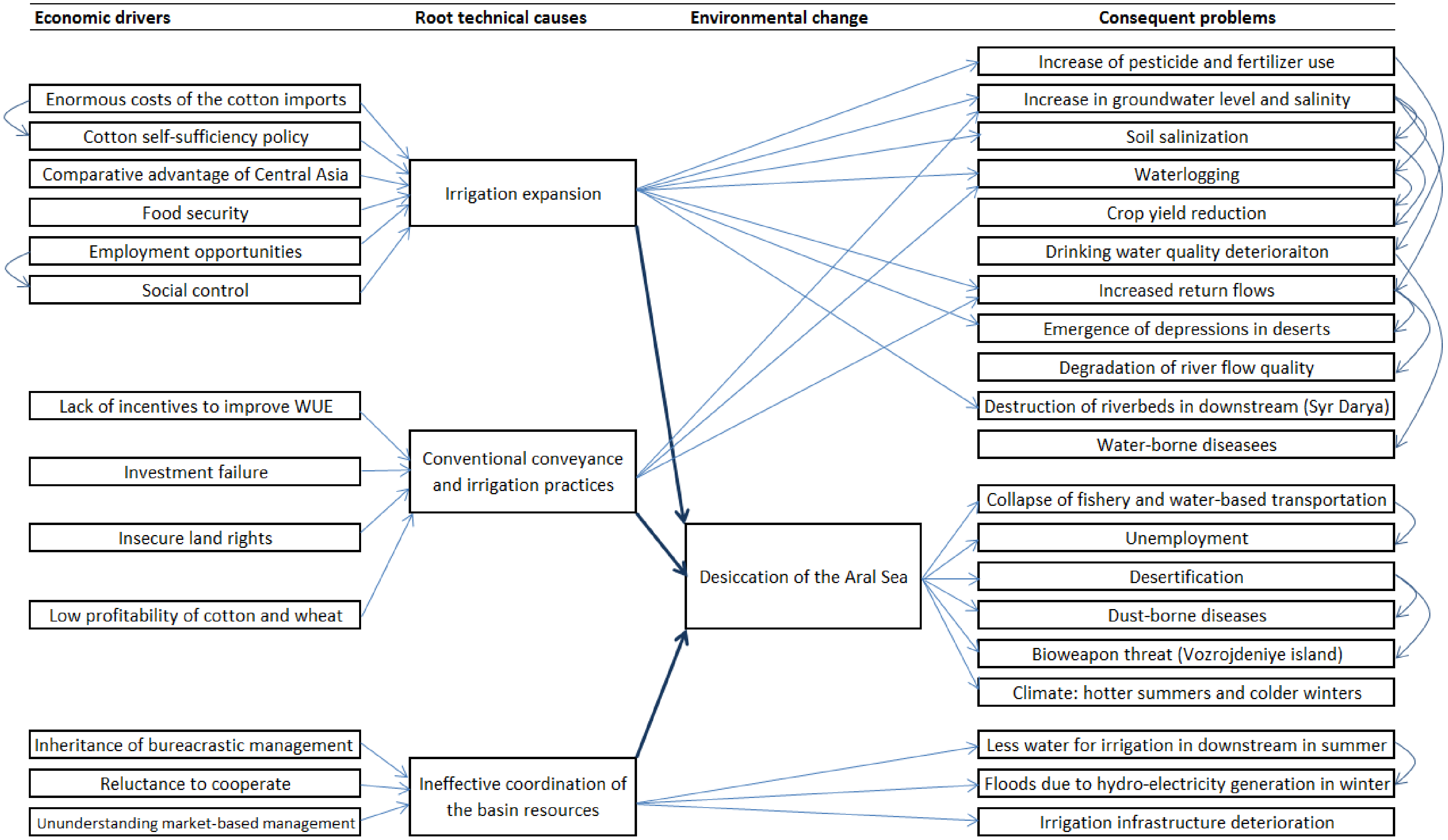
Based on the above discussion of socio-economic conditions, irrigation development, cropland patterns, water use and water management institutions, several water management problems in different parts of the ASB and at different levels of water management hierarchy can be implied. As all the water users within a single basin is interrelated to each other (Ringler 2003) problems related to water management in different parts of the basin are also correlated with one to another (Figure 2.22). Apparently, the most vivid consequence of inefficient water management in the ASB is the desiccation of the one of the largest lakes of the world - Aral Sea within short period. Irrigation expansion accompanied by the dominance of high water consuming crops and lack of the adoption of advanced irrigation technologies as well as ineffective coordination of water distribution at basin level were the root causes of this ecological catastrophe.

Since the Central Asian economies experienced a change from the centralized economic system towards market-based economy in the last decade of the 20th century, economic reasons of transformations in the water management system should be divided by two main periods: 1) changes under the administrative system before 1990s and 2) changes in transition period after 1991. Consequently, economic reasons for the emergence of the conditions for irrigation expansion before 1991 and for the continuation of inefficient water management practices even aftermath of 1991 should be also differentiated.

As noted earlier in this study, irrigation expansion in Central Asia was mainly driven by the increasing needs of the Soviet Union and its satellite states for cotton commodities in the last century. Political and economic costs of importing cotton from the US were extremely high. Meantime, Central Asia had very good climatic conditions, sufficient land and water resources, and cheap labor for growing cotton. Although land, water and labor resources were also abundant in eastern parts of Russia, cold temperature in these territories were not suitable to cultivate cotton. Irrigation expansion would also provide additional job opportunities and food supply in the densely populated region with high population growth rates. Damage costs incurred due to the cease of fish-processing plants and recreational cites located in the cities around the Sea such as Muynak and Aralsk were estimated lower than the benefits from irrigation expansion (Ashirbekov and Zonn 2003). Despite its huge environmental burden, high export revenues from raw cotton export and lack of technologies and skilled human resources to develop alternative production resulted in the continuation of cotton production practices even aftermath of independence.

Economic reasons for the dominance of inefficient conventional irrigation practices were mainly related to the lack of incentives to implement modern irrigation technologies. Water was not considered as scarce as now at the initial stages of irrigation expansion and thus there were no plans or incentives to use water efficiently. Considering environmental degradation which was serious after 1970s, the previous governments developed plans for irrigation modernization. However, since water delivered free of charge and the command-and-control based management was interested in only meeting production targets at whatever cost there were no incentives for farmers for efficient water use. The government started investing in improving irrigation infrastructure in late 1990s but these investments discontinued following the fall of the Soviet Union and consequent political and economic crisis. In early periods of independence, lack of sufficient investments in irrigation sector was a main reason of the accelerated deterioration of the infrastructure. Low incomes from state controlled cotton and wheat production and insecure land rights prevented the farmers to make any technological improvements. Water was not also charged sufficiently for giving incentives for more efficient use of water.

Figure 2.22 Causes and consequences of the Aral Sea desiccation



Source: author’s presentation

Currently, water prices based on volume have been introduced only in Kazakhstan and Kyrgyzstan. In contrast, agriculture is still heavily controlled by the government and water delivery costs are subsidized by governmental funds in Turkmenistan. Uzbekistan opted for a mediocre solution—the newly established Water User Associations (WUAs)—that only require payments from farmers to cover costs of local water management, but operation and maintenance costs of primary canals, pumping stations, reservoirs, and dams are not included in this water payment scheme (Bobojonov 2008). Charges that cover partial costs of water delivery through WUAs also exist in Tajikistan. Therefore, water use charges are only symbolic in these countries and water prices do not create sufficient incentives for the efficient use of water resources. Furthermore, funds collected through water use charges are not sufficient to improve water use efficiency.

Conflicting interests of five Central Asian countries complicated sharing common resources in the ASB. Coordination of the basin resources which was previously conducted by a unified water management system has been a hard task confronted by the water managers and policy makers of the region. Old mid-set based on administrative management principles, lack of understanding market-based principles of water management, and reluctance of the riparian countries for cooperation were main reasons for the failure of effective coordination of the common basin resources.

The root causes of the Aral Sea desiccation has also additional accompanied consequences which will be described here one-by-one. Irrigation expansion combined with inefficient water conveyance and application techniques resulted in huge water losses (Figure 2.22). These water losses have raised groundwater levels, which are highly polluted due to the seepage of agrochemicals and salt from cotton fields. High groundwater tables, in turn, caused waterlogging and salinization of irrigated lands, the degradation of drinking water quality, and accelerated the deterioration of rural and urban infrastructure. Waterlogging and soil salinization gradually decreased crop yields. For instance, over the period between 1976 and 1992 yields decreased in Karakalpakstan by 1.77 ton/ha for cereals, 0.98 ton/ha for cotton, 5.4 ton/ha for potato, 5.68 ton/ha for vegetables, 5.75 ton/ha for grapes, and 0.32 ton/ha for rice (Mirzaev and Khamraev 2000:361). Decreased quality of drinking water from wells due to the seepage of chemicals from the cotton fields also increased the number of water-borne illnesses such as typhoid, hepatitis A, and diarrheal diseases (Glantz 1999).

Because of high percolation losses during conveyance and irrigation, the volume of return flows has also increased and the greatest proportion of return flows end up in desert depressions at the tails of the irrigation zones, damaging natural landscapes (Chembarisov 1996, Mirzaev and Khamraev 2000). In 1990 the total area of these tail-end desert sinks reached 6,289 km^2 with a total water volume of about 51 km^3 or 1/6 of the total volume of the Aral Sea (Chembarisov 1996). Particularly in Turkmenistan, drainage water discharge into natural depressions resulted in the formation of about 275 lakes with the total combined area of 4,286 km^2 (Mansimov 1993), causing long-term flooding over 80,000 ha of formerly productive rangelands, periodical flooding of another 150,000 ha, and waterlogging of 2,300,000 ha (Babaev and Babaev 1994). Some of the return flows were released back in the rivers, consequently contaminating river flows and creating external costs to the downstream water users and the environment. It is estimated that the total drainage flow in the ASB accounts for 46–47 km^3, of which, 25–26 km^3 is discharged into rivers, 11–12 km^3 into lakes, and 14–15 km^3 into the desert (Levintanus 1992:63).

Diverting excessive amounts of water to irrigated lands in upstream and midstream sites decreases water flow to downstream reaches (Figure 2.22). This has become so severe that the riverbed in some parts of the lower reaches of the Syr Darya River has been replaced by buildings and crop. Some sections of the river in downstream has been blocked by several small dams to supply water to small lakes in the delta. Consequently, by the 1990s the river had practically lost its capacity to deliver floods and excess multiannual outflows from the reservoirs to the Aral Sea. For instance, in 1995, when winter-water releases from the Tokhtogul reservoir were excessive, 19 km^3 (50% of average annual flow of the Syr Darya) water was wastefully discharged into the Arnasay depression due to the impossibility of conveying water to the Aral Sea through the narrow and frozen downstream riverbed (Mirzaev and Khamraev 2000:360). Increased water levels in the depression in turn destroyed the landscape surrounding the lake aggravating environmental problems.

The desiccation of the sea as a result of irrigation expansion and unproductive use of water caused the collapse of the fishing industry and water-based transportation in the lower reaches of the Amu Darya, increasing unemployment in the circum-Aral region (Figure 2.22). The reduction of river flows into deltaic zones decreased the area of *tugai* forests[1] from 1,000,000 ha in 1950 to only 20–30,000 ha in 2000 (Micklin 2007) and damaged habitats for a diverse array of animals, including 60 species of mammals, about 3,000 species of birds, and 20 species of amphibians (Micklin 2010). In addition, storms blow toxic salts and dust from the dried seabed onto the surrounding irrigated areas, water bodies, and pastures, increasing soil salinization and further degrading natural ecosystems (Micklin 2010). Airborne salt and dust are the main factors associated with the increased frequency of a host of health issues in the circum-Aral region including illnesses of the respiratory organs, eye problems, and cancers of the throat and esophagus (Micklin 2007).

Due to changes in regional humidity, climatic conditions have also changed significantly, causing hotter summers and longer and colder winters in the circum-Aral region (Micklin 2010). In result, the annual growing season was shortened by 10 to 15 days (Mirzaev and Khamraev 2000). Annual precipitation has decreased. Additionally, desiccation of the Aral Sea and the complete exposure of the seabed unified Vozrozhdeniya Island with the mainland increasing the threat of exposure to biological weapons (Micklin 2007). Since Vozrozhdeniya Island was once an experimental site of the Soviet military for the development of secret biological weapons it is commonly feared that harmful organisms could have survived the decontamination measures and now more easily disperse to the mainland via infected terrestrial animals (Micklin 2007).

The Aral Sea shrinkage and related problems were aggravated by ineffective coordination of basin resources after the emergence of five independent Central Asian countries with contradictory purposes following the disintegration of the SU (Figure 2.22). On one hand, the collapse of the union provided important opportunities for the new Central Asian states to restore their sovereignty over the use of natural and capital resources within their territories (Dukhovny 2007, Dukhovny and Schutter 2011). On the other hand, the disappearance of a centralized government eliminated federal financial support and the previous socio-economic organization and production systems that tied Central Asia with the remaining Soviet countries.

Under the centralized management system, a comprehensive energy production and delivery grid was developed that provided a stable energy supply throughout the basin. This energy production and supply system allowed mutual compensation mechanisms among the hydroelectric power stations of Kyrgyzstan and Tajikistan, and the fossil-fuel power stations of Kazakhstan, Turkmenistan, and Uzbekistan. The emergence of five Central Asian countries with different interests after the disintegration of the SU in 1991 raised the issues of sharing common water resources and related infrastructural facilities in the basin. The limited availability of water resources, in contrast to its necessary role in the maintenance and development of the Central Asian economies, increased competition among these countries over common water resources. Conflicts

---

[1] *Tugai* is the name for riparian forests that emerge in the arid steppes and lowlands of Central Asia that are periodically inundated by floodwater. Euphratic poplar (*Populus euphratica*) is the dominant tree specy of tugai forests (Schlüter et al. 2006).

of interest between the irrigated agriculture and hydroelectric power generation sectors and the resulting change in the reservoir operation mode by prioritizing energy production have reduced water availability to downstream countries and environmental needs.

After the collapse of the SU determining property rights to the hydroelectric and other power generation infrastructure that wound up within the borders of the new states also became a problem. Currently the locations of 12 rivers, eight water reservoirs, 16 primary collectors, eight hydroelectric power stations and more than 60 small rivers and irrigation canals are shared between two or three countries (Medvedov no date). Sharing the operational costs of transboundary infrastructural facilities and regulating them to satisfy the interests of all of the ASB states is an elusive task. Because of the shortages of financial support for the rehabilitation, routine operations, and maintenance of water infrastructure, their functionality and efficiency have gradually decreased.

Since the reservoirs in the ASB were built to supply irrigation needs to downstream reaches, the changes to the seasonal reservoir storage regime and winter water releases for hydroelectric power generation have increased downstream flooding risks (Mirzaev and Khamraev 2000). In November to January 2003–2004, winter floods destroyed water control structures and damaged some settlements in the Kyzylorda region of Kazakhstan (UNEP 2005) and more than 2,000 people evacuated and more than 55,000 ha were flooded, causing $2.4 million USD worth of damages (Dukhovny and Schutter 2011). Flooding occurred again in 2005 and caused in excess of $7.2 million USD of damages (Dukhovny and Schutter 2011:290). Only after 2005 with the support of the World Bank, the Kazakhstan government initiated complex measures to improve the conveyance capacity of the Syr Darya riverbed located between the Aral Sea and Shardara reservoir, and to restore partially the northern part of the Aral Sea (the Small Aral Sea).

In order to prevent the inflows of the Syr Darya into the southern part of the Aral Sea (the Large Aral Sea), where it was lost by evaporation, the government constructed the 13 km-long Kok-Aral dike to replace previous dikes (Aladin et al. 2006, Sehring and Diebold 2012). The previous dikes made of local sand were washed away because of the water level rise in the Small Aral Sea. As part of the project, Aklak and Aitek weirs were rehabilitated to increase the conveyance capacity of the riverbed and reduce the risk of flooding in the lower reaches of the Syr Darya River. As a result, in the last five years water levels in the Small Aral Sea rose by 2 m and the surface of the watershed increased by 18% (Sehring and Diebold 2012). Furthermore, water salinity decreased, and fish production and harvesting improved, positively influencing the living standards of residents adjacent to the Small Aral Sea (including the city of Aralsk with a population of over 30,000). On the other hand, despite frequent flooding and excess water supply in downstream reaches during the winter and improved environmental conditions in the Small Aral Sea, farmers face severe water scarcity during the summer and irrigation areas are decreasing in the southern parts of Kazakhstan. Despite the rise of Small Aral Sea levels inspired hope for the improvement of the situation in the southern Large Aral Sea, in reality the construction of the dike disconnecting the two seas accelerated the shrinkage of the Large Aral Sea. Recently launched campaigns by Uzbekistan (Uzbekneftigas), Russia (Lukoil), China (CSEC), Malaysia (Petronas), and South Korea (KNOS) to excavate oil and gas on the dried seabed could also decrease desire of decision makers to increase water inflow and restore the Large Aral Sea (Aladin et al. 2006, Dukhovny and Schutter 2011:361).

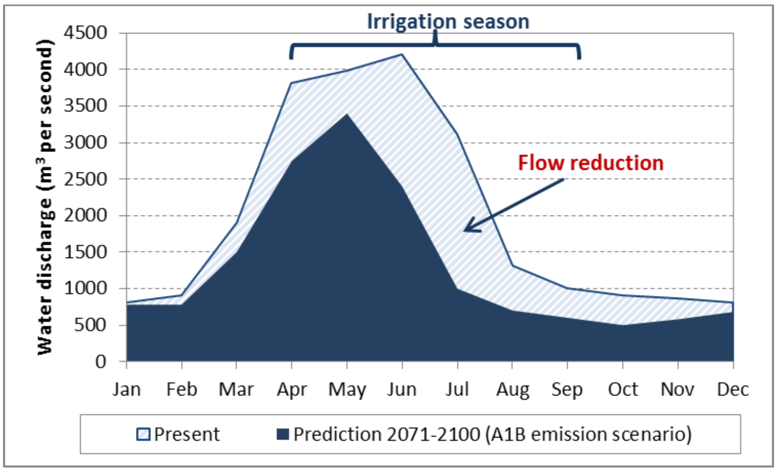
2.7.2 Perspectives of water availability and use in the Aral Sea basin

Although future water use and tensions over water resources are not entirely predictable, expectations for the future are not favorable for the improvement of the regional situation. As noted earlier *"the potential for conflict over the use of natural resources* nowhere in the world is as *strong as in Central Asia”* (Smith 1995:351). Despite many current environmental and water sharing problems, the intentions of the ASB countries are to develop even greater water diversion capacity from the rivers. As mentioned above, all countries except Kazakhstan have plans to increase the amount of irrigated lands to provide for the demands of growing populations (Medvedov no date, Antonov 1996, Sarbaev 1996, Shodiev 1996, O’Hara 1999, Antonov 2000). Kyrgyzstan and Tajikistan are particularly interested in building additional dams and in extending the capacity of existing reservoirs to increase hydroelectric production and export capacity. If the current Afghan government is successful in establishing a peaceful and functional nation-state in that country, it will likely want to develop its agrarian sector and thus may claim greater water rights. The construction of the Golden Century Lake in the Karakum desert of Turkmenistan in order to further re-use return flows to irrigate desert lands would also cause increased water diversions from the rivers, as has happened in the case of Sarykamish Lake which was built for a similar purpose.

At present the Karakum canal, which was the longest and largest canal in the territory of the former SU with a length of about 1,400 km and annual water discharge of 10–12 km^3, is already a vivid example of wasteful water use in Turkmenistan (Wegerich 2010). This open and unlined canal was constructed in 1950s following the Stalin’s proclamation of *“Man’s Conquest of Nature”* (Sehring and Diebold 2012). It delivers water through the Karakum desert to the capital city Ashkhabad and other main rural settlements along with the irrigated areas of Turkmenistan. Due to enormous losses of precious water resources to the sands of the Karakum, the operation of this waterway substantially contributes to the Aral Sea desiccation. Despite these facts the Turkmen government intends to further extend this canal.

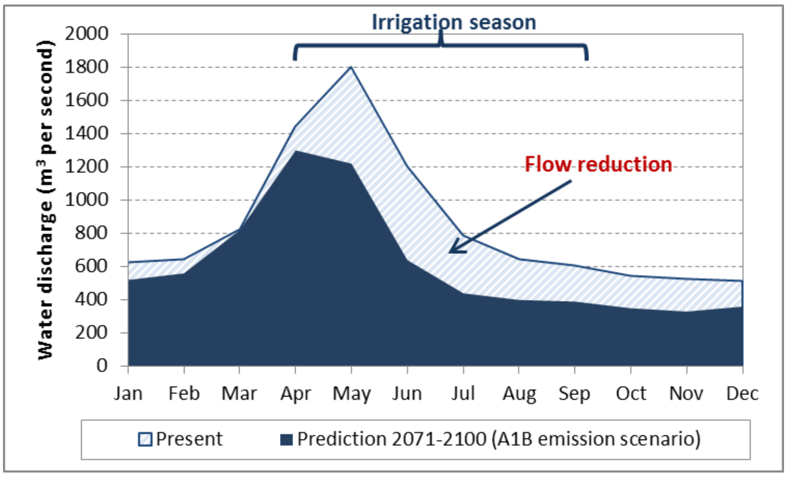
Natural levels of river runoff are expected to decrease due to global warming and particularly by the diminishment of the glaciers in the water accumulation zones of Central Asia, exacerbating existing water conflicts (Chub 2007, IPCC 2007, Savitsky et al. 2007, Dukhovny et al. 2008). Since the 1950s, 14–30% of the glaciers in Tian Shan and Pamir have been lost and continue to disappear at an annual rate of 0.2–1% (Sehring and Diebold 2012). Glacial melting in turn may increase river volumes in the short run, but decreases glacial mass and thus the long-term availability of water resources (Chub 2002). By the year 2050, it is predicted that river flow in the tributaries of the Amu Darya basin may decrease by 10–15%, while in the Syr Darya basin by 6–10% (Chub 2007:101). Water availability, particularly during the growing season, is expected to decrease more than during the non-growing season (Sehring and Diebold 2012; Figure 2.23 and Figure 2.24). Moreover, due to temperature increases plants would require more water to maintain productivity, increasing water demands even more in the midstream and downstream reaches (Dukhovny et al. 2008). Evaporation of rivers and other water bodies would accelerate further desertification and desiccation of the Aral Sea (Dukhovny and Schutter 2011). In order to deal with current and future water scarcity and thus prevent potential conflicts over water use rights, the timely implementation of appropriate technical, economic and institutional measures for efficient utilization of water resources is of utmost importance.

Figure 2.23 Average seasonal flow of the Amu Darya river (at the Kerki gauging station)



Source: Shiklomanov 2009

Figure 2.24 Average seasonal flow of the Syr Darya river (at the Tumen-Aryk gauging station)



Source: Shiklomanov 2009

2.7.3 Potential solutions to reduce water demand and save the Aral Sea

Several approaches have been suggested to either partially or entirely solve the Aral Sea desiccation problem. Though the unwanted ecological consequences of the Aral Sea desiccation became recognized as early as the 1970s, the problem of the Aral Sea desiccation became widely known to the public only in the mid-1980s, during the *glasnost*[1] period of Gorbachev (Weinthal 2002). Initial attempts to solve the intensifying environmental problem began with the establishment of the "Government Commission on the Development of Measures for Maintaining Ecological Sustainability in the Circum-Aral Sea Region" in the late 1980s. The commission organized a contest for the best solutions for restoring the Aral Sea and prepared a "Concept of Conservation and Restoration of the Aral Sea and Improving Ecological, Sanitary, Medical,

---

[1] A policy that called for openness and transparency in politics by permitting public discussion of government activities and freer dissemination of information.

Biological, and Socio-Economic Conditions in the Circum-Aral Sea Region" based on the results of the contest (Weinthal 2002:112). Attempts to improve the conditions in the ASB were continued with the support of international donors in the post-Soviet period (Weinthal 2002:152).

Generally, the options to combat water scarcity issues in the ASB can be grouped into one of two categories. One category of measures attempt to increase water supply, which involves activities to locate, develop, or exploit new water sources. The other category of measures involves mechanisms and incentives for water demand reduction through improving water use efficiency.

Supply management options primarily focus on water transfers from the other river basins to compensate for water scarcity in the ASB and to restore the Aral Sea. The delivery of water from outside Central Asia is technically feasible. In the 1980s water managers from Moscow and Central Asia proposed to divert up to 60 km^3 water from the Ob and Irtish rivers in Siberia to the basin as a panacea to water shortage issues (Micklin 2010). Although implementation of this project began with a plan to divert about 27 km^3 water at the initial stage, it was soon stopped by order of Gorbachev in 1986 due to possible ecological threats and the enormous investment costs of this large-scale project. There are still some supporters of this proposal, despite the fact that the realization of the project would cost at least $40 billion USD even without the enormous political costs that would be incurred due to increased dependence of the Central Asian states on Russia. Moreover even if the project was implemented as planned, less than 15 km^3 would actually reach the Aral Sea due to losses during conveyance (Micklin 2010).

Another proposal is water transfer from the Indus and Ganges rivers to the Amu Darya river (Khamraev 1996a, Khamraev 1996b, Zonn et al. 2009) through the establishment of a Arabian Aral Water Transportation Route (AAWTR). This scheme is a part of larger program of establishing a United Asian Water Management System (UAWMS), which proposes the unification of a hydrographic set of the ASB watershed with the rivers (Ob and Irtish) of the Kara Sea basin in the north and with the rivers of the Arabian Sea in the south (Khamraev 1996a). This grandiose project would not only divert water to the Aral Sea, but also develop a Central Asian-South Asian transportation corridor that would provide access to the world's oceans for the landlocked Central Asian states. However, institutional and political costs of this projection would be even costlier than the proposed Siberian water transfer project since its implementation would require agreements and cooperation among several states, including: Iran, Afghanistan, India, Pakistan, the Central Asian states, and some Arabian countries. Given growing water scarcity in the Indus and Ganges, it would be highly unlikely that either India or Pakistan would agree to such transfers (Claudia Ringler, personal communication 2012).

A more practical proposal, although with much less potential in terms of water delivery volume and still costly, would be a diversion from the Zaysan Lake of Kazakhstan to the Syr Darya (Micklin 2010). The feasibility of getting this project implemented is higher compared to the other proposals because its costs would be lower due to the relatively shorter water transfer route and the fact that water would flow by gravity to its destination in the Syr Darya. However, building a large diameter tunnel through 100 km of mountains would be quite costly. Moreover, removing water from the lake would expose several kilometers of the bed of the Irtish River, with negative impacts on the environment and ceasing hydroelectric power generation at the Buhtarma dam (Micklin 2010).

There was also a proposal to mitigate the negative impacts of the Aral Sea desiccation by diverting water from the Caspian Sea (UNESCO 2000). Like the other proposed solutions this measure would require a huge technical and financial effort to construct a canal between the two seas and gigantic pumping stations with high energy demands for lifting the water. The expected economic and environmental performance of this proposed inter-sea water transfer project is dubious. The water of the Caspian Sea is very saline and would not allow the restoration of the fishery in the

Aral Sea. In addition, the realization of this project may have additional negative impacts on the already deteriorated ecological conditions of the Caspian Sea.

Since the implementation of inter-basin water transfer schemes would incur enormous costs and may further raise already high groundwater levels in the ASB, it would be more rational to use the capital resources and efforts to improve the productivity of water resources already available within the basin rather than importing more water from other areas (Micklin 2010). For example, considering the fact that huge amounts of return flows are evaporating in the multiple desert depressions scattered at the tail ends of irrigation zones within the basin, one potential solution would be the diversion of these flows back to the Aral Sea via a system of canals running parallel to the rivers (Chembarisov 1996). However, some authors (Morozov n.d., Mirzaev and Khamraev 2000) have criticized this proposal stating that because of the high salinity levels of these returning flows, the sea would become a hazardous waste water sink that would be unsuitable for animal and plant life. Moreover, this and all the other proposals discussed above are designed to alleviate the consequences of the problems in the basin rather than focusing on resolving the root causes of the problem. From a water supply management perspective, more viable measures are augmenting water availability by building additional small reservoirs, improving irrigation networks, and increasing rain catchment capacity by expanding rainfed lands (Khamraev 1998). However, the implementation costs of these supply-oriented proposals would also be prohibitive.

Considering the high investment costs of water supply enhancement and the currently poor economic conditions of the Central Asian states (World Bank 1992), water demand management measures are more likely to be economically feasible than water supply management measures in order to reduce current water consumption and increase water availability for environmental flows. Higher water use per capita and per hectare in Central Asia than water use rates in the dryland regions such as Spain, Pakistan, Turkey, Mexico, North African countries and Middle Eastern countries (Varis and Rakhamanan 2008) also indicates the essentiality of reducing water demand rather than augmenting water supply.

Water demand management measures focus on obtaining more production gains or benefits per unit of available water (GEF 2003), which can be achieved through introducing water saving technologies (Bekchanov et al. 2010), replacing water intensive crops with the crops that use less water (Bobojonov et al. 2013), and developing low water consuming production activities. Water saving technologies such as drip and sprinkler irrigation, and laser guided land leveling allow to use of less water to obtain the same or higher yields. The introduction of high efficiency irrigation technologies would not only decrease demand in the field, but also demand at water diversion nodes and thus would reduce the conveyance and pumping costs. Cultivating crops with lower water requirements such as vegetables, fruits, and sunflower instead of rice and cotton permit substantial reductions in overall water use. Developing industrial and services sectors instead of relying on irrigated agriculture may also allow substantial reductions in water demand while providing higher income levels.

Decreasing water overuse due to inefficient water management institutions is another option to reduce water demand and increase water productivity. Water overuse can be prevented by enforcing water use quotas (limits) or charging fees for water use (GEF 2003). Enforcing water use and return flow quotas limit water withdrawals, making it sufficient to meet original demand. However, based on the low effectiveness of administrative and bureaucratic mechanisms and high costs of control, this option is limited to influence on the attitude of water users. Alternatively, water pricing would incentivize water users to use water more carefully as they do not want excessive payments for water services and thus try to use only abundant water for their needs. Treating water as an economic good would also signal the value of the resource and foster broader implementation of water saving technologies.

2.7.4 Investment costs of restoring the Aral Sea

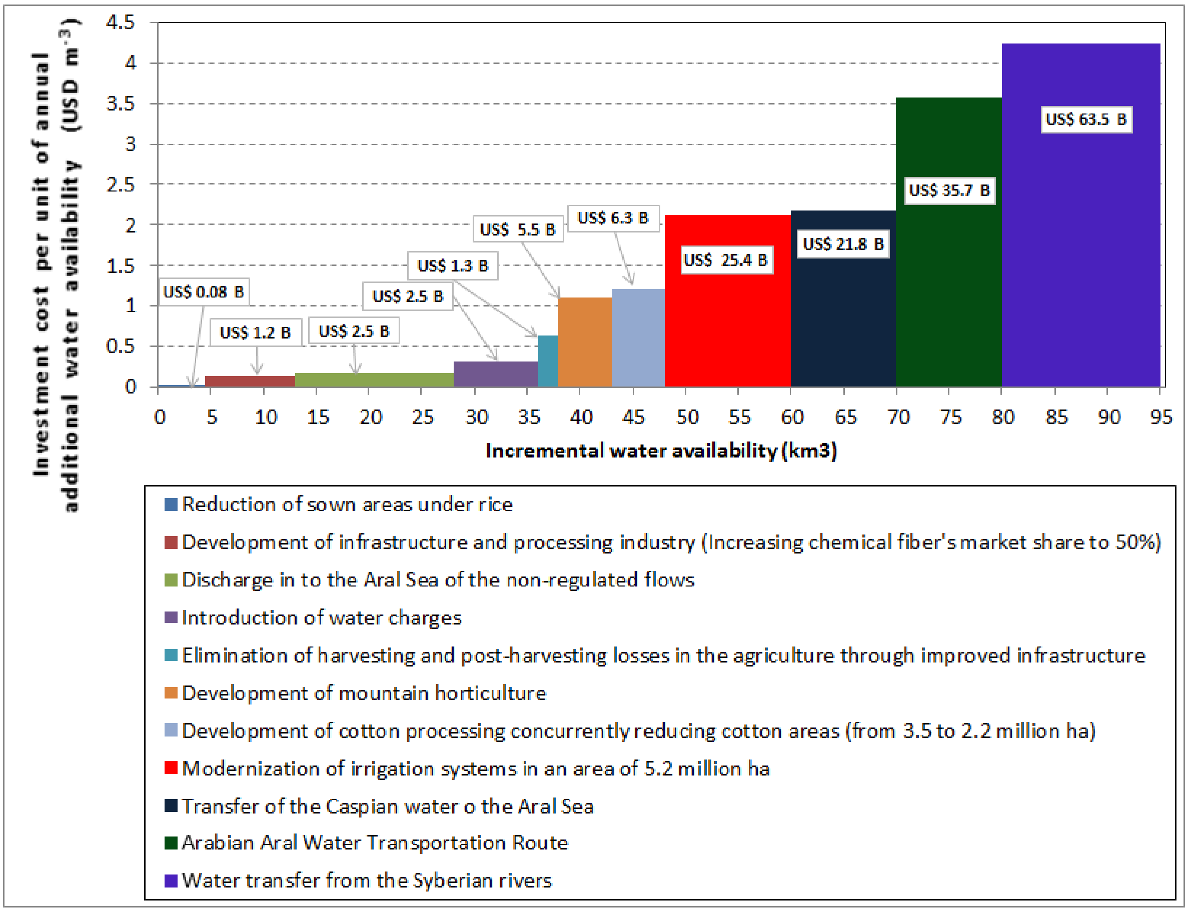
Since there are several solutions that can enhance the restoration of the Sea one must conceptualize the options based on some criteria. Despite technical feasibility of these options their practical implementation has been less successful due to unpredictable environmental and political risks and mainly due to their enormous financial costs. Therefore, the investment costs of different options were compared to assess their financial viability based on McKinsey marginal cost curve (Addams et al 2009) which will be described in the following. Different measures were ranked according to the ratio of their average investment requirement to the potential amount of water they would make available to the Aral Sea (Figure 2.25). Data on investment costs and improved water availability under each option were obtained from relevant studies (Levintanus 1992, Khamraev 1996a, Micklin 2010, Badescu and Cathcart 2011). Since some of these studies were conducted before 1990s and some in more recent years investment values were presented at the prices of different years. Considering inflation rates, the investment levels at the prices of different years were re-estimated at the price levels of 2006.

The ranking of the investment options showed that restricting rice production is the least costly measure of reducing water demand (Figure 2.25). Due to the high water consumption needs of rice (which are 5–6 time greater than cotton), reducing rice production areas by 150–200,000 ha would decrease water need for at least 4–5 km^3 annually (Levintanus 1992). The reduction in rice production could be compensated for by imports from countries with abundant water supplies at a cost of about $80 million USD (estimated originally at 1990 price levels but converted to the price levels of 2006 considering the inflation rate; Levintanus 1992). The second best option would be reducing cotton fiber production while increasing the share of chemical fiber production by 50% (Levintanus 1992). This option would require a total investment of $1.2 billion USD (Levintanus 1992). Diverting drainage flows from desert sinks is another option that would return 15 km^3 of water to the Aral Sea at a cost of about $2.5 billion USD (Levintanus 1992). The introduction of water payments that require the installation and operation of water measurement equipments at an investment cost of around $2.5 billion USD would reduce water demand by 8 km^3 (Levintanus 1992). Upgrading agricultural supply chains by improving the infrastructure for after-harvest transportation, storage, and processing would require investing $1.3 billion USD and would eliminate production losses and reduce water demand by 2 km^3 (Levintanus 1992). Investing $5.5 billion USD in afforestation efforts and the development of mountain horticulture could augment runoff by 5 km^3 (Khamraev 1996a). Investing $6.3 billion USD in the development of cotton-processing industries while reducing cotton production areas would decrease water demand by 5.2 km^3 (Levintanus 1992). Last but not least, modernization of existing irrigation systems over 5.2 million ha of irrigated lands at an investment cost of about $25.4 billion USD (16 billion USD in 1990 prices) could reduce water use requirements by 12 km^3 (Micklin 2010).

More than 35 km^3 of additional water would be available only with the investment costs of less than $6.5 billion USD. Implementation of all of the proposed water demand management measures would reduce water use by about 60 km^3 at an investment cost of less than $45 billion USD. Meantime, the investment costs of the water supply management measures are much higher than those of demand management measures. Water supply management options through water diversion from the other rivers and seas such as the Caspean Sea (Badescu and Cathcart 2011), the Indus rivers (Khamraev 1996a), and the Siberian rivers (Micklin 2010) to refill the Aral Sea would require investment costs of more than $121 billion USD and provide about 35 km^3 of additional water for the environment.

An annual inflow of 53 km^3 is required to restore the Aral Sea to its pre-1960 level in 50-60 years, and an annual inflow of 35 km^3 is enough to stabilize the sea level at 40–41 m as observed in 1985 (Micklin 1992). Therefore, water demand management measures alone can effectively deal with water scarcity problems in the ASB without water transfers from the outside basins that require exorbitant investment costs.

Figure 2.25 Investment costs of incremental water supply to the Aral Sea (at 2006 price levels) based on McKinsey abatement cost curve



Note: Numbers in the white text boxes represent the total required capital investment costs, B = billions. The costs at the price level of 1990 were inflated by factor of 1.58 to evaluate the costs in prices of 2006.
Source: Based on the techno-economic review and summary papers of Levintanus (1992), Khamraev (1996a), Micklin (2010), and Badescu and Cathcart (2011) on restoring the Aral Sea

2.7.5 Implications for dealing with scarcity of water for irrigation and environment needs

Although many corrective measures for the Aral Sea problem have become known in the 1980s, several political, institutional, and technological barriers in addition to financial hurdles prevented their implementation. Summarizing the points discussed above, the main causes of the water scarcity problems in the ASB, the constraints on implementation of appropriate water management measures, and the caveats in the reforms (or the reasons for the failure of the efforts) will be described in the following (Table 2.13).

The primary constraints on the implementation of improved water management options were the scarcity of financial resources, the lack of incentives for efficient water use, a traditional mindset based on expectations of the initiatives and orders from a central authority, and reluctance for cooperative management of common basin resources. High investment costs combined with enormous environmental and political risks prevented the construction of massive water transfer schemes and the implementation of other water supply augmentation measures. Despite higher financial feasibility and substantial contribution to environmental water availability, wide implementation of measures of water demand reduction did not take place because of the lack of incentives for efficient water use under the centralized water management system based on command-and-control principles.

In the aftermath of independence, ASB countries attempted to establish decentralized water management institutions through formal changes in legislation, but only with limited success. Since the bureaucratic water management system could not provide meaningful incentives to use water efficiently but was still perpetuated to the present days, visible positive changes in the Aral Sea level and improvements in environmental conditions in the circum-Aral Sea region remained negligible. Incentives can be effective means for improving compliance with rules designed to contribute to the broader good (Easterly 2001). Lansdburg (1993) put it more concisely by saying that, "*people respond to incentives; all the rest is commentary.*" Therefore, establishing more decentralized water management institutions that can create incentives for water users to increase water use efficiency and productivity is essential for the success of any project concerned with the water issues in the ASB. Furthermore, the interdependence of all water uses and production activities, and the importance of preserving the basin ecosystems for all regional stakeholders necessitate cooperation in sharing the costs and benefits of using scarce resources rather than individualistic approaches to water use by each country through neglect of the interests of neighboring states. Any self-serving attempts by one of the ASB countries to improve their own water access at the neglect of the interests of the others may cause conflicts and provoke countermeasures that may harm that country. To avoid tensions and mistrust among the ASB countries, workable and reliable mechanisms that incentivize cooperation on efficient water allocation need to be developed.

Some projects to improve environmental situations such as reforestation of the dried seabed of the Aral Sea and constructing channels along the rivers to divert return flows to the sea were initiated, but did not provide the expected results. These projects were not much successful since they only addressed the consequences (symptoms) of the Aral Sea desiccation but ignored the root causes of the problem. For example, the projects that focused on afforestation of the seabed aimed at reducing the impacts of windborne spread of the salts and dust (Morozov n.d.). The established forest would demand a continuous water supply, especially during the summer months, which could be possible through the cooperation and agreement of the all riparian regions. The other project intended to divert return flows back into the sea through canals running parallel to the rivers which was started but ultimately was not completed. Refilling the Aral Sea with highly saline return waters and investing scarce financial resources in excavating the canals, pumping water, and conveyance would not provide sufficient benefit since quality of water would limit the restoration of the animal and plant life in the Aral Sea and its delta. Thus, the policies of improving environmental sustainability and water use efficiency should first address the root causes of the Aral Sea desiccation to effectively cope with environmental degradation. From this perspective, sectoral transformation by prioritizing sectors with higher economic growth potential but less water demand, instead of currently dominant cotton cultivation, and changing command-and-control based water management institutions to more liberal and decentralized water allocation institutions that can create incentives for cooperation in water use are more promising. Considering very low efficiencies of irrigation systems a huge potential for hydropower production in the ASB, improvements of irrigation and conveyance efficiency through the implementation of modern technologies and infrastructural developments for better coordination of the basin resources may also enhance efficient water use. These three options and their roles in efficient water use will be analyzed in detail in the chapters that describe the empirical results.

Table 2.13 Causes of water problems, constraints to improve water use efficiency, and the caveats in water reforms in the Aral Sea basin

	Causes of decreasing water use efficiency, increasing water scarcity and worsening environmental conditions		Constraints to the adoption of the prevention/improvement measures		Caveats led to the failure of the attempts to change	
	Causes	Relevance[a)]	Constraints	Relevance[a)]	Caveats	Relevance[a)]
Socio-economic	• Population growth • Industrial development • Irrigation expansion • Inadequate investments in technological improvements • Dominance of water intensive production activities	+ + +++ +++ +++	• Low financial capability of the farmers/governments • High implementation and maintenance costs	++ +++	• Unseen costs • Lower benefits than expected • Discontinuation of donor support	+ + ++
Environmental	• Climate change • Water pollution • Groundwater depletion • Land salinization	+ + 0 ++	• Irrelevance to the local conditions	0		
Technical	• Deterioration of the irrigation infrastructure	+++			• Neglecting the root causes, focus on the symptoms of the problem	+++
Technological (Knowledge)	• Lack of environmental consciousness	+	• Lack of technologies • Lack of experts	--- --		
Institutional	• The 'command-and-control' based system	+++	• Lack of incentives • Traditional mindset • Religious perceptions	+++ +++ +	• Inefficient coordination	+++
Political	• Inter-state conflicts over sharing water and infrastructural resources	+++	• Lack of cooperation • The role of cotton in social control	+++ +		

Notes: [a)] Very weak - “---“; Weak – “--”; Fairly weak – “-”; Neutral – “0”; Fairly strong – “+”; Strong – “++”; Very strong – “+++”

3 SECTORAL TRANSFORMATION OPTIONS FOR SUSTAINABLE DEVELOPEMENT IN THE ARAL SEA BASIN: THE CASE OF UZBEKISTAN[1]

3.1 Introduction

This chapter describes potential sectoral transformation options for sustainable growth to address the issues of overdependence on irrigated agriculture, particularly lingered dominance of cotton in crop cultivation, which is one of the root causes of Aral Sea desiccation. Due to the lack of appropriate data for the rest of the ASB, only the case of Uzbekistan is illustrated in this chapter. Nevertheless, considering the similarity of environmental and economic conditions throughout the whole ASB and the facts that Uzbekistan accounts for more than half of both the irrigated croplands, and the population in the basin, the country is representative of the rest of the ASB.

Hard-cash revenues from the exports of cotton is a main reason for the continuation of water intensive cotton production practices even aftermath of independence in Uzbekistan (Box 3.1). Using input-output model in combination with multi-criteria assessment methods alternative production activities that has higher economic growth impact but less water requirement in contrast to cotton are analyzed in this chapter.

After the review of literature on the role of sectoral transformations in both international and the study area contexts and justification of the research needs, the methods used for the empirical analysis of potential sectoral transformation options are demonstrated. Next section illustrates the results of (i) ranking economic sectors to determine relevant options for sustainable sectoral transformation according to economic growth potential and total (direct plus indirect) water use by each sector. First, intersectoral relationships of the Uzbek economy based on IO model calculations are discussed. Intersectoral economic and water use linkage indexes are also demonstrated. Then, the results of the rankings of sectors according to the linkage indexes and water use levels are presented. Final section includes a detailed discussion of the results and conclusions.

3.2 Modeling the role of structural transformations for sustainable development: literature review

3.2.1 Sectoral transformations as an engine for growth: international perspective

As previously postulated in the three-sector hypothesis, the sectoral structure of an economy plays a pivotal role in economic development (Clark 1940, Fourastie 1949). According to the hypothesis, the GDP shares of primary sectors such as agriculture and mining industries shrink, while the shares of secondary (manufacturing) and tertiary sectors (services) are expected to increase along with improvements in national welfare. Sir W. Lewis Arthur (1954) conducted a seminal study on the role of sectoral transformations on economic development. Lewis's two-sector economy model explored how transformation of the labor forces from an overpopulated rural subsistence sector characterized by zero-marginal labor productivity to a modern industrial sector characterized by high labor productivity can lead to increased employment and expand overall economic production.

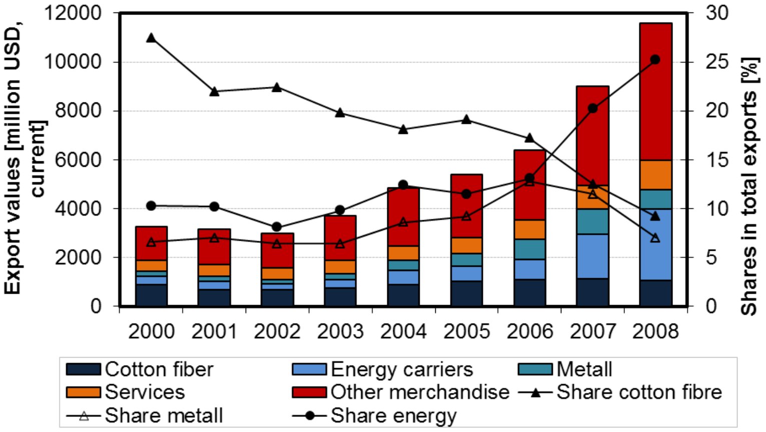
---

[1] This chapter was published as a ZEF Discussion Paper in modified form (Bekchanov et al. 2012). Some results were published in a peer-reviewed journal (Rudenko et al. 2013).

Box 3.1 Exports and imports in Uzbekistan

Before the 1990s Uzbekistan produced more than 60% of the total cotton fiber ("white gold") outputs in the SU and the cotton's share of export revenues were more than 45%. Reforms initiated after 1991 to facilitate a transition towards a market-oriented economy changed the structure of the exports. The cotton's share of total export revenues decreased from 28% to 10% between 2000 and 2008 (Figure 3.1) though physical amount of the cotton exports did not decrease. During the pre-independence period about 60% of Uzbekistan's total petroleum consumption was imported from other SU countries. Since independence Uzbekistan has not only become energy self-sufficient, but gradually turned into a net exporter of energy by increasing development of its oil and gas resources. The share of fossil fuels in total export revenues increased from 10% to 25% and export revenues increased from $3.2 billion to $11.6 billion USD. The export share of metallurgy did not exceed 13% during the period of 2000–2008 according to UzStat (2008), however, other studies indicate that the share of metallurgy was 25% to 30% (CEEP, 2006, Müller 2006, UNDP 2006).

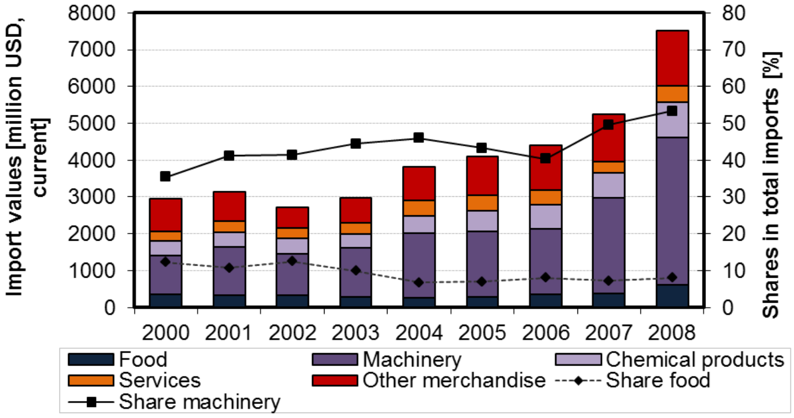
Figure 3.1 Change in exports structure of Uzbekistan, 2000–2008



Source: Based on UzStat (2008)

Because industrialization and modernization of the different economic sectors were prioritized between 2000 and 2008, export revenues were often used to import capital goods (Figure 3.2). As a consequence, the import share of machinery among total annual imports increased from 36% to 53%. The import share of food products and commodities exhibited a parallel decrease from 12% to 8% despite slight increases in absolute volume. Guided by policies and strategies that led to robust growth in grain and energy production (import substitution) and decreased dependence on cotton export revenues, Uzbekistan became less vulnerable to "resource curse" dynamics (McKinley 2008).

Figure 3.2 Change in imports structure of Uzbekistan, 2000–2008



Source: Based on UzStat (2008)

Empirical investigations of the ‘patterns of development’ through analysis of sectoral shares, market sizes and their impacts on production outputs across several countries also showed the importance of sectoral transformations in economic growth (Chenery 1960). It was also noted that the availability of natural and labor resources, suitable environmental-climatic conditions, technological access, and trade relationships with other countries all influence a country’s path with respect to sectoral structural changes and eventual specialization in particular activities (Chenery 1960). Development of the IO model (Leontief 1951) was important contribution to the empirical analysis of the structural change and economic development since the method allowed to consider the interdependence of all the economic sectors.

The early phase of development studies in the 1960s and 1970s accepted economic development as economic growth in terms of increases in outputs and the capacity of the economy to generate annual increases in GDP. Prioritization of the sectors for further expansion was discussed, mainly considering their economic growth potential, which is usually based on intersectoral linkage indexes (Rasmussen 1956, Hirschmann 1958). Increased welfare levels accompanied by environmental degradation, including: air pollution, depletion of water sources, desiccation of watersheds, deforestation, and land degradation, lead economists to differentiate the quality of economic growth rather than purely focusing on the maximization of the economic outputs. The Brundtland Commission report (WCED 1987) had a substantial impact on the emergence of environmentalist movements and thus to additional development research on the need to take into account environmental aspects of growth for providing sustainability. A broadly agreed definition of sustainability is *“practices and development that meet the needs of the present without compromising the ability of future generations to meet their needs*” (WCED 1987). Improving sustainability through sectoral transformation reforms typically intends to reduce the production of resource intensive activities, while expanding activities with higher resource use efficiency and high economic value added.

Sustainability is not limited to improved energy efficiency, but also includes improved efficiency of the use of other natural resources such as water (Markard et al. 2012). Efficient water use in this case is reached through reallocating water from its lower to higher value uses. Such reallocations require prioritizing sectors in accordance to their economic performance and water use requirements. Prioritization of lower water use as well as higher income is of utmost importance, particularly for economies in dryland regions (Rosegrant et al. 2002) where water scarcity used to be a primary constraint for economic development. Although only relatively smaller areas within dryland regions are suitable for irrigated crop production, they are vital for livelihood security and public welfare. The magnitude of water resource management urgency is illustrated by the facts that dryland regions account for about 40% of global irrigated areas and hosts a third of the present world population (Millennium Ecosystem Assessment 2005:1).

The integration of economic and environmental indicators into strategic national livelihood and welfare plans allows to determining options (economic activities) with higher potential for sustainable growth (Ekins 2000, UNESCAP 2009). For addressing not only economic growth but also environmental sustainability issues, the IO analysis was further extended by incorporating environmental accounts. IO approaches are ideally suited for integrating incommensurable physical indicators into a unified and consistent framework (Vardon et al. 2006). Indeed the United Nations has recognized the need for such integrated economic-environmental frameworks in their System of Environmental-Economic Accounting (UNSD 2011). Thus, IO models have been an essential part of sustainable consumption and production policy designs (Daniels et al. 2011).

Environmentally extended IO models have been widely used to analyze intersectoral water use and economic relationships (Velazquez 2006, Dietzenbacher and Velázquez 2007), and to determine key sectors based on economic and environmental performance indicators (Lenzen and Foran 2001, Lenzen 2003). These models were used also to estimate the virtual water embedded in international trade flows (Lenzen et al. 2012) and national water footprints (Zhao et al. 2009, Feng et al. 2011b). Gallego and Lenzen (2005) applied an IO model to estimate virtual water content and determine water consumption responsibilities of consumers and workers/investors according to their final demand and primary input use respectively. In their 'Triple Bottom Line' analysis of the Australian economy, Foran et al. (2005) used an IO model to compare economic sectors according to their socio-economic and environmental indicators such as virtual water consumption, greenhouse gas emissions, land disturbance, employment, family income, and government revenues.

The results of the sectoral performance according to multiple criteria are used to recommended undertaking the necessary changes in tax and subsidy policy reforms to influence the course of sectoral transformations (UNDESA 2010). For instance, environmental tax reform intends to shift the tax base from the traditional taxes, such as the ones based on labor, to the taxes with environmental relevance. Similarly, environmental subsidy reform intends to redirect subsidies from less environmentally attractive economic activities to more environmentally friendly ones. A detailed review and summary of the application of IO modeling tools on different policy purposes were provided by Daniels et al (2011).

Several multi-country, IO databases (WIOD[1], EXIOPOL[2], EORA[3], GTAP[4]) were developed to analyze global economic structure and resource use linkages. These databases are intended to help determine sectoral specialization of different countries considering their comparative advantages in the global market, while diminishing the disturbance of environmental resources. The main shortcomings of these databases are that they do not have data for all countries and some sectoral accounts are highly aggregated. Therefore, further improvements in the quality and usability of the databases are required.

3.2.2 Sectoral transformation options in the context of the Aral Sea basin

Sectoral transformations such as developing alternative options to raw cotton production and meeting domestic food demands in the context of the ASB were analyzed using different approaches. Based on cost-benefit analysis techniques it was argued that increased cotton processing, while reducing cotton production, can enhance additional incomes while reducing water consumption (Levintanus 1990, Rudenko 2008). Partial equilibrium models were used to assess crop structure changes due to population and income growth, as well as under different trading scenarios. IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade), a global partial equilibrium model[5], was applied to estimate food demand and supply, and thus respective agricultural production pattern changes in Central Asia (Pandya-Lorch and Rosegrant 2000). IMPACT projections showed that Central Asia would be self-sufficient in cereals and meat between 1995 and 2020 (Pandya-Lorch and Rosegrant 2000): the proportion of cereals consumption met through the net imports would be 2–3%; the proportion of meat consumption met through net imports was forecasted to increase from 8 to 13%. These favorable consumption levels would be balanced with annual increase rates of 1.15% and 1.33% in cereals and meat production respectively. However, as mentioned in the paper (Pandya-Lorch and Rosegrant 2000), attaining food self-sufficiency not only at national

---

[1] www.wiod.org

[2] www.feem-project.net

[3] www.worldmrio.com

[4] www.gtap.org

[5] The model allows different estimates of the changes in supply, demand, and prices for agricultural commodities due to changes in income, population size, yield, crop area/herd size, and irrigation (Rosegrant et al. 2005). Country and regional agricultural sub-models are linked to each other through trade (Rosegrant et al. 2005).

level but also at household level would depend on food availability at local/community markets, which requires well-functioning infrastructure, stable food prices, and free flow of information (von Braun et al. 1992). Despite its very well structured economic subcomponent the IMPACT model is highly aggregated at the Central Asian level and thus does not consider sub-regional differences in demography, economy, agriculture, and water use.

Another dynamic partial equilibrium model—WATERSIM[1]—was applied to analyze the impact of different agricultural market liberalization scenarios (‘business as usual’, ‘regulated trade plus internal market liberalization’, and ‘full internal plus external market liberalization’) on water use and crop production patterns in Uzbekistan (Abdullaev et al. 2009). ‘The full market liberalization’ scenario predicted the expansion of cotton production, occupying 52% of total crop croplands by 2020. Total water withdrawal increases by 8% under the ‘full market liberalization’ in contrast to 18% under the ‘business as usual’ scenario. The model results predicted an increasing role of cotton production in income generation and reduced water use under the ‘trade liberalization’ scenario. Despite potentially positive impacts of the liberalization on water use and incomes, increasing cotton production and supporting the dominance of cotton do not sound consistent with sustainable development objectives. The results ignore the fact that economic reliance on cotton did not improve irrigation efficiency, but led to environmental degradation during the Soviet era despite the fact that cotton fiber at that time had more than twice its current value in the world market (Baffes 2004). Furthermore, if the dramatic decline of the agriculture productivity in transition countries after 1990s are considered (von Braun and Bonilla 2008:14), the comparative advantages of producing cotton in Uzbekistan must be decreased.

The impact of cotton market liberalization on national income, governmental budget, and private sector revenues in Uzbekistan was tested also using a Computable General Equilibrium (CGE) modeling approach (Müller 2006). It was an influential contribution to rare studies of structural changes in the Central Asian countries based on IO modeling tools. The model showed that despite positive impact of the liberalization on governmental revenues it would reduce private sector revenues and total national income. Later, this CGE model was updated and applied to the case studies of both Uzbekistan and the Khorezm region within the country for comparing the macroeconomic effects of agricultural policies at national and regional levels (Bekchanov et al. 2012). The incorporation of water as a factor into the agricultural production function allowed estimates of the changes in water demand due to agricultural policy changes. The impact of total factor productivity improvements in livestock rearing and primary crop (cotton, wheat, and rice) production on water uses, the production patterns, and incomes were examined. The models indicated that the improvements of the productivity in livestock production sector would provide higher income growth than investing in crop production. Fodder production and thus water demand for fodder crops would be increased under the improved livestock productivity and consequent favorability of livestock sector expansion. However, no comprehensive studies were found that compare all economic activities within a single modeling framework according to their economic importance and environmental influence. Under increasing water scarcity conditions, comparing direct and indirect water uses and the economic importance of all sectors based on a comprehensive analytical framework such as IO model would allow an additional insight into water-economy relationships, facilitating decisions about sectoral transformation for sustainable growth in Uzbekistan and the ASB.

---

[1] The model consists of two sub-models: the “food demand and supply” model adapted from IMPACT (Rosegrant et al. 2005) and the “water demand and supply model” including combined elements of the PODIUMSIM (Yakubov et al. 2009) and IMPACT-WATER models (Abdullaev et al. 2009). The key drivers for the changes in the model are population growth and income.

3.2.3 Input-output modeling framework as a tool for analyzing sectoral interlinkages

Prioritizing the sectors for effective economic growth policy in arid countries with considerable water supply challenges can be supported by comparing total (direct plus indirect) water use requirements of all sectors in addition to the commonly used economic linkage indicators (Lenzen 2003). Although cost-benefit analysis tools, including: net benefit, net present value, and internal rate of return (EC 2008) allow ranking economic activities in terms of their economic growth potential, these methods ignore the fact that the sector under examination is interdependent with other sectors of the economy. In reality, the expansion of a particular sector may indirectly impact the growth of the other sectors by demanding commodities of these sectors as inputs or supplying its outputs to other sectors. The IO model of Leontief (1951) permits the analysis of these sectoral interdependencies (Hirschman 1958, Bharadwaj 1966, Hazari 1970, Jones 1976). The unique structural features of IO models also provide an opportunity to integrate the use of water and other resources in the analysis (Lenzen 2003).

IO models of resource chains are based on a top-down approach which provides some advantages over more common bottom-up approaches of estimating virtual water content discussed by Chapagain and Hoekstra (2003, 2004, 2007). The top-down approach is based on aggregated data on sectoral water consumption and production levels on a country-wide basis, while bottom-up approaches consider water use and production at the local level. In contrast to bottom-up approaches that allow analysis of individual production processes and only partially cover virtual water use, top-down approaches simultaneously consider production interrelationships among all economic sectors (Van Oel et al. 2009, Feng et al. 2011a, 2011b). For instance, a bottom-up approach based analysis of the virtual water content of raw cotton will indicate the amount of water directly consumed in cotton cultivation, but is limited in the sense that it does not include information on how much water is used to produce cotton production inputs such as seed, agrochemicals, and fuel during field operations. Water requirements in upstream sectors are especially relevant in cases where intermediate inputs into production are produced domestically. A top-down approach employing IO models allows the calculation of total (direct plus indirect) water use by considering not only water use by the sector and all intermediate inputs used in this sector, but also water use along the entire supply chain (Lenzen 2009, Duarte and Yang 2011). Thus mainstream bottom-up approaches of calculating virtual water tend to systematically underestimate virtual water contents.

Additionally, the conventional bottom-up approach of measuring the virtual water content as a physical water requirement per physical output is limited and inadequate if the intention is to compare commodities from different sectors. For example, a comparison of the virtual water content of 1 kg of meat to 1 kg of wheat neglects the fact that these two commodities have very distinct economic values. Due to the fact that values of different commodities in monetary terms are comparable to each other, estimating and comparing water use per unit relative to economic value is more relevant than simply water use per physical unit for this kind of analysis.

IO models can be also applied to identify so-called key sectors and sequentially formulate economic development strategies (Rasmussen 1956, Hirschman 1958). A key sector is one whose growth will promote above average expansion in the economy (Rasmussen 1956, Hirschman 1958). Impulses of growth from one sector can stimulate supplying sectors (backward linkage) or other end-use sectors (forward linkage) (Rasmussen 1956, Hirschman 1958). Considering sectors with stronger-than-average backward and forward linkages as “key sectors,” Hirschmann (1958) postulated that investments in such key sectors are an efficient way to improve overall economic development.

Chenery and Watanabe (1958) used the column and row sums of a technical production coefficients matrix as backward and forward linkages respectively. In contrast, Rasmussen (1956) and Hirschmann (1958) suggested using the column and raw sums of a Leontief inverse matrix as backward and forward linkages, since the inverse matrix based sums describe full linkage relationships. Hazari (1970) introduced a weighting scheme for backward and forward linkage measures, considering the relative importance of each sector in accordance with its final demand or value added. Another approach for estimating the importance of any economic sector is the hypothetical extraction method (HEM). This approach is characterized by the hypothetical elimination of a sector followed by estimating the impacts on multipliers (Strassert 1968). Different HEM forms were proposed by Hewings (1982), Cella (1984), and Sonis et al. (1995). A more recent linkage measure was proposed by Oosterhaven and Stelder (2002) in which the output generated by all sectors as a response to the final demand of a certain sector is normalized for the output generated in the sector. Despite substantial improvements, all alternative approaches to measuring intersectoral linkages have advantages and disadvantages and should be considered as complementary rather than mutually exclusive (Lenzen 2003). The approach introduced by Rasmussen (1956) and Hirschman (1958) is commonly used by practitioners and considered a standard way of estimating intersectoral linkages (Midmore et al. 2006).

Beyers (1976) and Jones (1976) identified several shortcomings of the Leontief inverse model for measuring forward linkages. For example, a raw sum of Leontief's inverse matrix is "the result of demand generated by user's backward linkage" (Jones 1976), and thus cannot be used to measure forward linkages. Therefore, these and other authors (Miller and Lahr 2001) recommended using the Ghosh inverse matrix (1958) as the only reasonable candidate for calculating forward linkage indices. However, the Ghosh model is heavily criticized for its implausibility in capturing causal relationships between primary inputs and economic growth (Oosterhaven 1988, 1989, 1996; de Mesnard 2009). Considering these efforts and also Dietzenbacher (1997), a Ghosh model can be used as a price model to capture the price effects without quantity effects. Consequently, a Ghosh inverse model can be used as a static and descriptive tool to measure forward linkages that are interpreted as the amount of output required to absorb primary inputs (Lenzen 2003). Non-causal interpretation of forward linkages discussed above can also be applied to environmentally extended IO models (Gallego and Lenzen 2005).

3.3 Data sources and methods for the analysis of alternative economic activities

3.3.1 Estimation of the input-output table of the Uzbekistan economy

Analyzing intersectoral linkages starts with estimation of input-output table (IOT). During the Soviet era, government statistical organizations were entrusted with the development of national and regional IOTs for Uzbekistan. After independence, IOTs have not been reported by national statistical organizations. Müller (2006) developed a national social accounting matrix (SAM) with twenty sectors for 2001 (referred to hereafter as SAM-2001). A more recent IOT of Uzbekistan including thirteen sectors was developed for 2005 (referred to hereafter as IOT-2005) by researchers at the Center for Effective Economic Policy (CEEP), the Center for Economic Research (CER), the Ministry of the Economy (MoE) and Colorado University (UNDP 2006). In contrast to SAM-2001, agriculture and agro-processing industries in IOT-2005 are aggregated.

Because IOT-2005 represents the most recent complete database, it served as the basis for calculations of IOT values in this study. Because the objective was a thorough analysis of the water intensive agricultural sector, an IOT with disaggregated agriculture and agro-processing industries accounts was developed based on IOT-2005. The disaggregation was based on the proportional shares of intermediate inputs derived from the SAM-2001 by Müller (2006). Secondary data on production values, GDP, added value, exports and imports, and consumption levels across the sectors of the economy were obtained from the Asian Development Bank (ADB 2008), the National Statistical Committee of Uzbekistan (UzStat 2008), and CEEP (2006).

Disaggregated calculations resulted in an IOT with unbalanced column and row sums, therefore it was transformed to a balanced national IOT with twenty sectors for 2005 using the standard maximum entropy approach (Golan et al. 1996, Wehrheim 2003, Müller 2006). Calculations based on maximum entropy approach were conducted using General Algebraic Modeling System (GAMS) software (Brooke et al. 2006). The values of the input-model components were estimated in Uzbek soum. Since the official exchange rates for Uzbek soum (UZS) to USD varied between 1080 and 1180 throughout 2005 (CEEP 2006), an average exchange rate of 1128 UZS per USD was used.

3.3.2 Estimation of direct water use by sectors

In water footprint analysis, "blue" and "green" water uses for crop production are differentiated. "Blue" water is related to water delivered to the crops through rivers and irrigation canals; "Green" water concerns with direct use of rainfall by crops. Considering low precipitation in the ASB and the heavy reliance of agriculture on irrigation water, (Section 2.2.2) only the "blue" water use was considered in the analysis. Aggregated water use data (UNDP 2007) was used to estimate water consumption by agricultural and industrial subsectors based on existing water consumption requirements per number of livestock, per hectare of cropped land, or per unit of production output. For instance, water consumption for livestock production was estimated based on the number of head of each type of livestock (cattle, sheep, goats, pigs, horses, and poultry) as derived from official statistics (UzStat 2008) and annual water consumption requirements per head of livestock (CRIIWRM 1980). To estimate water use for crop cultivation, the recommended water consumption for each agricultural subsector was based on cultivated land area (UzStat 2008) and recommended water use per hectare for each crop (Müller 2006). Then, each subsector's relative shares of total agricultural water consumption were calculated. Finally, water use by crop production subsector was derived by multiplying the relative shares by the difference between actual total agricultural water use and total livestock water consumption requirement.

The same procedure was repeated to estimate water use by industrial subsectors. Physical production volumes of industrial products were obtained from UzStat (2006), and water consumption norms per unit of product from the State Construction Office (1978). The prior water consumption for each industrial subsector was calculated based on total commodity production and recommended water consumption per unit of product. Next, the shares for prior water use for each industrial subsector in the total recommended industrial water consumption were calculated. These shares were multiplied by actual total industrial water use to estimate the actual water uses by industrial subsectors.

3.3.3 Leontief model

The intersectoral flows in a given economy were calculated using an IO system (Leontief 1951):

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \qquad (3.1)$$

where **x** is a *n*x1 vector of the total production volume for each sector, **y** is a *n*x1 vector of final demand including private and government consumption, investments, changes in inventories, and exports. **A** is a *n*x*n* matrix of technical production coefficients.

With simple transformations, final demand is treated as an exogenous variable that determines the level of total production:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-\mathbf{1}}\mathbf{y} = \mathbf{Ly} \qquad (3.2)$$

where $\mathbf{I}$ is an *n*x*n* identity matrix and $\mathbf{L}$ is the *n*x*n* Leontief inverse matrix. The element l_{ij} of the Leontief inverse $\mathbf{L}$ reflects the total requirements from sector i to provide a unit of the final demand for the commodities of sector j.

3.3.4 Ghosh model

A Ghosh (1958) model was used to estimate intersectoral allocations of primary and intermediate inputs:

$$\mathbf{x}' = \mathbf{x}'\mathbf{B} + \mathbf{v}' \qquad (3.3)$$

where **B** is a *n*x*n* matrix of allocation coefficients that is calculated as a ratio of intersectoral intermediate inputs to the total inputs (raw sums of IO table) and $\mathbf{v}'$ is a 1x*n* vector of primary factors which include capital, labor, and imports. The prime symbol ($'$) denotes matrix transposition.

Similar to Eq. 3.2, the relationship between the primary factors and the level of total production is obtained with simple transformations:

$$\mathbf{x}' = \mathbf{v}'(\mathbf{I} - \mathbf{B})^{-\mathbf{1}} = \mathbf{v}'\mathbf{G} \qquad (3.4)$$

where **G** is an *n*x*n* Ghosh inverse matrix. The element g_{ij} of the Ghosh matrix **G** reflects the total required outputs from sector j to absorb a unit of the primary factors of sector i.

3.3.5 The backward and forward linkage indices

The Leontief inverse matrix (Eq. 3.2) allows the measurement of direct and indirect effects of a change in the final demand over production, as well as the calculation of a backward linkage index (BLI). The BLI of sector j shows how much sector j influences the output of all other sectors through its purchases (input uses), and is calculated following the approach by Rasmussen (1956) and Hirschman (1958):

$$BLI_j = (L_{*j}/n)/L^* \qquad (3.5)$$

where L^* is the mean of all elements of the Leontief inverse matrix **L** (Eq. 3.2) and L_{*j} is the associated column sum of elements of the matrix **L** for sector j.

Considering the relevance of the Ghosh model (Eq. 3.4) for calculating the forward linkage index (FLI) (Beyers 1976, Jones 1976), the FLI of sector i, which indicates how much sector i influences the output of all sectors through its sales (output supplies) is elaborated based on the Ghosh model instead of the Leontief model as follows:

$$FLI_i = (G_{i*}/n)/G^* \qquad (3.6)$$

where G^* is the mean value of all elements of the Ghosh inverse matrix **G** (Eq. 3.4) and G_{i*} is the associated raw sum of the elements of matrix **G** for sector i.

BLIs and FLIs are useful for comparing sectors according to their influence and dependence on the remaining sectors, and through this their effects on the overall economy. BLI_j >1 indicates strong backward linkages of sector j, which means that a unit increase in the final demand of sector j would result in a greater-than-average increase in total economic output. In parallel FLI_i >1 shows strong forward linkages of sector i, meaning that a unit increase in primary inputs of sector i would require a greater-than-average increase in total economic output. If both conditions, BLI_j >1 and FLI_i >1, are fulfilled for any sector it is considered a 'key sector' that exhibits both greater-than-average influence and dependence on the other sectors (Lenzen 2001).

3.3.6 Total (direct and indirect) water use

Integration of the total (direct and indirect) water uses of products with BLIs and FLIs allows more rational decision making on economic restructuring as water is a main limiting factor in the economic development of countries in arid regions such as Uzbekistan. To estimate total (direct and indirect) water consumption (TWC), direct water input coefficients (dw_j) are initially estimated as the ratio of total direct water use (W_j) to the total production volume of a given sector j (Q_j):

$$dw_j = W_j/Q_j \qquad (3.7)$$

Based on these direct water use coefficients and the Leontief inverse matrix elements, TWCs (vw_j) or backward linkage based total (direct and indirect) water uses that indicates the total amount of water required to produce a unit of final demand in sector j, are calculated as (Lenzen 2003):

$$vw_j = \sum_i dw_i l_{ij} \qquad (3.8)$$

Similarly, forward linkage based TWCs indicate the total water use that is required to absorb a unit of primary factors in sector i, and are calculated as (Lenzen 2003):

$$vw_i^G = \sum_j dw_j g_{ij} \qquad (3.9)$$

3.3.7 Multi-criteria ranking

Since the ranks of the sectors according to each economic linkage index or water use based criteria are different, multi-criteria decision analysis (MCDA) is used for ranking and selecting the most efficient options (sectors) based on economic/environmental analyses (Wang et al. 2009). Within a MCDA framework, usually multiple indexes are integrated into a composite indicator for ranking the sectors, concurrently considering the tradeoffs between economic efficiency and environmental sustainability of different options. A single composite indicator based on BLI, FLI, and TWC was developed in this study for prioritizing the options and choosing the most appropriate ones.

Apparently, there are several methods of multi-criteria ranking or choice making, including but not limited to the weighted sum method (CLG2009, Simonovich 2009), Analytical Hierarchical Processes (AHP; Saaty 1980), and outranking methods (Roy 1991). Since none of the methods are strictly preferable over other methods, the weighted sum method was used in this study due to its ease of use. Before calculating the weighted sums indicators under each option were normalized considering their average value. Inverse values of total water use indexes were considered in calculations since higher water use is less favorable and should be adjusted properly for estimating multiple criteria based composite indicator. To rank the sectors according to economic importance and water use requirement, a composite indicator (CI_i) was calculated based on weighted averages of the separate linkage indicators as (CLG 2009):

$$CI_i = (1-\alpha)\left(\frac{\frac{BLI_i}{\sum_i BLI_i}+\frac{FLI_i}{\sum_i FLI_i}}{2}\right)+\alpha\left(\frac{\frac{1/vw_i}{\sum_i(1/vw_i)}+\frac{1/vw_i^G}{\sum_i(1/vw_i^G)}}{2}\right) \tag{3.10}$$

where α is a weight for water requirement that is a proxy for environmental sustainability and varies between 0 and 1.

3.4 Analysis of the intersectoral linkages and determination of activities with higher economic importance and lower water requirement

3.4.1 Sectoral and intersectoral structure of the Uzbek economy

According to the balanced IOT, the highest intermediate input uses were observed for the products of fossil fuel industry, trade, and the transportation and communications sectors (Table 3.1). These sectors are considered metaphorically as the “lifeblood” of the economy since production and inter-sector commodity exchanges in the economy cannot occur without them.

Private consumption was dominated by livestock products. This fact can be explained by high prices for milk, eggs, and meat and the popularity of livestock rearing among rural households (Djanibekov 2008), which account for more than 60% of the total population. Private consumption expenditures on the commodities from transport and communications sector were also high, which can be explained by the recent widespread use of cell phones and increased mobility of seasonal labor (CER 2010). Concurrently, private consumption of the electrical power and food industry sectors was also high because these sectors provide products that meet basic needs.

Products of the machinery and construction sectors are typically considered investments. Government expenditures were mostly spent for purchasing the public services such as education, health care, and banking. As explained earlier, most export revenues were generated from the metallurgy, cotton, and fossil fuel sectors, while imports were dominated by machinery goods.

Intersectoral flows of intermediate inputs, as well as labor and capital resources (including operations surplus) across the sectors are given in Table 3.2. Commodities from agriculture contributed substantially to the intermediate use of the cotton and food processing industries. In turn, agricultural activities mostly relied on goods from the fossil fuel sector, which can be explained by extensive mechanized agriculture and high prices for fuel. The construction sector depended heavily on other industrial sectors that contained the production of timber, bricks, and glass. The most labor intensive sectors turned out to be the ‘transportation and communications’ and ‘other services’ sectors that includes all state service organizations such as schools, hospitals, banks, etc. The technical production and allocation coefficients as well as Leontief and Ghosh inverse matrices were estimated based on the IOT. The Leontief and Ghosh inverse matrices were then used to calculate BLIs, FLIs, and TWCs.

Table 3.1 Input-Output Table (Quadrant II) of the Uzbekistan economy in 2005 (in billions of Uzbek soums)

		Intermediate use		Private consumption		Investment expenditures		Government expenditures		Exports		Imports		Total output	
Sectors		**Amount**	**Share (%)**	**Amount**	**Share (%)**	**Amount**	**Share (%)**	**Amount**	**Share (%)**	**Amount**	**Share (%)**	**Amount**	**Share (%)**	**Amount**	**Share (%)**
ACOT20	Cotton	1135	6.5	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	1135	3.5
AGRN20	Grains	310	1.8	438	5.6	0	0.0	200	9.4	0	0.0	63	1.3	886	2.7
ARIC20	Rice	23	0.1	41	0.5	0	0.0	0	0.0	0	0.0	0	0.0	64	0.2
AGAR20	Gardening	67	0.4	447	5.8	0	0.0	0	0.0	77	1.2	0	0.0	592	1.8
AFOD20	Fodder	301	1.7	49	0.6	0	0.0	0	0.0	0	0.0	0	0.0	350	1.1
AOTH20	Other crops	54	0.3	476	6.1	0	0.0	0	0.0	12	0.2	0	0.0	542	1.7
AANM20	Livestock	169	1.0	2600	33.5	60	1.5	0	0.0	0	0.0	0	0.0	2829	8.6
APOWE20	Energy industry	1287	7.3	46	0.6	0	0.0	0	0.0	22	0.4	24	0.5	1332	4.1
AFUEL20	Oil and gas	3192	18.2	114	1.5	0	0.0	0	0.0	712	11.4	102	2.1	3916	11.9
AMETL20	Metallurgy	1025	5.8	0	0.0	0	0.0	0	0.0	1736	27.8	472	9.5	2290	7.0
ACHEM20	Chemical industry	818	4.7	54	0.7	0	0.0	0	0.0	338	5.4	452	9.1	757	2.3
AMAEQ20	Machinery	1390	7.9	132	1.7	1624	39.6	0	0.0	536	8.6	1976	39.8	1706	5.2
ACTPR20	Cotton processing	596	3.4	54	0.7	0	0.0	0	0.0	1375	22.0	0	0.0	2025	6.2
ALGHT20	Light industry	374	2.1	584	7.5	0	0.0	0	0.0	0	0.0	119	2.4	839	2.6
AFOOD20	Food industry	310	1.8	516	6.7	0	0.0	0	0.0	562	9.0	338	6.8	1050	3.2
AOIND20	Other industries	1281	7.3	363	4.7	0	0.0	0	0.0	180	2.9	520	10.5	1304	4.0
ACON20	Construction	0	0.0	0	0.0	2329	56.8	0	0.0	0	0.0	14	0.3	2314	7.0
ATRD20	Trade	2122	12.1	0	0.0	0	0.0	0	0.0	0	0.0	231	4.6	1891	5.8
ATCM20	Transport and communication	2105	12.0	732	9.4	0	0.0	192	9.0	611	9.8	526	10.6	3113	9.5
AOTS20	Other services	1012	5.8	1112	14.3	89	2.2	1733	81.5	77	1.2	121	2.4	3902	11.9
TOT	Total	17572	100	7758	100	4101	100	2125	100	6239	100	4958	100	32837	100

Source: Based on CEEP (2006), Müller (2006), UNDP (2006), ADB (2008), and UzStat (2008)
Note: Average exchange rate for 2005 was 1,128 UZS = $1 USD

Table 3.2 Input-Output Table (Quadrants I and III) of the Uzbekistan economy in 2005 (in billions of Uzbek soums)

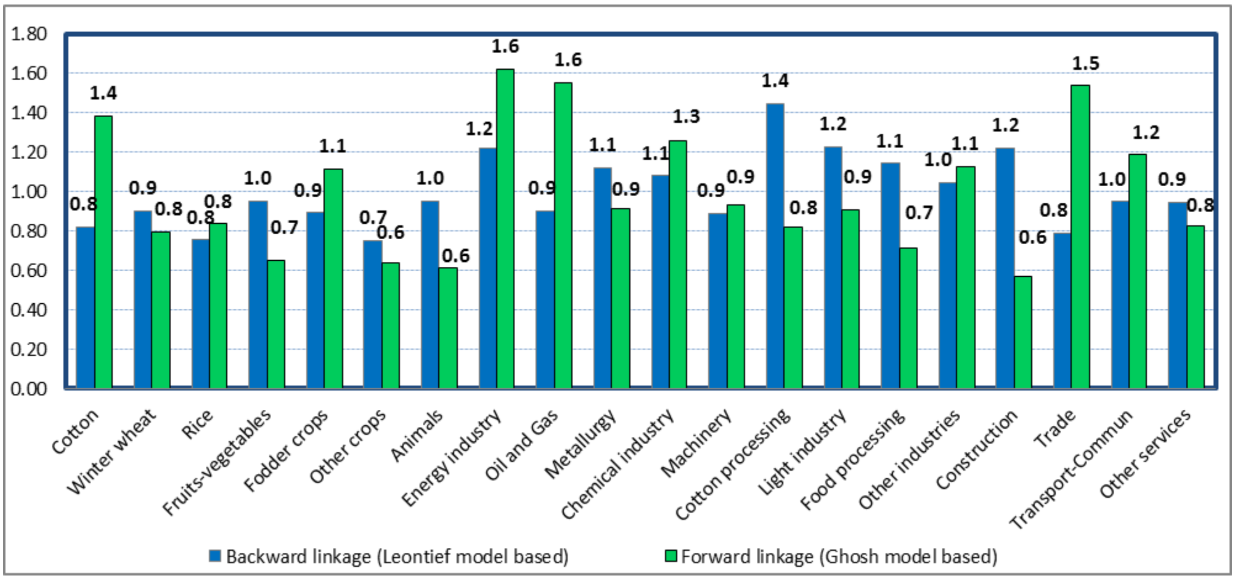
	ACOT20	AGRN20	ARIC20	AGAR20	AFOD20	AOTH20	AANM20	APOWE20	AFUEL20	AMETL20	ACHEM20	AMAEQ20	ACTPR20	ALGHT20	AFOOD20	AOIND20	ACON20	ATRD20	ATCM20	AOTS20
ACOT20	0	0	0	0	0	0	0	0	0	0	0	0	1135	0	0	0	0	0	0	0
AGRN20	0	18	0	0	0	0	79	0	0	0	0	0	0	0	208	0	0	2	0	3
ARIC20	0	0	2	0	0	0	0	0	0	0	0	0	0	0	21	0	0	1	0	1
AGAR20	0	0	0	26	0	0	0	0	0	0	0	0	0	0	33	0	0	4	0	5
AFOD20	0	0	0	0	15	0	287	0	0	0	0	0	0	0	0	0	0	0	0	0
AOTH20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54	0	0	0	0	0
AANM20	0	0	0	0	0	0	34	0	0	0	0	0	0	34	99	0	0	0	0	2
APOWE20	27	26	0	17	0	0	81	56	170	161	172	44	54	9	10	112	25	50	140	132
AFUEL20	134	144	0	96	58	0	235	724	743	135	49	30	0	0	9	108	79	34	313	302
AMETL20	0	0	0	0	0	0	0	0	0	652	88	162	0	0	0	37	86	0	0	0
ACHEM20	61	62	5	41	21	43	4	26	18	76	159	24	11	38	6	82	58	1	38	44
AMAEQ20	7	9	1	6	3	8	16	32	32	167	18	652	25	9	3	56	76	7	146	116
ACTPR20	19	0	0	0	0	0	8	0	0	0	0	0	404	110	41	14	0	0	0	0
ALGHT20	0	0	0	0	0	0	3	0	0	7	3	9	9	253	83	8	0	0	0	0
AFOOD20	0	0	0	0	0	0	171	0	0	0	0	0	0	0	138	1	0	0	0	0
AOIND20	4	4	0	3	2	0	22	7	18	16	5	18	10	0	3	115	719	67	126	142
ACON20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ATRD20	40	44	3	28	16	25	132	102	170	229	84	297	155	71	76	217	143	0	31	257
ATCM20	5	19	2	15	6	18	54	15	264	26	13	21	25	10	14	100	333	214	606	344
AOTS20	6	17	2	13	6	15	49	22	54	54	6	84	21	17	21	67	36	126	92	302
Labor	275	75	10	130	19	143	381	73	628	166	59	124	44	40	42	56	517	459	978	1493
Capital	556	467	40	216	204	290	1273	274	1819	600	102	241	134	248	190	329	243	927	643	758
Total	**1135**	**886**	**64**	**592**	**350**	**542**	**2829**	**1332**	**3916**	**2290**	**757**	**1706**	**2025**	**839**	**1050**	**1304**	**2314**	**1891**	**3113**	**3902**

Source: Based on CEEP (2006), Müller (2006), UNDP (2006), ADB (2008), and UzStat (2008)
Note: Average exchange rate for 2005 was 1,128 UZS = $1 USD/sectoral abbreviations are defined above in Table 3.1

3.4.2 Identifying key sectors of the economy

Economic linkage measures such as BLI and FLI values and environmental performance indicators such as direct and indirect water consumption were integrated to compare different economic activities and identify key sectors. The industrial sector generally had higher BLIs compared to the agricultural sector. The BLIs for agriculture varied between 0.7 and 1.0, while BLIs for the industrial sector varied between 0.9 and 1.4 (Figure 3.3). The fruit and vegetables subsector had the highest BLI among all crop production subsectors (1.0). The BLIs of all industrial sectors except in the fossil fuels and machinery sectors were higher than average.

Figure 3.3 Estimated backward and forward linkages of the Uzbekistan economy in 2005

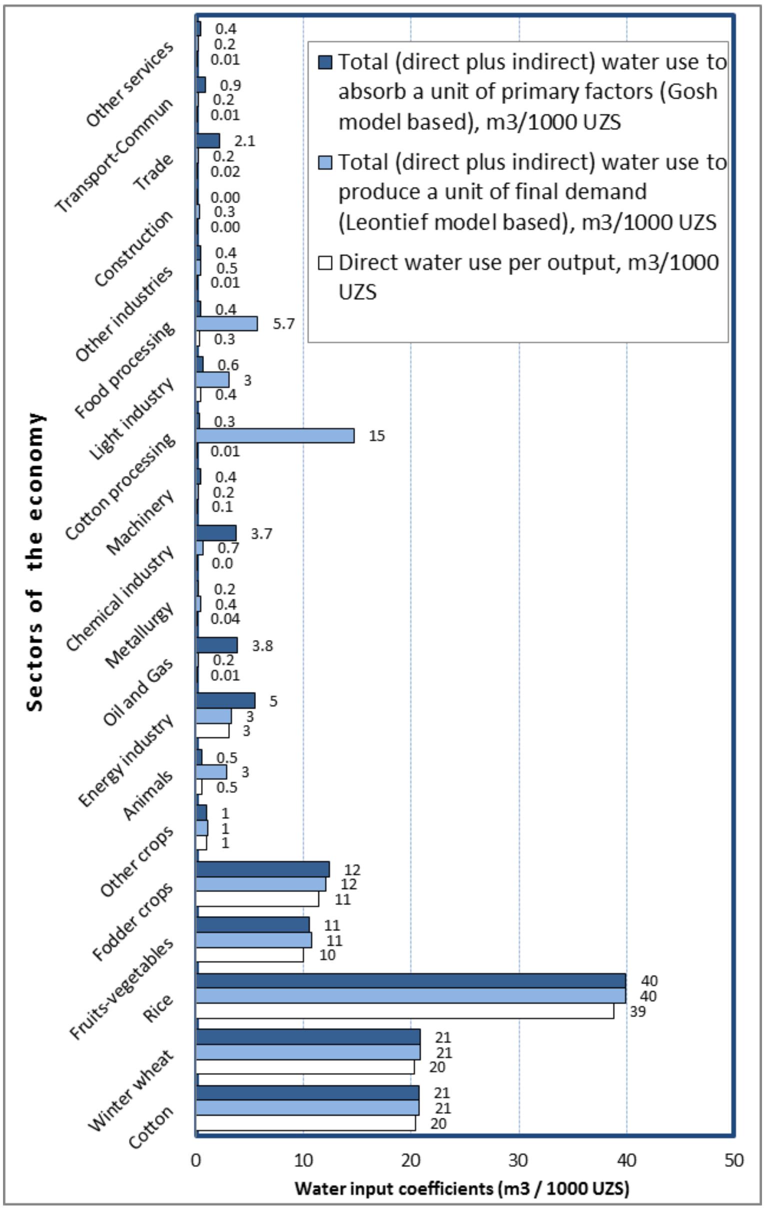


Source: Author’s calculations

The FLIs of industrial sectors were also generally higher than those in the agricultural sector (Figure 3.4). The FLIs for all agricultural sectors varied between 0.6–1.4, while for industrial sectors they varied between 0.7–1.6. The FLI for cotton production was the highest of all agricultural subsectors because cotton processing plants, which are the greatest consumer of raw cotton, are widespread throughout the country. The highest FLIs (1.6) were for the fossil fuel and energy sectors. The FLIs for the trade and for the transportation and communication sectors, with values of 1.5 and 1.2 respectively, were also higher than FLIS of most of the agricultural and industrial sectors. The key sectors based on both BLI and FLI values higher than one were the energy, chemical, and “other” industries, which mainly considered construction materials production.

The comparison of water uses across sectors was based on the direct and indirect water consumption requirements for producing any commodity or product equivalent to 1,000 Uzbek soums (UZS) (Figure 3.4). Comparisons of direct water use coefficients across the sectors showed that in general, agricultural commodities required substantially higher amounts of water per 1,000 UZS than the goods produced by all other sectors. Within the agricultural sector, rice required the highest amount of water at 39 m^3 to produce goods worth of 1,000 UZS (34.5 m^3/USD). The direct water use requirement per unit of output in cotton and winter wheat production sectors was about 20 m^3 (18.0 m^3/USD). Although the water requirement per hectare for winter wheat was comparatively lower than for the other crops examined, its direct water use coefficient is likely influenced by low prices for grain imposed by the national administration; whereas this is not the case with crops other than wheat and cotton. The production of fruit and vegetables required only 10 m^3 (8.9 m^3/USD) of water per unit of output worth of 1000 UZS, while the value was 11 m^3 (10.2 m^3/USD) per unit of fodder crops. Lower water uses and thus higher water productivities for these goods are likely because of their higher prices due to the lack of government production quotas and procurement mandates for these crops. Among the industrial sectors the highest direct water consumption per 1,000 UZS unit was in the energy industry, with a value of 3.0 m^3 (2.7 m^3/USD). Although the non-agricultural sectors produced about 75% of the GDP in 2005, their share of total water consumption was less than 10%. Hence, their direct water use per unit of production is negligible compared to the crop production sectors.

Figure 3.4 Direct and total water consumption by economic sectors of Uzbekistan in 2005



Note: The average exchange rate in 2005 was UZS 1.128/$1 USD

Source: Author’s calculations

TWCs to produce a unit of the final demand in crop production (except 'other crops') were higher than in the other sectors except cotton processing (Figure 3.4). The TWC of livestock production was substantially lower than the TWCs of crop production subsectors except 'other crops'. The TWCs for most sectors were considerably higher than the direct water input coefficients for these sectors. The most noticeable differences between these two indicators were observed for livestock, chemical industry, cotton processing, light industry, and food processing. The large differences between the TWCs and direct water use values for livestock, cotton processing, light industry, and food processing are due to a high water demand for producing the intermediate inputs consumed by these sectors. However, TWCs of these sectors in general were still lower than those of crop production sectors. For instance, light industry and food processing required about 3 m^3 and 5.7 m^3 per economic output worth of 1000 UZS (2.7 and 5.1 m^3/USD) of total water use respectively, whereas cotton and the fruit and vegetables production required 21 m^3 and 11 m^3 per economic output worth of 1000 UZS (18.4 and 9.5 m^3/USD) respectively.

Concurrently, forward linkage based TWCs were substantially larger than the direct water use for sectors such as energy, fossil fuels, chemical industry, and trade (Figure 3.4). In general, TWCs based on forward linkages for all crop production activities except other crops were higher than for the remaining sectors. Yet, insignificant differences were found between backward and forward linkage based TWC levels for crop production activities.

3.4.3 Multi-criteria ranking of economy sectors

Ranking the sectors according to their backward and forward linkages, and TWCs separately resulted in different rankings (Table 3.3). An integration of the separate indicators resulted in a composite measure which allowed assessment of the sectors based on their economic importance and TWCs. According to the multi-criteria ranking, the construction sector was ranked first, while rice production turned out to be the worst when equal weight was considered for both economic importance and water use intensity. Although it seems quite reasonable that paddy rice production is unfavorable due to its huge water requirements (ranked 20) and low backward linkage indexes (ranked 19), the construction sector turned out to be the most favorable due to its extremely low forward linkage-based water use (ranked 1), despite the lowest forward linkage index (ranked 20). Thus, the highest rank of the construction sector is primarily due to its very negligible water use requirement per unit of its economic output in comparison with the remaining sectors (Figure 3.4). To reduce this outlier impact since extremely large differences between the water use requirements of the sectors may reduce comparability of the normalized indicators consequently showing biased results, the rankings were re-assessed without considering the construction sector. When allotting equal weights to both economic importance and environmental influence, machinery, metallurgy, and other services (e.g., education, health, sport, culture, etc.) became the most favorable sectors. In general, all agriculture related sectors ended up at the bottom half according to multi-criteria ranking. The livestock sector ranked higher than all crop production activities. Agro-processing industries such as cotton processing, light industry, and food processing were more favorable than any other agricultural subsectors. When increased weights were considered to environmental influence criteria, the regional dominant crop cultivation activities such as cotton and grain production kept its initial low rank or ranked even further down, while the ranks of agricultural activities such as the production of fruit and vegetables and livestock went up.

Table 3.3 Single and multi-criteria rankings of the economic sectors in Uzbekistan

Sectors	Ranking the sectors due to single criterion				Multi-criteria ranking			Multi-criteria ranking without considering construction sector		
	SBL	SFL	SBWC	SFWC	α =0.2	α =0.5	α =0.8	α =0.2	α =0.5	α =0.8
Cotton	17	4	18	18	12	13	16	13	15	15
Grains	13	15	19	19	16	18	19	17	17	18
Rice	19	12	20	20	19	20	20	19	19	19
Gardening	11	17	15	16	18	19	18	18	18	17
Fodder	15	8	16	17	14	15	17	14	16	16
Other crops	20	18	10	11	20	16	10	16	14	12
Livestock	9	19	11	8	17	17	15	15	12	10
Energy industry	3	1	13	15	4	10	11	8	13	14
Oil and gas	14	2	3	14	2	4	4	2	6	7
Metallurgy	6	10	7	2	9	7	7	1	2	2
Chemical industry	7	5	9	13	7	9	9	10	11	13
Machinery	16	9	1	7	6	3	2	4	1	1
Cotton processing	1	14	17	3	11	11	13	7	8	8
Light industry	2	11	12	9	13	12	12	11	10	11
Food industry	5	16	14	4	15	14	14	12	9	9
Other industries	8	7	8	5	8	8	8	6	7	6
Construction	4	20	6	1	1	1	1	-	-	-
Trade	18	3	2	12	3	2	3	3	5	5
Transport and communication	10	6	4	10	5	5	5	5	4	4
Other services	12	13	5	6	10	6	6	9	3	3

Notes: SBL-Standardized backward linkages, SFL-Standardized forward linkages, SBWC- Standardized backward linkage based total water consumption, SFWC-Standardized forward linkage based total water consumption, and weights of 0.2, 0.5, and 0.8 were used for environmental sustainability

Source: Author’s calculations

The results discussed here are useful only comparing the sectors to each other according to economic and efficient water use criteria defined by BLI, FLI, and TWC. Prioritizing any sector to the other should depend on the weight to the criteria given by decision makers and thus the results obtained here should be carefully considered while not forgetting weighting and other factors. The indicators discussed here are not only measures to select the key sectors for sustainable growth. International comparative advantages, technology access, human capital, innovation and knowledge interactions, social networks, institutional settings, income distribution, and many other economic and ecologic indicators play important role to determine key sectors for economic growth (Bryan et al. 2005). Nevertheless, our analysis can be complementary to more comprehensive, multi-criteria, multi-sectoral, quantitative, and qualitative analysis of determining key sectors for economic growth mentioned by Bryan et al. (2005).

3.5 Discussion of the options for sustainable economic restructuring and conclusions

Achieving sustainable growth is dominating worldwide discussions on economic development, and there is some debate on (i) which production technologies can be adjusted and (ii) how to decouple economic growth from the consumption of critical natural resources such as land and water. This is particularly challenging in arid regions such as the ASB, which are heavily dependent on irrigated agriculture for economic development. The combined effects of the expected climate change (Chub 2000, 2007) and increased hydroelectric generation by upstream countries (Eshchanov et al. 2011) will undoubtedly decrease water availability for irrigation. This poses challenges for implementing economic transformation policies guided by the prioritization of sectors with relatively high economic growth potential but low water demand.

The findings based on the indicators derived from the IO model for the case study of Uzbekistan showed that crops such as cotton, wheat, and rice dominated its agricultural sector posing a high demand of water per economic output under current technological levels. In spite of its low water productivity, cotton production continues on at least 40% of the total irrigated cropland under strict government quotas for cotton production (Djanibekov 2008) to maintain export revenues. Obviously, cotton production has been acknowledged for increasing the welfare of rural inhabitants and securing livelihoods over the past four decades in Central Asia (Rudenko et al. 2012). Nevertheless, past cotton production practices have also contributed to the desiccation of an entire sea-sized lake - the Aral Sea that was accompanied by unemployment, land degradation, and health deterioration in the deltaic zones (WBGU 1998, Micklin 2010). Continued reliance on increasingly scarce water resources that are also in excessive demand for environmental needs and dependence on revenues from the exports of primary commodities that are subject to high price volatility in the global market (Rudenko et al. 2009) would lead Uzbekistan to face an environmental-economic dilemma unless measures are taken to follow a path of long-term sustainability and real income growth.

Fruit and vegetable production turned out to have a much higher potential than the present state-ordered crops cotton and wheat when higher weight is given to water use intensity (environmental) criteria in comparing these economic activities. An increased development of fruit and vegetable production, however, must go hand-in-hand with the creation of appropriate storage and processing facilities that have deteriorated since independence (Bobojonov and Lamers 2008). The pursuit of improving the storage and processing systems can lead a stabilization of fruit and vegetables prices simultaneously reducing the hidden hunger in winter and spring periods (Bekchanov and Bhaduri 2013). However, the present practice of differential crop support in Uzbekistan creates disincentives for farmers to use water resources more efficiently for example through crop diversification and rotation (Djanibekov 2008; Bobojonov et al. 2012, 2013). To reach sustainable resource use, this differential support to cotton and wheat should either be phased out, or else equal importance should be given to other crops as well.

Although it is generally argued that the production of livestock products such as meat, milk and eggs requires much more water per physical output than the production of crops such as cereals (Chapagain and Hoekstra 2003, 2004, Mekonnen and Hoekstra 2010), amount of meat is not comparable to the same amount of crop commodities. With this regard, the TWC per unit of economic output is more meaningful measure than the TWC per physical output to compare water use intensities of different products. According to the results, the TWC per economic output of livestock products in Uzbekistan was lower than the TWCs of the crop production. Therefore, the maintenance and further development of the livestock production sector has a higher potential than the production of cotton, wheat, rice, vegetables, and fruits in the region to enhance higher economic growth with less use of water. Previous analyses of regional agricultural production using partial and general equilibrium models also postulated a higher profitability and better environmental sustainability when intensifying the livestock production sector rather than the crop production sector (Müller 2006, Djanibekov 2008, Bekchanov et al. 2012).

From a pure water use reduction perspective, an obvious choice for a development path could include the promotion of agro-processing industries rather than solely concentrating on the production of raw agricultural commodities which fact is in line with previous conclusions (Rudenko et al. 2009). Particularly supporting the development of the entire cotton value chain and increasing the production of the products with high added value has the potential for increasing income for producers while reducing water needs. However, the current lack of sufficient investment resources, limited access to up to date technologies, and the lack of qualified personnel (Weinthal 2002) may impede a further development of a stable and profitable agro-processing sectors.

Indeed, in terms of economic growth impacts and total water use only, the non-agricultural processing industries and service sectors has higher potential for sustainable development than the agricultural or agro-processing industries since water is not a driving factor for industrial and services sectors. In general, according to a multi-criteria assessment of ranks of the sectors while considering equal weight for both economic growth impact and water use intensity, construction, machinery, metallurgy, and ‘other services’ sectors ranked as the most important sectors with high potential for sustainable development.

The findings based on the input-output model analysis are not only relevant for Uzbekistan, but also for the four other countries in Central Asia—Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan— at least partially, due to the many similarities in economic conditions, legal-political environments, and geographical location, as well as due to their common historical background. Turkmenistan, a country mostly covered by desert and located at the lower reaches of the Amu Darya River, perceived the opportunity for more productive water use through economic restructuring and already developed its cotton processing sector by increasing the share of domestically processed cotton from 6% to 42% between 1991 and 2001 (Dukhovny and Schutter 2011). The cotton value chain improvements in Turkmenistan indicate the importance and possibility of sectoral transformation in the rest of the Central countries as well for achieving more sustainable economic growth.

Although several alternative crop and non-agricultural production options have huge income growth and water use reduction potential than the currently dominant cotton production, Weinthal (2002) argued that diversifying crop production is not a priority interest of the national administration because of the important role of cotton production in social control, particularly in Uzbekistan. That explains also the continuation of the dominance of cotton production in crop portfolio and preservation of state control over cotton production even in the aftermath of independence. Even though such conclusions bear much truth during the first decade of independence, the reason for a continued reliance on cotton was since then more likely due to the lack of qualified employees and reduced access to technological innovations to initiate the development of the non-cotton industries. Therefore, efforts to maintain adequate human and knowledge resources are essential at present for further economic and institutional reforms.

Indeed, economic growth and water use reduction potential are necessary, but not sufficient determinants of the key sectors for economic growth. Although water requirements in the industrial sector are currently much lower than those in the agricultural sector, return water from industrial processes is often much more hazardous than agricultural return flows (Chapagain and Hoekstra 2004). Thus, when developing the industrial sector, this issue should be taken into account and means to minimize the negative influences of industrial effluent on the environment should be reflected. In addition to return flows, hazardous atmospheric emissions from the industrial sector are also much more harmful to the environment than those from the agricultural sector. Since the present analyses excluded environmental performance indicators other than total (direct plus indirect) water consumption, the inclusion of more environmental indicators in multi-criteria decision making analysis would enable more robust conclusions on the sustainable development potential of the sectors in Uzbekistan. Moreover, international comparative advantages, technological upgrading, institutional and governance settings, and many other factors as well as the weights for these criteria which are subject to the decision makers are also essential elements (Bryan et al. 2005). Therefore, the findings in this study can be seen as a first step towards more broader multi-criteria evaluation framework.

The findings for Uzbekistan together with the studies by Lenzen (2003) for Australia, Dietzenbacher and Velázquez (2007) for Andalusia (Spain), Zhao et al. (2009) for China, and Feng et al. (2011b) for the United Kingdom illustrate that the IO model approach is a powerful tool for estimating and comparing direct and indirect water use requirements of different economic sectors. It has clear advantages over cost-benefit methods and bottom-up approaches of estimating water footprints, allowing the analysis of the economic impacts and water use intensities of the sectors while considering the interdependence of all economic sectors. Despite its advantages over several methods because of a comprehensive analysis of economic and water use interlinkages across the sectors (Dudu and Chumi 2008), the IO model is not free of limitations for making economic decisions over water allocation. One shortcoming of this method is rooted in the assumption of linear relationships among consumption and production patterns, and a fixed amount of water use per unit of outputs. Marginal water productivity, which is based on a non-linear water-output response function, is more decisive for economic decision making over the allocation of scarce water resources (ANWC 2008). The model also does not consider the availability and cost-benefits of technical innovations for improving water use efficiencies in crop production. Therefore, the results of the model are valid only under the assumption of constant amount of water requirement per unit of economic output, linear relationships between consumption and production variables, and lack of technical innovations. Furthermore, this method does not capture the more detailed hydrological and biogeochemical processes (Brouwer and Hoffkes 2008) and does not allow solving for spatial or temporal water allocation problems (Mukherjee 1996). Additionally, since IO datasets are usually available for the entire country rather than its regions another modeling approach is needed for analyzing water resource allocation among different water demand sites within the basin. More detailed water use and economic relationships within a river basin and spatial water allocation are usually formulated based on hydro-economic river basin management models which will be discussed in the next chapter.

4 THE POTENTIAL OF WATER MARKETS FOR IMPROVED WATER MANAGEMENT IN THE ARAL SEA BASIN[1]

4.1 Introduction

This chapter describes market-based water allocation as an option to deal with water sharing conflicts and consequent inefficiency of water allocation in the ASB. Water allocation practices based on current administrative management in the ASB do not create incentives for efficient water use, as discussed in Chapter 2 in the study area description. Under conditions of water scarcity, measures of treating water as an economic good such as water pricing or institutional arrangements such as market-based water allocation schemes creates incentives for improving water use efficiency (Dublin Conference 1992). Market-based water allocation under clearly defined legal access for a specific amount of water withdrawal for each user enables efficient distribution of water resources by allowing water rights trading. Additional water transfers can occur when users with higher water productivity acquire voluntarily relinquished water rights of other users for compensation (Dinar et al. 1997). Trading can increase general welfare and water productivity for the entire basin because water is generally transferred from lower-value to higher-value uses (Howe et al. 1986, Rosegrant and Binswanger 1994, Easter et al. 1998, Ringler 2001). In addition to considering water as an economic resource, adopting holistic approaches such as the implementation of the IWRM paradigm that combines social and economic development with ecosystem protection through the coordinated management of land and water resources also improves water management efficiency. River basins are generally accepted as an appropriate unit of spatial water allocation analysis considering the interdependence of all water users and hydrologic systems within a basin (Keller and Keller 1995, Keller et al. 1996, Rosegrant 1997, Ringler et al. 2004). Moreover, increased competition for water among different users and anthropogenic environmental interventions can only be effectively addressed on a basin-wide basis (Ringler 2001).

This chapter begins with a detailed review of the river basin management models to identify research gaps. Next, comparisons of different water management institutions are presented and the justifications for water markets as appropriate tools for efficient water allocation are discussed. The incentives for water users to cooperate under tradable water use rights such as to gain additional revenues are demonstrated based on a theoretical hydro-economic model. Evidence on how the implementation of tradable water rights has worked in different countries such as the US, Australia, Chile, and India, and a discussion on their relevance for the case of the ASB are provided. Then, an analytical hydro-economic model of optimal water allocation and water rights trading is demonstrated. It is followed by a hydro-economic model based analysis of the potential economic and environmental effects of introducing water rights trading in the ASB. The chapter ends with the discussion of the results and some concluding remarks.

4.2 Hydro-economic river basin management modeling: literature review

4.2.1 *International research experiences on hydro-economic modeling*

4.2.1.1 Historical overview of hydro-economic river basin management modeling practices

The development of hydro-economic river basin management models has a long history (Harou et al. 2009). In the early 1800s, Charles Navier introduced cost-benefit analysis methods to estimate

---

[1] This chapter was published as a ZEF Discussion Paper in modified form (Bekchanov et al. 2013a).

the financial viability of engineering works (Lund et al. 2006). Later the French engineer Jules Dupuit (1844) introduced the fundamental economic concept of consumer surplus, recognizing not only the need to consider construction and operating costs, but also the benefits of public hydrological structures and operating schemes (Harou et al. 2009). Throughout the 19th and 20th centuries economists and engineers have incorporated economic principles in the context of the analysis of hydrological systems. In 1955, a group of professors with engineering, economics, and political science backgrounds joined the Harvard Water Program for developing an integrated approach to water resource planning and management by combining engineering practices with economic theory (Maas et al. 1962, Mirchi et al. 2010). The researchers of the program introduced the river node based hydro-economic modeling approach in water management studies.

Early applications of economic water demand curves to optimize water allocation were made by Jacob-Bear et al. (1964, 1966, 1967, 1970), Rogers and Smith (1970), and Gisser and Mercado (1972) to analyze water issues in arid regions such as Israel and the southwestern United States (Harou et al. 2009). Hartman and Seastone (1970) theoretically demonstrated the potential economic gains of water markets. Howe and Orr (1974) analyzed tradable water rights while considering water quality. Several studies (Vaux and Howitt 1984, Howe et al. 1986, Booker and Young 1994, Becker 1995, Easter et al. 1998) quantified the potential gains from the reallocation of water through voluntary transfers. Recently hydro-economic river basin models have been improved extensively in order to portray complex hydrologic, economic, and institutional relationships more precisely. A CALVIN model developed by the researchers of the University of California is an example that includes many modern features of theoretical and empirical hydro-economic modeling techniques and addresses a wide range of water management problems (Lund et al. 2012).

4.2.1.2 Hydro-economic river basin modeling approaches: limitations and advantages

Currently hydro-economic river basin models are available that represent complex hydrological, agricultural, institutional, and economic aspects of water management systems. Linking relevant hydrological and agricultural processes to economic laws of demand and supply within integrated hydro-economic models would facilitate assessment of complex river basin management system (McKinney et al. 1999, Brouwer and Hofkes 2008). These models aim to identify more efficient water management schemes and examine water use policy strategies in order to provide sustainable use of water resources (Harou et al. 2009).

Traditionally there are two main approaches to hydro-economic modeling (Table 4.1):

1) Modular (compartmental) approach in which model components run separately, usually using outputs of one sub-model as an input (exogenous variable) in the next sub-model
2) Holistic (integrated) approach in which all subcomponents run within a single modeling framework that includes all variables endogenously

Each approach has its advantages and limitations resulting from model structure. The modular approach allows analysis of each sub-field in greater detail, but each model component should be updated and developed independently (Harou et al. 2009). Alternatively, holistic models can reveal causal relationships and interdependencies more effectively. Scenarios such as climate change impacts on water availability and economic outputs are easier to execute with holistic models since each sub-model does not need to be run separately as a result of changing policies or conditions (Harou et al. 2009). One limitation of this latter approach is the application of simpler formulation due to the complex nature of the linkages between the economy and water use. However, it should be noted that neither approach to combined modeling can provide an in-depth analysis of the economic sub-components and intersectoral interlinkages, which is relevant within IO modeling frameworks as discussed in earlier chapters.

Table 4.1 Hydro-economic river basin modeling approaches and their properties

	Options	Description	Advantages	Limitations
1	**Modular**	Components of final model are developed and run separately	Easier to develop, calibrate and solve individual models; allows detailed analysis of each sub-field	Each model must be updated and run separately; difficulty exists in connecting models with different scales
2	**Holistic**	All components are housed within a single modeling framework	Effective representation of causal relationships and interdependencies; easy performance of scenario analyses	Increased complexity of the holistic models requires simpler model components

Source: Adapted from Brouwer and Hofkes (2008) and Harou et al. (2009)

4.2.1.3 Empirical implementation of hydro-economic models

Hydro-economic river basin management models were applied to analyze a wide variety of water issues in different river basins throughout the world, including: spatial and intersectoral water allocation, water quality control, environmental management, flood damage and regulation, introduction of water markets, infrastructural development, and climate change adaptation. More detailed reviews of these studies were documented by Lee and Dinar (1996), McKinney et al. (1999), Lund et al. (2006), Heinz et al. (2007), Brouwer and Hofkes (2008), Cai (2008), Harou et al. (2009), Mayer and Munoz-Hernandez (2009), and Mirchi et al. (2010). In this study, the review was restricted to examples that address efficient water allocation and improved water management institutions.

Several hydro-economic models have addressed efficient water allocation in river basins. Ringler (2001) and Ringler et al. (2004) investigated the impacts of upstream hydroelectric power development and interbasin water transfer on the economies of upstream and downstream water users in the Mekong River basin. Bhaduri and Barbier (2008) analyzed the potential of cooperation on water sharing and negotiable transfers between upstream-India and downstream-Bangladesh in the Brahmaputra and Ganges river basins. Changes in long-term profits due to crop-mixing strategies were estimated using a modular model with three separate components—economic, hydrological, and agricultural—in the case of the Arkansas Valley of southeastern Colorado (Lefkoff and Gorelick 1990).

The benefits of introducing alternative water management institutions such as water use rights trading and water pricing have been also investigated by several studies. Booker and Young (1994), Draper et al. (2003), and Walter (2010) compared benefits under inter- and intra-state water rights trading. Ringler and Huy (2004) evaluated the economic efficiency and potential water transfers under brokerage and market clearing mechanisms. Rosegrant et al. (2000) and Cai et al. (2006) developed an integrated hydro-economic framework to analyze interactions between water rights trading and water technology adoption in the Maipo River Basin of Chile. Heidecke et al. (2008)

and Heidecke and Heckelei (2010) applied hydro-economic models to assess the impact of water pricing on surface and groundwater demand and agricultural income in the Middle Draa river basin of Morocco. While considering the role of geographic dimensions and associated political sovereignties, White et al. (2008) analyzed the potential, institutional structure, and implementation mechanisms of benefit sharing based water allocation. In contrast to mainstream approaches of optimizing water allocation based on the assumption of an omniscient social planner, a recent study by Cai et al. (2011) addressed decentralized river basin management within a multi-agent system framework. Overcoming the shortcomings of the mathematic optimization method in multi-agent based models, Kuhn and Britz (2012) offered a method of converting decentralized water allocation problems into a Mixed Complementary Programming (MCP) model. Despite the originality of the approach, the model is applied to the case of a hypothetical basin with oversimplified hydrological and production relationships. Possibilities of applying the model to the case of real basins with complex water uses and production relationships should be addressed further.

4.2.1.4 Issues in basin management modeling

In spite of rapid advancements in hydro-economic modeling, the integration of economic and hydrologic components within a single modeling framework is not an easy task (Cai 2008). Problems occur when different spatial scales, time intervals, and time horizons are relevant for economic and hydrological analyses. For instance, usually economic variables such as crop outputs, cropland areas, and prices are available for administrative regions, but water use and distribution variables are available for the area within the hydrological or sub-basin boundaries. Appropriate adjustments to match the spatial boundaries of both economic and hydrological systems is an important but difficult task. Aggregation of water user sites for modeling purposes may also reduce the robustness of results. In contrast, inclusion of detailed and disaggregated spatial scales may complicate finding solutions to these problems. Furthermore, economic models usually consider larger temporal intervals and longer time horizons than hydrological planning. Temporal intervals in economic analyses are usually one year. The period required for the long-term impacts of salinization on the benefits and deterioration of irrigation infrastructure and machinery to manifest should be considered in choosing the appropriate time horizon in economic modeling. In hydrological planning, considering weekly or monthly time intervals for crop water use and ground and surface water exchange processes is required. Time horizons should capture the climate driven cycles of water availability. However, data for detailed analysis of all these hydrologic processes and economic activities are not always available.

Despite comprehensive analyses of water markets, the incorporation of environmental benefit values into the allocation process is a common challenge in hydro-economic modeling research (Colby 1990a, Griffen and Hsu 1993). Most studies integrate environmental water needs via minimum inflows and thus do not consider the economic aspects of environmental water needs (Draper et al. 2003, Harou et al. 2009). Some studies estimate the value of environmental water indirectly, such as by assessing the alternative costs of increasing minimum environmental flow while reducing off-take water use and benefits (Green and O'Connor 2001, Qureshi et al. 2007). However, the direct inclusion of economic benefits of environmental systems in models is rarely found and evaluating the benefits of ecosystem services is subject to considerable debate (Harou et al. 2009). Difficulties in the evaluation of environmental benefits are due to the lack of markets for ecosystem services and the implicitness of their contributions to public welfare.

Another issue in hydro-economic modeling is the consideration of transaction costs that are incurred due to the establishment and maintenance of water management institutions. Since transaction costs are substantial, accounting for these costs will affect the optimal choice of policy instruments (McCann et al. 2005). To include these costs in modeling and policy analyses they must be measured (McCann et al. 2005). Despite this pressing need, only few studies have tried to quantify transaction costs because "*the measurement of transaction costs poses formidable difficulties*" (Williamson 1996:5). Difficulties arise because the magnitude of transaction costs depends on many factors, including the physical attributes of water use, the capabilities of water management institutions, and general institutional environments such as the legal system (Easter et al. 1998, 1999; Saleth and Dinar 2004; McCann and Easter 2004). In water market modeling practices, transaction costs are usually estimated with scenario-based analyses and considered as fixed amounts per unit of water volume traded (Challen 2000:42, Cai et al. 2006, Pujol et al. 2006b, Wang 2012). For example, Cai et al. (2006) considered scenarios with transaction costs that varied between \$0.00 to 0.20 USD per m^3 to analyze their impacts on total net benefits, gains from water rights trading, and the volume of water transfers. Similarly, Wang (2012) assessed the influence of the transaction costs on the changes in gains of water rights trading and water use efficiency assuming a range of transaction costs from 0 to 10 Yuan per m^3.

4.2.2 River basin management modeling in the context of the Aral Sea basin

4.2.2.1 General overview

River basin management models were also widely used to address water allocation and irrigation development issues in the ASB. Despite a considerable amount of research conducted on water management in the ASB by Soviet researchers, the results of these efforts were mainly available for internal use within water management organizations. The SU's cotton self-sufficiency policy motivated the expansion of irrigated areas in the ASB by gradually transforming desert areas with advanced irrigation networks, and early water management modeling efforts focused on the minimization of capital and labor costs of irrigation development. In the post-Soviet period, interest in water management issues in the ASB among the international academic community increased, and together with local scientists, foreign researchers actively participated in research projects, contributing to the improvement of water management modeling practices..

Water management models applied for the ASB case study can be categorized into two groups: 1) simulation; and 2) optimization. Simulation models deal with "what if…?" type questions, while optimization models search for answers to "what is the best…?" type questions (Harou et al. 2009). Simulation models were applied to estimate water needs for different activities such as food production, and residential and industrial uses under different scenarios of population growth, income increases, climate change, and technological progress. Concurrently, optimization models intended to maximize economic proceeds or minimize production and water delivery costs through the optimal allocation of resources. It should be mentioned that despite the differences in the objectives of these two types of models, simulation models can be transformed into optimization models with minor changes in their equation systems, or conversely optimization models can be transformed into simulation models with few changes and then be used for simulation purposes. Furthermore, simulation models sometimes can be also developed as part of multi-component optimization models.

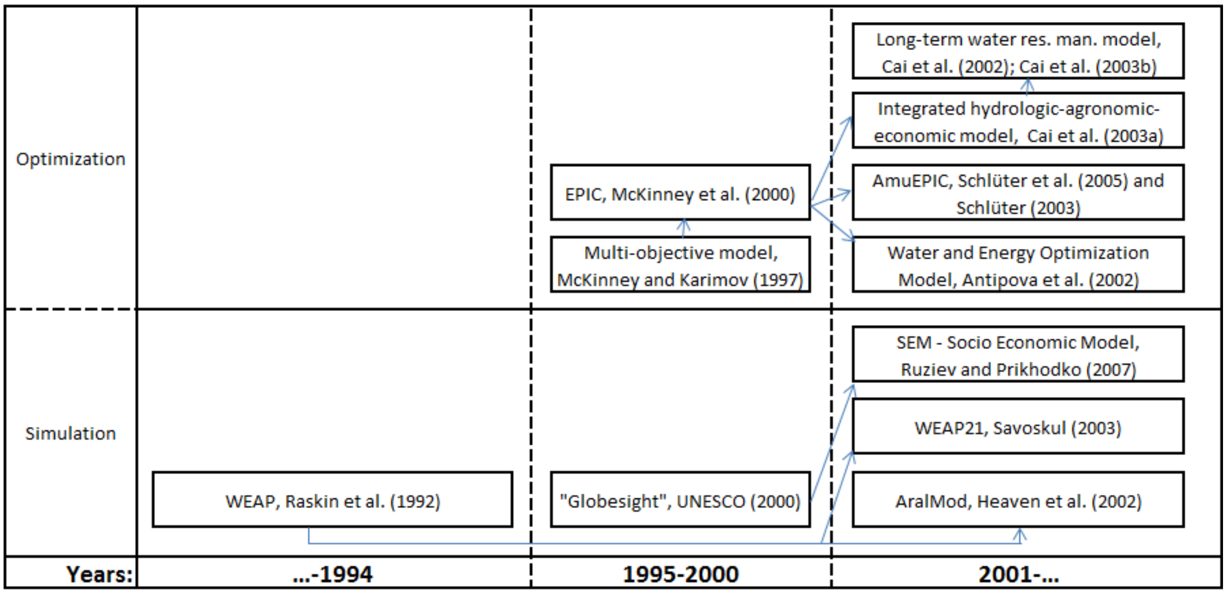
The historical development of different water management models is briefly discussed in this section, beginning with descriptions of simulation models followed by optimization models. Brief descriptions of the models and their purposes are presented in Table 4.2. The historical development of water management approaches in the ASB and their interdependencies are presented in Figure 4.1.

Table 4.2 Water allocation models applied to the case of the Aral Sea basin

Model	Modeling approaches						Major problem(s) addressed	Location	Novelty/approach/striking results	Citation
	Hyd	HE	Sim	Opt	Dyn	Sta				
AralMod	x	-	x	-	x	-	Water demand and supply simulation	Syr Darya basin	Modeling hydrological processes with more detailed temporal steps	Heaven et al. (2002)
SEM-Socio Economic Model	-	x	x	-	x	-	Water demand and supply forecasting	Aral Sea basin	Adapted version of the Globesight; Food self-sufficiency in the ASB until 2020	Ruziev and Prikhodko (2007)
WEAP21	-	x	x	-	x	-	Water demand and supply management measures	Syr Darya basin	Integrated quantitative/qualitative approach to modeling water scarcity and adoption of mitigation measures	Savoskul et al. (2003)
EPIC	x	-	-	x	-	x	Water, salt, and energy management	Amu and Syr Darya basins	User-friendly computer software that incorporates GIS with multiple-objective optimization model	McKinney and Savitsky (2000)
Water and Energy Optimization Model	x	-	-	x	-	x	Irrigation and energy production trade-offs	Naryn-Syr Darya Cascade	In-detail analysis of energy production and trade relationships	Antipova et al. (2002)
AmuEPIC	x	-	-	x	x	-	Long-term water allocation; delta ecosystem sustainability	Amu Darya basin	Detailed analysis of Amu Darya River delta and impacts of water availability on ecosystems;	Schlüter et al. (2005); Schlüter (2003)
Integrated hydrological-agronomic-economic model	-	x	-	x	-	x	Economically optimal intersectoral interspatial water allocation	Syr Darya basin	Endogenous modeling of investment costs and irrigation efficiencies; crop patterns and irrigation efficiency should change for sustainability	Cai et al. (2003a)
Long-term water management model	-	x	-	x	x	-	Sustainable water resources management	Syr Darya basin	Multi-disciplinary approach; Sustainability indicators; salt accumulation impact on yield	Cai et al. (2002); Cai et al. (2003b)

Notes: Hyd-hydrologic; HE-hydro-economic; Sim-simulation; Opt-optimization; Dyn-dynamic; Sta–static

Figure 4.1 River basin management models in the Aral Sea basin



Source: Author's presentation

4.2.2.2 Simulation models

Shortened time intervals allowing simulation of more detailed and realistic hydrological relationships were the focus of "*a real-time mass balance river/reservoir model*" called AralMod developed by Heaven et al. (2002). The model was developed for the Syr Darya basin with time intervals of six days and a time horizon of 20 years. AralMod is a hydrological dynamic simulation model similar to WEAP. The model estimates the overall water balance for the river, the main reservoirs, the North Aral Sea and the irrigation zones, and enables planners to analyze the impacts of different water management measures on water availability in the different river nodes. In addition, the model calculates irrigation efficiency in all irrigation schemes and indicates the zones with lower water use efficiency that can be as low as 20%. It was also shown that the amount of water flowing to the North Aral Sea under the existing irrigation water use regime would not be sufficient to restore the sea to 1960s levels.

The Globesight model (UNESCO 2000) was used to analyze sustainable development opportunities in Kazakhstan (Kenzheguzin and Yessekina 2004). In this case a water deficit of about 6 km^3 and energy demand that was almost two times higher than the supply were predicted by 2030. Later Ruziev and Prikhodko (2007) adapted another version of Globesight for the entire ASB and called it the "Socio-Economic Model" (SEM). Since the targeted values for population growth, income increase, and consumption are comparatively lower in this study than in the Irina and Gundo models, water scarcity in the ASB was not predicted until at least 2020.

Savoskul et al. (2003) applied WEAP21, an improved version of WEAP (Raskin et al. 1992), to analyze the impacts of climate change on water availability, water use, growing season length, crop yields, and food production in the Syr Darya basin. The authors found insignificant impacts of climate change on water flows, duration of growing period, and cropland and pasture productivity during the 2010–2030 period. However, increased probability of droughts and floods, less water availability despite increasing growing period length in the middle parts of the basin, and decreased productivity of the rangelands in semi-arid and alpine areas in the period 2070–2090 were predicted. The authors also analyzed the potential of different adaptation measures and strategies to cope with climate change impacts from environmental, food security, and industrial perspectives. As environmental options they suggested developing dikes, preventing desertification, and establishing sewage treatment plants. From food security perspective they examined improving water use efficiency, changing crop patterns, increasing water storage capacity, decreasing water losses in the irrigation network, increasing crop area, and reviving cattle breeding. Building new reservoirs and hydroelectric power plants and generating hydroelectric power in winter were tested from an industrial development standpoint. Based on different mixes of these measures, four strategic options featuring particular types of measures were developed: environmental, food, industry, and mixed. Under the implementation of any strategies, no considerable additional flows to the Aral Sea were predicted although considerable increases in food production, farm incomes, and energy production were possible.

4.2.2.3 Optimization models

Extending single-objective optimization models, McKinney and Karimov (1997) constructed a multi-objective water allocation model for the Amu Darya and Kashka Darya River basins with detailed water (linear) and salt (non-linear) balances. The main objectives of this model are to satisfy projected water demands, to minimize the difference between water deficits for all water user sites, and to minimize salt concentrations in the river. It was the basis for the model called the EPIC (abbreviation of Environmental Policies and Institutions for Central Asia) which considers energy, irrigation, and salt management for the entire ASB (McKinney and Savitsky 2000, 2001a, 2001b). The model focused on water use and distributional relationships between the water rich (hydroelectric energy producing upstream countries) and water dependent (irrigated agriculture oriented downstream) countries. The main criteria in the model are to minimize water deficits for all water users, to minimize energy production costs, and to minimize ‘energy supply-internal demand’ gaps in the Central Asian countries.

A shortened version of EPIC, but with detailed account of the energy production system in the Syr Darya Naryn Cascade was developed by Antipova et al. (2002) to estimate the compensation required for reduced energy production in upstream countries in favor of irrigation production in downstream countries. Though the shortcomings of the model such as summing indicators with different dimensions in the objective function, emphasis on the interests of Kyrgyzstan, and neglect of the downstream flooding/drought effects are obvious, based on the model results the authors argued that increased amounts of compensation from downstream countries are needed for the long-term and balanced use of water.

Schlüter et al. (2005) applied a spatially expanded EPIC model (AmuEPIC) for a detailed analysis of water management and environmental systems in the deltaic zones of the Amu Darya River. AmuEPIC facilitates the development of future water management simulations for the Amu Darya River “*on a rather large spatio-temporal scale as the basis for evaluation of their potential ecological effects in the delta region”* (Schlüter et al. 2005). Schlüter and Rüger (2007) combined AmuEPIC with spatially explicit statistical models of landscape change and estimated groundwater levels and flooding/drought frequencies and their impacts on the riverine forests in the delta regions under different levels of river runoff. This model was also used to analyze the impacts of a guaranteed annual supply of water to the Aral Sea (10 km^3) and annual decreases of irrigation demand (1% per annum) on environmental sustainability in delta zones (Schlüter et al. 2006). The authors found worsening environmental conditions due to reduced water availability, improved environmental conditions along the river under the guaranteed minimum water delivery to the Aral Sea, and improved habitat quality for wildlife in the central and northeastern parts of the delta under the reduced irrigation demand through implementing water-saving technologies.

A comprehensive analysis of the water management system in the ASB based on total economic benefit optimization was conducted by Cai et al. (2002, 2003a, 2003b). The authors (2003a) applied the short-term (annual) integrated hydrologic-agronomic-economic model for the case of the Syr Darya basin to maximize the total benefits of water use in irrigation, hydroelectric power generation, and environmental systems. This model was based on a river basin network, including several supply nodes such as reservoirs, aquifers, river reaches, and demand sites such as irrigation zones, industrial, and municipal water use sites. The main components of the model are: water and salinity balance in the river basin network and crop root zone, irrigation and drainage processes, crop yield functions in response to water stress and soil salinity, production functions for each sector, tax and subsidy schemes, and infrastructural investment. The model results under the optimization scenario indicated that additional investments amounting to $366 million USD were necessary, that help increase conveyance efficiencies from 0.5–0.6 to 0.7–0.8 and irrigation efficiencies from 0.5–0.65 to 0.8–0.85, with different changes across the irrigation regions.

Considering the limitations of a short-term hydro-economic model for capturing environmental factors that decrease yield in the long-term such as the degradation of groundwater quality and soil salinization, Cai et al. (2002, 2003b) extended the Syr Darya model and developed a “*long-term water resources management model*” for analyzing sustainability. The modeling framework consists of an “*inter-year control program*” and a sequence of yearly models. The focus of the inter-year model is to maximize the long-term objective function, which is a linear combination of different sustainability indicators that includes risk (agricultural and environmental water supplies), environmental integrity, equity (temporal and spatial), and economic acceptability. The findings indicated that increasing water flows to the Aral Sea up to the level of the 1960s would diminish irrigation benefits unless appropriate infrastructural improvements and crop pattern changes take place (Cai et al. 2002, 2003b). Cotton areas would be largely replaced by other crops to attain optimal sustainability in contrast to the results of the WATERSIM model, which showed that cotton production expansion was necessary to increase income (Abdullaev et al. 2009). Despite many methodological contributions to hydro-economic modeling studies, the main limitations of these integrated hydrologic-agronomic-economic models are that spatial scales were aggregated at the irrigation zone level and only a limited number of crops were considered (Cai et al. 2002, 2003a, 2003b).

4.2.2.4 Limitations of the Aral Sea basin water management models and research needs

Based on the discussion of models applied to deal with water management issues in the ASB and according to their interrelationships with each other, five major groups of the models that use different approaches in water allocation can be differentiated:

1) Hydrological simulation models (e.g., similar to AralMod and WEAP) which estimate water demand, supply, and environmental water availability, and usually use equal or priority-based water allocation considering fixed proportional shares;
2) Socio-economic hydrologic simulation models (e.g., similar to SEM and Globesight) which examine water availability under specified food, feed and energy demand using a similar approach to water allocation as in the previous case; equal distribution of water scarcity by reducing water use limits of all users proportional to the water scarcity level is assumed;
3) Multi-objective demand-supply gap minimization models (e.g., similar to EPIC) that minimize water scarcity levels across demand sites through minimization of energy scarcity and energy production costs;
4) Integrated hydrologic-agronomic-economic models (e.g., Cai et al. 2002) that optimize water use benefits and consider water use and yield relationships in efficient water allocation.

Despite the gradual improvements in water allocation modeling, review of the studies at ASB level showed that there is no study addressed the potential role of market-based water allocation for efficient water distribution rather than continuing the current practices based on administrative management. Integration of the concept of water value on the basis of economic demand and supply functions to currently used river basin models would increase the applicability and value of hydro-economic models (Hoekstra et al. 2001). Since the social optimum for the entire basin in terms of economic benefits would be attaining the highest possible benefit at the basin level, this option requires reallocations of the water rights from the users with lower water productivity to the users with higher productivity. However, since users have different and often conflicting interests over common water resources the social optimum concept does not work in reality—the users with lower productivity do not sacrifice their private benefits for the overall benefits to society at the basin scale. This is particularly true when the user with lower productivity is located in an upstream region. Compensation mechanisms that incentivize both higher and lower water productivity users to cooperate in order to attain basin scale (synergetic) benefits and share them equitably are required for improving overall water productivity. Water pricing and market-based water allocation are recommendable tools for incentivizing water users for more efficient water use, both through cooperation and adopting efficient water management technologies. Before moving to the empirical analysis of the potential gains from water markets in the case of the ASB, the functioning mechanisms of these market-based water allocation institutions from both conceptual and theoretical point of view, as well as empirical evidence from existing water markets in other parts of the world are discussed in the next chapter.

4.3 Theoretical-conceptual aspects of water allocation and water markets

4.3.1 Conceptual aspects of market-based water allocation

4.3.1.1 Water allocation institutions

The existence of multiple water users sharing river basin water resources necessitates setting water allocation rules among these users to avoid conflicts. This task is particularly challenging under conditions of water scarcity and should consider social and environmental impacts of water allocation decisions. Water allocation options can be grouped as centralized (top-down) and decentralized (bottom-up) approaches according to the type of governance. In centralized water allocation a single administrative unit (usually a government) takes control over water resources use and allocation. In contrast, the decentralized approach provides more opportunities to water users to participate in decision making processes and to cooperate with each other in water sharing and management. However, this is not the only way of classifying water allocation options. Dinar et al. (1997) distinguished four types of water allocation mechanisms and described their advantages and disadvantages (Table 4.3):

1) Marginal cost pricing;
2) Public (administrative) water distribution;
3) Water markets;
4) User-based allocation.

Marginal cost pricing is characterized by charging for water use based on the marginal cost of each additional unit of water. Since this option equates the marginal value of water with its marginal cost, it is considered an economically efficient way of determining water allocation. Marginal cost pricing can be applied to develop differential prices based on water quality and reliability (i.e., higher prices for higher quality or higher reliability). Advantages of this approach are its theoretical efficiency, its ability to reflect the scarcity of water and prevent overuse, and its implementability and compatibility with efforts to collect pollution and tax charges. Disadvantages include the difficulty of estimating marginal cost values, the neglect of equity issues, and implementation difficulty due to the volumetric monitoring requirement; and in the case of canal irrigation systems, a general lack of reliability of water supplies.

Table 4.3 Water allocation mechanisms

Water allocation mechanism	Description	Centralized (CD) or Decentralized (DCD)?	Advantages	Disadvantages
Marginal cost pricing	Targets a price for water equal to the marginal cost of water supply	CD	Theoretically efficient; prevents water overuse under conditions of drought	Difficult to estimate correct marginal cost; neglects equity; requires volumetric monitoring (which is very costly)
Public (administrative) water allocation	State decides what water resources should be used and allocates and distributes water among users	CD	Can be used to promote equity; can protect the poor; can consider environmental needs	Does not take into account the value of water in time and space, and generally fails to allocate water to the highest value
Water markets	Referred to as a trade of water (use) rights	DCD	Induces efficient water management; empowers water users	Difficulties in measuring water, defining water rights when flows are variable, and investing in conveyance systems; third party effects; need for and difficulty of considering transaction costs
User-based allocation	Based on collective action institutions with authority to make decisions on water rights	DCD	Flexible to adapt water delivery patterns to meet local needs; administratively feasible and sustainable; politically acceptable	Requires a very transparent institutional structure; effectiveness for inter-sectoral water allocation is limited

Source: Adapted from Dinar et al. (1997)

Public water allocation is characterized by the dominant role of government intervention in granting permits to use different water sources, and allocating and distributing water. Public distribution is usually associated with physical water use norms and political influence. Public intervention in water resources development and management is justified since water is a common resource that belongs to an entire community and the investment costs of water development are usually beyond the capacity of private sector actors. Advantages of this approach are that public water allocation can promote equity objectives, can help protect the poor, and can help to ensure water supply for environmental needs. Disadvantages of public options are that water prices, if charged, often do not reflect the real value of water, leading to water overuse or misallocation, and the option, unless linked with economic objectives, does not create incentives for users to use resources efficiently.

Market-based water allocation operates based on tradable water use rights. Water markets can provide additional water supply for high value uses without developing new sources and create incentives for more efficient water use by compensating for sales of water normally used for less valued applications. The necessary conditions for establishing formal water markets generally include government intervention, such as: (1) defining initial water use rights for each user, (2) organizing the institutional and legal frameworks for trading, (3) and building necessary basic infrastructure for water transfers (Holden and Thobani 1995). Rosegrant and Binswanger (1994) enumerated several advantages of market-based water allocations, such as: (1) empowering water users by considering their interests in water reallocation and compensating for sales, (2) increasing water rights tenure security, which incentivizes investment in water-saving technologies, (3) providing opportunities to gain additional benefits through the sale of water saved through increased efficiency, (4) providing incentives for water users to consider external costs caused by their water use, and (5) greater acceptability among water users relative to volumetric pricing, which is generally seen as expropriation of traditional water use rights. Water rights trading can occur among the users at the scale of the small sub-catchment as well as at the entire river basin scale. Additionally market-based water allocation is more responsive to climate, crop price, and water supply changes than centralized water allocation (Dinar et al. 1997). Disadvantages of market based systems are derived from the difficulty of measuring water volume, difficulty of defining initial water use rights when water flows are variable, the necessity to invest in water delivery infrastructure, and third party effects of changes in return flows.

User-based allocation of water resources requires collective action institutions with the authority to regulate water use rights as evidenced by farmer-managed irrigation systems (Dinar et al. 1997). A wide variety of rules for water distribution exists within such systems, such as rules based on timed rotation, water depth, land area, or flow share restrictions (Yoder 1994). The effectiveness of the system largely depends on social norms and the power of local institutions (Dinar et al. 1997). The advantages of the system are its adaptability for meeting local needs, the feasibility of administrative regulation, and acceptability to governments. Disadvantages include the size limitation of farmer-based systems, usually restricted to local communities, the challenge of dealing with inter-sectoral water allocation, and the need for very transparent institutions. Elite capture is a potential problem in such systems.

Summing up, although all water allocation institutions have advantages and disadvantages while being relevant at different scales (local, national, basin), water markets have the potential to improve allocation efficiency and are particularly relevant for basin level water management.

4.3.1.2 Conceptual framework: water market mechanism, initial water rights, and transaction costs

Increased competition among water users for limited water supplies in river basins necessitates effective water allocation institutions that provide efficient, equitable, and sustainable distribution of water resources (Ringler 2001). Unilateral water abstractions by upstream water users will not be efficient for the entire system under water scarcity conditions as it prevents equal marginal water productivity for all water users. An equitability criterion requires that any reallocation of water resources should increase overall basin-wide benefits without diminishing the welfare of any water user, and ensures compensation for the lost benefits to less productive water users. Environmental sustainability suggests that future water users will be able to enjoy the same benefits and similar levels of ecosystem and environmental services as current users do. Maintaining the efficiency, equitability, and sustainability of water allocation at the basin level in turn depends on several factors, such as the relative power balance among water users, prioritization of the specific sectors within national economies, and national strategies on food security or export revenue earnings (Ringler 2001).

Traditional administrative methods of water allocation have been based on the consideration of water as a public good emphasizing on equitability of water sharing. However, water overuse and misallocation, increased costs of developing new sources, and the poor quality of public agency services point to the need for alternative ways of efficient water allocation and management. Water markets offer a mechanism for incentivizing water users to increase water use efficiency.

Additional gains from water rights trading are feasible because of the heterogeneity of the economic value of water, variation of marginal water profitability across the water user sites, and the differential water needs by sectors across space and time. In addition to economic efficiency, equity in water distribution can also be addressed through compensation to users with low water use efficiency who voluntarily transfer their water (use) rights to more productive users. In river basins shared by several states such as the ASB, upstream users generally divert abundant water resources to meet their internal demands, releasing less water to downstream users and the environment in dry years (Sokolov and Dukhovny 2002, Müller 2006). Tradable water use rights under these conditions may lessen the burden of scarcity by compensating less productive water users through sales and benefiting more productive water users through increased water availability. As a result, the overall benefit to water use in the basin can be increased without adversely affecting any user.

While markets have strong advantages for incentivizing to use resources more efficiently under scarcity conditions, the function of markets depends on specified and transferable property rights (Coase 1960). In the case of water markets, their establishment requires clear, secure, and transferable water use rights. Despite several attempts to develop general rules for sharing river basin resources based on principles of equity, reasonability, sustainability, and optimality (ILA 1966, UNECE 1992, UN 1997), there is no universal guideline or legal treatment for establishing initial water use rights. The following major principles of water use rights are practiced in different river basins (Wolf 1999):

1) *The doctrine of absolute territorial sovereignty* (or *the Harmon Doctrine*): often claimed by upstream regions this policy reserves state rights to control water resources within national territory without regard for effects on other regions/users;
2) *The doctrine of natural water flow* (or a*bsolute riverine integrity*): bases access rights on natural river flow crossing users territory;
3) *The principle of prior appropriation* (first come, first serve): bases water use rights on historical use;

4) *The principle of community of interests*: treats river basin as a unified economic system and implies allocation of water to maximize benefits of all user regions in an integrated manner;
5) *The principle of equitable utilization of river waters*: bases water access rights on equitable allocation through mutual agreements, usually with regards to the size of user populations.

The selection and implementation of these rules depend on hydrography, historical water use patterns, social values, and the political authority of distinct users.

The transaction costs of establishing and maintaining water markets are also essential for evaluating overall economic gains from trading and choosing policy instruments. Transaction costs occur due to conducting research, seeking information on potential buyers and sellers, designing and implementing water rights trading rules, coordinating and administering water transfers, monitoring water use and distribution, and enforcing agreements (McCann and Easter 2004). The level of transaction costs varies depending on physical attributes of water use, water related institutions, and the general institutional environment (McCann and Easter 2004). Physical attributes include the availability and conditions of irrigation infrastructure, reliability of the water supply, the size of transfers, effects on third parties, and water attributes (quality, quantity, temporal, and spatial). Water related institutions that impact transaction costs include: existing (initial) water rights regimes, the power and rent seeking behavior of participating parties, and the existence of conflict resolution and contract enforcement mechanisms. Transaction costs are also influenced by general institutional environment factors such as the governance system, the legal system, social norms, and social capital.

Due to heterogeneous physical and institutional conditions, and due to the inclusion of different elements into the calculation, transaction costs vary by country and study. Transaction costs in the western United States averaged 6% of the price paid for water transfers (Colby 1990b). The overhead costs paid by the State Department of Water Resources for the California Water Bank were nearly 8% of the total costs of purchased water (Howitt 1994). Water transaction costs incurred by farmers in Chile were 7–23% of the price of water transfers (Hearne and Easter 1995). In Australia, expenditures on water transfers varied from 3% to 12% of the price of water entitlements (Challen 2000, ACG 2006). Water rights trading is only justifiable if transaction costs are lower than the additional gains by water market participants. Once transaction costs are low enough and the initial water rights are established consensually, water markets can provide mutually beneficial water transfers.

4.3.2 Theoretical models of efficient water allocation and water rights trading

Before considering the potential gains of introducing market-based water allocation mechanisms in real life conditions based on extensive data analysis it is better understand the availability of potential gains of market-based water allocation through a simplified theoretical framework of mathematical equations and geometrical illustrations. The theoretical models address water allocation between upstream and downstream users in a hypothetical river basin with two water users (agents). Initial model considers optimization of water use benefits for the entire basin while the other subsequent models include additional components of water rights trading, asymmetric distribution of power in the water market, and transaction costs of water rights trading.

4.3.2.1 Efficient water allocation scheme

For simplicity and explanatory purposes, the theoretical framework is based on a hypothetical river basin where common water resources are shared by two users—water user A and water user B. Without loss of generality, water user A is designated as an upstream agent and water user B is designated as a downstream agent along a shared riparian system. Several assumptions must be made about the users, the features of benefit functions, and resource availability. The first assumption is that each water user has a single aggregated economic sector. The second assumption is that water benefit functions to users follow concave, quadratic-like functions. Quadratic functions satisfy most of the properties of the theoretical benefit function commonly described in microeconomics textbooks. Due to their simplicity, their results are also relatively simple to calculate and interpret (Booker and Young 1994). The third assumption is that water resource availability is restricted in the hypothetical river basin. The fourth assumption is that there is only one shared resource—water—and that profit levels depend only on the availability of water. The last assumption considers absolute riparian rights that provides priority to upstream region in initial water rights distribution. Although some of these assumptions are too restricted to encompass all real life situations, they are still adequate to explain the efficient resource use concept under scarcity conditions.

Let's define w_A and w_B as actual water withdrawals by agents A and B respectively. Let $\pi_A(w_A)$ and $\pi_B(w_B)$ be the quadratic benefit functions of agent A and agent B with respect to water consumption respectively. w_A^{**} and w_B^{**} are optimal water consumption levels that accord the maximum individual benefits to agent A and agent B respectively. Agents try to use as much water as possible to attain the greatest benefit, but they do not use more water than the optimal water consumption level because increased water use above this point decreases benefit. If we define water availability in the entire basin with w, the following total water use constraint comes into force:

$$w = w_A + w_B \tag{4.1}$$

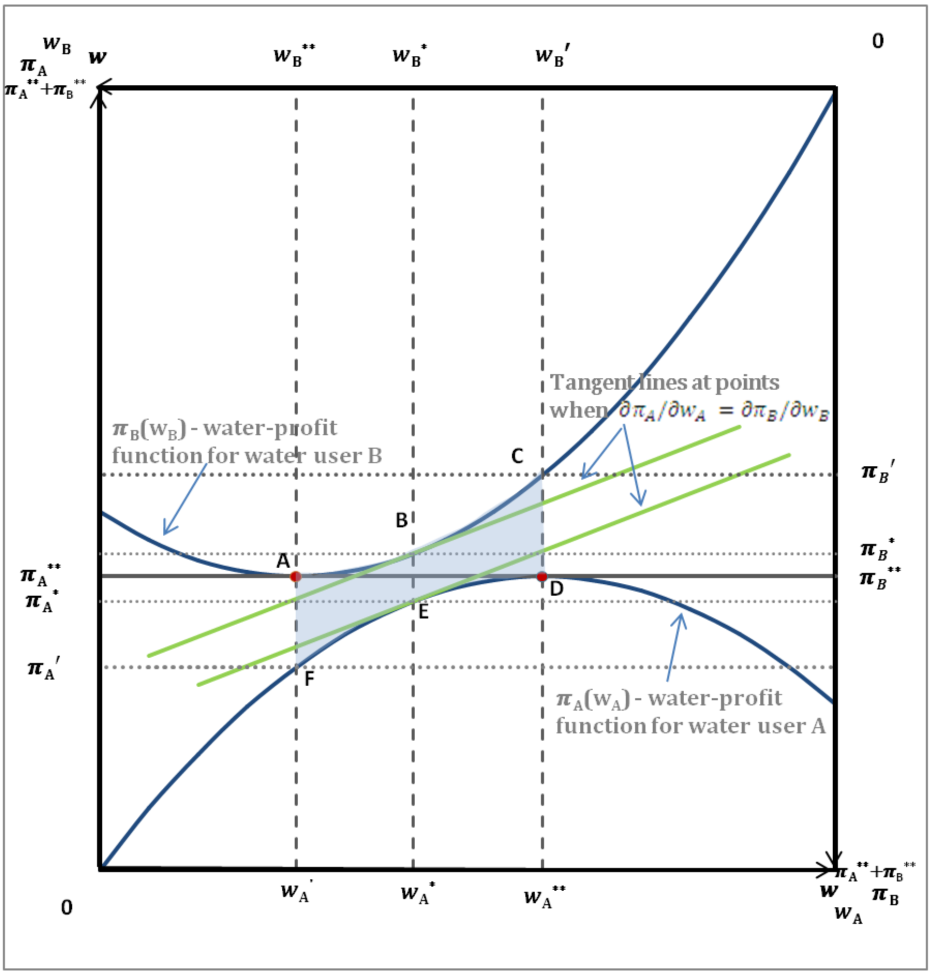
According to the third assumption, water availability should be less than the sum of optimal water use values:

$$w \leq w_A^{**} + w_B^{**} \tag{4.2}$$

π_A^{**} and π_B^{**} are defined as the maximum individual benefits from optimal water consumption for agents A and B respectively. Now the problem can be presented in a graphical format.

The graph below (Figure 4.2) was developed in a manner similar to the popular "Edgeworth Box" graph in microeconomic theory. The benefit of agent A (π_A) lies on the OY axis, in contrast to its water consumption level (w_A) on the OX axis. The benefit function of agent B is similar to the coordination plot of the benefit function for agent A, but in reversed order. The maximum available water to either agent, thus the full length of the OX axis, is equal to total basin water availability (w). However, both water users prefer to consume the amount of water that provides maximum individual profit. Thus, the most favorable water consumption level (w_A^{**}) to user A is at point ($w_A^{**}; \pi_A^{**}$), when it maximizes its benefit at π_A^{**}. Similarly, the most favorable water use level (w_B^{**}) to user B is at point ($w_B^{**}; \pi_B^{**}$) when the agent maximizes its benefit at π_B^{**}. If water resources are abundant these two points coincide with each other, allowing both agents to have their optimal profit. However, due to water scarcity total benefit is always less than the sum of individual optimal benefits.

Figure 4.2 Hypothetical scheme of efficient water allocation



Notes: Dark blue lines are for describing benefit functions of the water users A and B under optimization scenario; Water uses lie on the OX axis while benefits lie on the OY axis.

Source: Author's presentation

The full length of the OY axis is considered as equal to the sum of individual optimal benefits ($\pi_A^{**}+\pi_B^{**}$) of both agents. The total basin-wide benefit (π) is equal to the sum of individual benefits (π_A and π_B):

$$\pi = \pi_A + \pi_B \tag{4.3}$$

Knowing that additional water use above the optimal level decreases benefits, agents do not use more water than the optimal water consumption level:

$$w_A \leq w_A^{**} \text{ and } w_B \leq w_B^{**} \tag{4.4}$$

Considering conditions (4.1) and (4.4), water consumption of the user A is higher than w_A' (or $w - w_B^{**}$) but lower than w_A^{**}. Similarly, water use by agent B is higher than w_B' (or $w - w_A^{**}$) but lower than w_B^{**}.

The location of the water user is important for achieving the most favorable individual benefit. Without strong institutions managing the distribution of water in the basin or without power of agent B to influence agent *A* to consider its needs, agent *A* will prefer to consume the amount of water (w_A^{**}) that allows optimal individual benefit (π_A^{**}) while neglecting the interests of agent *B*. However, overall benefit in this case would be less than optimal basin-wide benefit level. As can be seen from Figure 4.2, when agent *A* agreed for the cooperation, the benefits lost by agent *A* ($\pi_A^{**} - \pi_A^*$) by reducing water consumption from w_A^{**} to w_A^* to release water for meeting the needs of agent *B* is less than the additional profit ($\pi_B^* - \pi_B'$) gained by agent *B* by increasing its water consumption from w_B' to w_B^*. In other words, the marginal productivity of water for agent B is greater than marginal productivity of water for agent *A*:

$$\frac{\pi_B^* - \pi_B'}{w_B^* - w_B'} \geq \frac{\pi_A^{**} - \pi_A^*}{w_A^{**} - w_A^*} \tag{4.5}$$

It can be mathematically proven that optimal basin-wide benefit is attained when the marginal benefits of the water users are equal to each other: $\partial \pi_A / \partial w_A = \partial \pi_B / \partial w_B$. The task in this case is to find water consumption levels for agent *A* and agent *B* (w_A^*, w_B^*) that provide the maximum overall basin-wide benefit:

$$\begin{cases} \pi = \pi_A(w_A) + \pi_B(w_B) \rightarrow max \\ s.t.: w = w_A + w_B \end{cases} \tag{4.6}$$

A Lagrangian function to solve this mathematical optimization problem is:

$$\mathcal{L}(w_A, w_B, \lambda) = \pi_A(w_A) + \pi_B(w_B) - \lambda \cdot (w_A + w_B - w) \tag{4.7}$$

Taking derivatives from this equation (4.9) allows the following series of equations:

$$\begin{cases} \dfrac{\partial \mathcal{L}(w_A, w_B, \lambda)}{\partial w_A} = \dfrac{\partial \pi_A(w_A)}{\partial w_A} - \lambda = 0 \\ \dfrac{\partial \mathcal{L}(w_A, w_B, \lambda)}{\partial w_B} = \dfrac{\partial \pi_B(w_B)}{\partial w_B} - \lambda = 0 \\ \dfrac{\partial \mathcal{L}(w_A, w_B, \lambda)}{\partial \lambda} = w_A + w_B - w = 0 \end{cases} \tag{4.8}$$

The condition that allows optimal overall basin benefit under cooperation can be derived from the first and second components of the system of equations (4.7) above:

$$\lambda = \frac{\partial \pi_A(w_A)}{\partial w_A} = \frac{\partial \pi_B(w_B)}{\partial w_B} \tag{4.9}$$

In the graphical illustration, the optimal basin-wide benefit level matches the points of ($w_A^*; \pi_A^*$) and ($w_B^*; \pi_B^*$) for each water user, respectively, when the slopes of the tangent lines to the benefit functions are equal to each other. As the objective function was $\pi = \pi_A + \pi_B \rightarrow max$, the problem can be alternatively reformulated as $\pi_A^{**} + \pi_B^{**} - G \rightarrow max$, where π is basin-wide water benefit and G is the sum of actual benefit deviations from individual optimal benefits for each user. Considering that $\pi_A^{**} + \pi_B^{**}$ is fixed, $\pi_A^{**} + \pi_B^{**} - G \rightarrow max$ is equivalent to $G \rightarrow min$. The latter in turn is equivalent to finding the shortest distance between the two benefit functions on the graph. The shortest distance between these two production functions is reached when the slopes of the tangent lines to these functions are equal to each other which is the case at water use level of w_A^* for agent A and water use level of w_B^* for agent B when marginal water productivities to the both users are equal to each other.

However, when an omniscient decision maker for the entire basin is assumed, individual profit (π_A^*) of agent A at the optimal basin-wide benefit level is lower than its profit level (π_A^{**}) when the agent acted egotistically. If agent B agrees to compensate agent A for reduced benefit (agent A's) and additionally offers some portion of its increased (agent B's) benefit, agent A would be more likely to participate in the cooperation arrangement of achieving optimal basin-wide benefit. Alternatively, agent B can purchase water use rights ($w_A^{**} - w_A^*$) from agent A at a price per unit of water ranging between $\frac{\pi_B^* - \pi_B'}{w_B^* - w_B'}$ and $\frac{\pi_A^{**} - \pi_A^*}{w_A^{**} - w_A^*}$. Thus, cooperation to achieve optimal basin-wide benefit would provide additional benefits to both agents if cooperative basin-wide gains were fairly shared among the users. Necessary water re-allocations to reach optimal basin-wide gains through introducing tradable water use rights will be discussed in the next section.

4.3.2.2 Water market mechanism

In the case of establishing a water market, the benefit functions of the water users would also be dependent on the amount of water sold or bought and the market price of water. However, before establishing a water market, the initial water rights of each water user should be clearly defined. Although, for simplicity, we assume absolute riparian rights in the theoretical examples in reality it can be based on population size, irrigated area, or mix of the options. Initial water rights distribution also depends on the political power of the riparian countries and water users. Considering specific characteristics of water such as its liquidity, the importance for basic needs of humans and other living beings it is important that the initial water rights distribution is based on the principles of equitability and morality. Moreover, when multiple users are considered it is better considering a single basin organization that coordinates water rights transfers knowing the demand by each user. For instance, at first knowing approximate annual water availability in the basin this organization distributes the water use rights or limits for each user as it is presently done by ICWC in the ASB. Then, each water user site evaluates and delivers its willingness to sell or purchase water use rights at different price levels based on its production functions and water demand curves. Based on the water demand curves across the water user sites the basin coordination unit decides about the amount and prices of water rights transfers within the basin.

Under the conditions of free market for water use rights, when we consider water user A is a seller of the rights based on the assumption of absolute riparian rights rule for initial water use rights distribution, total benefit (${\pi_A}^M$ and ${\pi_B}^M$ for agents A and B respectively) of the water users will consist of production benefit ($\pi_A(w_A)$ for agent A and $\pi_B(w_B)$ for agent B) and the water trading turnover ($WTP_A \cdot ws = WTP_A \cdot (w_A - {w_A}^0)$ for agent A or $WTP_B \cdot wb = WTP_B \cdot (w_B - {w_B}^0)$ for agent B):

$${\pi_A}^M = \pi_A(w_A) + WTP_A \cdot ws = \pi_A(w_A) - WTP_A \cdot (w_A - {w_A}^0) \qquad (4.10)$$

and

$${\pi_B}^M = \pi_B(w_B) - WTP_B \cdot wb = \pi_B(w_B) - WTP_B \cdot (w_B - {w_B}^0) \qquad (4.11)$$

where WTP_A and WTP_B are the willingness to trade water use rights of user A and B respectively, ws and wb are the amounts of water use rights bought and sold while ${w_A}^0$ and ${w_B}^0$ are the initial water use rights for agents *A* and *B* respectively. The willingness to trade water use rights is evaluated based on water demand curves (marginal water productivities) for each water user site. The difference between actual water use and water use rights $(w_I - {w_I}^0)$ equals to water trading transfer, e.g. if $w_I \geq {w_I}^0$ the value of $(w_I - {w_I}^0)$ indicates the amount of water use rights bought by the user *I* while if $w_I \leq {w_I}^0$ the value of $({w_I}^0 - w_I)$ indicates the amount of water use rights sold by the user *I*.

The following condition is true for initial water use rights:

$$ {w_A}^0 + {w_B}^0 = w = w_A + w_B \tag{4.12}$$

Under market equilibrium conditions, the amounts of water use rights sold and bought should be also equal to each other:

$$ ws = wb \tag{4.13}$$

If agent B purchases additional water use rights $(wb = w_B - {w_B}^0 \geq 0)$, the agent will be able to increase its production benefits $(\pi_B(w_B))$ due to increased water use but decrease water trading turnover $(WTP_A \cdot wb = WTP_A \cdot (w_A - {w_A}^0))$ as it must pay the price of WTP_A per unit of the purchased water. In contrast, when agent A sells water use rights $(ws = {w_A}^0 - w_A \geq 0)$ its production benefits decrease due to reduced water use but trading turnover increases because of revenue from selling water use rights.

Total basin-wide benefit under market conditions can be formulated as:

$$\begin{cases} \pi^M = \pi_A(w_A) + WTP_A \cdot ws + \pi_B(w_B) - WTP_B \cdot wb \rightarrow max \\ s.t.: w = w_A + w_B \\ w_A \leq {w_A}^0 - ws \\ w_B \leq {w_B}^0 + wb \\ WTP_A = \frac{\partial \pi_A(w_A)}{\partial w_A} \\ WTP_B = \frac{\partial \pi_B(w_B)}{\partial w_B} \\ P^e = WTP_A = WTP_B \\ ws = wb \end{cases} \tag{4.14}$$

Under market equilibrium, willingness to pay and sell of the water use rights of the users should be equal to each other. These values are simultaneously equal to the market price for water use rights (P^e):

$$P^e = \frac{\partial\, \pi_A(w_A)}{\partial\, w_A} = \frac{\partial\, \pi_B(w_B)}{\partial\, w_B} \qquad (4.15)$$

Once this relationship and the equality of the amounts of the water use rights sold and bought are considered the problem described in the system of equations 4.14 will be equivalent of the equation 4.8 in the case of the optimal water allocation. **The equation 4.15 indicates that water use levels under the conditions of free market for water use rights are the same as in the case of optimal water allocation scenario.** Thus, the water allocation levels except the state when marginal productivities of water uses for both users are equal to each other cannot be optimal under market-based water allocation. Indeed, in our hypothetical example, hydrological constraints including water use capacities, minimum water use requirements because of the social and environmental needs that cannot be easily monetized, maximum/minimum land availability, and return flows were not considered. However, in real life these constraints exist and may prevent the coincidence of the market equilibrium and optimization solutions as also previously postulated (Ringler et al. 2004 and Cai et al. 2006).

Additional gain (AG^M) from introducing tradable water use rights can be formulated as a difference between the optimal benefit (π^{M*}) when water use rights trading is considered and the benefit ($\pi({w_A}^0\,; {w_B}^0\,)$) under the initial water rights distribution:

$$AG^M = \pi^M(w_A^*, w_B^*) - \pi({w_A}^0, {w_B}^0\,) = {\pi_A}^M\,(w_A^*) + {\pi_B}^M\,(w_B^*) - \pi_A({w_A}^0) - \pi_B({w_B}^0) \qquad (4.16)$$

For a graphical presentation of the solution, the initial water use rights were assumed based on the “absolute sovereignty” doctrine of water sharing as in the case of the model formulation. Thus because of its upstream location user *A* is considered as a seller of water use rights (Figure 4.3). In this case if there is no market, upstream agent *A* would use the amount of water (w_A^{**}) that maximizes its benefit (π_A^{**}) leaving agent *B* in the least favorable condition at the point of (w_B'; π_B'). However, as soon as there is a possibility to trade water agent *A* may wish to release some amount of water if agent *B* is willing to pay for additional water appropriately.

Based on the formulations described above, under the known water prices that is equal to market equilibrium level one may derive the water-benefit curves $\pi_A(w_A|P^e)$ and $\pi_B(w_B|P^e)$ for agents *A* and *B* respectively (Figure 4.2):

$${\pi_A}^M\,(w_A) = \pi_A(w_A) - P^e \cdot (w_A - {w_A}^0\,) = \pi_A(w_A) - P^e \cdot (w_A - {w_A}^{**}\,) \qquad (4.17)$$

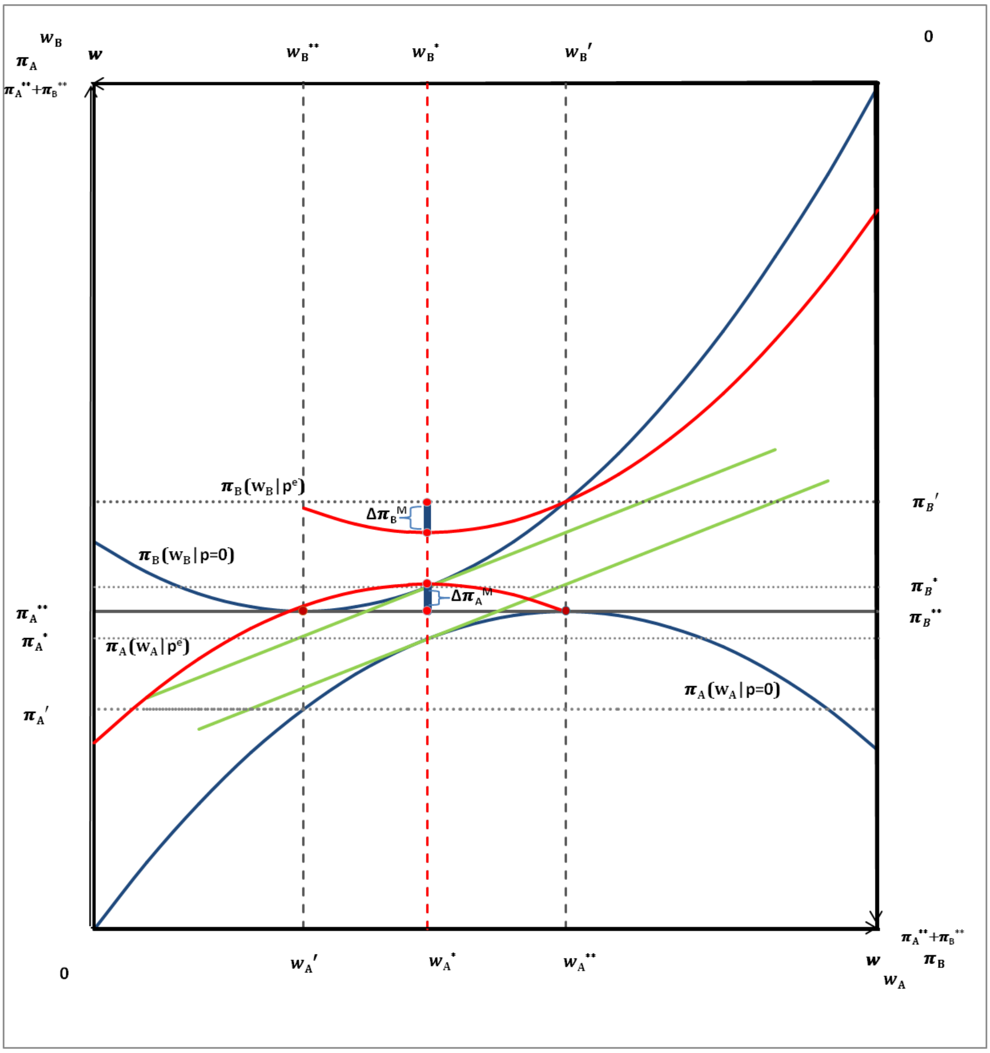
and

$${\pi_B}^M(w_B) = \pi_B(w_B) - P^e \cdot (w_B - {w_B}^0\,) = \pi_B(w_B) - P^e \cdot (w_B - {w_B}') \qquad (4.18)$$

These equations 4.17 and 4.18 indicate that the graph of ${\pi_A}^M(w_A)$ lies above $\pi_A(w_A)$ when $0 \le w_A \le {w_A}^{**}$ while the graph of ${\pi_B}^M(w_B)$ lies below $\pi_B(w_B)$ when ${w_B}' \le w_B \le {w_B}^{**}$.

Furthermore, based on the equation 4.15, maximum values of these benefit functions are attained at the water use levels of $w_A{}^*$ and $w_B{}^*$. Relying on these facts water benefit functions for both users can be illustrated graphically (Figure 4.2).

Figure 4.3 Scheme of efficient water allocation under water rights trading



Notes: Dark blue lines are for describing benefit functions of the water users A and B under optimization scenario; Red lines express the respective benefit functions under free market scenario without considering transaction costs; Water uses lie on the OX axis while benefits lie on the OY ordinates axis.

Source: Author's presentation

As shown in Figure 4.2, the slopes of tangent lines to the benefit functions are equal to each other at the water use levels of $w_A{}^*$ and $w_B{}^*$ for agents A and B respectively. These water consumption levels are also the optimal values for providing maximum basin-wide benefit under cooperation. Introducing a tradable water use rights allows additional benefits $\Delta\pi_A{}^M$ and $\Delta\pi_B{}^M$ for each user respectively compared to the benefits under the initial water use rights allocation. Therefore, **the introduction of water rights markets creates incentives for cooperation and the optimal use of water.** As shown from equations (4.17) and (4.18), **the size of the additional benefit and**

thus distribution of the overall additional benefit among the water users are dependent on initial distribution of the water use rights.

Despite its mutually favorable conditions for all users, free competitive markets are rare in the real world, including the water sector. The location, political power of the agents, and degree of information asymmetry among agents influence the market price, creating favorable conditions for upstream users to seek optimal individual benefit. Thus, how would water uses and benefit levels under asymmetric power diverge from the levels under free markets and also from the optimization scenario? In the following section these issues are analyzed further by assuming that agent *A* has more power to influence the water price level due to its strategic geographic location.

4.3.2.3 Water market mechanism under asymmetric power

Using the advantage of its geographical position, agent *A* has more power to influence benefit sharing and can get a greater proportion of the cooperative benefit. Based on the assumption of absolute priority rights that allows to withdrawing abundant water to user *A*, this user can be considered as a seller of water use rights which can influence on the course of water trading when asymmetric power in the water market is specified. Therefore, agent *A* can set the price for water which can provide higher benefit to agent *A* than the benefit under the case of a symmetric power distribution while leaving less benefit to agent *B* from cooperation. This situation is discussed in this subsection using a hypothetical example. However, it must be cautioned that when multiple users with a willingness to sell or buy water use rights exist in the river basin it is hard that any user can regulate the price of water use rights. To make a decision on water use levels and consequent water price (P^{PA}) agent *A* must first be aware of the water benefit function of agent *B*:

$$\pi_B{}^{PA} = \pi_B(w_B) - P^{PA} \cdot wb = \pi_B(w_B) - P^{PA} \cdot (w_B - w_B{}^0) \qquad (4.19)$$

As derived from the total benefit function in equation (4.19), the marginal productivity of water and thus willingness to pay water of agent *B* depends on the price (P^{PA}) for water use rights offered by user *A*:

$$\frac{\partial\, \pi_B{}^{PA}(w_B)}{\partial\, w_B} = \frac{\partial\, \pi_B(w_B)}{\partial\, w_B} - P^{PA} = 0 \qquad (4.20)$$

Based on this relationship, the total benefit of agent *A* is:

$$\pi_A{}^{PA} = \pi_A(w_A) + P^{PA} \cdot ws = \pi_A(w_A) - \frac{\partial\, \pi_B(w_B)}{\partial\, w_B} \cdot (w_A - w_A{}^0) \qquad (4.21)$$

Agent *A* can gain maximum benefit when its marginal water productivity is equal to 0:

$$\frac{\partial\, \pi_A{}^{PA}(w_A)}{\partial\, w_A} = \frac{\partial\, \pi_A(w_A)}{\partial\, w_A} - \frac{\partial^2\, \pi_B(w_B)}{\partial w_B\, \partial w_A} \cdot (w_A - w_A{}^0) - \frac{\partial\, \pi_B(w_B)}{\partial\, w_B} = 0 \qquad (4.22)$$

Equations (4.20) and (4.22) allow to assessing market price level for water use rights under asymmetric power that permits the greatest benefit to agent *A*:

$$P^{PA} = \frac{\partial\, \pi_A(w_A)}{\partial\, w_A} - \frac{\partial^2\, \pi_B(w_B)}{\partial w_B\, \partial w_A} \cdot (w_A - {w_A}^0\,) = \frac{\partial\, \pi_B(w_B)}{\partial\, w_B} \tag{4.23}$$

Since water user *A* is a seller in this hypothetical example, its actual water use is lower than its water use rights ($w_A - {w_A}^0 < 0$). Moreover, since benefit function of water user *B* is a monotonous and concave function as initially assumed, $\frac{\partial\, \pi_B(w_B)}{\partial\, w_B} > 0$ and $\frac{\partial^2\, \pi_B(w_B)}{\partial {w_B}^2} < 0$.

Considering the total water use constraint ($w = w_A + w_B$) where w is total fixed water amount, water use of user *A* equal to the difference between total water use and water use of the user *A*: $w_A = w - w_B$. Thus,

$$\frac{\partial^2\, \pi_B(w_B)}{\partial w_B\, \partial w_A} = \frac{\partial\, \pi_B\!\left(\frac{\partial\, \pi_B(w_B)}{\partial\, w_A}\right)}{\partial\, w_B} = \frac{\partial\, \pi_B\!\left(\frac{\partial\, \pi_B(w_B)}{\partial\, (w - w_B)}\right)}{\partial\, w_B} = -\frac{\partial^2\, \pi_B(w_B)}{\partial {w_B}^2} > 0 \tag{4.24}$$

Given the fact that actual water use of agent *A* is lower than its water use rights and based on the equation (4.24):

$$\frac{\partial^2\, \pi_B(w_B)}{\partial w_B\, \partial w_A} \cdot (w_A - {w_A}^0\,) < 0 \tag{4.25}$$

This equation 4.25 indicates that the marginal water productivity of agent *A* ($\frac{\partial\, \pi_A(w_A)}{\partial\, w_A}$) is lower than the marginal productivity of agent *B* ($\frac{\partial\, \pi_B(w_B)}{\partial\, w_B}$) when asymmetric distribution of power in water rights markets is considered. Thus, considering the assumed concave shape of the water benefit functions, the water user *A* uses more water than the amount in the case of market equilibrium under symmetric power. Moreover, the price that the user *A* asks the user *B* to pay for water use rights also will be higher than the free market price of the rights.

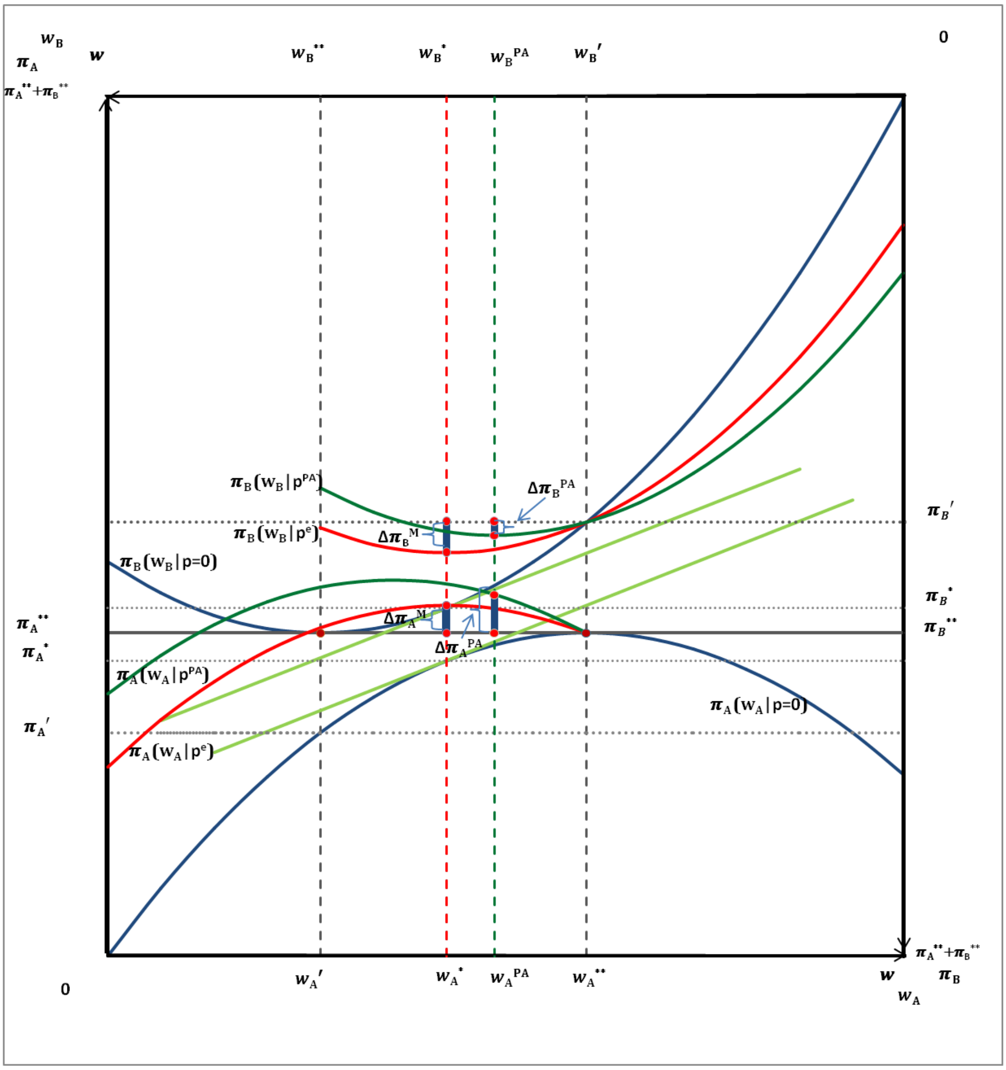
After determining the water price levels under conditions of asymmetric power as discussed, the fact that agent *A* can gain even higher benefit than in the case of free water rights market by controlling the price of water use rights can be also illustrated graphically (Figure 4.4). The condition that the water price level is higher than the price level under a free water market determines the moving direction of the water-benefit relationship curves under asymmetric power distribution:

$$\begin{gathered} {\pi_A}^{PA} = \pi_A(w_A) - P^{PA} \cdot (w_A - {w_A}^0\,) > \pi_A(w_A) - P^{e} \cdot (w_A - {w_A}^0\,) = {\pi_A}^{M}\,(w_A) \\ \text{when } w_A < {w_A}^0 \text{ (or } {w_A}^{**}\text{) since } P^{PA} > P^{e}. \end{gathered} \tag{4.26}$$

Likewise,

$$\begin{gathered} {\pi_B}^{PA} = \pi_B(w_B) - P^{PA} \cdot (w_B - {w_B}^0\,) < \pi_B(w_B) - P^{e} \cdot (w_B - {w_B}^0\,) = {\pi_B}^{M}(w_B) \\ \text{when } w_B > {w_B}^0 \text{ (or } {w_B}'\text{) since } P^{PA} > P^{e}. \end{gathered} \tag{4.27}$$

Figure 4.4 Water allocation scheme under water rights trading with monopolistic power held by one of the participating agents (agent *A* in this hypothetical example)



Dark blue lines are for describing benefit functions of the water users A and B under optimization scenario; Red lines express the respective benefit functions under free market scenario without considering transaction costs; Dark green lines stands for the respective benefit functions under water rights market with asymmetric power; Water uses lie on the OX axis while benefits lie on the OY axis.

Source: Author's presentation

Implying from the equation (4.25), when user *A* has monopolistic power over determining water rights prices, the user *A* uses more water than the case of free market at the optimal level. Based on this implication and equations (4.26) and (4.27), the water benefit functions of each user under the conditions of the asymmetric power in water rights market while considering the known prices of the water use rights can be graphically demonstrated (Figure 4.4). Higher prices for water use rights under asymmetric power distribution result in an upward shift of the profit function curve for agent *A* ($\pi_A(w_A|P^e) \rightarrow \pi_A(w_A|P^{PA})$) and a downward shift of the profit function curve for agent *B* ($\pi_B(w_B|P^e) \rightarrow \pi_B(w_B|P^{PA})$). As seen in the figure, under conditions of asymmetric power distribution agent *A* can gain an additional benefit ($\Delta\pi_A{}^{PA}$), which is even higher than its additional gains under free market ($\Delta\pi_A{}^{M}$), while consuming $w_A{}^{PA}$ amount of water and selling $({w_A}^* - {w_A}^{PA})$ amount at price P^{PA}. Although agent B gains additional benefit at the level of $\Delta{\pi_B}^{PA}$, it is less than the benefit $\Delta{\pi_B}^M$ under free market conditions. Thus, **even under a water market scenario with asymmetric power distribution, water users are still in a better condition than in the case of being without a market institution. However, agent *B*'s inability to prevent the user *A* of influencing on the water price level in a way that would maximize individual total benefit of the user *A* does not allow to achieving the highest overall basin benefit**.

Among many other factors heterogeneous distribution of power to control water resources among the users incurs transaction costs. Transaction costs are not only due to power asymmetry, but also to other factors such as the legal environment, the general condition of physical infrastructure, information costs, and human and social capital (Williamson 2000; Saleth and Dinar 2004), which are important considerations for unbiased estimation of the potential economic gains from water rights trading (see subsection 4.3.1.2 for more details).

4.3.2.4 Water markets considering transaction costs

Despite economic gains can be achieved from market-based water allocations, this trading process will not be without cost (Coase 1937, 1960). Neglecting the transaction costs that occur due to the design and establishment of any kind of market institutions, collection of information, monitoring, and enforcement of the rules may not ensure positive economic outcomes (North 1989, 1990). According to the market-based explanation of adopting institutional innovations in public choice theory, institutional change should be initiated only if benefits exceed the (transaction) costs of undertaking the change (Demsetz 1967, Saleth and Dinar 2004:37). Therefore, consideration of the transaction costs is essential for evaluating gains from water rights trading.

The impact of transaction costs on the outcomes of water rights trading can be also explained with the employment of the simplified model with two agents. Absolute riparian rights rule in the distribution of initial water use rights is assumed here as well. Under the conditions of this rule agent A is able to divert as much water as it wants and may decrease its consumption or transfers its water use rights to agent B if its benefit losses due to water use reduction are compensated by agent B. Here, we additionally assume that power in the market is equally distributed and thus free market functions in water allocation. Based on these assumptions the profit functions of the water users under the consideration of transaction costs (${\pi_A}^{TC}$ and ${\pi_B}^{TC}$ for agent A and agent B respectively) will be:

$${\pi_A}^{TC} = \pi_A(w_A) + (WTP_A - tc) \cdot ws = \pi_A(w_A) - WTP_A \cdot (w_A - {w_A}^0) + tc \cdot (w_A - {w_A}^0) \quad (4.28)$$

and

$${\pi_B}^{TC} = \pi_B(w_B) - (WTP_B + tc) \cdot wb = \pi_B(w_B) - WTP_B \cdot (w_B - {w_B}^0) - tc \cdot (w_B - {w_B}^0) \quad (4.29)$$

where tc are the transaction costs per unit of traded water. Transaction costs related to identifying legal characteristics of water use (ability to transfer, return flow obligations, and timing of transfers) and complying with the national and international laws regarding transfer application are paid only by the sellers of the water use rights. Meantime transaction costs for administrative establishment such as marketing and negotiating the trade terms occur for both the sellers and buyers (Archibald and Renwick 1998). Thus, both the buyer and seller of water use rights pay the transaction costs. For simplicity, the transaction costs were assumed to be equally split between the agents (Challen 2000). Furthermore, the transaction costs were assumed to be proportional to the size of the transfer and fixed per unit of transferred water.

Total basin-wide benefit under free market conditions while considering transaction costs can be formulated as:

$$\begin{cases} \pi^{TC} = \pi_A(w_A) + (WTP_A - tc)\cdot ws + \pi_B(w_B) - (WTP_B + tc)\cdot wb \rightarrow max \\ s.t.: w = w_A + w_B \\ w_A \le {w_A}^0 - ws \\ w_B \le {w_B}^0 + wb \\ WTP_A = \frac{\partial\, \pi_A(w_A)}{\partial\, w_A} + tc \\ WTP_B = \frac{\partial\, \pi_B(w_B)}{\partial\, w_B} - tc \\ P^{TC} = WTP_A = WTP_B \\ ws = wb \end{cases} \tag{4.30}$$

Considering the equilibrium market price for both seller and buyer, the objective function of the water market model considering transaction costs (Equation 4.30) can be also reformulated as follows:

$$\pi^{TC} = \pi_A(w_A) - tc\cdot ws + \pi_B(w_B) + tc\cdot wb \rightarrow max \tag{4.31}$$

This objective function differs from the objection function of the optimization model and the model for the free market of water use rights without considering transaction costs. Moreover, under the price level of market equilibrium, the following functional relationship between the market price and marginal water productivities of the users holds true:

$$P^{TC} = \frac{\partial\, \pi_A(w_A)}{\partial\, w_A} + tc = \frac{\partial\, \pi_B(w_B)}{\partial\, w_B} - tc \tag{4.32}$$

This equation indicates that the trading price (P^{TC}) and water use levels under water rights trading while considering transaction costs are different from levels under trading without considering transaction costs. It also indicates that water market price is a function of transaction costs. Like in the case of water market under asymmetric power, marginal water productivity of user *A* is lower than marginal productivity of user *B*. This means higher water consumption by user *A* when transaction costs of water trading is considered than the water use levels of water rights market without considering transaction costs. Furthermore, this higher water consumption by the user *A* indicates lower amounts of water rights transfers in the market. Due to the increased transaction costs, the price for a unit of water use rights also will be higher than the water rights market price without considering transaction costs.

Knowing the water market price under consideration of transaction costs (P^{TC}), we can plot the total water-benefit curves $\pi_A(w_A|P^{TC},tc)$ and $\pi_B(w_B|P^{TC},tc)$ for agents A and B respectively (Figure 4.5). The following relationships allows to determining the possible shift of benefit functions of the water users under the consideration of transaction costs of introducing water rights market:

$$\pi_A{}^{TC} = \pi_A(w_A) - P^{TC} \cdot (w_A - w_A{}^0) + tc \cdot (w_A - w_A{}^0) <$$

$$\pi_A(w_A) - P^e \cdot (w_A - w_A{}^0) = \pi_A{}^M(w_A) \tag{4.33}$$

$$\text{when } w_A < w_A{}^0 \text{ (or } w_A{}^{**}\text{) since } P^{TC} > P^e.$$

and

$$\pi_B{}^{TC} = \pi_B(w_B) - P^{TC} \cdot (w_B - w_B{}^0) - tc \cdot (w_B - w_B{}^0) <$$

$$\pi_B(w_B) - P^e \cdot (w_B - w_B{}^0) \quad (4.34) \tag{4.34}$$

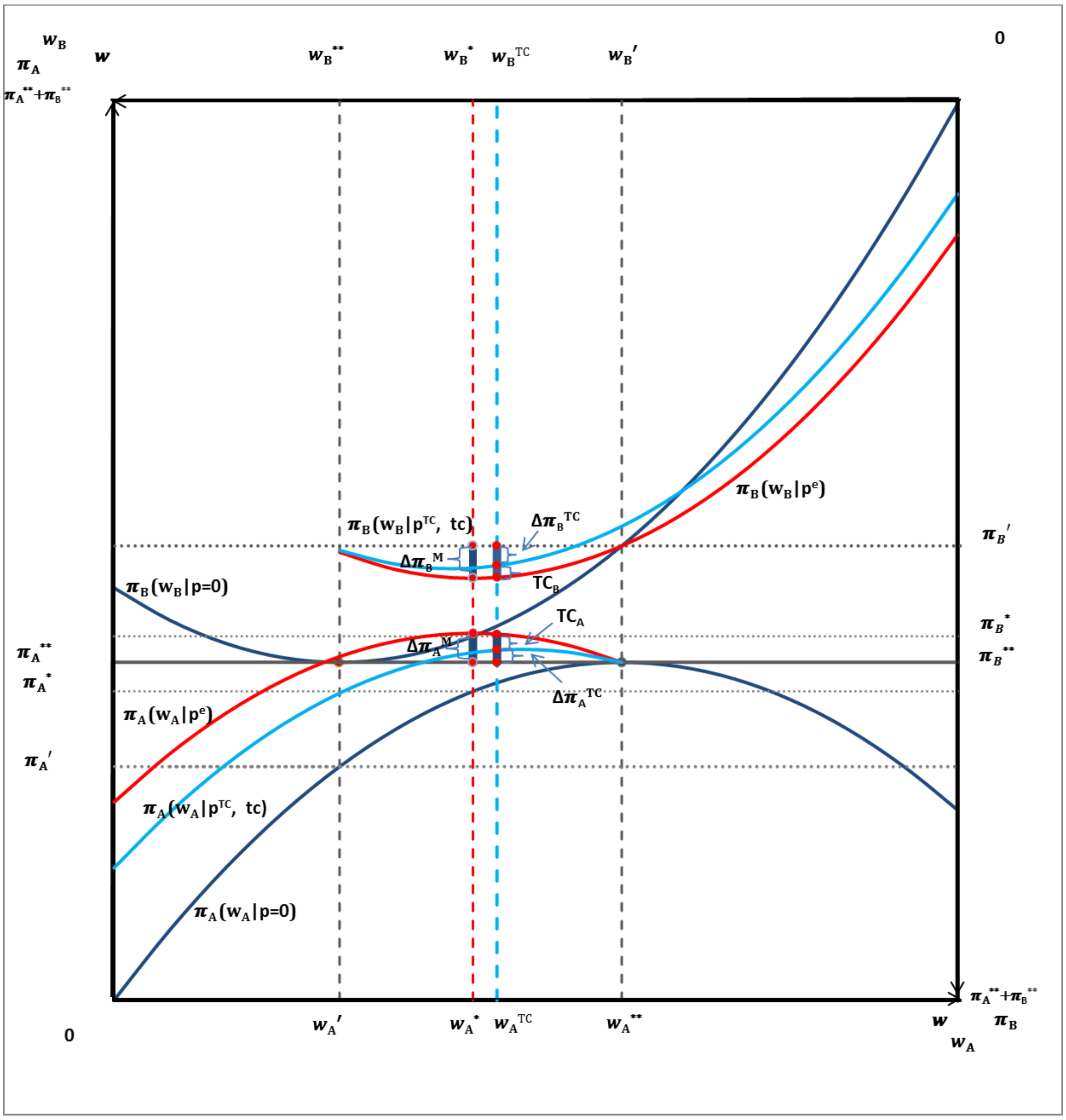
$$\text{when } w_B > w_B{}^0 \text{ (or } w_B{}'\text{) since } P^{TC} > P^e.$$

Based on these equations, we can conclude that the benefit curves in the case of water rights markets considering transaction costs lies below the benefit curves in the case of free water rights market without considering transaction costs (Figure 4.5). Furthermore, optimal water use levels for water user A is higher when transaction costs are considered than the case without the consideration of the transaction costs implies that this water use level is higher than $w_A{}^*$ but lower than $w_A{}^{**}$. Thus, optimal water use points will shift to w_A^{TC} and w_B^{TC} when transaction costs are considered.

If water rights trading without transaction costs provided economic benefits of $\pi_A{}^M$ and $\pi_B{}^M$ for agents A and B, respectively, considering transaction costs can decrease the availability of additional economic gains from water rights trading. In our example agent A and agent B obtain reduced additional gains of $\Delta\pi_A{}^{TC}$ and $\Delta\pi_B{}^{TC}$, respectively, due to transaction costs (TC_A and TC_B for agent A and agent B, respectively). Additional gains here were calculated based on the benefit levels under the baseline scenario that is the case of initial water use rights distribution. Thus, the level of transaction costs determines the availability of additional gains from water rights trading.

The hypothetical model discussed here and the theoretical and empirical models of other studies (Challen 2000) indicated considerable economic gains and improvements in water use efficiency through water rights markets compared to an alternative water allocation based on administrative management when the transaction cost of water rights trading is sufficiently low. Besides this and other theoretical justifications, water markets are already being practiced formally or informally in arid regions of several countries at present. Lessons on the drivers of success and causes of failure of water market mechanisms in real life situations are the topic of the next section.

Figure 4.5 Water allocation scheme considering transaction costs



Notes: Dark blue lines are for describing benefit functions of the water users A and B under optimization scenario; Red lines express the respective benefit functions under free water market scenario without considering transaction costs; Sky blue lines stands for the respective benefit functions under free water rights market considering the transaction costs; Water uses lie on the OX axis while benefits lie on the OY axis.

Source: Author's presentation

4.3.3 Review of water rights trading practices across the selected countries and their relevance to the case of the Aral Sea basin

Different forms of water rights trading are being practiced in water scarce regions of several countries, such as the USA, Australia, Spain, Chile, South Africa, India, and China. Water markets were successful in some countries, while they failed in others. Water rights trading in China is in its infancy (Grafton et al. 2010). Well developed markets are found in India, but they operate at local levels and remain informal. In Chile, despite the fact that legislation of water rights is well designed, the scale of the formal and permanent sales of water rights is small, but the temporary, non-recorded market is much larger. Despite some institutional problems water markets are well developed in parts of developed countries such as the USA and Australia. In this section four case studies from Chile, India, the USA and Australia are discussed to explore the conditions that allow additional gains from water rights trading. Chilean water markets were selected as an example of the controversial effects of water rights trading. The Indian case illustrates informal water rights trading at the local level of water distribution. The western USA and Australian cases are examples of success stories that help determine the factors that provide additional benefits from water rights trading. Relevant lessons are derived for the successful design and implementation of a water market mechanism in the ASB and other shared river basins in developing countries.

4.3.3.1 Water markets in Chile

In Chile transferable water rights that are separate from land use and ownership were established by the National Water Code of 1981. The main purposes of this law were to strengthen private property rights in agriculture and other sectors, and to maintain free-market relationships over water use and allocation. The most common way of water rights trading in Chile is "renting" water between neighboring farmers in which one farmer leases a portion of his or her water rights for a brief period of time and the other compensates in kind or in another form of monetary or non-monetary benefit (Dinar et al. 1997).

Despite the law allows water rights trading nationwide in Chile, market-based water allocation was common only in north-central part of the country. In an analysis of water transfers in four Chilean river valleys, Hearne and Easter (1995) found that water transactions were rare in the Maipo and Azapa valleys and infrequent in the Elqui valley. Frequent water transactions occurred mainly in Limari valley which has a well-equipped irrigation network. Substantial net economic gains from water rights trading were found for the cases in the Limari and Elqui valleys (Hearne and Easter 1995). However, almost a decade later Bauer (2004) reported that the idea of the relevance of water market forces for supporting Chilean peasants and poor farmers by improving their access to water supplies had generally failed. In most parts of Chile, the hydrological constraints, complications in institutional framework, and cultural resistance by farmers prevented successful implementation of water rights trading. He argued that previous studies had exaggerated the success of water markets by neglecting a more balanced outcome of mixed results and placing heavy emphasis on the economic gains of water rights trading with less attention on social equity, environmental protection, and conflict resolution. Countable number of water transactions occurred mainly within the agricultural sector and among rich land owners while people with small land plots lost their access to water or could not engage in water rights trading because of lack of transparency and high transaction costs. Protection of environmental ecosystems was often neglected in water allocation decisions.

The Chilean case of introducing water market rules can be a lesson to the Central Asian water users and managers of mistakes not to repeat in designing water markets in the region. In addition to efficiency, equity and sustainability should be inevitable targets of water management decisions and water market reforms.

4.3.3.2 Water markets in India

In contrast to the case of Chile, the groundwater markets observed in the Gujarat region of India are highly advanced, but remain informal and operate at local levels (Dinar et al. 1997). Water selling is an old tradition and a specialized subsidiary (part-time) occupation in Gujarat (Dinar et al. 1997). Richer farmers who can afford large wells equipped with diesel/electric pumps sell water to smaller farmers who do not have sufficient financial capacity to construct a well with pumping system. Since competition among water sellers is so high, farmers substantially invest in water extraction technologies (e.g., modern pumps) and improve conveyance networks for increasing the sales of water. This example proves the high potential of water markets for incentivizing water use efficiency among farmers through regular improvement of irrigation technologies at local levels.

Although the majority of the population perceives water as free natural good, informal trading of water also frequently occurs at the local level in water scarce years in Central Asia (*personal observation*). Since gravity irrigation does not work under limited water supplies, especially in areas that are remote from the main water conveyance systems, the owners of pumps and irrigation wells deliver water to the fields of the farmers who pay an appropriate charge. However, since the number of suppliers of such services is limited in the market, there is less competition among them and they can usually obtain much higher prices than the incurred costs. Establishing competitive markets for this kind of water delivery service such as exist in India would decrease the costs that are being paid by water users. Moreover, the existence of a system of payment for water delivery at the local level shows that despite the perception of water as a free public good by the majority they are ready to pay for water delivery under scarcity conditions. This indicates that the possibility also exists for water users to agree to water rights trading at the basin level through well-established institutions to lessen the burden of water scarcity.

4.3.3.3 Water markets in the USA

The western states of the US has a long history of market-based water transfers (NPC 1992). Water distribution is based on the rule of prior appropriation rights which is based on the principle of “first in time, first in use”. The rule of prior appropriation emerged in mid-19th century during the California Gold Rush since newly came miners were diverting water to extract and filter ore while diminishing downstream flow needed to earlier-established irrigation and mining activities (Kenney 2005). To prevent growing conflicts, prior appropriations rule provided senior rights to the earlier-water-users while restricting water use by latecomers. Water rights trading was also allowed in parallel to the introduction of the prior appropriation rule but did not become common till 1980s (Brown 2006).

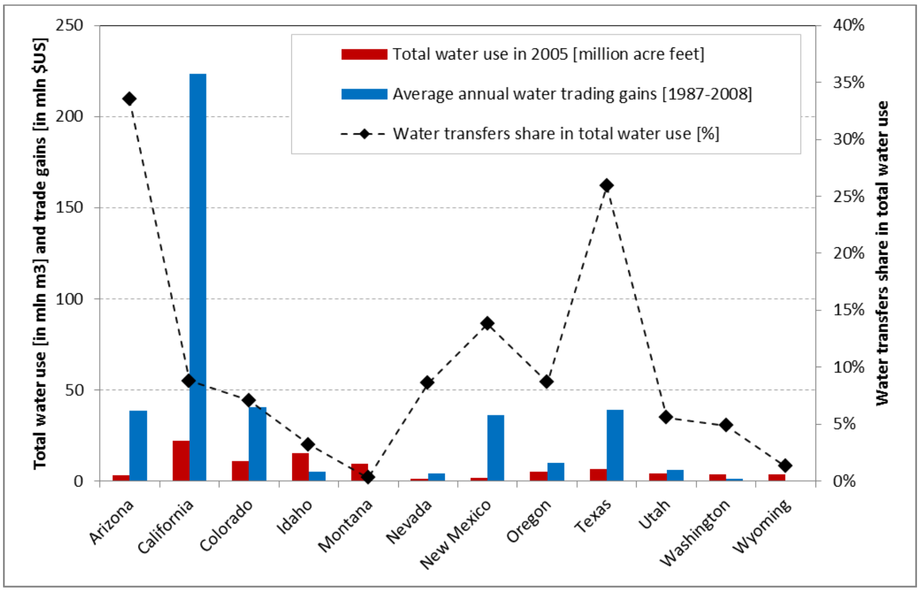
Because of its arid climate, rapid population growth, and regional development, water scarcity became a serious problem in the southwestern USA (Kenney 2005). Supply augmentation measures exhausted to meet increasing water demands by 1970s consequently necessitating water demand management measures while allowing reallocation of water from its lower to higher value uses. Despite many opponents of the market-based water transfers, water rights trading increased since 1980 (Brown 2006). Dairy farming, horticulture, and non-agricultural industries were main beneficiaries of tradable water use rights, particularly in dry years. Water transfers from irrigation sites to the municipal needs occurred more often than “irrigation-to-irrigation” or other types of transfers (Brown 2006). Furthermore, transactions of temporary water use rights rather than permanent transfer of water use rights took place more frequently (Brown 2006).

Studies (Grafton et al. 2010, Libecap 2010) report that intra-state water markets are more common than inter-state ones, as rules and consequently potential for water rights trading are different in each state. Moreover, intensity and price traded water rights transfers are geographically variable: markets are very active in some areas of western states but infrequent in the other areas whereas average price of water is very variable both within and across states

(Brown 2006). In the western USA, the greatest ratios of water rights transfers over total water withdrawals are found in Arizona (33%), Texas (27%), and New Mexico (14%). The average annual value of gains from water rights trading through transfers from the agriculture sector to urban settlements across twelve states during the period from 1987 to 2008 was estimated at $406 million USD (Figure 4.6; Grafton et al. 2010). Annual benefits from water transactions varied from less than $1 million USD in Montana and Wyoming to about $40 million USD in Arizona, Colorado, Nevada, and Texas, and more than $200 million USD in California.

Environmental flows and benefits are considered in market-based water allocations in dry years. Independent agencies like the Texas Water Trust can buy water use rights for environmental needs. Following this example, establishing an organization that buys water for the needs of the Aral Sea and its deltaic zones in parallel to the establishment of tradable water use rights would improve environmental conditions in the basin since there is currently very limited water flow to the Aral Sea, especially to its southern part, in extremely water scarce years.

Figure 4.6 The amounts and gains of water rights trading in the western United States of America



Source: Based on Libecap (2010).

4.3.3.4 Water markets in Australia

In Australia water rights transfers occur at the national (inter-state) level and the introduction of transferable water entitlements dates back to the 1980s (Dinar et al. 1997). Decreased willingness of governments to invest in large water infrastructural facilities, doubts on the effectiveness of government-based water allocation, increased competition in agricultural sector due to increased integration to the global economy, raising awareness of the increasing impacts of dam construction on environmental systems gave impetus to introduce market-based water allocations (NWC 2011).

The traded water volumes and their shares of total water withdrawals increased between 1983 and 2010. For instance, if the water trade share of the total water withdrawals was in average 10% between 2000 and 2005, it increased to more than 30% by 2011 (NWC 2011). Considering the dynamic changes in the volume of water rights transfers, three phases of Australian water market development are distinguished: (1) the emergence of water markets (1980s to 1994), (2) water market expansion (1995-2006), and (3) transition to sustainable water markets (2007 and afterwards).

Water rights trading provided an additional tool to water users to cope with water scarcity and to be more flexible in their water use and production decisions. Particularly, horticultural crops, rice and irrigated dairy farming as well as urban settlements benefited from water rights trading during the driest periods. Substantial economic gains were available due to the reallocation of water from its lower to higher value uses which would not be reached under the bureaucratic water management system.

The lessons learned from two decades of experience in establishing water markets in Australia are as follows (NWC 2011):

- well-organized markets can provide substantial benefits under water scarcity conditions by signalling the value of water;
- water rights trading is most beneficial in places where water resources are fully exploited for consumption, seasonal water availability is variable, and water demands for residential, industrial, and environmental uses are increasing.

Furthermore successful and effective performance of water markets requires good planning considering the sustainability of extraction, clear specification of initial water rights (entitlements), organization of a sound governance framework, and the establishment of water metering and accounting.

4.4 Analytical framework for market-based water allocation

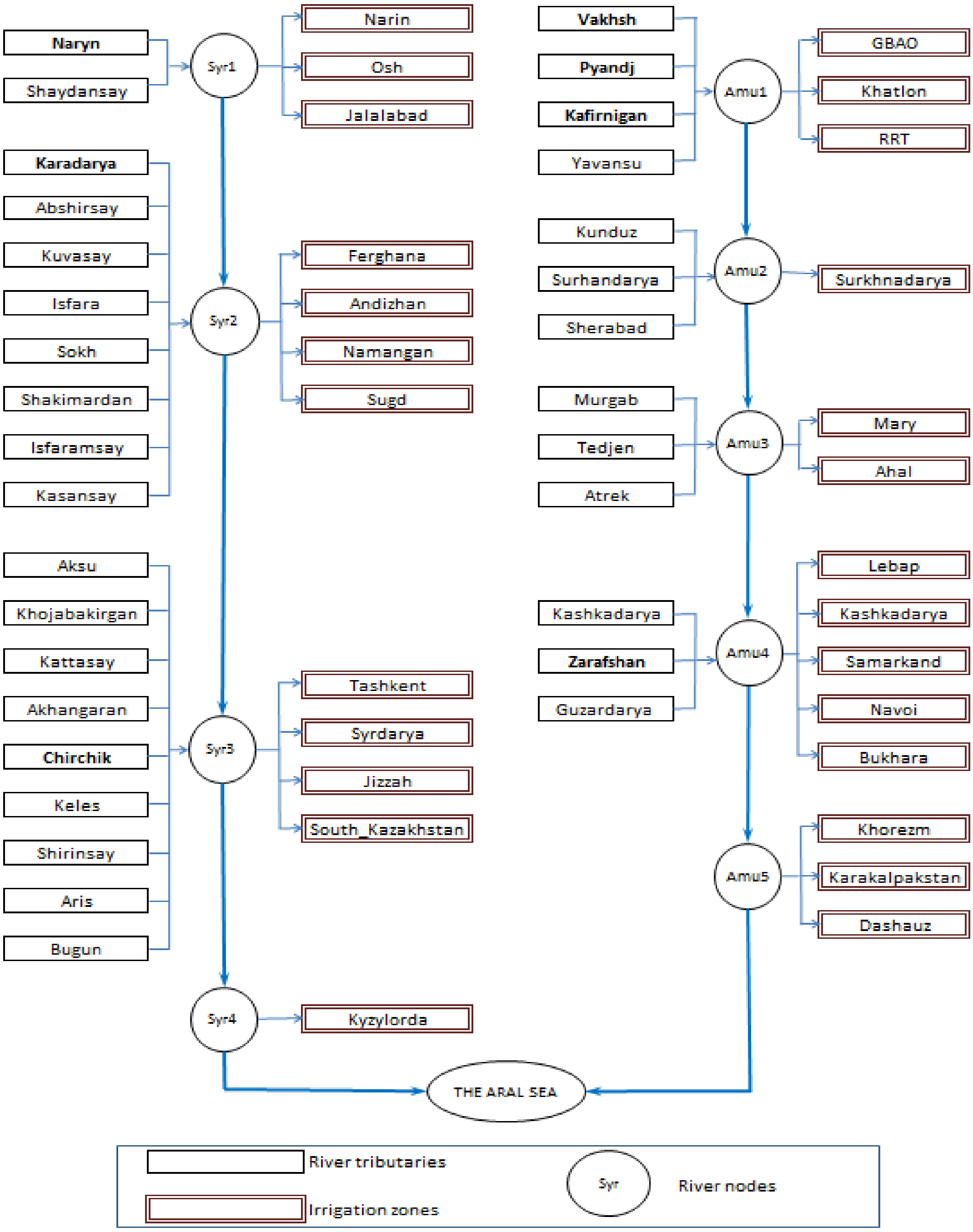
Despite substantial improvements in water productivity under marker-based water allocation as evidenced by both theoretical and case-study based analyses, the potential benefits of water markets in the ASB were not yet empirically investigated. This section describes the development of an analytical model to implement the theoretical concepts of water rights trading (section 4.3.2) under the conditions found in the ASB.

4.4.1 River network scheme

To model river flow and off-takes along the river system, a river network scheme was developed. Tributaries and irrigation water intake nodes along the two largest rivers (Amu Darya and Syr Darya) which flow from the east to the west towards the Aral Sea are delineated in the ASB river network scheme (Figure 4.7).

Despite introduction of management schemes based on basin boundaries in the system administrative units (regions) are still responsible for water intake from the rivers and internal distribution. Therefore, administrative regions rather than hydrologic irrigation units are used as water demand sites (water users) in the model. River network scheme of the model considered 12 regions and 19 river tributaries in the Syr Darya basin and 14 regions and 13 river tributaries in the Amu Darya basin. These regions were grouped into separate water catchments (river nodes; *Syr1…Syr4*; *Amu1…Amu5*) according to their proximity to one another.

Figure 4.7 The Aral Sea basin river network scheme



Source: Author's presentation

Due to the priorities of municipal and industrial sectors in water use and allocation, and the fact that agriculture accounts for almost 90% of total water consumption (SANIIRI 2004), water allocation to municipal and industrial use is considered as exogenous and fixed, and trading of water use rights is analyzed only among the irrigation zones. Since the purpose of the study is the analysis of market-based water allocation at the basin level to distribute water among different irrigation zones and environmental uses rather than real-time reservoir operation and crop water use scheduling, monthly or weekly time intervals were not considered and the model was applied to the time horizon of one year. Furthermore, trading of water use rights is allowed only among irrigation regions within each river basin of the ASB since irrigation water users in the different rivers are not connected to each other through a conveyance system. It was assumed that there is a basin management organization (BMO) that organizes trading of water use rights (e.g., all water transaction agreements occur through this organization), which buys and sells water use rights after taking into account the willingness of individual water users to pay for or sell water use rights given their demand function. Alternatively, a model that considers direct trading of water use rights and implies face-to-face agreements was also developed, but the results were not reported here because they were only slightly different from the results of the model with a BMO that acts as an intermediary betwen different water users. This kind of model also allows analyzing trading of water use rights under asymmetric power (see subsection 4.3.2.3) through the availability of higher than free market prices for water selling agents in which case water buyers accept the price offered by the sellers. However, since we have multiple water users the results of decentralized trading with asymmetric power did not differ much from the results of centrally organized trading assuming a single (BMO) that buys and sells water use rights.

4.4.2 Data sources

The model uses different types of data related to river flow, water use across irrigation regions, and crop production costs and benefits that were collected from different sources. Data on cultivated land area, irrigation water use, and yields were obtained from the CAREWIB database (SIC-ICWC 2011, Appendix B and tables B.1, B.2, and B.3), which is a single source that provides detailed data on crop production systems across the ASB. Prices of the agricultural commodities/products and input costs were estimated based on market survey results of the ZEF project (2010), data by OblSelVodKhoz (2010), and SIC-ICWC (2008). Cotton prices were based on SIC-ICWC (2008) and Anderson and Swinnen (2008:40). Data on water delivery (conveyance) costs were taken from MAWR (2007; Appendix B and Table B.4). All economic cost and benefits were estimated at 2006 prices considering that most of the data related to the costs and benefits were available for that year.

Data on water supplies in the source nodes (tributaries) is from SIC-ICWC (2011) and return flow rates were estimated based on EC-TACIS (1997; Appendix B and tables B.5 and B.6). Municipal and domestic water uses were assumed as fixed amounts equal to 10% of the total withdrawals (FAO 2012). Data on rainfall, evaporation, and inflows to the Aral Sea were obtained from INTAS project reports (2001, 2004, 2006). Economic benefit levels and losses of ecosystem services at different levels of the Aral Sea volume and inflows to the Sea were estimated based on INTAS (2001, 2004, 2006) and TEEB (2011).

4.4.3 Objective function

It is assumed that omniscient decision maker (e.g., WMO that is in charge of introducing water rights trading) maximizes overall basin-wide benefit that is the sum of annual economic benefits from irrigation, environmental systems, and water rights trading:

$$\begin{aligned} obj \; = \; \sum_{dm} (Ben_{dm}\, AR_{dm} - CC_{dm}\, WD_{dm} \; + \; EB \; + \; WTP_{dm}(WS_{dm} - WB_{dm}) \\ - \; tc\; (WS_{dm} + WB_{dm})) \rightarrow max \end{aligned} \tag{4.35}$$

where Ben_{dm} is irrigation benefit per hectare across the demand sites (dm), AR_{dm} is the total cultivated area in the region, CC_{dm} is conveyance and pumping costs to deliver one cubic meter of water from the river (water intake) node to the irrigation site, WD_{dm} is the total irrigation water withdrawal, EB is the environmental benefit, WTP_{dm} is the marginal willingness to pay for water by water users given their demand function and considered as an endogenous variable, WS_{dm} and WB_{dm} are the amounts of water rights sold and bought by irrigation regions respectively, and tc is the transaction cost per unit of water traded, which was assumed to be shared equally by both the buyers and sellers.

4.4.4 River water balance

Water flow relationships among the tributaries, water withdrawals to the irrigation regions, and flows from one river node to other nodes are modeled as:

$$\sum_{(rn\_up,rn)\in RVLINK} Q_{rn\_up,rn} + Src_{rn} + \sum_{(dm,rn)\in NDLINK} Ret_{dm,rn} = \sum_{(rn,rn\_lo)\in RVLINK} Q_{rn,rn\_lo} + \sum_{(rn,dm)\in NDLINK} (WDR_{rn,dm} + \overline{WID}_{rn,rm}) \tag{4.36}$$

where $Q_{rn\_up,rn}$ is river water flow to the node (rn) from the upper node (rn_{up}) and Q_{rn,rn_lo} is river flow from the node (rn) to the next lower node (rn_lo) if a link between the nodes $(RVLINK)$ exists, Src_{rn} is the source flow in the tributary node, and $Ret_{dm,rn}$, $WDR_{rn,dm}$ and $\overline{WID}_{rn,dm}$ are return flows from irrigation demand sites (dm) to the river node (rn), and water withdrawal from node (rn) to the irrigation water user site (dm) and municipal-domestic water use respectively if a link between the node and the water user site $(NDLINK)$ exists.

Total water application in the field depends on water withdrawals to the irrigation regions (WD_{dm}):

$$WD_{dm} = \sum_{rn} WDR_{rn,dm} = w_{dm}\, AR_{dm} \tag{4.37}$$

where w_{dm} is water use (withdrawal) per hectare.

4.4.5 Regional irrigation benefit functions

Deductive and inductive methods of estimating irrigation benefit functions are differentiated in the literature (Harou et al. 2009). Deductive methods are based on mathematical optimization models of the agricultural sector at each irrigation zone. Simulating the model under different levels of irrigation water availability, optimal values of benefit are generated and these simulated values are regressed to estimate the relationship between total water use and irrigation benefits. The deductive method is usually used to evaluate irrigation benefit functions when necessary time-series data on water use and crop production outputs are not available. In contrast to this normative approach, the inductive method is based on real observations of water use and benefits to estimate regression based irrigation benefit functions, but requires data based on observations in the long term. Inductive method based on real observations is preferred over the normative method since the former provides more realistic functional relationships between water uses and benefits.

Regression functions based on real observations were applied in this study. Quadratic functions were chosen to estimate the empirical relationship between water use and irrigation benefits. Quadratic functions are commonly used to evaluate the relationships between the value of crop production and water use in the literature (Zilberman et al. 1994, Ringler et al. 2006, Qureshi et al. 2007). Crop output and thus benefit per hectare increase in parallel to water use at lower water application rates, but decrease beyond a certain threshold of water application rate due to the lack of aeration in the root zone (Qureshi et al. 2007). These properties of benefit functions are well captured through concave-down (umbrella-shape) quadratic functions. Irrigation benefit functions were developed for each water user site by regressing the total regional crop production benefits with the total water withdrawals using the Ordinary Least Squares (OLS) method (Greene 2003):

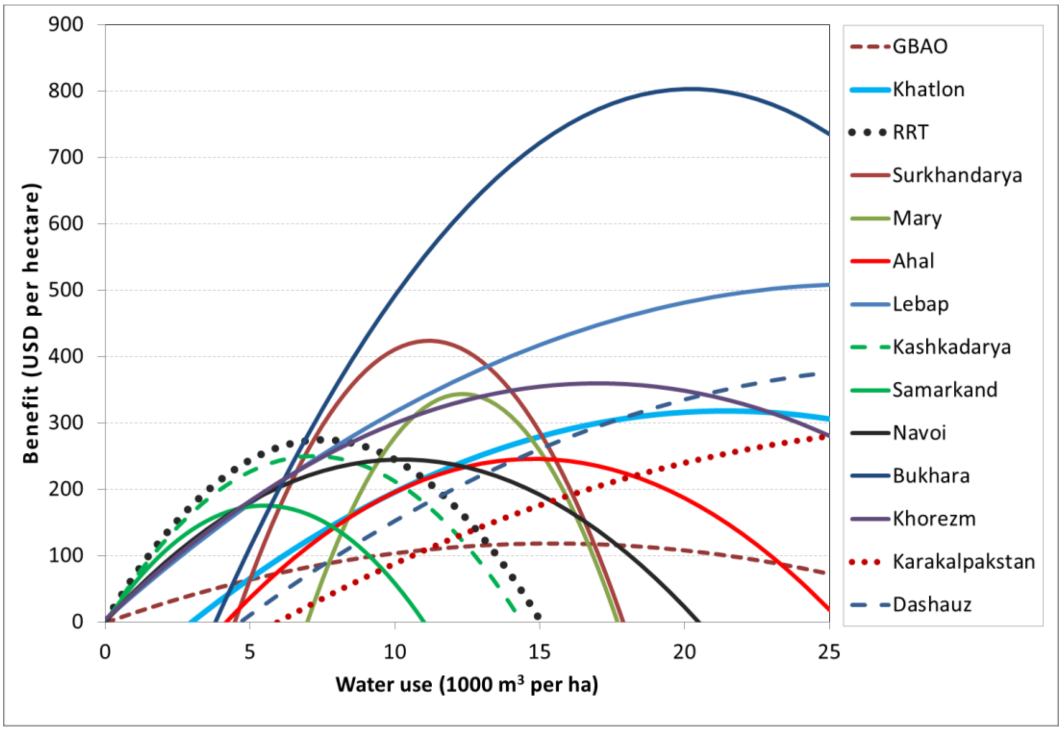
$$Ben_{dm} = a0_{dm} + a1_{dm}\ w_{dm} + a2_{dm}\ w_{dm}^2 \tag{4.38}$$

where w_{dm} is water use per hectare, and $a0_{dm}$, $a1_{dm}$, and $a2_{dm}$ are the parameters of the benefit function. Because in most irrigated areas of the ASB precipitation plays a lesser role since it mainly occurs outside of growing season and is much lower than the evaporation rate (de Pauw 2007; see also section 2.2.3), its impact on the yields are assumed to be negligible. The necessary parametrical conditions for concave-down quadratic functions are: $a1_{dm}$>0 and $a2_{dm}$<0.

The parameters of irrigation benefit functions were evaluated considering annual water withdrawals across the regions for the period between 1980 and 2000 and aggregated regional crop production benefits for the same period. Regional crop production benefits or profits were calculated as the sum profits for each crop. Profit for each crop is evaluated as a difference between total revenue of selling the crop product and its production costs. Annual regional crop production benefits were estimated at the constant crop price levels of 2006 since it is the most recent year for available data. Considering constant prices for crop production allows the reflection of crop yield fluctuations due to water availability over the years in aggregated regional irrigation benefits. Indeed, updating the database of the model while considering crop production levels and water uses for the period after 2000 once this data is released will improve the results of the model.

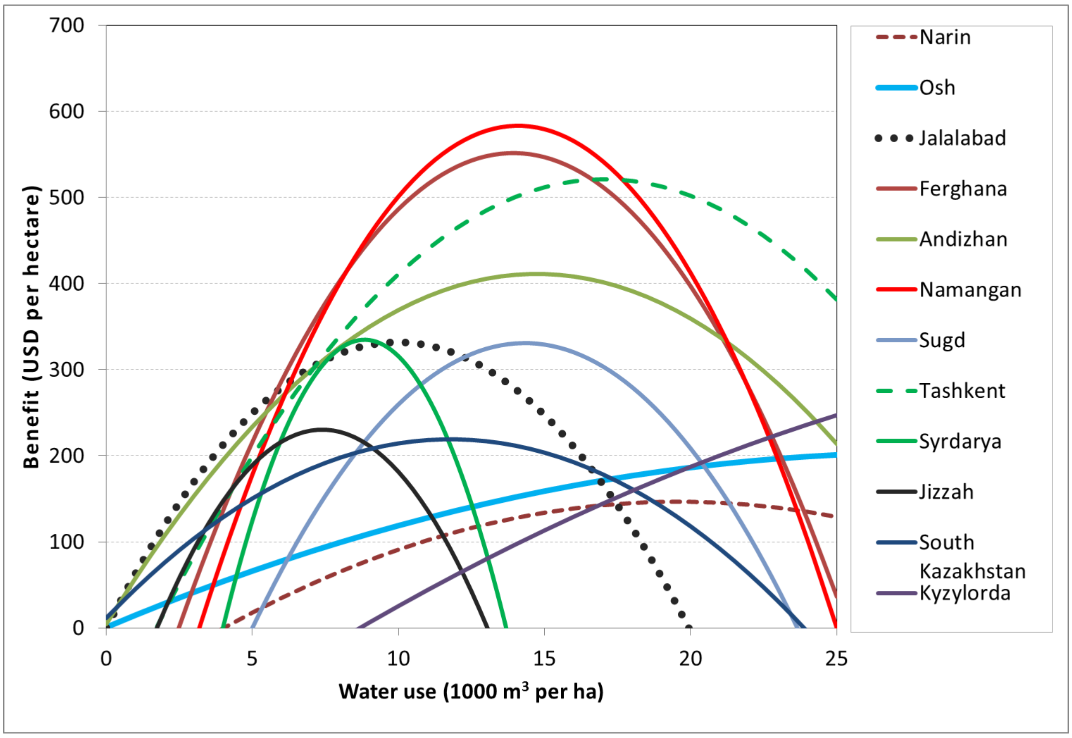
Estimated parameters of the irrigation benefit functions and their statistical significance are shown in Table 4.4. Graphical illustrations of the regression based irrigation benefit functions are given in Figure 4.9 and Figure 4.10. Determination coefficients are sufficiently high for most of the regional benefit functions, but were low in Jizzakh and South Kazakhstan. The estimated regression parameters of most of the regions are statistically significant as shown by low p-values for the coefficients of linear and quadratic variables. However, regression coefficients were not significant for the regions Bukhara, Narin, Syr Darya, and Jizzakh. According to F-tests, fittedness of all regression models to observed data was statistically significant. Due to the lack of data, the number of observations for Samarkand and Narin was low. Despite the fact that some regression functions have deficiencies due to the low statistical significance of some coefficients and a low number of observations, these results are potentially estimable based on available data. Since the econometric approach to estimating the relationships between water use and irrigation benefits at disaggregated levels for the entire basin is the first experience there is still a room for improving the benefit function results by increasing observation periods as well as including non-water use inputs such as fertilizer, labor, and capital. Nevertheless, the models still can be used for further water reallocation analyses considering the high significance of the regression coefficients in most of the models and the reliance of agricultural production primarily on irrigation water use across the ASB.

Figure 4.8 Estimated irrigation benefit functions by regions in the Amu Darya basin



Source: Author's calculations

Figure 4.9 Estimated irrigation benefit functions by regions in the Syr Darya basin



Source: Author's calculations

Table 4.4 Parameters of the regional irrigation benefit functions

Region	Node	Constant - a0				Linear coefficient - a1				Quadratic coefficient - a2				R^2	F-test	F-significance	N
		Coeff	St Dev	t-stat	p-value	Coeff	St Dev	t-stat	p-value	Coeff	St Dev	t-stat	p-value				
GBAO	Amu1	-1.2	16.56	-0.07	0.945	15.5	2.60	5.94	0.000	-0.5	0.12	-4.29	0.000	0.71	23.78	0.000	21
Khatlon	Amu1	-111.4	35.39	-3.15	0.005	40.1	8.98	4.47	0.000	-0.9	0.44	-2.12	0.047	0.92	115.03	0.000	21
RRT	Amu1	2.2	22.57	0.10	0.922	72.5	9.75	7.44	0.000	-4.8	1.19	-4.08	0.001	0.87	66.21	0.000	21
Surkhandarya	Amu2	-752.8	289.18	-2.60	0.017	210.6	72.69	2.90	0.009	-9.4	4.47	-2.11	0.049	0.75	28.58	0.000	21
Mary	Amu3	-1477.1	329.98	-4.48	0.000	295.4	63.79	4.63	0.000	-12.0	3.06	-3.92	0.001	0.79	35.27	0.000	21
Ahal	Amu3	-231.5	64.51	-3.59	0.002	64.5	13.55	4.76	0.000	-2.2	0.71	-3.09	0.006	0.84	49.91	0.000	21
Lebap	Amu4	3.6	60.46	0.06	0.954	38.7	8.82	4.39	0.000	-0.7	0.34	-2.18	0.042	0.74	27.07	0.000	21
Kashkadarya	Amu4	-0.3	22.93	-0.01	0.991	69.5	12.37	5.62	0.000	-4.8	1.66	-2.91	0.009	0.85	55.00	0.000	21
Samarkand	Amu4	0.4	13.54	0.03	0.977	63.6	9.49	6.71	0.000	-5.8	1.66	-3.49	0.005	0.93	73.55	0.000	13
Navoi	Amu4	1.0	16.55	0.06	0.952	47.7	5.14	9.26	0.000	-2.3	0.45	-5.16	0.000	0.92	96.32	0.000	18
Bukhara	Amu4	-414.7	259.40	-1.60	0.126	120.5	47.09	2.56	0.019	-3.0	2.14	-1.39	0.179	0.69	20.89	0.000	21
Khorezm	Amu5	3.8	35.32	0.11	0.916	41.9	5.49	7.63	0.000	-1.2	0.24	-5.21	0.000	0.83	45.05	0.000	21
Karakalpakstan	Amu5	-158.7	40.69	-3.90	0.001	29.4	5.70	5.16	0.000	-0.5	0.20	-2.36	0.031	0.86	52.46	0.000	19
Dashauz	Amu5	-165.0	66.03	-2.50	0.022	38.5	8.30	4.64	0.000	-0.7	0.26	-2.61	0.017	0.85	55.01	0.000	21
Narin	Syr1	-85.5	50.29	-1.70	0.120	23.7	10.47	2.26	0.047	-0.6	0.52	-1.17	0.270	0.77	16.82	0.001	12
Osh	Syr1	0.8	16.87	0.05	0.963	14.3	2.82	5.09	0.000	-0.3	0.13	-2.02	0.059	0.86	54.18	0.000	19
Jalalabad	Syr1	0.1	6.87	0.01	0.992	66.6	3.27	20.36	0.000	-3.3	0.29	-11.46	0.000	0.99	1103.80	0.000	21
Ferghana	Syr2	-264.7	90.52	-2.92	0.009	117.2	22.53	5.20	0.000	-4.2	1.33	-3.16	0.005	0.90	82.72	0.000	21
Andizhan	Syr2	4.6	21.16	0.22	0.831	55.2	4.15	13.31	0.000	-1.9	0.22	-8.54	0.000	0.95	158.69	0.000	18
Namangan	Syr2	-390.0	158.93	-2.45	0.024	138.1	36.51	3.78	0.001	-4.9	1.99	-2.46	0.024	0.84	49.44	0.000	21
Sugd	Syr2	-449.6	43.68	-10.29	0.000	109.0	9.69	11.25	0.000	-3.8	0.51	-7.49	0.000	0.97	355.22	0.000	21
Tashkent	Syr3	-122.8	52.63	-2.33	0.031	75.5	11.69	6.46	0.000	-2.2	0.62	-3.57	0.002	0.91	96.99	0.000	21
Syrdarya	Syr3	-778.2	323.34	-2.41	0.026	251.8	110.47	2.28	0.034	-14.2	9.40	-1.52	0.146	0.74	27.74	0.000	21
Jizzah	Syr3	-162.9	129.93	-1.25	0.225	106.4	65.44	1.63	0.120	-7.2	8.27	-0.87	0.394	0.52	10.20	0.001	21
South Kazahstan	Syr3	16.7	30.73	0.54	0.593	25.8	6.43	4.01	0.001	-0.9	0.35	-2.59	0.018	0.63	16.26	0.000	21
Kyzylorda	Syr4	-191.9	90.01	-2.13	0.046	24.5	7.03	3.49	0.002	-0.3	0.13	-2.08	0.051	0.75	29.09	0.000	21

Notes: R^2 – coefficient of determination/ N-number of observations; Source: Author’s calculations

4.4.6 Environmental benefit function

4.4.6.1 Overview of approaches to model economic benefits from environmental systems

Despite the increased importance of incorporating environmental values of water use for sustainable development analyses, measuring environmental benefits is a challenging task. Since most of the environmental services are not marketable several methods such as contingent valuation, hedonic pricing, choice modeling, travel cost methods, and meta-analysis exist to estimate the economic value of environmental benefits (Young 1996). Contingent valuation is based on directly surveying consumers' willingness to pay for particular ecosystems services such as water quality or recreation. Hedonic pricing is based on the differences in property prices and salaries between locations and isolation of the values of the attributes ascribed to wetland existence or quality. Choice modeling is based on a survey of respondents requesting their preferences for particular services or goods with different attributes. The travel cost method considers the expenditures to visit wetlands, which includes transport, food, accommodation, time, etc. Meta-analysis tools are based on regressing already investigated ecosystem service values to different characteristics of the study area such as population density or GDP per capita, and extrapolating the ecosystem values in uninvestigated study areas based on their known attributes, which is included as an independent variable in the regression function. With the exception of meta-analysis, these methods have some shortcomings since they may provide biased estimates and require expensive surveys. They may also work better for estimating environmental benefits at small scales rather than larger scale basin level environmental benefits.

Additional approaches for evaluating environmental benefits include the replacement costs, effects on production, and avoided damage costs (Barbier 1994). The replacement costs method considers the costs of marketable commodities that are alternatives to products which are freely available from an ecosystem. The effects on production can be exemplified by the role of ecosystems as inputs to some production activities. The avoided damage costs method is reflected by the impact of environmental degradation on reduced productivity of economic sectors.

Usually estimations based on ecosystem evaluation methods provide ecosystem value per land or surface area of the watershed or particular land cover types. These values can be later used to estimate environmental flow-benefit relationships to incorporate into the hydro-economic modeling. Simplified approaches from hydro-economic modeling research based on minimum environmental flows (Colby 1990) or fixed benefit per unit of water use (Cai 2002) were also used. More sophisticated approaches include non-linear functional relationships between flow and environmental benefits. For instance, in their study of the Mekong River basin Ringler and Cai (2006) used an arctan function to evaluate relationships between flows and benefits from fisheries, and a quadratic function to estimate the relationship between deviations in water flow, lake volume, and wetland benefits. However, the authors acknowledged that there is no standard functional forms to evaluate ecosystem service benefits. In this study, different types of ecosystem services (fishery, wetlands, etc.) were selected for evaluation based on previous studies and different functional forms were chosen to regress these benefits to the environmental flows based on data availability.

Several studies discussed the benefits from the Aral Sea and deltaic zones, while emphasizing the value of fish production, water transportation, biodiversity, wetlands, and public health (Micklin 1988, 2007, 2010, Mirzaev 2000). However, only a few studies (INTAS 2001, 2004, TEEB 2011) quantified approximate economic losses due to environmental degradation. An approximate general environmental benefit function was estimated by combining the benefit functions of different ecosystem services such as wetlands, recreation, prevention of storms (prevention of damage to agriculture and health), fishing, and water-based transportation. The area of wetlands located in the delta zone is assumed to be dependent on river flows, while the benefits from the remaining ecosystem services are dependent on the volume of the Aral Sea. The benefit functions of separate ecosystem services were estimated by regressing the literature-survey based economic benefits from the inflows to the Aral Sea. In order to find relationships between river flow and the benefits of volume-dependent ecosystem services, the relationship between the sea volume and the inflow amount required to stabilize this volume was initially estimated. Due to the data limitations only bounded linear relationships for the most of the environmental benefit functions were assumed. Therefore, environmental flow estimations are rough estimates based on the limited available dataset and thus further improvement would increase the validity of the model. Nevertheless, since the dataset used is the most adequate to date and this study is one of the initial attempts to evaluate environmental benefits from the flows to the Aral Sea, this analysis should be accepted as an important first step to catalyze further research and discussions.

4.4.6.2 Aggregated environmental benefit function

As the environmental benefit estimates based on the literature survey were available at the price levels of different years, they were converted to 2006 prices considering annual inflation rates. A linear relationship between the environmental flow (EW) and its economic benefit (EB) is elaborated as:

$$EB = b0 \ + b1\, EW \tag{4.39}$$

where $b0$ and $b1$ are parameters of the regression function and the environmental flow (EW) is the sum of the inflows from the Amu Darya (the node link "Amu5 → THE ARAL SEA") and Syr Darya (the node link "Amu5 → THE ARAL SEA") rivers into the Aral Sea ($Q_{'Amu5','Aral'}$ and $Q_{'Syr4','Aral'}$ respectively). The procedure of estimating values of different ecosystem services such as wetlands, recreation, dust and salt storm protection, fisheries, and water-based transportation as well as combining them to evaluate the aggregate environmental benefit function in equation 4.33 was shown in the following sub-sections.

4.4.6.3 Stabilizing environmental flow

The water balance in the Aral Sea stipulates that the annual change in volume (V) is the difference between the sum of environmental inflow and rainfall (RF), and evaporation (EP) in year t:

$$\frac{dV}{dt} = EW \ + RF - EP \tag{4.40}$$

It was assumed that rainfall over the sea does not depend on the Aral Sea volume and that evaporation is a function of sea volume. Considering the stability of the Sea volume over the long term ($\frac{dV}{dt} = 0$), the relationship between volume and stabilizing inflow (EW^*) is estimated as:

$$EW^* \ + RF - EP(V) = 0 \quad \Rightarrow \quad EW^* = RF - EP(V) \tag{4.41}$$

4.4.6.4 Wetlands value based on the 'meta-analysis' method

The area of wetlands decreased from 550,000 ha to 27,500 ha during the period between 1960 and 1990 (TEEB 2011). According to a meta-analytic value function analysis (Brander et al. 2006), the estimated annual economic loss due to the decreased size of wetlands was around \$190 USD per hectare or \$100 million USD in total (TEEB 2011). The meta-analytic function analysis is based on the comparability of ecosystem values in the regions with similar wetland types and sizes, GDP per capita, and population density. Estimated ecosystem values across different project sites around the globe were regressed on physical and socio-economic parameters of the wetlands and this model was used to extrapolate unknown wetland values in non-investigated sites. Based on this meta-analytic function from the literature and wetland area data, wetland economic values over the years in the ASB were first assessed. Then these values were regressed with annual environmental flows in order to estimate the relationship between environmental flow and wetland economic values (EB_{wshed}, in millions of USD). Maximum wetlands areas and threshold inflow levels (EW_+, in km^3) in the 1960s were the basis for estimating potential wetland benefits and thus build a bounded linear function:

$$EB_{wshed} = \begin{cases} 2.0326 \cdot EW, & if\ EW < 52.4 \\ 2.0326 \cdot EW_+, & if\ EW \geq 52.4 = EW_+^* \end{cases} \tag{4.42}$$

4.4.6.5 Recreation values based on the 'effects on production' approach

Tourism was well developed on the shores of the Aral Sea in the 1960s. About 50,000 people were visiting the site with an average stay of five days, during which they spent around \$45 USD (at price levels of 2006) per day in 1960 (INTAS 2004). These numbers were used as the basis to calculate potential income from tourism in the surroundings of the Aral Sea. Substantial losses in tourism income occurred due to the desiccation of the sea. By 1990 the number of tourists had decreased to about 5,000 people, yet their expenses had doubled. Based on tourism incomes in 1960 and 1990, a piece-wise linear function of recreation (touristic) benefits (EB_{recr}) that depends on environmental inflow was estimated as follows:

$$EB_{recr} = \begin{cases} 0.0114 \cdot EW^*, & if\ EW^* < 27.7 \\ 0.473 \cdot EW^* - 9.9377, & if\ 27.7 \leq EW^* < 58.8 \\ 0.473 \cdot EW_+^* - 9.9377, & if\ EW^* \geq 58.8 = EW_+^* \end{cases} \tag{4.43}$$

4.4.6.6 Dust and salt storm protection benefits to human health (based on the 'avoided damage cost' approach)

Health benefits were assessed based on benefit losses due to health degradation as a result of the desiccation of the Aral Sea and consequent spread of dust and salt from the dried seabed through the storms. Health benefits were assumed to be zero in 1999, and equal to the average annual benefit losses due to health degradation between 1960 and 1999. It was also assumed that health status in 1960 cannot be influenced by further increase in the volume of the Aral Sea. Annual benefit losses due to health degradation amounted to \$5.2 million USD (at price levels of 2006), of which \$1.7 million USD were due to increased frequency of illness and \$3.5 million USD were due to reductions in life expectancy in the Amu Darya River delta (INTAS 2001, 2004). The benefit losses due to increased illness were estimated based on the loss of working days and associated income, while the benefit losses due to reduced life expectancy were quantified based on per capita GDP losses and shortened life duration (INTAS 2001, 2004). Estimations based on the proportional relationships between social benefit losses in Uzbekistan and Kazakhstan showed total health benefit losses of $14.0 million USD for the entire delta zone. Based on these figures and assumptions, the approximate bounded linear relationships for health benefit (EB_{health}) and environmental flow were estimated as:

$$EB_{health} = \begin{cases} 0, & if\ \ EW^* < 27.7 \\ 0.4496 \cdot EW^* - 12.45, & if\ 27.7 \leq EW^* < 58.8 \\ 0.4496 \cdot EW_+^* - 12.45, & if\ \ EW^* \geq 58.8 = EW_+^* \end{cases} \tag{4.44}$$

4.4.6.7 Dust and salt storm protection benefits to irrigated lands (based on the 'avoided damage cost' approach)

The spread of toxic salts from the dried seabed of the Aral Sea is one of the main causes of degraded lands, reduced yields, and decreased crop production in the surrounding regions. A total of $22 million USD (at price levels of 2006) in annual agricultural benefit losses occurred in 1997 compared to 1970 according to INTAS (2001, 2004). As in the case of the health benefit assessment, agricultural impact benefits were evaluated on the basis of benefit losses due to yield reduction. No benefits were assumed in 1997 and the benefits in 1970 were equal to the amount of annual average benefit losses. A bounded linear relationship between stabilizing inflow and agricultural benefits (EB_{agr}) were estimated as:

$$EB_{agr} = \begin{cases} 0, & if\ \ EW^* < 20.6 \\ 0.799 \cdot EW^* - 16.498, & if\ 20.6 \leq EW^* < 48 \\ 0.799 \cdot EW_+^* - 16.498, & if\ \ EW^* \geq 48 = EW_+^* \end{cases} \tag{4.45}$$

4.4.6.8 Fishery benefits based on the 'effects on production' approach

The Aral Sea's commercial fishery was the backbone of the regional economies in the Amu Darya and Syr Darya deltas in the past, employing about 40,000 people and producing more than 15% of the SU's seafood catch. The average annual harvest was reached 50,000 metric tons before the 1960s. However, the fishery collapsed in the southern Aral Sea by the mid-1980s and decreased to 2,000 metric tons in the northern Aral Sea due to the shrinkage of the sea (UNEP and ENVSEC 2011). Fishery benefit functions were built by regressing annual stabilizing inflow and total fish harvest benefits, while considering average profits of $264 USD per metric ton in the fishing sector, which was estimated based on fish production cost-benefit data (Timirkhanov et al. 2010). A bounded exponential function was found to be the most appropriate to illustrate the relationship between water inflows and fishery benefits (EB_{fish}):

$$EB_{fish} = \left\{ \begin{array}{ll} 0.0092 \cdot e^{0.1277 \cdot EW^*}, & if\ EW < 59.8 \\ 0.0092 \cdot e^{0.1277 \cdot EW_+^*}, & if\ EW \geq 59.8 = EW_+^* \end{array} \right\} \tag{4.46}$$

4.4.6.9 Water transportation

Marine transportation was well developed in the deltaic regions of the ASB. Annual cargo traffic between the ports of Aralsk and Muynak was about 2.5 million ton/km in the 1960s (Zonn 2010). The value added per ton of transportation was around $0.5 USD (INTAS 2005). Due to the desiccation of the sea, marine transportation decreased by a factor of eight by 1978, and the ports were closed in 1979 (INTAS 2004). Approximate water transportation benefits were calculated based on the cargo traffic volume and value added per unit of transportation. A bounded quadratic relationship between shipping benefits (EB_{trans}) and environmental inflow was estimated as:

$$EB_{trans} = \begin{cases} 0, & if\ EW^* < 44.4 = EW_-^* \\ -0.0065 \cdot EW^{*2} + 0.7639 \cdot EW^* - 21.107, & if\ 44.4 \leq EW^* < 58.8 \\ -0.0065 \cdot EW_+^{*2} + 0.7639 \cdot EW_+^* - 21.107, & if\ EW^* \geq 58.8 = EW_+^* \end{cases} \tag{4.47}$$

4.4.6.10 Estimated overall benefits from inflows to the Aral Sea and deltaic zones (environmental flow)

Environmental water use benefits from different ecosystem services were simulated depending on different levels of water inflows to the Aral Sea and deltaic zones, and these simulated values were combined to obtain an aggregate environmental benefit (EB_A) function at the end (Figure 4.8):

$$EB_A = EB_{wshed} + EB_{recr} + EB_{health} + EB_{agr} + EB_{fish} + EB_{trans} \tag{4.48}$$

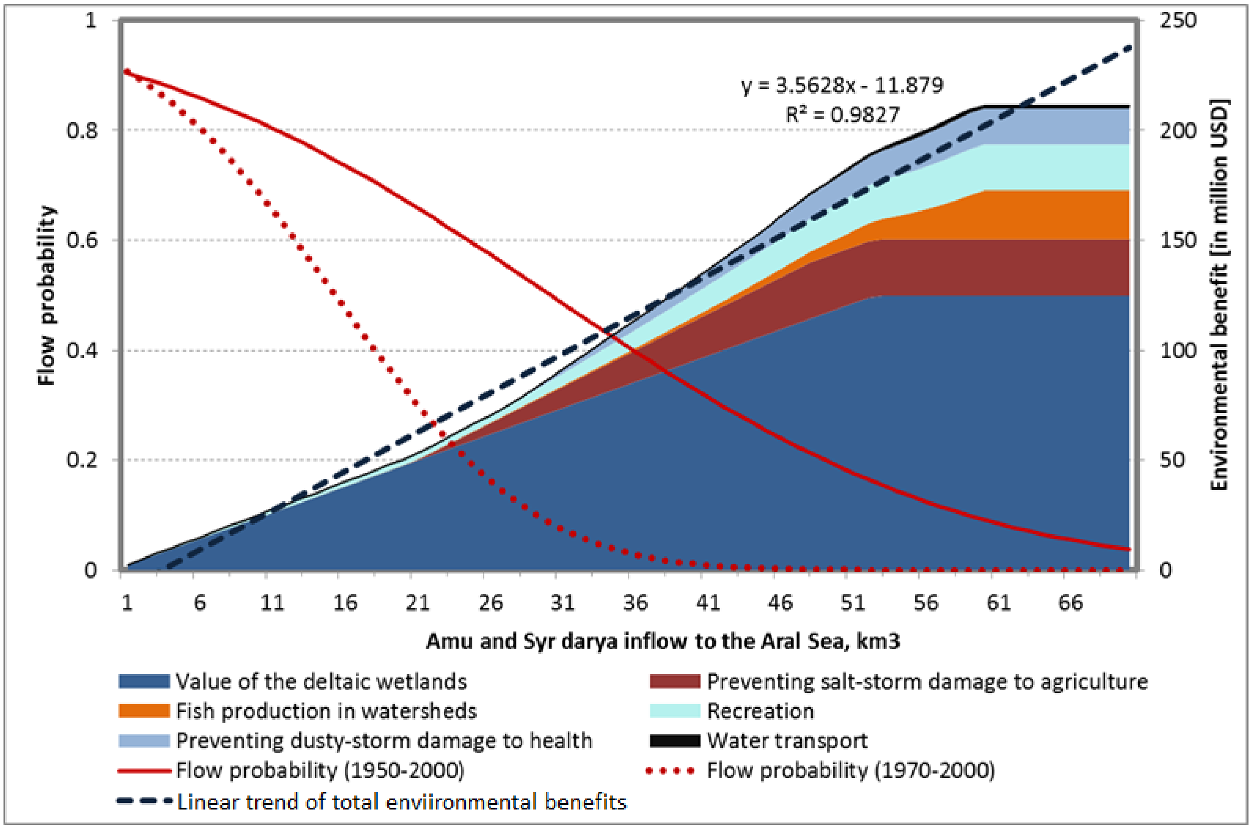
According to the estimations the contribution of wetlands to total environmental benefits is substantial, while benefits from water transportation in the sea were negligible in comparison with other ecosystem values. Crop yield improvement due to increased protection from wind-borne salt and the revival of tourism can provide annual revenues of $26 million USD and $21 million USD respectively if average annual inflows to the Aral Sea are at least 50 km^3.

Based on an environmental benefit function, the damage costs due to the reduced environmental flow over the certain period also can be estimated. The average flow into the Aral Sea decreased from 61 km^3 to about 17 km^3 during the period between the 1950s and 1990s (INTAS 2006). As a result the annual environmental benefits related to the inflows to the Aral Sea decreased from $211.4 million USD to $42.8 million USD, consequently causing annual economic losses of almost $170 million USD (at 2006 prices). This estimation is comparable with the previous estimation of $144 million USD (at 2000 prices) by INTAS (2001) if inflation rates between 2000 and 2007 are considered.

Based on different levels of environmental flows and simulated values of environmental benefits, linear regression function parameters were estimated and further used in the hydro-economic model (Eq. 4.33). The linear functional form was chosen for further modeling calculations due to its simplicity and high determination coefficient ($R^2 = 0.98$). Although S-shape functions like the arctan function are preferred for estimating environmental flow and benefit relationships (Ringler and Cai 2006), the linear function was a still better fit to reflect the estimated environmental benefits in the ASB when environmental flows are below 60 km^3. To determine if the probability of more than 60 km^3 of water inflow to the Aral Sea is negligible, the probabilities of inflow to the Aral Sea being more than a certain amount was also computed. Normal distribution of the observed series of environmental flow was assumed. According to the computations, when the probabilities are based on the observations from the period between 1950 and 2000 the probability of 30 km^3 of inflow is at least 50%, while the probability of inflow higher than 60 km^3 is 10%. If we consider that most of the irrigation developments in the ASB occurred after the 1960s and therefore shorten the observation period of the computations to the period between 1970–2000, the probability of inflows at a level of 15 km^3 is 50%, more than 30 km^3 is 10%, and more than 60 km^3 is practically 0%. Thus, a linear function can be used in further modeling analysis.

The average economic benefit from each additional m^3 of water (marginal water productivity) to the Aral Sea is about $0.0036 USD as derived from a linear environmental benefit function. Cai et al. (2002) assumed the value of environmental flow equal to $0.1 USD per m^3 (Cai 1999), which is much higher than the estimates made in this study. Unfortunately, the analysis of Cai et al. (2002) was based on previous reports (Anderson 1997) that do not mention anything about the methods used to calculate environmental benefits. Moreover, the report showed values of $0.025–0.05 USD per m^3 of environmental flow not $0.1 USD per m^3. According to the report, environmental flow value is slightly lower than the values of water for irrigation and industry. For instance, the value of 1 m^3 water was $0.06–0.1 USD for cotton, $0.0–0.04 USD for wheat, $0.0–0.12 USD for rice, and $0.1 USD for industrial uses. Assuming that the value of environmental flow is equal to the value of water for industrial use does not appear sound.

Figure 4.10 Environmental benefit function for the Aral Sea and its deltaic zone



Source: Author’s calculations

4.4.6.11 Limitations

In contrast to the assumptions on environmental benefits from the Aral Sea from previous studies, which are likely overestimations of real values (Cai et al. 2002), it is important to note that environmental flow benefit in this study is perhaps underestimation since the values of direct use of the inflows to the Aral Sea and its delta were primarily relied upon. In addition to the values of direct use of environmental flows such as fisheries and shipping, values of indirect use such as wildlife reservation is also important for sustainability (Dziegielewska et al. 2009). Overall environmental benefits also include the non-utilitarian values of water (Dziegielewska et al. 2009) such as option values, existence values, and bequest values. Option values, which can also be grouped with direct use values, reflect the potential use of environmental resources in the future and can be exemplified by the will to have the goods in the future for biodiversity preservation. Existence value is existent, as many people want and are ready to pay for the protection of habitats of endangered species and other wildlife. The bequest value is related to the will of preserving certain environmental goods for future generations at the same quality as their current state. The share of non-utilitarian values of ecosystem services in total environmental benefit usually are over 50%, but in some cases reach 80–98% (Dziegielewska et al. 2009). Therefore, considering the limitedness of the available datasets for estimating indirect environmental benefits in the ASB, additional scenario analyses assuming higher value of water for environmental uses or alternatively increasing minimum environmental release are recommendable for determining the optimal volumes of environmental release or the alternative costs of additional environmental flow. Furthermore, due to data limitation the differences between the values of water inflow into the Aral Sea and deltaic zone are not separated in this study. Separation of these environmental flow benefits would allow improved results since the share of the value of wetlands is substantial in total environmental benefits, while requiring lower water use than the ecosystem benefits that directly depend on the volume of the sea.

4.4.7 Water rights trading component

Based on Eq. (4.30), the shadow price of water was derived directly from the water benefit function considering transaction costs (tc) of water rights trading:

$$WTP_{dm} = \frac{\partial\, Ben_{dm}}{\partial\, WD_{dm}} + tc\ \frac{WS_{dm} - WB_{dm}}{WS_{dm} + WB_{dm}} \qquad (4.49)$$

or

$$WTP_{dm} = a1_{dm} \ + a2_{dm} w_{dm} \ + tc\ \frac{WS_{dm} - WB_{dm}}{WS_{dm} + WB_{dm}} \qquad (4.49')$$

Moreover, additional constraints were introduced regarding water rights trading.

A water user site either buys or sells water use rights:

$$WS_{dm}\, WB_{dm} = 0 \qquad (4.50)$$

Total water use rights sold are equal to the total water use rights bought for either river system:

$$\sum_{dm} WS_{dm} = \sum_{dm} WB_{dm} \tag{4.51}$$

Water intake to the water user region should be lower than the sum of its water use rights and the additional water bought if the user buys water, or than the difference between water use rights and the amount of water sold if the user sells water:

$$WDR_{dm} \le WUR_{dm} - WS_{dm} + WB_{dm} \tag{4.52}$$

where WUR_{dm} is the water use right of the demand site (dm), which is determined here according to proportional fixed water use shares calculated based on water distribution in the baseline year (Cai et al. 2006).

Total expenditures to buy water use rights should be sufficient to cover the value of the rights offered by the potential sellers, i.e., total benefits from selling water use rights should be less than total expenditures for buying water use rights:

$$\sum_{dm} WTP_{dm}\, WS_{dm} \le \sum_{dm} WTP_{dm}\, WB_{dm} \tag{4.53}$$

In addition, to prevent the model from the elimination of water deliveries to any irrigation zone, minimum water use constraints in each region that is 50% of the initially observed level is considered. This constraint is needed to prevent unrealistic and socially or politically unacceptable optimal solutions which imply elimination of the irrigation in some regions with the lowest water productivity and thus imply full migration from these zones.

4.4.8 Scenarios

4.4.8.1 Baseline (fixed water use rights) and optimization scenarios under different levels of water availability

The model was calibrated to the real conditions of land and water use and hydrologic flow in 1999, a year with normal water supply. The year was chosen based on the average value of the observed water supplies between 1980 and 2008. For analyzing the impact of water availability on water distribution among the water users, two alternative water supply scenarios were assumed to be equivalent to 90% and 80% of the normal supply.

The baseline scenario is based on water distribution on fixed water use rights, which were derived according to fixed water use shares as of 1999. An optimization scenario was run to show ideal water distribution in economic terms as a target for water users. The latter scenario did not consider water market conditions, thus the objective function (4.35) was changed accordingly:

$$obj' = \sum_{dm} Ben_{dm}\, AR_{dm} - \sum_{dm} CC_{dm}\, WD_{dm} + EB \to max \tag{4.35a}$$

Guaranteed minimum environmental flow ($WSA_{'Amu'}$, $WSA_{'Syr'}$) restrictions were included considering the intergovernmental agreement[1] on preventing environmental degradation in the Aral Sea delta:

$$Q_{'Amu5','Aral'} \geq WSA_{'Amu'} \tag{4.54}$$

$$Q_{'Syr4','Aral'} \geq WSA_{'Syr'} \tag{4.55}$$

Minimum environmental flows were considered as equal to 1.5 km^3 and 3.5 km^3 from the Syr Darya and Amu Darya rivers respectively based on the intergovernmental agreement.

4.4.8.2 Fixed water use rights vs. intra- and inter-catchment water rights trading

The water rights trading scenario allows water users to sell or buy water rights, thus increasing the scope of water withdrawal beyond the fixed water rights and boosting additional benefits in the regions with higher marginal water benefits. Intra-catchment (intra-node) and inter-catchment (inter-node) water rights trading are differentiated from each other considering that the introduction of water markets is easier between the irrigation sites that are geographically closer to each other. These two main water rights trading scenarios were compared to the fixed water use rights distribution (baseline scenario) for analyzing the effects of water rights trading on income levels of different water users. Trading scenarios were also compared to the results of the optimization scenario to show how much they distort from the ideal case. Intra-catchment or restricted (RWT) water rights trading means that water transfers are allowable only among the water users within a catchment (a node, see Figure 4.7). Inter-catchment or unrestricted (UWT) water rights trading can occur freely among the water users located in different catchments.

The impacts of introducing “within catchment” boundaries on full water rights trading were tested by including additional model restrictions that allow water rights trading only within individual water catchments. Under this restriction, total water withdrawals should be equal to the total water use rights within each catchment:

$$\sum_{(rn,dm)\in NDLINK} WDR_{dm} = \sum_{(rn,dm)\in NDLINK} WUR_{dm} \tag{4.56}$$

Moreover, the amount of water bought and sold within the catchment are equal to each other:

$$\sum_{(rn,dm)\in NDLINK} WB_{dm} = \sum_{(rn,dm)\in NDLINK} WS_{dm} \tag{4.57}$$

---

[1] The “Agreement on Joint Activities for Addressing the Crisis of the Aral Sea and the Zone around the Sea, Improving the Environment and Ensuring the Social and Economic Development of the Aral Sea Region”, March 26 1993

These water rights trading scenarios were run assuming zero transaction costs for water market institutions, therefore the objective function did not include a transaction costs component:

$$obj'' = \sum_{dm}(Ben_{dm}\,AR_{dm} - CC_{dm}\,WD_{dm} + WTP_{dm}(WS_{dm} - WB_{dm})) \\ + EB) \rightarrow max \tag{4.35b}$$

Additional constraints on regional irrigation benefits were also considered that imply not to worse off the benefits of any water user with the introduction of tradable water use rights compared to the benefit levels initially observed under the baseline scenario (fixed water use rights).

4.4.8.3 Alternative costs of increased environmental flow under water rights trading

Considering increased need to improve environmental conditions, payment schemes to the irrigation farmers for reducing irrigation water withdrawal would allow increased water supply into the delta. Knowing the costs of additional water supply to the Aral Sea and its delta, IFAS may decide to purchase water for increased environmental flow based on the willingness of donors and the riparian governments to pay for it.

The objective function of the model was changed to estimate the alternative costs of increased inflows to the Aral Sea, while allowing water rights trading among the water users as well as considering compensation to irrigators for reduced water use:

$$obj''' = \sum_{dm}(Ben_{dm}\,AR_{dm} - CC_{dm}\,WD_{dm} + WTP_{dm}(WS_{dm} - WB_{dm})) \\ + EB - WTPA \cdot WBA) \rightarrow max \tag{4.35c}$$

where $WTPA$ is the purchase costs of additional water for environmental needs, WBA is the amount of purchased water delivered to the Aral Sea and its delta.

Appropriate changes were also introduced to water rights trading balance conditions:

$$\sum_{dm} WS_{dm} = \sum_{dm} WB_{dm} + WBA \tag{4.51c}$$

Since benefits from the environmental system were estimated to be very low in this study, additional water supply to the Aral Sea through purchasing irrigation water rights were considered based on a scenario analysis. In each scenario the minimum level of purchased water delivered to the Aral Sea and its delta was gradually increased. Twenty-one scenarios were run considering minimum purchased environmental flow of 0 to 20 km^3 differentiated by 1 km^3 increments in each scenario.

For comparison purposes, the same procedure was repeated neglecting water rights trading opportunities among the irrigation zones and only allowing water rights sales for environmental needs. The objective function and trading balance restrictions were changed accordingly as:

$$obj''' = \sum_{dm}(Ben_{dm}\,AR_{dm} - CC_{dm}\,WD_{dm} + WTP_{dm}\,WS_{dm}) + EB - WTPA \cdot WBA) \rightarrow max \tag{4.35c'}$$

and

$$\sum_{dm} WS_{dm} = WBA \tag{4.51c'}$$

4.4.8.4 Transaction costs

The impact of transaction costs on the economic profitability of water rights trading was assessed based on a scenario analysis. Transaction costs were varied between \$0.012 USD and \$0.125 USD per cubic meter or alternatively 3% to 30% of the water prices in Australia as previously reported (Challen 2000). In this study, twenty-one simulations of transaction costs varying between \$0.0 USD and \$0.1 USD per m^3 of water volume were considered. Similar to the case in the theoretical model of Challen (2000), transaction costs were assumed to be shared equally between the buyer and seller.

4.4.9 Model solution

The model was coded in GAMS and solved using CONOPT 3 non-linear programming solver (Brooke et al. 2006). Detailed description of the GAMS code for analyzing water rights trading and the scenarios of increasing transaction costs is provided in Appendix C.

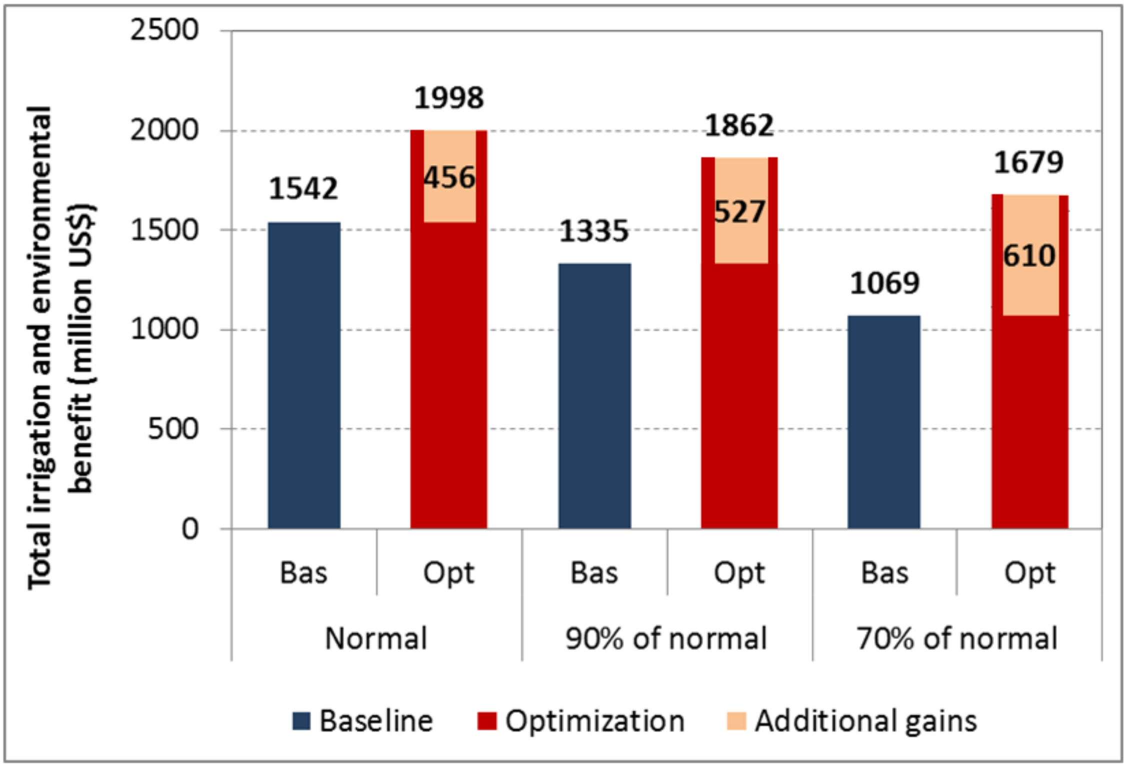
4.5 Results of optimal water allocation and water rights trading

The benefit functions developed and the hydrological river basin model were combined into a single modeling framework to evaluate optimal water allocation in the ASB economically. First, the benefits under fixed water rights and optimization scenarios were compared. Next, because optimization is not favorable to some water users, particularly upstream ones, optimal water allocation was estimated when water rights trading is allowable among the users and the environment. Considering that water rights trading is more feasible among neighboring regions that share a single water catchment, the benefits from intra-catchment water rights trading were also assessed. Furthermore, alternative costs of additional water supply to the Aral Sea due to reduced water availability to irrigation were estimated. Higher gains were predicted under water allocation with water rights trading than without water rights trading among irrigation zones. In the end the impacts of different transaction cost scenarios on the gains from water market were analyzed.

4.5.1 Baseline (fixed water use rights) vs. optimization

Although the costs of establishing an omniscient decision maker who optimizes water use benefits for the entire basin is too high and unrealistic considering the multiple number of independent water users involved, optimization results can still serve as a target point for comparing the benefits from alternative water management institutions. The results indicated that the potential annual basin-wide benefits (from irrigation and environmental demand sites) of optimal water use in the ASB vary between $1,680 million USD and $2,000 million USD depending on water availability (Figure 4.11). This signifies additional economic benefits of $450 million USD to $610 million USD compared to the baseline (fixed water use rights) benefits.

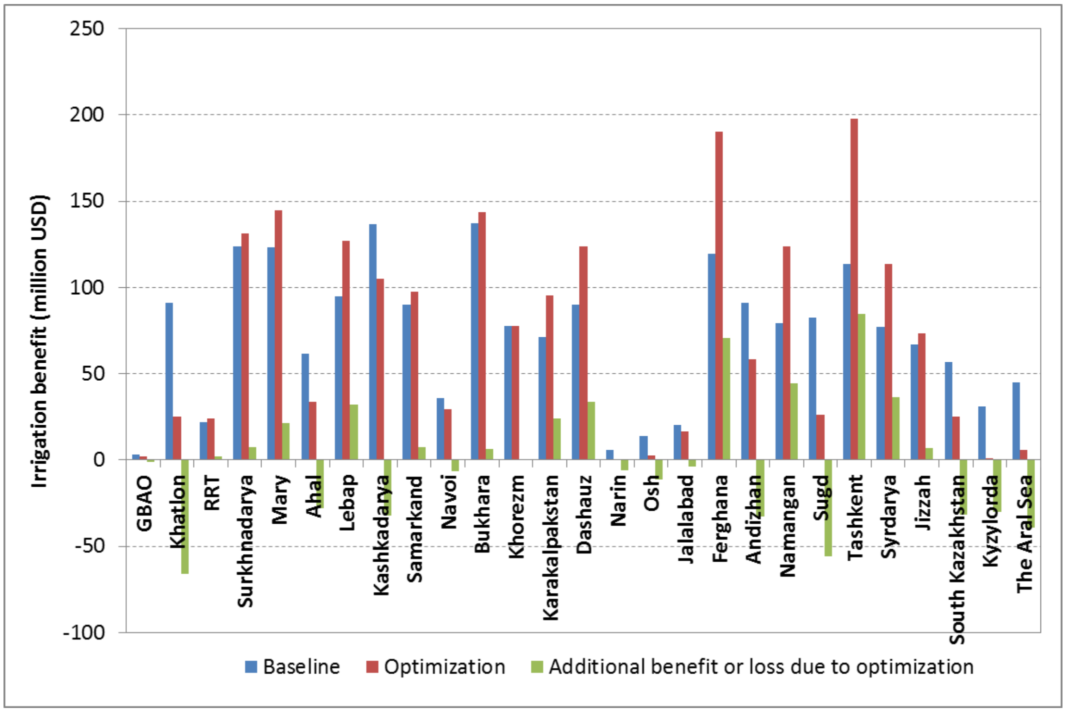
Figure 4.11 Total water use benefits under baseline and optimization scenarios at different levels of water availability



Source: Author’s calculations

Despite substantial increases in basin-wide water use benefits under optimization, benefits were not equally distributed for all regions, i.e., while some users got higher benefits from optimization of water allocation, some lost benefits due to decreased water use (Figure 4.12). For instance, optimal water allocation would be reached by diverting more water resources to irrigation in high fertile valleys and oases like Tashkent and Ferghana, at the same time water consumption and benefits would decline in Khatlon, Ahal, Kashkadarya, Andizhan, Sugd, South Kazakhstan, and Kyzylorda.

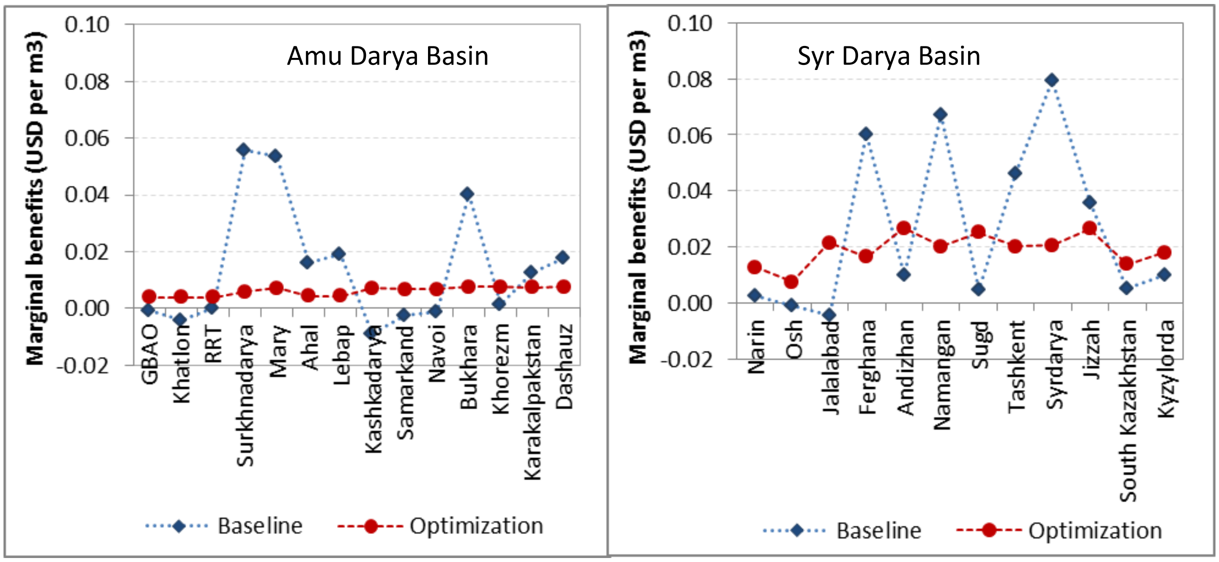
Figure 4.12 Water use benefits by water user sites of the Aral Sea basin under normal water supply



Source: Author's calculations

Marginal water benefits across the Amu Darya and Syr Darya basins were highly variable under the fixed rights based water allocation (baseline), but stabilized under optimization (Figure 4.13). Under optimization, marginal benefits varied between \$0.004 and \$0.027 USD per m^3 across the regions. Particularly in the Syr Darya basin, marginal benefits varied between \$0.008 and \$0.027 USD per m^3, which is comparable to the results by Cai et al. (2003a) that varied between \$0.008 and \$0.043 USD per m^3. Different spatial dimensions of the Syr Darya model (Cai et al. 2003a) and the model developed in this study does not allow region-by-region comparisons. Marginal benefits were lower in the regions of the Amu Darya basin, indicating higher water availability or lower profitability of water use in this basin than in the Syr Darya basin. Theoretically, marginal water use benefits should be equal across regions in each river basin under optimization if the only restriction is water availability. However, additional restrictions due to differences in hydrological, land use, and productivity conditions along the rivers and water catchment zones also had impacts on marginal benefits and prevented equal marginal benefits across all regions. Under the optimization scenario, marginal water use benefits in each river basin should also be equal to each other since inflows to the Aral Sea from both rivers has the same value due to a single environmental benefit function for the entire sea. Due to very low marginal benefit from environmental flows as estimated compared to marginal benefits to irrigation in the Syr Darya basin indicating water scarcity for irrigation needs in the basin, equimarginal benefits in the river basins were not observed. Only marginal benefits of irrigation in the Amu Darya basin were very close to the marginal environmental benefits of \$0.0036 USD per m^3 since water availability to irrigation was close to the level of satisfying potential irrigation water demand in this river basin.

Figure 4.13 Marginal irrigation benefits by regions in the Amu Darya and Syr Darya basins under normal water supply

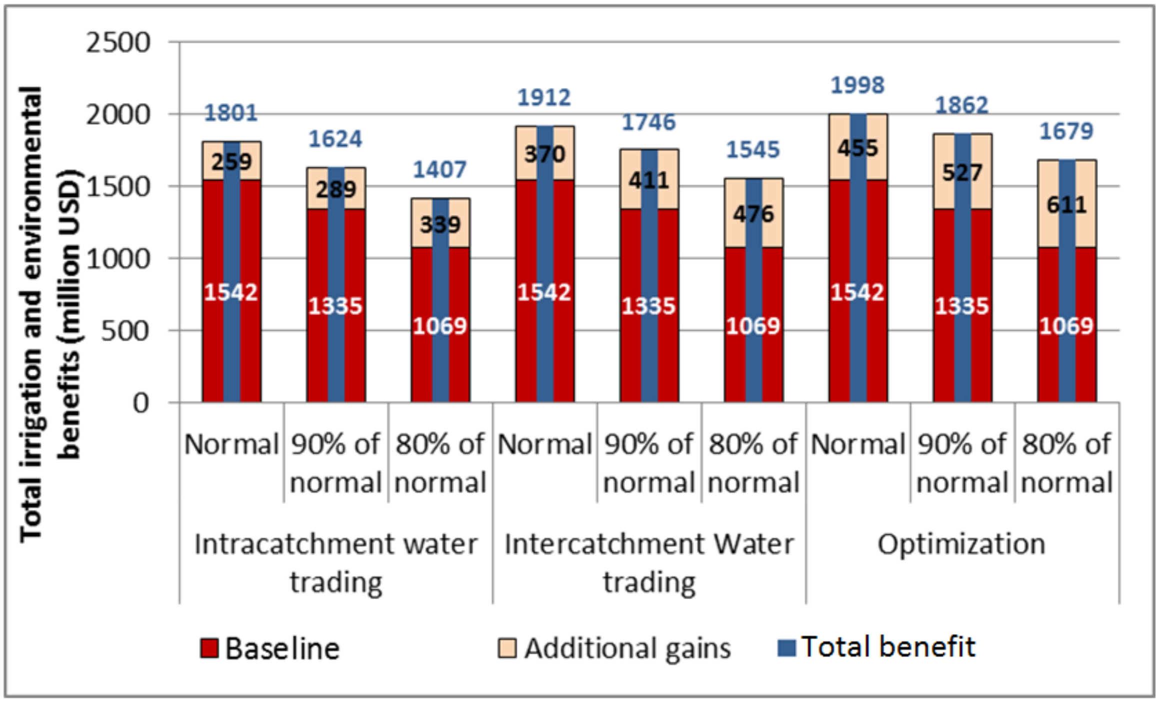


Source: Author's calculations

4.5.2 *Intra-catchment and inter-catchment water rights trading*

Despite substantial increases (30%, 39%, and 50% under normal water supply levels, 90% of normal, and 80% of normal respectively) in overall basin benefits under optimal water allocation, the regions with lower marginal water productivity will only cooperate to achieve optimal basin-scale benefits if they are compensated for lost income due to reduced water use. Introducing tradable water use rights would provide incentives for cooperation by increasing willingness of less productive regions to transfer part of their water rights for appropriate compensation to more productive regions. Results indicated that although additional gains from water markets were less than those of the pure optimization scenario, economic gains were substantially higher than those under fixed water rights (Figure 4.14). Lower benefits of water markets than the optimal benefits can be explained by the consideration of initial water use rights and thus additional restrictions on maximum water sales of each water user in the model when water rights trading was addressed. Impact of initial water rights distribution on basin-wide irrigation benefits were also shown by previous studies (Ringler 2001). Moreover, hydrological, return flow, and maximum/minimum regional water use constraints also may prevent the distortion of the additional benefits of water rights trading from the additional benefits under the optimization scenario (Cai et al. 2006). Additional benefits from inter-catchment water rights trading vary between $373 million to $476 million USD and increased in parallel with the level of water scarcity. Lesser, but still higher than baseline gains were available under intra-catchment water rights trading. Furthermore, the scarcer water becomes the more beneficial water rights trading is, as reflected in the increased trend of additional gains in parallel with decreased water availability. Those results are consistent with the findings of Booker and Young (1994) and Cai et al. (2006).

Figure 4.14 Comparing benefits and additional gains from water rights trading and optimal water allocation under various levels of water supply



Source: Author's calculations

Irrigation benefits across the regions varied between $2 million and $151 million USD under normal water availability (Table 4.5). The total irrigation benefit was lowest in upstream regions such as the Gorno-Badakhshan (GBAO) and RRT regions of the Amu Darya basin, and in the Naryn, Osh, and Jalalabad regions of the Syr Darya basin due to their mountainous landscapes, limited irrigated areas, and the high energy (pumping/conveyance) costs to deliver water to fields.

Additional gains from water rights trading were achieved in all regions. The top gains from trading are expected in the Surkhandarya and Mary regions of the Amu Darya basin and in the Ferghana and Tashkent regions of the Syr Darya basin. Additional regional gains under intra-catchment trading (restricted) compared to the benefits under inter-catchment trading (unrestricted) depended on the marginal water profitability of the regions within the catchment.

The results of the analysis of water transfers and willingness to pay illustrate the routes of water trade flows and market prices. Major water rights buyers are the Mary, Lebap, and Bukhara regions of the Amu Darya basin and the Ferghana, Namangan, Tashkent and Syrdarya regions of the Syr Darya basin. Furthermore, allowing tradable rights smoothened marginal water productivity values or water prices across regions. Smoothening of the prices was higher under unrestricted water rights trading (UWT) than restricted water rights trading (RWT) as expected. The average water prices were $0.012 USD per m^3 in the Amu Darya basin regions and $0.02 USD per m^3 in the Syr Darya basin regions.

Table 4.5 Benefits, water use, water transfers, and water prices by regions and the Aral Sea under fixed water use rights (FWR), intra-catchment (RWT), and inter-catchment water rights trading (UWT) under normal water supply

	Total irrigation profit, 10^6 USD			Water withdrawal (million m^3)			Water transfer (million m^3)		Shadow price of water (USD/m^3)		
Regions	FWR	RWT	UWT	FWR	RWT	UWT	RWT	UWT	FWR	RWT	UWT
Amu Darya basin:											
GBAO	2	2	3	362	335	104	0	-258	-0.001	0.002	0.007
Khatlon	25	26	43	5115	4262	2461	0	-2654	-0.004	0.002	0.010
RRT	20	24	25	660	660	596	0	-64	-0.003	0.004	0.010
Surkhandarya	96	101	120	3075	3075	4131	0	1055	0.056	0.033	0.010
Mary	115	137	134	4423	5415	5358	993	935	0.054	0.008	0.011
Ahal	21	25	29	3346	2353	1918	-993	-1428	0.016	0.008	0.011
Lebap	89	93	100	3151	4034	5040	883	1889	0.019	0.015	0.010
Kashkadarya	90	116	111	3747	2663	2973	-1083	-774	-0.009	0.017	0.012
Samarkand	81	99	97	2802	2372	2638	-429	-164	-0.002	0.016	0.011
Navoi	29	34	32	1390	864	1016	-526	-374	-0.001	0.016	0.012
Bukhara	104	119	126	2735	3891	4145	1156	1411	0.040	0.017	0.011
Khorezm	71	81	81	3408	2749	2805	-659	-603	0.001	0.012	0.012
Karakalpakstan	64	66	65	5956	4654	4824	-1302	-1132	0.013	0.012	0.012
Dashauz	80	85	87	5203	7164	7364	1961	2161	0.018	0.012	0.012
Syr Darya basin:											
Naryn	3	3	5	646	646	247	0	-399	0.003	0.005	0.013
Osh	7	10	12	1539	1328	318	0	-1221	-0.001	0.005	0.007
Jalalabad	16	19	22	585	585	330	0	-255	-0.004	0.006	0.029
Ferghana	109	129	151	2461	3858	4478	1397	2017	0.060	0.032	0.019
Andizhan	73	91	86	2490	1133	1385	-1357	-1105	0.010	0.032	0.029
Namangan	55	75	96	1837	3019	3502	1182	1664	0.067	0.033	0.018
Sugd	41	60	60	3185	1963	1943	-1222	-1241	0.005	0.032	0.032
Tashkent	109	115	140	2708	3840	5229	1132	2520	0.046	0.036	0.022
Syrdarya	72	108	101	2123	3154	3063	1031	940	0.080	0.008	0.015
Jizzah	57	62	62	1765	1264	2371	-500	607	0.036	0.050	0.023
South Kazakhstan	42	48	48	2813	1150	1150	-1663	-1663	0.005	0.014	0.014
Kyzylorda	27	27	34	3133	3133	1268	0	-1865	0.010	0.010	0.018
The Aral Sea:	45	46	42	15947	16242	15041	0	0	0.003	0.003	0.003
Total profit	1542	1801	1912	86603	85808	85697	0	0			

Note: Total water withdrawals in the ASB varies from each other under different water allocation system because of different return flow rates across the demand sites cause different levels of return flow depending on changes in regional water withdrawals.

Source: Author’s calculations

Additional gains from water rights trading across all regions were achieved also under drier conditions (90% of normal water supply) (Table 4.6). Average water prices under inter-catchment water rights trading were \$0.014 and \$0.023 USD per m^3 in the Amu Darya and the Syr Darya basin regions respectively.

Table 4.6 Benefits, water use, water transfers, and prices by regions and the Aral Sea under fixed water rights (FWR), intra-catchment (RWT) and inter-catchment water rights trading (UWT) under 90% of normal water supply

	Total irrigation profit, 10^6 USD			Water withdrawal (million m^3)			Water transfer (million m^3)		Shadow price of water (USD/m^3)		
Regions	FWR	RWT	UWT	FWR	RWT	UWT	RWT	UWT	FWR	RWT	UWT
Amu Darya basin:											
GBAO	2	2	2	319	254	104	0	-215	0.001	0.004	0.007
Khatlon	26	26	43	4512	4110	2018	0	-2494	0.000	0.003	0.013
RRT	20	24	24	582	582	559	0	-23	0.000	0.011	0.014
Surkhandarya	73	89	112	2713	2713	4058	0	1345	0.073	0.041	0.013
Mary	80	120	124	3902	5235	5298	1333	1396	0.082	0.017	0.014
Ahal	14	33	29	2952	1619	1749	-1333	-1203	0.021	0.017	0.014
Lebap	81	85	89	2780	3597	4342	817	1562	0.021	0.018	0.014
Kashkadarya	92	113	108	3306	2272	2731	-1033	-574	-0.001	0.022	0.015
Samarkand	81	95	93	2472	2073	2441	-398	-30	0.005	0.022	0.015
Navoi	29	34	31	1227	702	897	-525	-330	0.004	0.021	0.015
Bukhara	89	103	117	2413	3553	3993	1140	1580	0.048	0.025	0.015
Khorezm	70	77	78	3007	2453	2435	-554	-571	0.006	0.015	0.016
Karakalpakstan	54	59	61	5255	3938	3732	-1250	-1522	0.015	0.015	0.015
Dashauz	68	72	71	4590	6395	5670	1805	1080	0.020	0.015	0.015
Syr Darya basin:											
Naryn	3	3	4	568	567	247	0	-321	0.005	0.005	0.013
Osh	7	8	11	1353	1052	318	0	-1035	0.000	0.006	0.007
Jalalabad	16	18	21	514	514	301	0	-213	0.003	0.012	0.032
Ferghana	90	112	131	2164	3655	4165	1492	2001	0.067	0.036	0.025
Andizhan	69	81	81	2189	1133	1133	-1056	-1056	0.014	0.032	0.032
Namangan	40	61	82	1615	2269	3331	654	1716	0.074	0.037	0.023
Sugd	37	55	66	2800	1710	1433	-1089	-1367	0.016	0.040	0.049
Tashkent	93	97	109	2381	2629	4196	248	1815	0.050	0.040	0.032
Syrdarya	49	100	100	1867	3094	3093	1227	1227	0.100	0.012	0.012
Jizzah	49	50	50	1551	1399	1594	-152	43	0.044	0.045	0.037
South Kazakhstan	40	43	43	2473	1150	1150	-1323	-1323	0.007	0.014	0.014
Kyzylorda	23	23	28	2755	2755	1268	0	-1487	0.012	0.012	0.018
The Aral Sea:	40	40	38	14658	14658	14071	0	0	0.003	0.003	0.003
Total profit	1335	1624	1746	76917	76081	76330	0	0			

Source: Author’s calculations

Similarly, average marginal water use benefits under 80% of the normal water supply were \$0.016 and \$0.025 USD per m^3 in the Amu Darya and Syr Darya basins respectively (Table 4.7). Comparison of marginal benefits under different levels of water availability indicated that marginal water use benefits increase in parallel with decreased water availability making water rights trading more beneficial.

Table 4.7 Benefits, water use, water transfers, and water prices by regions and the Aral Sea under fixed water rights (FWR), intra-catchment (RWT) and inter-catchment water rights trading (UWT) under 80% of normal water supply

	Total irrigation profit, 10^6 USD			Water withdrawal (million m^3)			Water transfer (million m^3)		Shadow price of water (USD/m^3)		
Regions	FWR	RWT	UWT	FWR	RWT	UWT	RWT	UWT	FWR	RWT	UWT
<u>Amu Darya basin:</u>											
GBAO	2	2	2	277	239	104	0	-173	0.002	0.005	0.007
Khatlon	25	25	35	3910	3848	2018	0	-1892	0.003	0.004	0.013
RRT	20	23	23	504	504	534	0	29	0.009	0.019	0.016
Surkhandarya	43	70	103	2351	2351	4008	0	1657	0.090	0.062	0.016
Mary	30	98	113	3381	4597	5258	1216	1877	0.110	0.023	0.016
Ahal	5	32	26	2558	1342	1631	-1216	-927	0.025	0.023	0.017
Lebap	73	75	80	2409	2858	3842	449	1433	0.023	0.022	0.016
Kashkadarya	91	107	101	2865	1945	2561	-920	-303	0.007	0.027	0.018
Samarkand	78	88	87	2142	1824	2302	-318	161	0.012	0.027	0.018
Navoi	28	33	29	1063	543	812	-520	-251	0.009	0.026	0.018
Bukhara	73	90	107	2091	3400	3885	1309	1795	0.056	0.029	0.017
Khorezm	67	71	72	2606	2422	2172	-183	-433	0.010	0.016	0.018
Karakalpakstan	43	45	53	4554	3873	2952	-348	-1601	0.016	0.015	0.018
Dashauz	56	62	65	3978	4508	2607	531	-1371	0.022	0.015	0.018
<u>Syr Darya basin:</u>											
Naryn	2	2	3	490	486	247	0	-243	0.007	0.006	0.013
Osh	7	8	9	1167	956	318	0	-849	0.002	0.006	0.007
Jalalabad	16	17	18	443	443	301	0	-143	0.011	0.019	0.032
Ferghana	69	94	117	1866	3430	4025	1564	2159	0.073	0.041	0.028
Andizhan	64	69	71	1888	864	1133	-1024	-755	0.019	0.032	0.032
Namangan	23	50	56	1393	1866	2101	473	708	0.081	0.043	0.033
Sugd	29	49	50	2415	1402	1349	-1013	-1066	0.027	0.050	0.052
Tashkent	76	82	84	2054	2118	2627	64	573	0.053	0.046	0.039
Syrdarya	21	84	103	1610	2579	3139	969	1529	0.121	0.013	0.009
Jizzah	39	41	41	1338	1288	1516	-50	178	0.052	0.050	0.040
South Kazakhstan	37	38	38	2133	1150	1150	-983	-983	0.009	0.014	0.014
Kyzylorda	18	18	21	2376	2376	1268	0	-1108	0.013	0.013	0.018
<u>The Aral Sea:</u>	36	36	35	13368	13368	13180	0	0	0.003	0.003	0.003
Total profit	1069	1407	1545	67231	66583	67042	0	0			

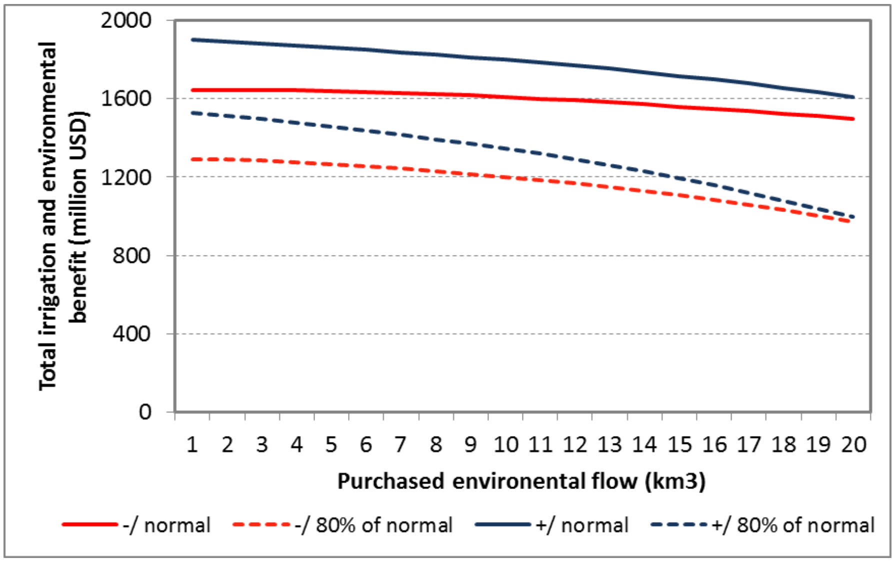
Source: Author’s calculations

As can be seen from tables 4.5–4.7, inflows to the Aral Sea did not change much under water rights trading scenarios compared to the baseline scenario. Lack of additional flows to environmental needs is mainly because of low marginal productivity of the environmental flow. The disclusion of the non-utilitarian values of ecosystem services in the calculations as already explained above resulted in low marginal productivity of water use for environmental needs. Since no data is available on non-utilitarian values of the flows to the Sea, additional scenarios related to the increased amount of the minimum water purchases for environmental needs were considered. Potential environmental benefits of water market were tested by assessing reductions in total benefit under increased amount of minimum water purchases for environmental needs with and without considering water rights trading among the irrigation zones.

4.5.3 *Alternative costs of environmental flows with and without tradable water use rights*

Since short-term marginal benefits of environmental flows are lower than marginal irrigation water use benefits, increasing the minimum requirements of purchasing water for environmental needs would reduce total (irrigation and environmental) benefits (Figure 4.15). According to previous estimate, about 33–34 km^3 of water flow is required to maintain minimal sanitary and environmental conditions in the Aral Sea and its delta (GEF 2002:15). Since the baseline year already considers 13 km^3 of water flows to the Sea in normal year, to meet minimum sanitary and environmental conditions would require about 20 km^3 water additionally. Thus, several scenarios of increased purchases of water rights from irrigation demand sites were simulated considering the purchases up to 20 km^3.

Figure 4.15 Total (irrigation and environmental) benefit changes in response to increases in minimum requirements to purchase water for environmental needs, with and without water rights trading among irrigation zones



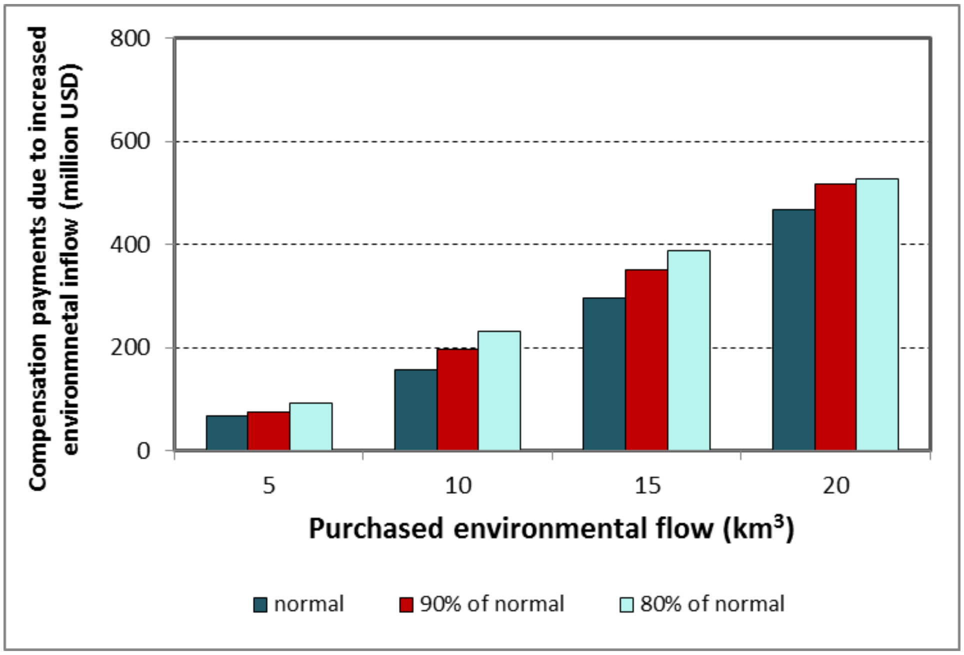
Source: Author’s calculations

Note: ‘+’ - Total irrigation and environmental benefits under water rights trading among irrigation zones/ ‘-’ - Total irrigation and environmental benefits without considering water rights trading among irrigation zones

When the minimum purchase of irrigation water use rights for environmental needs increased from 1 to 20 km^3, overall benefits decreased from $1,901 to $1,608 million USD and from $1,644 to $1,496 million USD with and without considering water rights trading among the irrigation zones respectively. Likewise, under 80% of normal water availability, overall benefits reduced from $1,528 to $999 million USD and from $1,292 to $972 million USD with and without considering water rights trading among the irrigation zones respectively. Despite decreased total benefits due to increased minimum requirements of purchasing water to the Aral Sea and its delta, total benefits when water rights trading among the irrigation zones was allowed were higher than the scenario without water rights trading among irrigation sites.

In normal year, total compensation cost required to purchase 5 km^3 of additional water for the environmental needs is $67.8 million USD when water rights trading among the irrigation zones was allowed (Figure 4.16). Meantime, the compensation cost of delivering 20 km^3 of water into the Aral Sea and its deltaic zones is $467 Million USD. Compensation requirements of providing additional environmental supply increases in parallel with reduced water availability (river runoff).

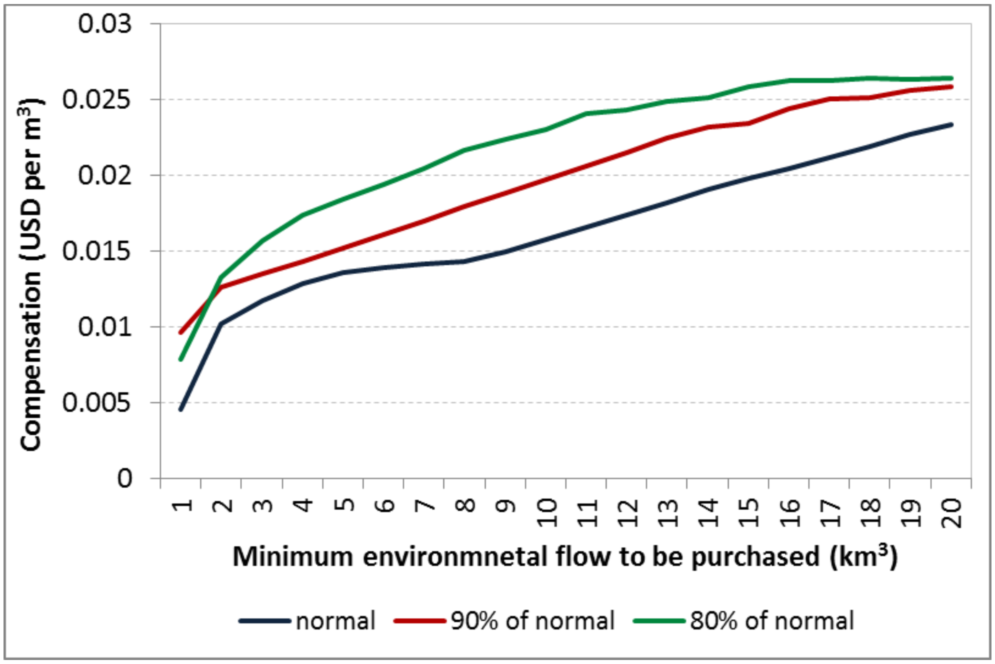
Figure 4.16 Required compensation payments to the irrigation zones due to increased environmental flows to the Aral Sea considering water rights trading among irrigation zones



Source: Author’s calculations

Compensation payment per unit of water required for meeting minimum requirements of purchasing water for environmental needs increases in parallel with the amount of minimum water requirements to be purchased (Figure 4.17). The payments increase since marginal benefits of irrigation water increase in parallel to reduced water availability for irrigation. Under normal water supply conditions, if the compensation of \$0.004 USD per m^3 is required to buy 1 km^3 of water for environmental needs this amount reached to \$0.023 USD per m^3 when at least 20 km^3 of water are required to buy. Under drier conditions, the required payments to buy additional water for the needs of downstream ecosystems will be even higher, for instance, reaching to \$0.026 USD per m^3 when only 80% of normal water supply is available. Nevertheless, purchasing costs of additional water supply for environmental needs is much less expensive than investing in the frequently referenced interbasin-water transfer projects such as diverting water from Siberian rivers (Figure 2.25).

Figure 4.17 Compensation payments per unit of water required for meeting minimum purchased environmental flow under water rights trading scenario



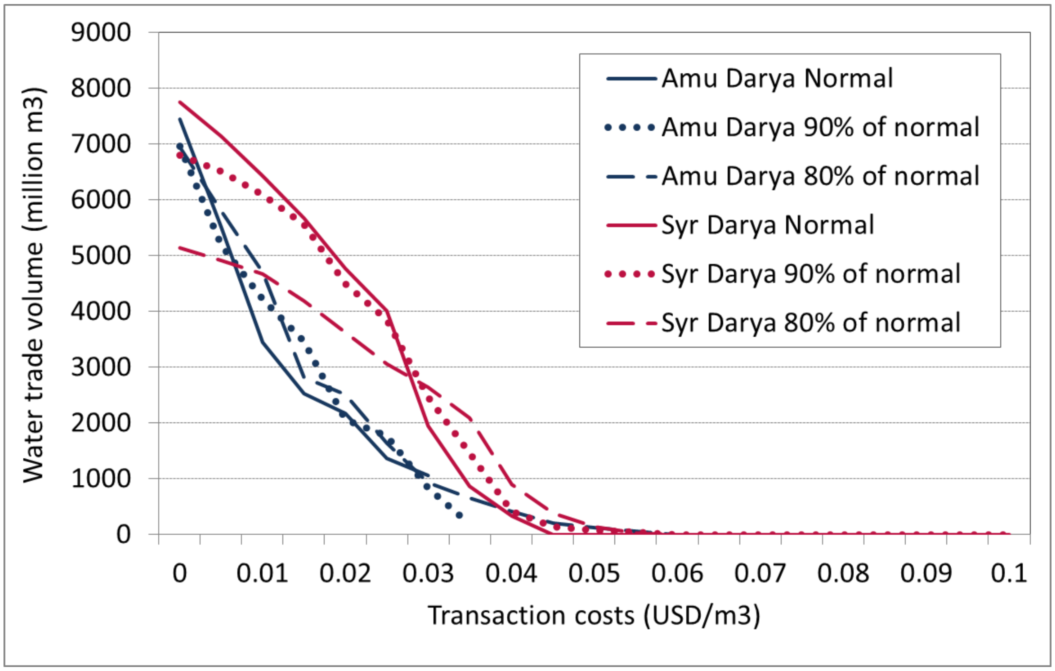
Source: Author's calculations

4.5.4 *Water rights trading benefits considering transaction costs*

Consideration of the transaction costs of introducing tradable water use rights slightly decreased overall irrigation water use, while substantially decreasing water trade volume (Figure 4.18) and benefits from water rights trading (Figure 4.19) in both the Amu Darya and Syr Darya basins. When transaction costs were not considered, the optimal volume of water traded under normal water availability was more than 7.5 km^3 in each basin. Increase in transaction costs up to \$0.05 USD per m^3 of traded irrigation water volume practically nullified the potential additional economic gains of water rights trading (Figure 4.19). Since there were only five regions whose marginal productivity was higher than \$0.05 USD per m^3 (which varied between \$0.05 and \$0.08

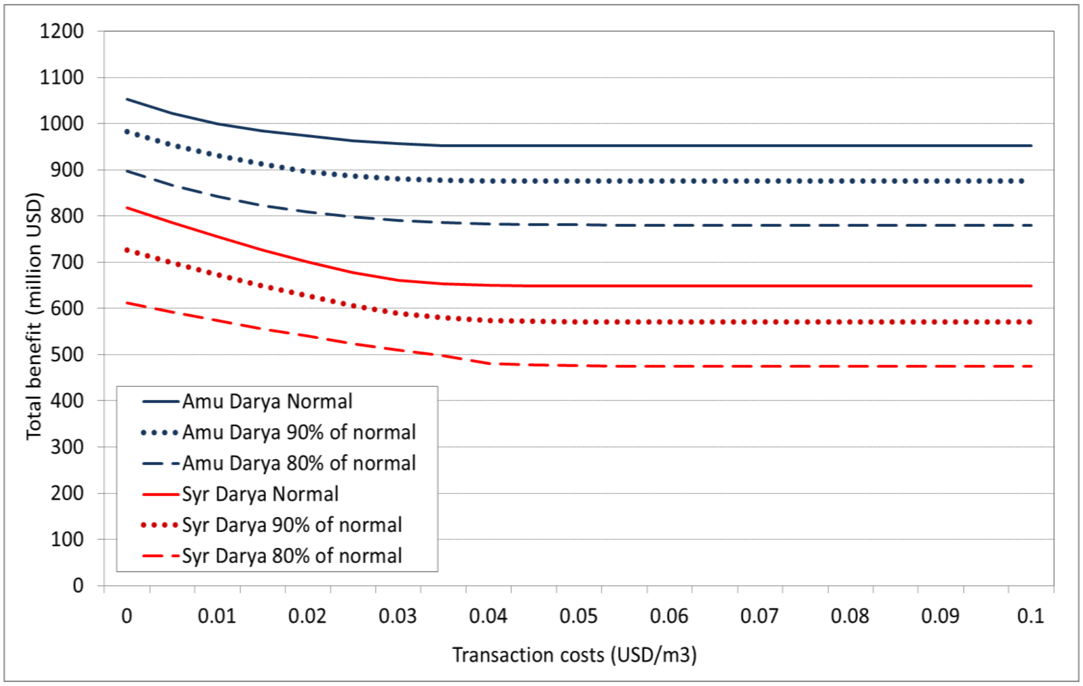
USD per m^3 in the baseline scenario, see Figure 4.13), water rights trading among the remaining regions were obviously not beneficial. Meantime trading among these five sectors was mainly limited by other land and water use constraints. According to the comparison of total benefits under different levels of transaction costs and different levels of water availability, overall benefits without considering transaction costs under water rights trading were more than $1,050 and $800 million USD in the Amu Darya and Syr Darya basins respectively (Figure 4.19). However, once transaction costs per cubic meter of water exceed $0.05 USD per m^3, total benefits fell to $950 and $650 million USD in these two river basins respectively. Reduced water transfers, decreased net benefits, and lowered gains of water rights trading due to increased costs were also found by Cai et al. (2006) in the case of the Maipo River Basin in Chile.

Figure 4.18 Changes in water trade volume due to increases in transaction costs in the Amu Darya and Syr Darya basins under different water availability



Source: Author's calculations

Figure 4.19 Changes in total water use benefits due to increases in transaction costs in the Amu Darya and Syr Darya basins under different water availability



Source: Author's calculations

4.6 Discussion of economic and environmental benefits and transaction costs of market-based water allocation and conclusions

Given the heterogeneous distribution of water productivity across the irrigation zones, a reallocation of water from less productive water users to the more productive users would result in increased economic gains and improved water productivity over the basin. As an alternative to the command-and-control based management system, market-based water allocation institutions could incentivize the riparian irrigation sites for voluntary cooperation in order to obtain additional gains from more efficient water use through reallocation. Findings showed that, under market-based water allocation institutions, more productive users would obtain additional water and consequently additional economic gains. Part of these gains is paid as compensation for forgone water use rights by less productive water users. The findings indicated also that additional economic gains from water rights trading, thus its importance, increases in parallel with growing water scarcity.

Alternative formulation of the model considering compensations for the irrigation benefit reductions due to additional water for environmental needs showed that overall gains will be higher when water rights trading among the irrigation zones are allowed, than when water rights trading among the irrigation sites is not allowed. The additional purchase of 20 km^3 water from the irrigation demand site for environmental needs under the assumption of inter-regional water rights trading would cost about $0.023 USD per m^3. This is only a fraction from the costs of often cited options of water transferring from other rivers such as Ob and Irtish. Additionally purchased water and natural water inflow in a normal year would yield about 33 km^3 of water which is quite low compared to the annual inflows of 50 km^3 in 1950s. However, water management in the Aral Sea basin should purpose a balanced development of the economy with consideration of environmental sustainability rather than pursuing a full restoration of the Aral Sea to its state in 1950s. Considering the greater benefits from the wetland areas in the Aral Sea delta than the direct benefits of shipping and fishery from the sea itself (section 4.4.6), environmental restoration policies and projects should prioritize improving the environmental conditions in deltaic zone. Considering the limited availability of water resources, particularly in the downstream reaches of the Amu Darya and Syr Darya Rivers, the possibilities of improving water use efficiency in deltaic zones should be investigated further.

Newly launched campaigns of oil and gas drilling on the exposed areas of the Aral Sea bed may make decision makers reluctant to increase water inflow to the southern Aral Sea, thus intentionally preventing restoration efforts of the sea. However, since the environmental resources benefit the entire society over generations, unilateral benefits from oil and gas mining should be reconsidered. Although environmental benefit estimates provided in this study are negligible (Tables 5.4–5.6) and thus seem to justify the lack of governmental interests to increase flows into the sea as no additional environmental flows were recommended under the overall basin benefit maximization scenarios, these estimates addressed only the partial value of the ecosystem services. Avoiding underestimation of the environmental benefits by including the non-utilitarian values of environmental inflows, which can be much higher than the utilitarian values, in further research efforts may provide better results (Dziegielewska et al. 2009), showing the improved balance of water for natural and irrigation needs.

Market-based water allocation would allow substantial economic gains and environmental benefits under the assumption of zero transaction costs. However, establishing and enabling any type of market system require additional expenditures (Coase 1960; North 1989, 1990). Dependence of additional gains from water rights trading on the level of transaction costs was previously argued by several studies (Colby 1990b, Challen 2000, Saleth and Dinar 2004). Confirming the claims of these previous researches, this study illustrated an inverse relationship between the transaction costs of establishing water markets and additional benefits from water rights trading (e.g., the lower the transaction costs, the higher the benefits from water rights trading). Lower transaction costs can be achieved by improving irrigation infrastructure and legal and governance frameworks (McCann et al. 2005). A maintenance of sufficiently low transaction costs for effective performance of water markets must be possible, since increasing trade of water use rights in the USA and Australia would occur only if transaction costs were sufficiently low (Garrick et al. 2011). The successful performance of relatively productive market institutions elsewhere in the world can provide a strong incentive to make relevant institutional changes in poorly performing economies (North 1990:137). If this general statement is applied to the case of water markets and the specific situation in this study, systems of water rights trading in the USA and Australia are good examples to Central Asian countries for maintaining successive performance of market-based institutional reforms.

Even though substantial improvements in water use efficiency and environmental situations are possible through introducing tradable water use rights, such changes can confront with not only economic, but also institutional and political barriers. For instance, considering the dominance of Islamic concepts in the cultures and traditions of Central Asian nations, the possibility that the traditional Islam regards water as God’s gift may hinder efforts to establish water as an acceptable “good” for commercial transactions. In turn, it feeds the doubts on the cultural acceptability of introducing water markets and pricing water to a majority of the population in Central Asia. However, there are different opinions on the tolerance of Islamic acceptance of water as an economic good. Although some scholars doubt that Islam can accept water allocation through market forces (Webb and Iskandarani 1998), recent studies show that water pricing and market-based water allocation established for the benefit of all users and based on fairness and social justice is not controversial to Islamic rules (Kadouri et al. 2001). Islamic Law does not ignore water pricing or water rights trading if they reflect the costs of water delivery, the costs of purification, and the scarcity value of water without speculation. In contrast, public water management that neglects economic efficiency and environmental requirements as well as preventing fair water distribution due to the unheard voices of downstream water users may be even more contrary to Islamic concepts of justice than water markets.

It has also been argued that because of the inheritance of top-down decision making from the former political-economic system, the negotiation of water sharing agreements and formulation of water use policies are highly dependent on the will of government authorities (Weinthal 2002:145), leaving less room for decentralized decision making and market-based water allocation. Although the system based on the supremacy and dominance of the government and dependence on authorities in all decision making processes can perhaps enhance economic or social stability in short-term, empowering the ordinary people to make decisions over their own fates can effectively work for long-term social and economic sustainability. The emergence of the middle-income class with greater power and knowledge would contribute to better governance and thus the stability of institutional changes (Easterly 2001). Under conditions of water rights trading, direct government interventions through control of water market prices or intentional tax increases on water uses are not allowable. However, the involvement of governmental organizations is essential in water rights trading agreements for distributing initial water use rights, ensuring the rule of law, and guaranteeing the realization of the agreed compensation and water transfers. Moreover, government organizations must participate actively in development programs, but indirectly through maintaining research and educational capacities, and by establishing necessary institutional and legal frameworks.

Indeed, differing from the countries in which the economy is closer to market-based systems, the transaction costs of introducing tradable water use rights could be relatively high, considering that Central Asian economies were under the rule of centralized Soviet governance for more than seventy years. Though a market based economy and governance through gradual reforms is the selected path for the future in all of these countries, the evolution of market based management systems and their performance cannot be fully separated from the early course of institutional development processes (North 1990). In other words, institutional changes are path-dependent. Furthermore, the necessary institutional changes cannot happen overnight, but will require time to realize since institutional transformations occur not only through formal changes in laws and organizational structures, but also due to changes in informal cultural rules, behavioral codes, and the collective mental construct (North 1990). For instance, Williamson (2000:597) showed that changes in the property rights regimes and their potential economic performance may require 10 to 100 years to realize, involving substantial changes in the thought processes of stakeholders and decision makers. The alteration of cultural norms, ideologies, and mental constructs can be accelerated through greater transparency and access to information (North 1990:138). The recommendations of this study for overcoming the barriers to the necessary institutional changes are also valid for the other river basins with similar water issues and institutional settings.

5 TECHNOLOGICAL IMPROVEMENTS AND INFRASTRUCTURAL DEVELOPMENTS TO COPE WITH WATER ISSUES IN THE ARAL SEA BASIN[1]

5.1 Introduction

This chapter is the continuation of the previous chapter on hydro-economic modeling analysis of intersectoral water allocation. At present, the transformation of the reservoir releases from irrigation mode to energy production mode in the upper reaches and the restart of the construction of new upstream reservoirs of regulating river flow confronted a strong opposition of downstream regions in the ASB. Despite hot debates on the construction of new reservoirs, still no academic study objectively estimates the potential changes in water availability and profits due to these constructions. Additionally, considering already scarce water resources in the regions even without climate change or increased upstream water demand impacts, adoption of water conservation technologies is essential to reduce the unproductive water uses. It would in turn require preliminary estimations of potential places and magnitudes of adopting irrigation technologies across the basin. Indeed, addressing these infrastructural and technological developments would require a more detailed modeling framework that considers seasonal water flows and water uses by crops. Therefore, an analysis using a hydro-economic model that focused on irrigation water allocation based on regional water-benefit functions was further deepened now by considering seasonal water withdrawals to irrigation sites and seasonal water releases from the reservoirs. Groundwater and return water balances in addition to the river balance were considered. Based on the model, water allocation between irrigation, energy sector, and environment, and the impact on crop production and incomes of irrigation modernization and infrastructural improvements are discussed. The model has similar content to the previous hydro-economic models that were used for analyzing water uses in the the Mekong (Ringler 2001) and Maipo River basins (Cai et al. 2006) but was modified considering special hydrological and economic conditions in the ASB.

The chapter consists of two sections. The first section includes the description of the analytical framework of the model. The second section describes the results.

5.2 A disaggregated hydro-economic model of the Aral Sea basin

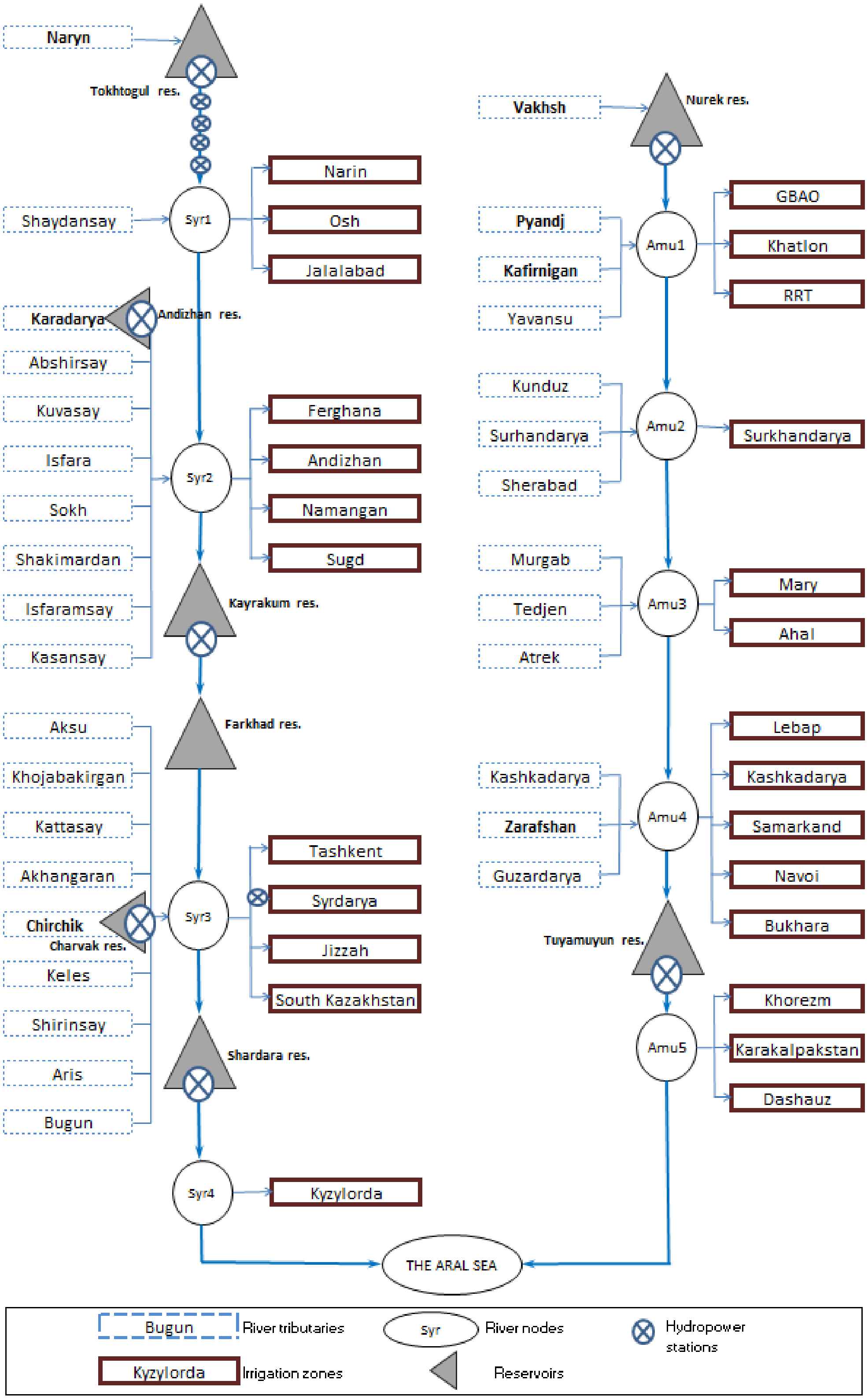
5.2.1 *River basin scheme*

Since hydropower production component was also included in the disaggregated hydro-economic model differing from the previous annual aggregated hydro-economic model reservoirs were also considered in the river basin scheme (Figure 5.1). Although there are over 80 reservoirs operating or newly planned in the ASB, only the largest and the most important ones that produce most of the hydropower were taken into account in this study. Some power production stations such as the ones located in the Narin Cascade are run-of-the-river power stations. The remaining parts of the scheme are the same as the basin scheme of the aggregated model.

---

[1] Some results of this chapter were published in the Proceedings of International Conference and Young Researchers' Forum that took place in Giessen (Bekchanov et al. 2013b)

Figure 5.1 River basin scheme



Source: Author’s presentation

5.2.2 *Modeling framework*

Objective function

In the disaggregated model an omniscient BMO is assumed to optimize benefits of irrigation (IB_{dem}) across the demand sites (dem), hydropower production (HP_{st}) by power production stations (st), and environmental system (EB)[1]:

$$\pi = \sum_{dem} IB_{dem} + \sum_{st} HP_{st} + EB \tag{5.1}$$

Irrigation benefits

Irrigation benefits were calculated as a difference of total crop production revenues and the costs of crop production, technology adoption, water delivery, conveyance improvement, and groundwater pumping:

$$\begin{aligned} IB_{dem} = & \sum_{cp} \left(A_{dem,cp} \left(pr_{dem,cp} Y_{dem,cp} - pc_{dem,cp} \right) \right) \\ & - \sum_{cp} \left(itc_{dem,cp} \left(IE_{dem,cp} - ie0_{dem,cp} \right) FCW_{cp,dem} \right) \\ & - dsc_{dem,cp} \left(DE_{dem,cp} - de0_{dem,cp} \right) \left(\sum_{pd} \sum_{rn \in NDLINK} RW_{rn,dem,pd} \right) \\ & - cc_{dem} \sum_{pd} TWF_{dem,pd} \\ & - ruc_{dem} \sum_{pd} \sum_{cp} RU_{dem,cp,pd} \\ & - wpc_{dem} \sum_{gw \in gwdlink} \sum_{pd} \sum_{cp} WP_{gw,dem,cp,pd} \end{aligned} \tag{5.2}$$

where $A_{dem,cp}$ is area of a particular crop (cp) in a certain demand site (dem), $pr_{dem,cp}$ is crop rice, $Y_{dem,cp}$ is crop yield, $itc_{dem,cp}$ is irrigation technology adoption costs per unit of irrigation water use, $IE_{dem,cp}$ is irrigation efficiency, $ie0_{dem,cp}$ is baseline (observed) irrigation efficiency, $FCW_{cp,dem}$ is total water use by crops at field level, $dsc_{dem,cp}$ is the cost of improving distribution efficiency per unit of regional water intake, $DE_{dem,cp}$ is distribution (conveyance) efficiency, $de0_{dem,cp}$ is baseline (present) distribution efficiency, $RW_{rn,dem,pd}$ is regional water

---

[1] Endogenous variables are written using upper case letters while exogenous variables are written with lower case letters in this section

intake from river node (rn) by months (pd) if there is a link between the region and the node ($NDLINK$), cc_{dem} is conveyance costs per unit of water delivered, $TWF_{dem,pd}$ is water delivered to the field in each month, ruc_{dem} is costs of reusing return water flows for irrigation, $RU_{dem,cp,pd}$ is re-use of return flow, wpc_{dem} is groundwater pumping costs, and $WP_{gw,dem,cp,pd}$ is pumped water from groundwater sources (gw) to irrigate crop.

Crop yield levels in turn depend on maximum attainable yields ($my_{dem,cp}$) and real yield rate that varies between 0.1 and 1 ($RY_{dem,cp}$):

$$Y_{dem,cp} = my_{dem,cp} RY_{dem,cp} \tag{5.3}$$

Benefits of hydropower production

Benefits from electricity generation was estimated as:

$$HP_{st} = \sum_{pd} epr_{pd} EP_{st,pd} \tag{5.4}$$

where epr_{pd} is price per unit of electricity output and $EP_{st,pd}$ is the volume of electricity generation.

Electricity production for the stations ($EP_{st,pd}$) accompanied by reservoirs ($(rev, st) \in RPLINK$) is modeled as (Ringler et al. 2004):

$$EP_{st,pd} = 2.725\, ste_{st} \sum_{rev \in RPLINK} \Big(\Big(\sum_{rn \in RNLINK} RSN_{rev,rn,pd} + \sum_{rev\_lo \in DDLINK} RRS_{rev,rev\_lo,pd} \Big) \big(0.5\, H_{rev,pd} + 0.5\, H_{rev,pd-1} - htail_{rev}\big)\Big) \tag{5.5}$$

where $RSN_{rev,rn,pd}$ is river flow from reservoir (rev) to node (rn) if a link between two of them ($RNLINK$) exists, $RRS_{rev,rev\_lo,pd}$ is flow from the reservoir to next reservoir (rev_lo) if there is a link ($DDLINK$) between two of them, $H_{rev,pd}$ is water level at the reservoir, $htail_{rev}$ is tail-end level of the reservoir, and ste_{st} is production efficiency of the reservoir.

Hydro-electricity generation for run-of-river power stations is estimated as (Ringler 2001):

$$EP_{st,pd} = 2.725 \left(\sum_{rn \in NPLINK} \sum_{rn\_lo \in RVLINK} FL_{rn,rn\_lo,pd} \right) ry_{rev}\, ste_{st} \tag{5.6}$$

where $FL_{rn,rn\_lo,pd}$ is river flow from the node (rn) to the next lower node (rn_lo) at each moth (pd) if a link between the nodes ($RVLINK$) exists and ry_{rev} is reservoir yield that indicates the amount of electricity generation per unit of river water flow.

Environmental flow

Economic values of the inflows into the Aral Sea and deltaic zones (EB) are considered as the same as in the case of the aggregated annual model but only the annual environmental flow (Env_w) was replaced by the sum of monthly environmental flows (EF_{pd}):

$$EB = b0 \ + b1 \sum_{pd} EF_{pd} \tag{5.7}$$

where $b0$ and $b1$ are parameters of the environmental benefit function and EF_{pd} is monthly environmental flow from the Amu Darya (the node link "Amu5 → THE ARAL SEA") and Syr Darya (the node link "Amu5 → THE ARAL SEA") into the Aral Sea.

River node flow balance

Water balance in river node was formulated as:

$$\begin{aligned} &\sum_{rn \in RVLINK} FL_{rn\_up \quad ,rn,pd} + src_{rn,pd} + \sum_{rev \in RNLINK} RSN_{rev,rn,pd} \\ &+ \sum_{dem \in DNLINK} RFR_{dem,rn,pd} + \sum_{gw \in GWRLINK} DSCH_{gw,rn,pd} \\ &= \sum_{rn\_lo \in RVLINK} FL_{rn,rn\_lo,pd} + \sum_{rev \in NRLINK} NRS_{rn,rev,pd} \\ &+ \sum_{dem \in NDLINK} (RW_{rn,dem,pd} + idw_{rn,dem,pd}) \end{aligned} \tag{5.8}$$

where $FL_{rn\_up,rn,pd}$ is river flow to the node (rn) from the upper node (rn_up), $src_{rn,pd}$ is the flow from source node (river tributary), $NRS_{rn,rev,pd}$ is river flow from reservoir to node, $RFR_{dm,rn,pd}$ is return flow from irrigation demand site to the river node, $DSCH_{gw,rn,pd}$ is water seepage to the river from groundwater sources (gw) if a link ($GWRLINK$) between groundwater source (gw) and river node (rn) exists, and $RW_{rn,dm,pd}$ and $idw_{rn,dm}$ are water withdrawals from node (rn) to the irrigation water user site (dem) and municipal-domestic water use respectively if a link between the node and the water user site ($NDLINK$) exists.

Reservoir storage balance

Water balances in reservoirs were modeled as:

$$\begin{aligned} V_{rev,pd-1} &+ \sum_{rn \in NRLINK} NRS_{rn,rev,pd} + \sum_{rev\_up \in DDLINK} RRS_{rev\_up,rev,pd} \\ = V_{rev,pd} &+ \sum_{rn \in RNLINK} RSN_{rev,rn,pd} + \sum_{rev\_lo \in DDLINK} RRS_{rev,rev\_lo\ ,pd} \\ &+ evapr_{rev,pd}\,(0.5\,S_{rev,pd-1} + 0.5\,S_{rev,pd}) \end{aligned} \tag{5.9}$$

where $V_{rev,pd}$ is reservoir storage volume, $RRS_{rev\_up,rev,pd}$ is flow to the reservoir (rev) from upper reservoir (rev_up), $evapr_{rev,pd}$ is the rate of evaporation from the surface of the reservoir, $S_{rev,pd}$ is the surface area of the reservoir.

Reservoir morphological parameters

The storage volume and surface area of the reservoir are related to each other following the functional relationship of:

$$S_{rev,pd} = c0 + c1\,V_{rev,pd} + c2\,V_{rev,pd}^{2} + c3\,V_{rev,pd}^{3} \tag{5.10}$$

where $c0$, $c1$, $c2$, and $c3$ are the parameters of the function.

Water level in the reservoir ($H_{rev,pd}$) also depends on the reservoir storage volume:

$$H_{rev,pd} - htail_{rev} = d0 + d1\,V_{rev,pd} + d2\,V_{rev,pd}^{2} \tag{5.11}$$

where $d0$, $d1$, and $d2$ are the parameters of the function.

Groundwater balance

Groundwater volumes change depending on water percolation from fields and irrigation canals, groundwater use and water seepage to the river:

$$\begin{aligned}
&0.01\, gws_{gw}\, agw_{gw}\left(GH_{gw,pd} - GH_{gw,pd-1}\right) = \\
&\sum_{dem \in GWDLINK} \sum_{cp} DPSTG_{dem,cp,pd}(1 - drn_{dem}) \\
&+ \sum_{dem \in GWDLINK} \sum_{rn \in NDLINK} \left(RW_{rn,dem,pd}(1 - DE_{dem})(1 - drn_{dme})\right) \\
&+ \sum_{dem \in GWDLINK} \sum_{cp} WP_{gw,dem,cp,pd} \\
&+ \sum_{rn \in GWRLINK} DSCH_{gw,rn,pd}
\end{aligned} \tag{5.12}$$

where gws_{gw} is yield of groundwater aquifer, agw_{gw} is the surface area of groundwater aquifer, $GH_{gw,pd}$ is groundwater depth, $DPSTG_{dm,cp,pd}$ is deep percolation from crop fields in each month.

Groundwater discharge to the river system depends on water volume in the groundwater aquifer and transitivity coefficient ($trs_{gw,rn}$):

$$DSCH_{gw,rn,pd} = trs_{gw,rn}\, gws_{gw}\, agw_{gw}\, GH_{gw,pd} \tag{5.13}$$

Water use balances in irrigation demand site

Total water delivered to a demand site ($TWF_{dem,pd}$) was calculated considering conveyance efficiency and water intakes to the region from the river node:

$$TWF_{dem,pd} = \sum_{rn \in NDLINK} RW_{rn,dem,pd}\, DE_{dem} \tag{5.14}$$

Additional constraints related to water use at demand site level were included as well. The sum of total surface water used for crops ($WCP_{dem,cp,pd}$) in each site should be balanced with water delivered to a demand site ($TWF_{dem,pd}$):

$$\sum_{cp} WCP_{dem,cp,pd} = TWF_{dem,pd} \tag{5.15}$$

Total water applied for the use of each crop ($WACP_{dem,cp,pd}$) should be equal to the sum of total surface water used for crops ($WCP_{dem,cp,pd}$), water from groundwater aquifers ($WP_{gw,dem,cp,pd}$), and re-use of return flows ($RU_{dem,cp,pd}$):

$$WACP_{dem,cp,pd} = WCP_{dem,cp,pd} + \sum_{gw \in GWDLINK} WP_{gw,dem,cp,pd} + RU_{dem,cp,pd} \tag{5.16}$$

Only part of return flows ($RFL_{dem,pd}$) is re-used for irrigation since full re-use is not acceptable due to low quality of return flows:

$$\sum_{cp} RU_{dem,cp,pd} \leq rru_{dem} RFL_{dem,pd} \tag{5.17}$$

where rru_{dem} is the rate of return water re-use.

Total seasonal water use by crops in each region ($TWACP_{dm,cp}$) is equal to the sum of total water applied for the use of each crop ($WACP_{dem,cp,pd}$) and total effective rainfall over the months:

$$\sum_{pd} (WACP_{dem,cp,pd} + A_{dem,cp} er_{dem,cp,pd}) = TWACP_{dem,cp} \tag{5.18}$$

where $er_{dem,cp,pd}$ is effective rainfall measured in mm.

Total seasonal deep percolation ($DP_{dem,cp}$) is the sum of monthly deep percolations ($DPSTG_{dem,cp,pd}$):

$$DP_{dem,cp} = \sum_{pd} DPSTG_{dem,cp,pd} \tag{5.19}$$

Monthly deep percolation depends on irrigation efficiency ($IE_{dem,cp}$) and total water delivered to the field of each crop ($WACP_{dem,cp,pd}$):

$$DPSTG_{dem,cp,pd} = WACP_{dem,cp,pd}(1 - IE_{dem,cp}) \tag{5.20}$$

For each crop, seasonal actual crop evapotranspiration ($ETS_{dem,cp}$) is lower than the total seasonal water use ($TWACP_{dem,cp}$) reduced by total seasonal deep percolation ($DP_{dem,cp}$):

$$ETS_{dem,cp} \leq TWACP_{dem,cp} - DP_{dem,cp} \tag{5.21}$$

Water effectively used by crop is equal to the difference between seasonal actual crop evapotranspiration and seasonal total effective rainfall:

$$IE_{dem,cp}\left(\sum_{pd} WACP_{dem,cp,pd}\right) = ETS_{dem,cp} - \sum_{pd}(A_{dem,cp}\ er_{dem,cp,pd}) \tag{5.22}$$

Actual crop evapotranspiration by months ($ETST_{dem,cp,pd}$) should be less than the sum of efficiently used water by crops and total effective rainfall:

$$ETST_{dem,cp,pd} \leq IE_{dem,cp}\ WACP_{dem,cp,pd} + A_{dem,cp}er_{dem,cp,pd} \tag{5.23}$$

Actual crop evapotranspiration by months ($ETST_{dem,cp,pd}$) should be less than total crop reference evapotranspiration:

$$ETST_{dem,cp,pd} \leq A_{dem,cp}etm_{dem,cp,pd} \tag{5.24}$$

where $etm_{dem,cp,pd}$ is crop reference evapotranspiration measured in mm.

Return flow rates from each irrigation site across the months ($RF_{dem,pd}$) depends on evaporation losses in drainage networks, water percolation from crop fields and irrigation canals, and the proportion of water losses flowed to the drainage networks (DRN_{dem}):

$$\begin{aligned} RF_{dem,pd} = {} & (1 - evapd_{dem})(\sum_{cp} DPSTG_{dem,cp,pd}DRN_{dem} \\ & + \sum_{rn \in DNLINK} RW_{rn,dem,pd}(1 - DE_{dem,cp,pd})\,DRN_{dem}) \end{aligned} \tag{5.25}$$

where $evapd_{dem}$ is evaporation loss rates from the drainage networks.

Part of the return flow ($RF_{dem,pd}$) is discharged into the river node ($RFR_{dem,rn,pd}$) and the remaning goes to the tail end lakes ($RFL_{dm,pd}$):

$$RF_{dem,pd} = \sum_{rn \in DNLINK} RFR_{dem,rn,pd} + RFL_{dem,pd} \tag{5.26}$$

Return flows discharged into the river node should be less than the predetermined shares of the regional water intake ($RW_{rn,dem,pd}$):

$$\sum_{rn \in DNLINK} RFR_{dem,rn,pd} \leq\ rr_{dem,pd} \sum_{rn \in NDLINK} RW_{rn,dem,pd} \tag{5.27}$$

where $rr_{dem,pd}$ is maximum ratio of return flows discharged into the river to the regional water withdrawal.

Cropland restriction

The sum of the cropland areas by crops should be less than total irrigation area (ta_{dm}) in each demand site:

$$\sum_{cp} A_{dem,cp} \leq ta_{dem} \tag{5.28}$$

The impact on crop yield of monthly water deficits

As previously shown by several studies (Ringler et al. 2004, Cai et al. 2006), real yield rate ($RY_{dem,cp}$) is related to the maximum stage deficit ($MDFT_{dem,cp}$) as follows:

$$RY_{dem,cp} \leq 1 - MDFT_{dem,cp} \tag{5.29}$$

The maximum stage deficit is in turn estimated based on monthly stage deficits ($DFT_{dem,cp,pd}$):

$$MDFT_{dem,cp} = \max_{pd}\{DFT_{dem,cp,pd}\} \tag{5.30}$$

or

$$MDFT_{dem,cp} \geq DFT_{dem,cp,pd} \tag{5.30‘}$$

Monthly stage deficits were estimated following popular FAO method (Doorenbos and Kassam 1979, Ringler 2001):

$$DFT_{dem,cp,pd} = ky_{cp,pd}\left(1 - \frac{ETST_{dem,cp,pd}}{A_{dem,cp}etm_{dem,cp,pd}}\right) \tag{5.31}$$

where $ky_{dem,cp}$ is crop coefficient.

The impact on crop yield of seasonal water deficit

Real yield rate ($RY_{dem,cp}$) should be also lower than seasonal relative crop yield ($SRY_{dem,cp}$):

$$RY_{dem,cp} \leq SRY_{dem,cp} \tag{5.32}$$

Seasonal relative crop yield ($SRY_{dem,cp}$) is defined following the FAO formula (Doorenbos and Kassam 1979, Ringler 2001):

$$SRY_{dem,cp} = 1 - kyc_{cp}\left(1 - \frac{\sum_{pd}(A_{dem,cp}ETST_{dem,cp,pd})}{\sum_{pd}A_{dem,cp}etm_{dem,cp,pd}}\right) \qquad (5.33)$$

where kyc_{cp} is seasonal crop coefficient.

5.2.3 Database of the model

Considering huge size of the model and the study area, a large and consistent database were elaborated based on multiple sources (Appendix D). Particularly, monthly water flows in the supply nodes, water withdrawals for irrigation, industrial, and municipal uses by demand sites and over the months were based on CAREWIB database (SIC-ICWC 2011). Cropland patterns and crop yields across the irrigation regions were also based on this database. Data on potential crop evapotranspiration coefficients and effective rainfall were based on the database of the IMPACT model of IFPRI (2013). Crop production costs and benefits across the regions of Uzbekistan were based on the reports of the SIC-ICWC (2008). Crop production costs and benefits for the other ASB regions of the remaining countries were estimated considering costs and benefits in the closest region of Uzbekistan. Conveyance costs across the regions are from MAWR (2007). Electricity production capacity, electricity prices, reservoir storage capacity and releases are based on Cai (1999) and the databases of BEAM (EC IFAS 2013) and ASBOM (SIC-ICWC 2003) models. Parameters of the functional relationships between reservoir head and volume and reservoir surface area and volume are from EC IFAS (2013) and SIC-ICWC (2003). Costs of improving irrigation, conveyance efficiencies, and using groundwater and return flows were reevaluated based on Cai (1999) and considering the inflation rates between 1998 and 2006. More detailed description of the data and their sources are provided in Appendix D. Additional data used in the model are also provided as a web-source (https://www.dropbox.com/s/3hhzfmzb72mrh8q/Data%20for%20seasonal%20ASB%20HEM.XLS?n=254818113).

5.2.4 Scenarios

Several scenarios were considered in the study. Similar to the case of the aggregated model, water supplies in different tributaries across the basin were calibrated to the water supply levels of 1999 since it is a year with normal water supply based on the observations between 1980 and 2008. Crop production, power generation, and environmental revenues and costs were considered at the price levels of 2006 considering data availability. Model is run based on the approach of normative mathematical programming. Despite well-known limitations of optimization programming due to the assumption of omniscient decision maker for the entire water management system yet it is useful to analyze the potential impact of different technological and infrastructural changes on social and economic welfare when all stakeholders cooperate towards attaining basin-wide gains while equitably sharing the additional gains of cooperation.

Since the crop demand and price relationships in agricultural market were not considered in the model due to limited data availability, additional restrictions on cropland uses were considered to prevent unrealistic solutions that indicate enormous expansion of high valued crops. Thus, like the assumptions made in the previous studies (Ringler et al. 2004, Cai et al. 2006), model solutions for the cropland areas across the regions can be 20% lower or higher than the initially observed cropland areas in 1999.

The optimization model results are compared first with the observed water and land use indicators in order to analyze the differences between the actual and optimal levels of water and land use. Irrigation and conveyance efficiency rates were kept constant based on the observed efficiency levels in the baseline-optimization scenario. Additionally the effect of the constructions of new water reservoirs for regulating river flow was not considered in the baseline case. To test the sensitivity of the model and check the impact on water and land use and benefits of reduced water supply due to the expected climate change, two more scenarios additional to the normal water availability are studied. Thus, 90% and 80% of normal water supply is considered under each additional scenario, respectively.

Policy oriented experiments considered two measures: 1) improvements in efficiency of irrigation/conveyance systems and 2) developments of hydro-infrastructural facilities through constructing water reservoirs. To determine the place and magnitude of irrigation and conveyance improvement measures under reduced water supply, additional scenario was run considering the flexible rates for irrigation and conveyance efficiencies. Since the conflicts among the neighboring countries of the ASB are intensifying over the construction of the large water reservoirs such as the Rogun and Kambarata in upstream locations, their potential impact on downstream irrigation and electricity production and benefits was also analyzed. Combinative scenario included the analysis of the effects of both irrigation efficiency improvements and infrastructural developments.

5.2.5 Model solution

The disaggregated hydro-economic model was coded in GAMS and solved using CONOPT 3 — non-linear programming solver (Brooke et al. 2006). Detailed description of the GAMS code of the model is not provided here because of its enormous size but the description of the model is demonstrated through the Equations 5.1-5.33.

5.3 Results and discussion of infrastructural and technological developments

5.3.1 Baseline vs optimal water and land use indicators

Based on the modeling framework described in the previous section, optimal levels of water and land use in different irrigation demand sites are estimated. According to the results, 4.6% and 7.1% less land than the observed levels in the Amu and Syr Darya basins, respectively, is sufficient for optimal basin-wide gains (Table 5.1). Particularly, 3.6% and 11.6% less land for cotton production, 8.8% and 1.0% less land for wheat cultivation, and 3.6% and 1.8% less land for rice in each river basin respectively is abundant for obtaining optimal benefits in the ASB.

Table 5.1 Cropland pattern change (in 1000s ha)

Scenarios	Cropland areas											Total
	Cotton	Fodder	Fruit	Wheat	Maize	Cords	Potato	Rice	Beet	Vegetables	Grapes	
Amu Darya basin												
Observed	1505	368	299	1617	47	45	48	189	1	99	103	**4321**
Optimal	1451	377	308	1475	53	35	44	182	1	98	101	**4124**
Change	-54.1	8.2	8.5	-142.0	5.6	-9.9	-3.5	-6.8	0.0	-0.6	-2.4	**-197**
Change (in %)	-3.6	2.2	2.8	-8.8	11.8	-22.2	-7.4	-3.6	0.0	-0.6	-2.4	**-4.6**
Syr Darya basin												
Observed	929	337	467	839	75	48	55	99	2	107	81	**3040**
Optimal	821	289	453	831	62	46	48	97	2	97	79	**2825**
Change	-107.7	-48.8	-14.5	-8.8	-12.4	-1.9	-7.0	-1.8	0.0	-9.5	-2.2	**-214**
Change (in %)	-11.6	-14.5	-3.1	-1.0	-16.5	-3.9	-12.6	-1.8	0.0	-8.9	-2.7	**-7.1**

Source: Author's calculations

However, irrigation water uses under optimization scenario are expected to be 27.7% and 11.6% higher than the observed total water diversions in the Amu and Syr Darya basins respectively (Table 5.2). Although total water supply from river tributaries is not changed under optimization scenario, increased total irrigation diversions can be explained by increased use of water in the regions with high return flow rates and also with high groundwater reservoirs that increased water availability to downstream. Higher water uses boost yields for some crops which in turn can impose the irrigation income growth.

Table 5.2 Irrigation water uses by months under observed and optimization cases (km^3)

Scenarios	Irrigation water uses by months											Total
	m01	m02	m03	m04	m05	m06	m07	m08	m09	m10	m11	m12	
Amu Darya basin													
Observed	2.3	2.9	4.0	4.1	6.6	8.7	11.1	10.5	4.4	2.1	1.9	1.0	**59.6**
Optimal	4.6	6.4	1.2	5.4	8.9	13.8	13.9	12.2	7.3	2.3	0.1	0.0	**76.1**
Change	2.3	3.5	-2.8	1.2	2.4	5.2	2.8	1.6	2.9	0.2	-1.8	-1.0	**16.5**
Change (%)	103.2	117.9	-70.7	29.9	36.3	59.7	25.5	15.6	65.4	10.4	-96.7	-96.0	**27.7**
Syr Darya basin													
Observed	0.6	0.6	1.1	2.2	4.4	5.1	6.3	5.2	2.1	1.6	0.8	0.1	**29.9**
Optimal	2.0	3.3	0.1	1.4	2.6	6.3	7.7	5.5	3.7	0.8	0.0	0.0	**33.4**
Change	1.5	2.7	-1.0	-0.8	-1.8	1.1	1.4	0.3	1.6	-0.8	-0.7	-0.1	**3.5**
Change (%)	267.6	481.1	-89.2	-38.1	-40.3	22.3	22.5	5.5	74.9	-48.4	-99.2	-93.1	**11.6**

Notes: Indexes m01, … , m12 stands for months January, February, … , December

Source: Author's calculations

The comparison of the observed and optimal crop yields shows that attaining optimal basin-wide benefits would require the enhancement of the crop yields (Table 5.3). Particularly, cotton yields are required to increase in most of the regions in the ASB even reaching up to 70% in the sites such as Lebap of Turkmenistan. The results for the cereals and rice are mixed: yields are expected to decrease in some regions but increase in the others under optimization scenario.

Table 5.3 Main crop (cotton, cereals, and rice) yields across the irrigation sites under the baseline and optimization scenarios (in ton per ha)

Demand sites	**Cotton yield**			**Cereals yield**			**Rice yield**		
	OBS	**OPT**	**CHN**	**OBS**	**OPT**	**CHN**	**OBS**	**OPT**	**CHN**
Amu Darya basin									
GBAO	0	0	0	2	2	24	0	0	0
Khatlon	3	3	9	7	11	63	4	5	39
RRT	3	3	10	3	4	50	3	7	154
Surkhandarya	2	2	13	2	2	20	2	3	76
Mary	3	3	11	4	7	61	0	0	0
Ahal	2	2	21	1	1	-49	0	0	0
Lebap	2	3	69	1	1	-29	3	3	14
Kashkadarya	3	3	20	5	10	111	0	0	0
Samarkand	2	2	12	12	14	14	3	3	17
Navoi	2	2	42	1	1	-41	0	0	0
Bukhara	2	2	31	1	3	148	0	0	0
Khorezm	2	2	5	1	1	1	2	1	-28
Karakalpakstan	2	1	-39	2	4	82	3	2	-47
Dashauz	2	3	16	2	3	19	2	1	-44
Syr Darya basin									
Narin	0	0	0	2	2	35	0	0	0
Osh	3	3	16	3	4	18	2	1	-50
Jalalabad	2	2	21	10	11	7	2	1	-32
Ferghana	3	3	7	2	1	-32	2	1	-40
Andizhan	2	3	43	14	19	42	3	8	155
Namangan	2	1	-40	1	1	-42	3	1	-47
Sugd	2	3	16	1	1	-33	2	2	7
Tashkent	2	3	44	1	1	-49	4	2	-55
Syrdarya	3	3	12	2	2	-34	3	2	-40
Jizzah	2	1	-45	2	1	-47	0	0	0
South Kazakhstan	2	3	12	3	1	-47	3	2	-49
Kyzylorda	0	0	0	10	19	96	3	1	-51

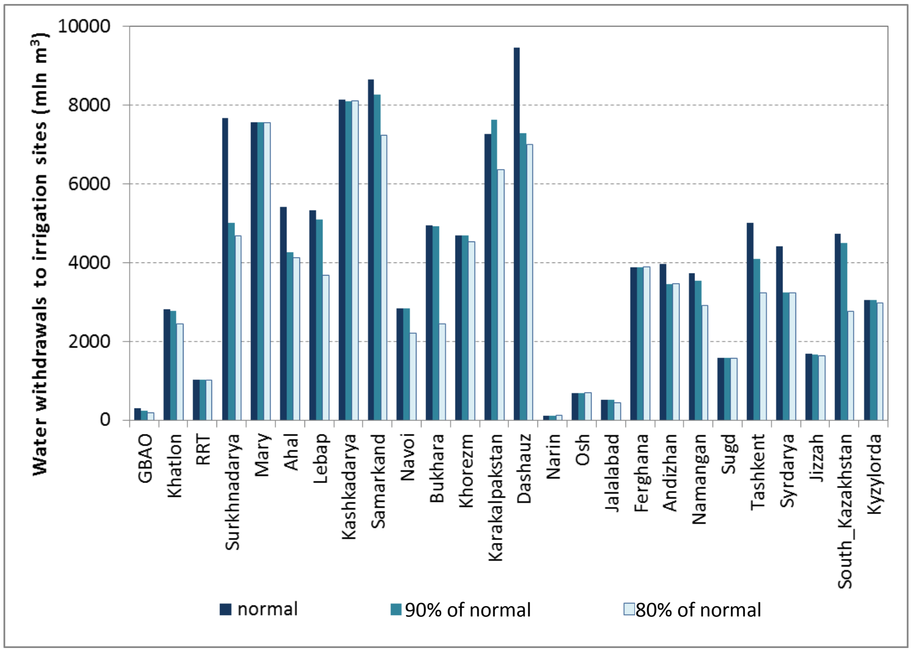
Notes: OBS-observed; OPT-Optimal; CHN-Change (%).

Source: Author's calculations

5.3.2 Optimal solution under various levels of water availability

For analyzing the sensitivity of the model as well as studying the impact of reduced water supply that may occur due to climate change, optimization model was formulated under reduced levels of water supply. Two additional scenarios were run considering 90% and and 80% of normal supply in all source nodes. In general, reduced water diversions to irrigation sites are expected when water supply is reduced (Figure 5.2). For providing optimum benefit, substantial water intake reduction should take place in the regions such as Surkhandarya, Lebap, Bukhara, Tashkent, and South Kazakhstan when water supply reduced to 80% of normal water supply.

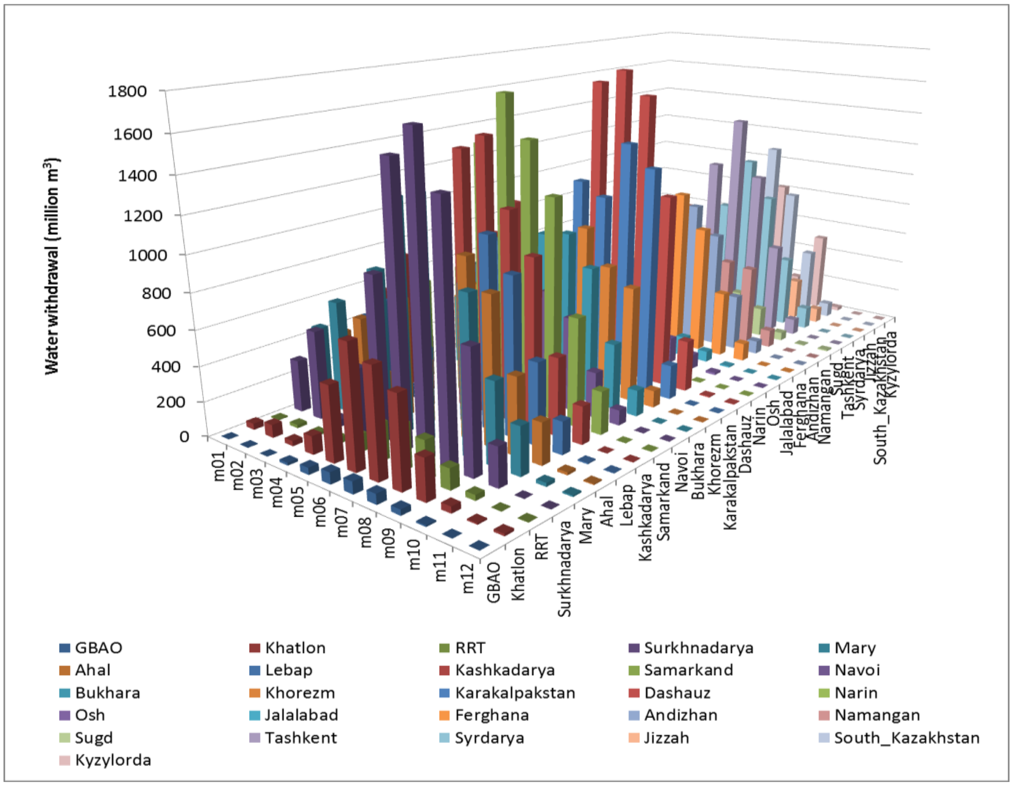
Figure 5.2 Annual water withdrawals by demand sites under changing water availability



Source: Author's calculations

The model also allows to analyzing the water use in more detail by considering monthly water diversion rates (Fig 5.3). As expected, main water withdrawals take place during the vegetation period, particularly in summer. Water withdrawals are also high in January and February, according to the model results since these months are included in the model as the months for conducting leaching practices.

Figure 5.3 Monthly water withdrawals by demand sites under changing water availability



Source: Author's calculations

Shadow price (marginal value) of water for irrigation also increases in vegetation period reaching up to \$0.09 USD per m^3 in the downstream regions such as Khorezm of Uzbekistan and Dashauz of Turkenistan in July (Table 5.4). The lowest marginal values of water decreasing by less than \$0.006 USD per m^3 are specific for the late autumn (November) and early winter (December).

In the Amu Darya basin, marginal values of water varies between \$0.01 and \$0.21 USD per m^3 in upstream (GBAO, Khatlon, RRT) and midstream (Surkhandarya, Kashkadarya, Mary, Ahal, Lebap, Samarkand, Navoi, Bukhara) in vegetation months. Meantime, marginal water productivities in downstream (Khorezm, Karakalpaksta, and Dashauz) vary between \$0.01 to \$0.091 USD per m^3.

Likewise, in the Syr Darya basin, marginal productivities in upstream (Narin, Osh, and Jalalabad) vary between \$0.009 to 0.058 USD per m^3. At the same time, marginal water productivities of downstream regions (The South Kazakhstan and Kyzylorda) are higher than \$0.009 USD per m^3 but lower than \$0.069 USD per m^3.

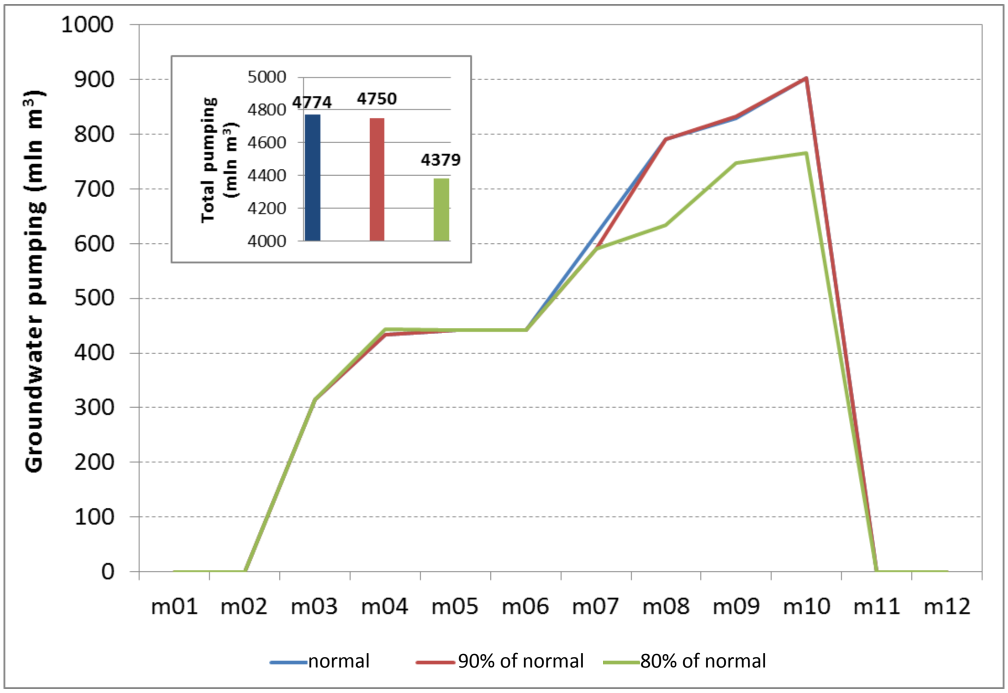
Table 5.4 Shadow prices of water across the irrigation demand sites under normal water supply

River basin	Demand sites	Shadow prices of water by months											
		m01	**m02**	**m03**	**m04**	**m05**	**m06**	**m07**	**m08**	**m09**	**m10**	**m11**	**m12**
Amu Darya	GBAO	0.03	0.03	0.02	0.019	0.019	0.02	0.02	0.016	0.011	0.006	0.006	0.003
	Khatlon	0.03	0.03	0.02	0.019	0.019	0.02	0.02	0.016	0.011	0.006	0.006	0.003
	RRT	0.03	0.03	0.02	0.02	0.02	0.021	0.021	0.016	0.012	0.006	0.006	0.003
	Surkhandarya	0.025	0.025	0.017	0.017	0.018	0.018	0.019	0.015	0.01	0.005	0.005	0.002
	Mary	0.027	0.027	0.018	0.018	0.018	0.019	0.02	0.015	0.011	0.005	0.005	0.002
	Ahal	0.027	0.027	0.018	0.018	0.018	0.019	0.02	0.015	0.011	0.005	0.005	0.002
	Lebap	0.027	0.027	0.018	0.018	0.018	0.019	0.02	0.015	0.011	0.005	0.005	0.002
	Kashkadarya	0.028	0.028	0.018	0.018	0.018	0.019	0.019	0.015	0.011	0.005	0.005	0.002
	Samarkand	0.026	0.026	0.017	0.017	0.017	0.017	0.018	0.014	0.01	0.005	0.005	0.002
	Navoi	0.025	0.025	0.017	0.016	0.017	0.017	0.018	0.014	0.01	0.005	0.005	0.002
	Bukhara	0.025	0.025	0.017	0.016	0.017	0.017	0.018	0.014	0.01	0.005	0.005	0.002
	Khorezm	0.029	0.029	0.019	0.019	0.019	0.02	0.091	0.019	0.011	0.005	0.005	0.005
	Karakalpakstan	0.027	0.026	0.017	0.017	0.018	0.018	0.085	0.018	0.01	0.005	0.005	0.005
	Dashauz	0.027	0.027	0.018	0.018	0.018	0.019	0.089	0.018	0.011	0.005	0.005	0.005
Syr Darya	Narin	0.054	0.054	0.053	0.049	0.051	0.055	0.058	0.058	0.009	0.004	0.004	0.003
	Osh	0.055	0.055	0.055	0.051	0.053	0.055	0.058	0.058	0.01	0.006	0.005	0.004
	Jalalabad	0.055	0.055	0.055	0.051	0.052	0.055	0.058	0.058	0.01	0.005	0.005	0.004
	Ferghana	0.037	0.037	0.037	0.044	0.046	0.048	0.051	0.051	0.008	0.004	0.005	0.004
	Andizhan	0.037	0.037	0.037	0.044	0.046	0.048	0.051	0.051	0.008	0.004	0.005	0.004
	Namangan	0.044	0.044	0.044	0.052	0.054	0.057	0.06	0.06	0.01	0.005	0.006	0.005
	Sugd	0.054	0.054	0.053	0.053	0.055	0.058	0.061	0.061	0.01	0.006	0.006	0.005
	Tashkent	0.042	0.042	0.042	0.049	0.051	0.054	0.057	0.057	0.009	0.004	0.005	0.004
	Syrdarya	0.056	0.056	0.055	0.055	0.057	0.06	0.064	0.064	0.01	0.006	0.005	0.004
	Jizzah	0.056	0.056	0.056	0.056	0.058	0.061	0.065	0.065	0.01	0.006	0.005	0.004
	South Kazakhstan	0.056	0.056	0.056	0.059	0.062	0.065	0.069	0.069	0.011	0.006	0.005	0.004
	Kyzylorda	0.055	0.055	0.056	0.052	0.054	0.056	0.059	0.061	0.009	0.005	0.005	0.005

Notes: Indexes m01, … , m12 stands for months January, February, … , December. Source: Author’s calculations

Increased water demand for irrigation in summer and autumn requires water use from other alternative sources to the surface water. For instance, groundwater use for irrigation increases from 400-500 mln m^3 in spring to 500-900 mln m^3 in summer (Figure 5.4). Overall groundwater use in normal year under optimization scenario should be about 4.8 km^3 while decreasing to 4.4 km^3 when water availability reduced by 80%.

Figure 5.4 Groundwater pumping by months under different levels of water availability

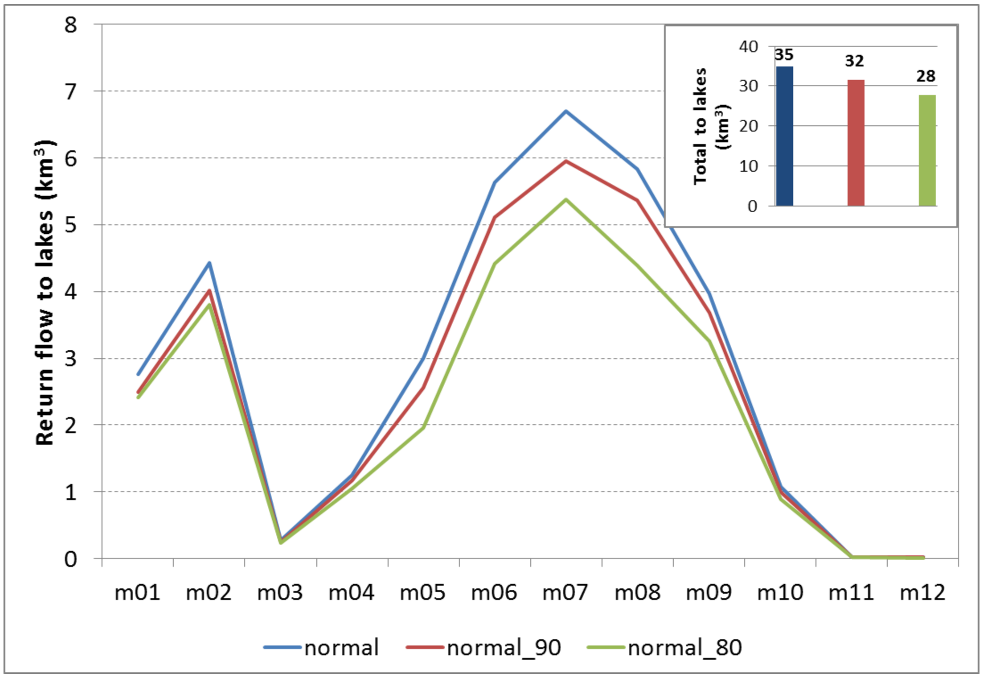


Source: Author's calculations

Due to the dominance of the inefficient furrow and basin irrigations and unlined conveyance system, return flows are high in both of the river basins. Return flows also increase in parallel with the increase in irrigation water intake, e.g. during the leaching in late winter months and in vegetation period in summer (Fig. 5.5). According to the model results, under normal water supply overall about 35 km^3 of total water withdrawals end up in the lakes located at the tail ends of the irrigation networks without bringing any benefit.

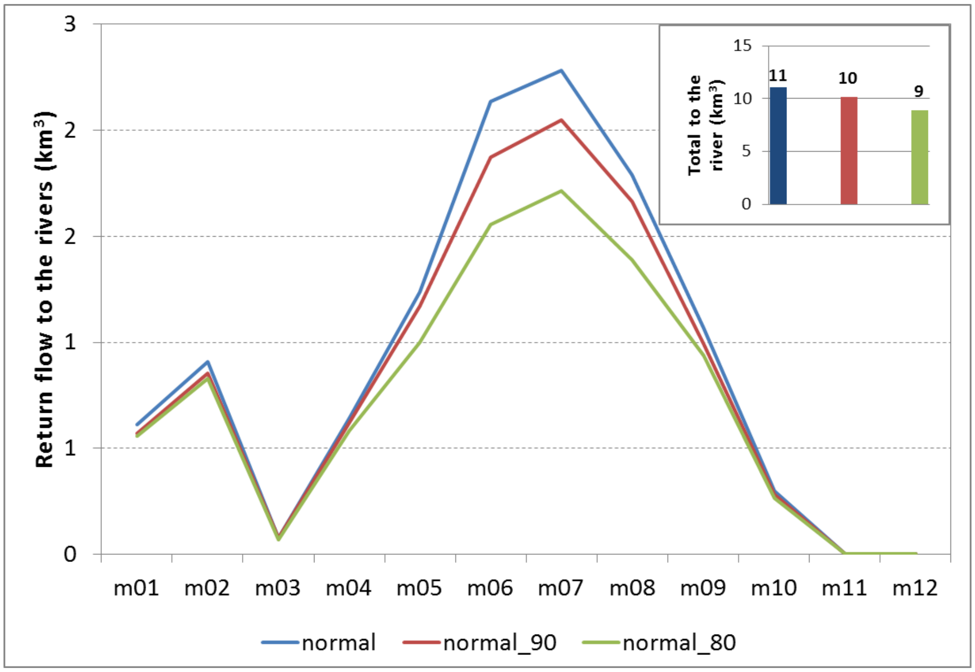
Part of return flows is discharged into the rivers (Fig 5.6). Although return flows discharged into the rivers increase water availability in downstream, they may harm downstream users due to low quality of the return flows. Thus, increased return flows to the river should be carefully treated before the discharge into the sea to reduce the externalities to downstream. Total of about 10 km^3 water is discharged into the rivers in the ASB.

Figure 5.5 Estimated values of return flows discharged to the lakes at the tail-ends of the irrigation networks by months under various levels of water availability



Source: Author's calculations

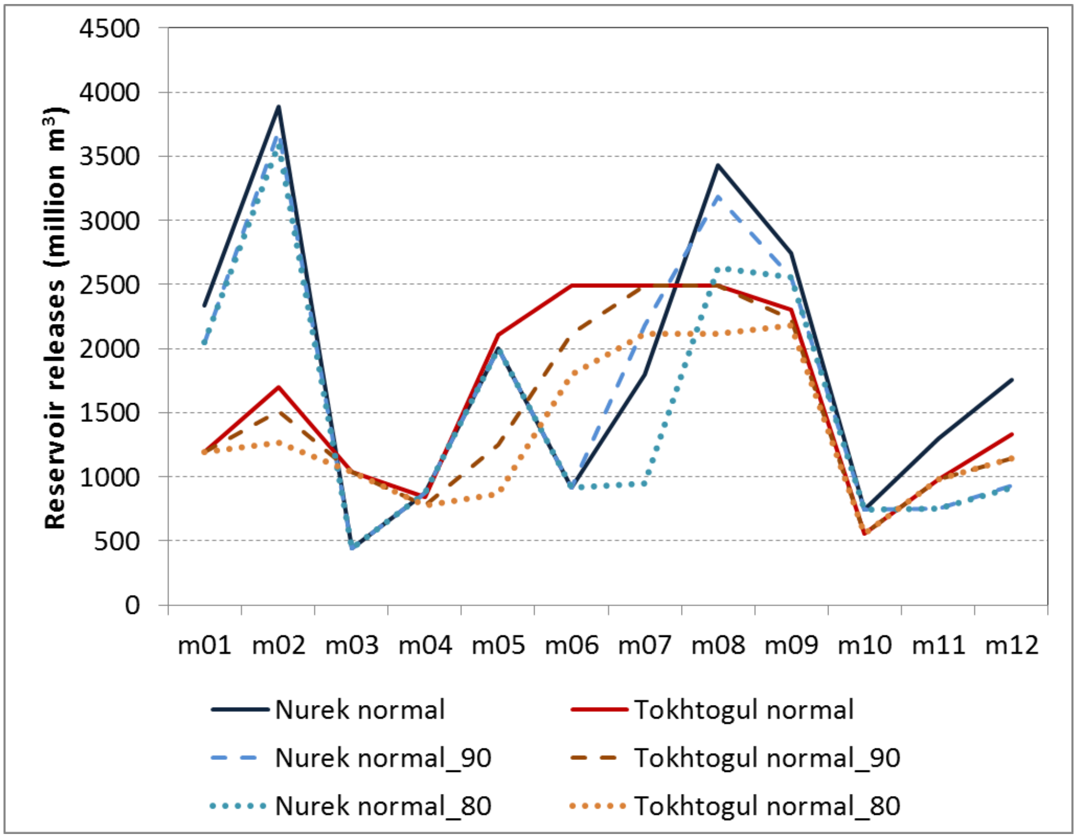
Figure 5.6 Estimated values of return flows discharged to the river by months under various levels of water availability



Source: Author's calculations

For providing optimal basin-wide benefits, reservoir releases are also to be adjusted to stabilize water supply for irrigation (Fig 5.7). Nurek reservoir releases are substantially high in leaching months (January and February) and when there is a peak irrigation demand in vegetation period (July and August). Meantime, Tokhtogul reservoir should release large amounts of water between May and September for achieving optimal basin-wide benefits. Releases from both reservoirs decrease in parallel with reduced water availability. This indicates that reservoirs serve to regulate the seasonal water distribution and do not create additional water for meeting irrigation demand.

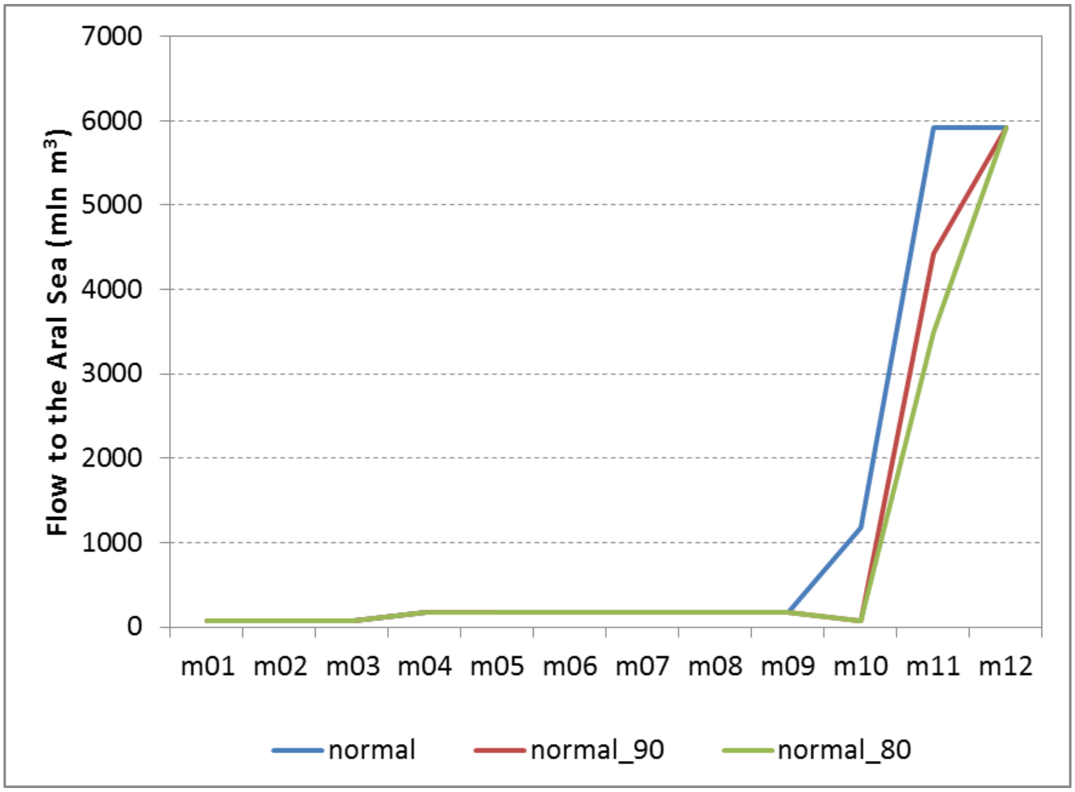
Figure 5.7 Water releases from Nurek and Tokhtogul reservoirs in normal year under optimization scenario



Source: Author’s calculations

According to the optimal plan, The Aral Sea should receive about 14 km^3 water under normal water supply but mostly in winter months such as November and December (Fig. 5.8). Although winter releases does not seem useful for improving biodiversity in the deltaic zones and improving the ecological conditions of the Sea, water discharged into the Sea in winter is stored and thus can be used for the improvement of the ecosystems in summer. Lakes and groundwater reservoirs in the deltaic zone can be filled in winter months and this water can be used for maintaining sustainable ecosystems in this area. The principle of “the Ganges machine” that intends to store water resources in groundwater reservoirs during the flood time and use them when necessary was proposed to improve water availability in the Ferghana Valey of the Syr Darya Basin (Karimov et al. 2010). This principle also works well to the case of the deltaic zones.

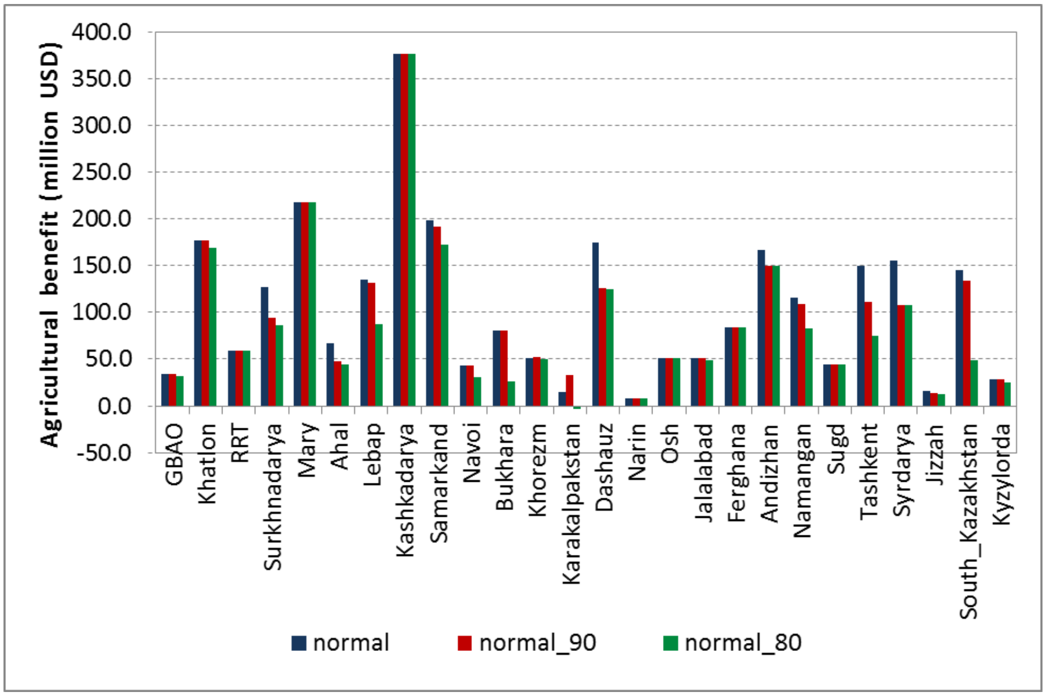
Figure 5.8 Environmental flow to the Aral Sea and deltaic zones under optimization scenario at various levels of water availability



Source: Author’s calculations

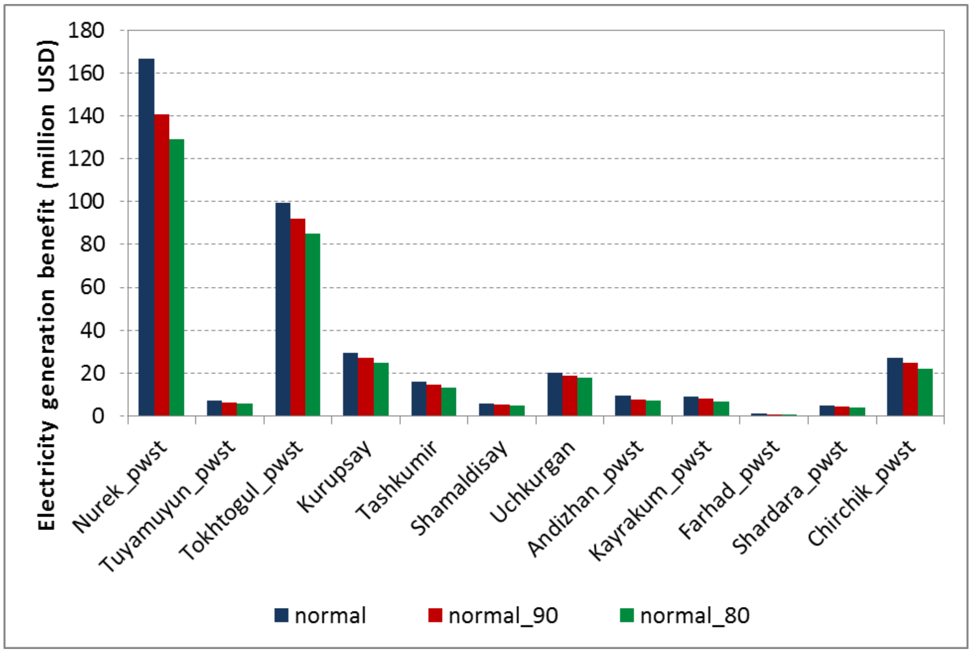
Reduced water supply impacts on irrigation and power generation benefits but at different rates. For instance, substantial proportional reductions in irrigation benefits occur in the regions such as Surkhandarya, Bukhara, Karakalpakstan, Tashkent, Syrdarya, and South Kazakhstan under 80% of normal water supply (Fig 5.9). Significant benefit losses from reduced electricity generation in Nurek and Tokhtogul reservoirs are expected as well due to decreased water supply (Figure 5.10). Overall optimal irrigation benefits decrease from $2,776 mln USD under normal supply to $2,213 mln USD when the water availability reduced to the 80% of normal (Fig 5.11). Total hydropower generation benefit also decreases from $395 mln USD of normal water supply to $320 mln USD under 80% of normal supply. Therefore, according to the model results total benefit from irrigation, energy, and environmental system decreases from $3,210 mln USD to $2,560 mln USD when water availability is reduced by 80% of normal supply.

Figure 5.9 Agricultural benefits across the irrigation demand sites under various levels of water availability



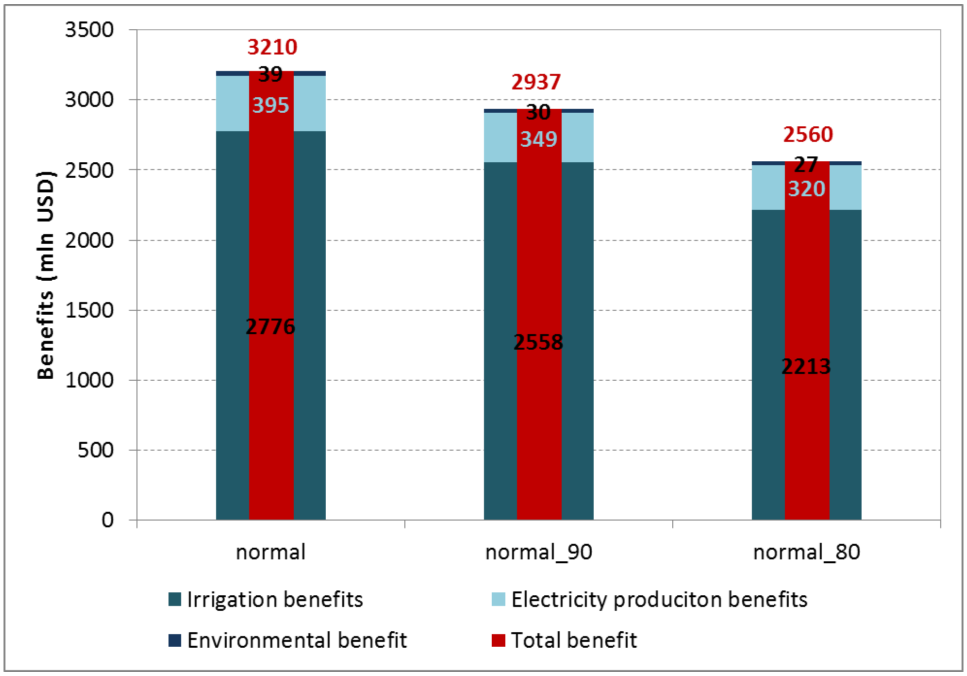
Source: Author’s calculations

Figure 5.10 Electricity production benefits by hydropower stations under various levels of water availability



Source: Author’s calculations

Figure 5.11 Irrigation, hydroelectricity generation, and environmental benefits at various levels of water availability



Source: Author's calculations

5.3.3 *Optimal improvements of irrigation and conveyance efficiencies*

Differing from the previous optimization scenarios which assumed fixed rates of irrigation and conveyance efficiencies, the model was run also considering flexible irrigation and conveyance efficiency rates. According to the model results, optimal irrigation efficiency rates increase in parallel with reduced water availability (Table 5.5). When water availability decreased by 80% of normal supply, maximum irrigation efficiency improvements in cotton production are required in the regions - Khatlon, Ahal, and Kashkadara of the Amu Darya basin and all cotton producing regions of the Syr Darya basin except Jizzakh for attaining optimal basin-wide benefits. Irrigation efficiency of wheat production should be maximally improved in the regions - Khatlon, RRT, Surkhandarya, Ahal, and Kashkadarya of the Amu Darya basin and Namangan, Sugd, and South Kazakhstan of the Syr Darya basin. Rice production should be fully upgraded by improving irrigation efficiency in all rice producing regions of the ASB for achieving optimal basin-wide benefits.

Requirements for improving conveyance efficiency to attain optimal basin-wide gains also increase in parallel to reduced water supply (Table 5.6). Improvements in conveyance efficiency are particularly essential in downstream regions of the Amu Darya basin — Khorezm, Karakalpakstan, and Dashauz — and mid- and downstream regions of the Syr Darya basin — Tashkent, Syrdarya, Jizzakh, South Kazakhstan, and Kyzylorda — for providing optimal basin-wide welfare. Dominance of sandy soils with high percolation rates and relatively cheapness of conveyance improvement made conveyance improvements more recommendable in downstream areas.

Table 5.5 Optimal irrigation efficiency rates for main crops (cotton, wheat, and rice) by demand sites under various levels of water availability

Demand sites	Cotton				Wheat				Rice			
	OBS	OPT			OBS	OPT			OBS	OPT		
		normal	90% of normal	80% of normal		normal	90% of normal	80% of normal		normal	90% of normal	80% of normal
GBAO	0.00	0.00	0.00	0.00	0.62	0.62	0.62	0.62	0.00	0.00	0.00	0.00
Khatlon	0.62	0.80	0.80	0.90	0.62	0.90	0.90	0.90	0.22	0.90	0.90	0.90
RRT	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.90	0.22	0.90	0.90	0.90
Surkhandarya	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.90	0.22	0.90	0.90	0.90
Mary	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.00	0.00	0.00	0.00
Ahal	0.58	0.58	0.90	0.90	0.58	0.65	0.90	0.90	0.00	0.00	0.00	0.00
Lebap	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.18	0.90	0.90	0.90
Kashkadarya	0.62	0.62	0.90	0.90	0.62	0.62	0.90	0.90	0.00	0.00	0.00	0.00
Samarkand	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.90	0.90	0.90
Navoi	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.00	0.00	0.00
Bukhara	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.00	0.00	0.00	0.00
Khorezm	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.90	0.90	0.90
Karakalpakstan	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.15	0.90	0.90	0.90
Dashauz	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.16	0.90	0.90	0.90
Narin	0.00	0.00	0.00	0.00	0.55	0.55	0.55	0.55	0.00	0.00	0.00	0.00
Osh	0.55	0.90	0.90	0.90	0.55	0.55	0.55	0.55	0.17	0.90	0.90	0.90
Jalalabad	0.55	0.90	0.90	0.90	0.55	0.63	0.55	0.55	0.17	0.90	0.90	0.90
Ferghana	0.55	0.78	0.90	0.90	0.55	0.61	0.55	0.55	0.17	0.90	0.90	0.90
Andizhan	0.55	0.76	0.90	0.90	0.55	0.90	0.56	0.63	0.17	0.90	0.90	0.90
Namangan	0.63	0.90	0.90	0.90	0.63	0.90	0.90	0.90	0.23	0.90	0.90	0.90
Sugd	0.55	0.90	0.90	0.90	0.55	0.90	0.90	0.90	0.18	0.90	0.90	0.90
Tashkent	0.55	0.55	0.55	0.90	0.55	0.55	0.55	0.55	0.18	0.90	0.90	0.90
Syrdarya	0.73	0.73	0.73	0.89	0.73	0.73	0.73	0.73	0.24	0.90	0.90	0.90
Jizzah	0.63	0.63	0.90	0.76	0.63	0.71	0.69	0.63	0.00	0.00	0.00	0.00
South Kazakhstan	0.63	0.63	0.63	0.90	0.63	0.63	0.63	0.90	0.23	0.90	0.90	0.90
Kyzylorda	0.00	0.00	0.00	0.00	0.48	0.48	0.48	0.48	0.15	0.90	0.90	0.90

Notes: OBS – Observed; OPT - Optimization

Source: Author’s calculations

Table 5.6 Observed (OBS) and optimal (OPT) conveyance efficiency rates across the demand sites under different levels of water availability

Demand sites	OBS	OPT		
		normal	90% of normal	80% of normal
GBAO	0.64	0.64	0.64	0.64
Khatlon	0.64	0.64	0.64	0.64
RRT	0.64	0.64	0.64	0.90
Surkhandarya	0.64	0.64	0.64	0.64
Mary	0.70	0.70	0.70	0.70
Ahal	0.70	0.70	0.70	0.90
Lebap	0.70	0.70	0.70	0.83
Kashkadarya	0.64	0.64	0.72	0.79
Samarkand	0.64	0.64	0.64	0.90
Navoi	0.65	0.65	0.65	0.65
Bukhara	0.65	0.65	0.65	0.65
Khorezm	0.65	0.90	0.90	0.90
Karakalpakstan	0.70	0.90	0.90	0.90
Dashauz	0.70	0.90	0.90	0.90
Narin	0.73	0.74	0.76	0.73
Osh	0.73	0.77	0.83	0.83
Jalalabad	0.73	0.73	0.79	0.86
Ferghana	0.73	0.73	0.73	0.77
Andizhan	0.73	0.73	0.73	0.73
Namangan	0.62	0.64	0.63	0.63
Sugd	0.73	0.75	0.74	0.75
Tashkent	0.73	0.90	0.90	0.85
Syrdarya	0.71	0.90	0.90	0.90
Jizzah	0.70	0.90	0.90	0.90
South Kazakhstan	0.70	0.90	0.90	0.90
Kyzylorda	0.70	0.90	0.90	0.90

Source: Author's calculations

5.3.4 The impact of dam constructions on downstream water availability and irrigation/hydropower production benefits

Comprehensive structure of the model also allows analyzing the effects of developing hydro-infrastructural facilities such as reservoirs. The upstream countries try to convince increased water supply for irrigation because of the construction of the dams in contrast to the fears of downstream regions for reduced water availability due to increased use of the reservoirs for hydroelectricity generation. Therefore, it would be interesting to see the impact of the upstream reservoir constructions on downstream water availability that is considered as equivalent to the releases from Tokhtogul and Nurek reservoirs (Table 5.7).

Table 5.7 Impact on optimal water releases (in mln m^3) from Nurek and Tokhtogul reservoirs of constructing the Rogun and Kambarata reservoirs

Water availability	Reservoirs	Scenarios	Monthly water releases												Total
			m01	m02	m03	m04	m05	m06	m07	m08	m09	m10	m11	m12	
normal	Nurek	OPT	2.3	3.9	0.4	0.9	2.0	0.9	1.8	3.4	2.7	0.7	1.3	1.8	22
		OPT+ROG	2.3	3.9	0.4	0.9	2.0	0.9	0.9	3.2	2.7	0.7	1.5	3.5	23
		OPT+ROG+KAM	2.3	3.9	0.4	0.9	2.0	0.9	0.9	3.2	2.7	0.7	1.5	3.5	23
	Tokhtogul	OPT	1.2	1.7	1.0	0.8	2.1	2.5	2.5	2.5	2.3	0.6	1.0	1.3	20
		OPT+ROG	1.2	1.7	1.0	0.8	2.1	2.5	2.5	2.5	2.3	0.6	1.0	1.3	20
		OPT+ROG+KAM	1.2	1.9	1.0	0.8	2.1	2.5	2.5	2.5	2.3	0.6	1.0	1.3	20
90% of normal	Nurek	OPT	2.0	3.7	0.4	0.9	2.0	0.9	2.2	3.2	2.6	0.7	0.8	0.9	20
		OPT+ROG	2.1	3.8	0.4	0.9	2.0	0.9	2.6	3.4	2.7	0.7	0.8	0.9	21
		OPT+ROG+KAM	2.1	3.8	0.4	0.9	2.0	0.9	2.6	3.4	2.7	0.7	0.8	0.9	21
	Tokhtogul	OPT	1.2	1.5	1.0	0.8	1.2	2.1	2.5	2.5	2.2	0.6	1.0	1.1	18
		OPT+ROG	1.2	1.5	1.0	0.8	1.9	1.6	2.5	2.5	2.1	0.6	1.0	1.1	18
		OPT+ROG+KAM	1.2	1.7	1.0	0.8	0.8	2.5	2.5	2.5	2.2	0.6	1.0	1.1	18
80% of normal	Nurek	OPT	2.0	3.6	0.4	0.9	2.0	0.9	0.9	2.6	2.6	0.7	0.8	0.9	18
		OPT+ROG	2.2	3.8	0.4	0.9	2.0	0.9	1.1	3.0	2.6	0.7	0.8	0.9	19
		OPT+ROG+KAM	2.2	3.8	0.4	0.9	2.0	0.9	1.1	3.0	2.6	0.7	0.8	0.9	19
	Tokhtogul	OPT	1.2	1.3	1.0	0.8	0.9	1.8	2.1	2.1	2.2	0.6	1.0	1.1	16
		OPT+ROG	1.2	1.3	1.0	0.8	0.9	1.8	2.1	2.1	2.2	0.6	1.0	1.1	16
		OPT+ROG+KAM	1.2	1.4	1.0	0.8	0.4	1.2	2.5	2.5	2.4	0.6	1.0	1.1	16

Notes: OPT - Optimal water allocation; ROG – The scenario considering the construction of the Rogun reservoir; KAM - The scenario considering the construction of the Kambarata reservoir

Source: Author's calculations

Table 5.8 Comparing the benefits under different individual and combined scenarios

Scenarios	Water availability			Change compared to the optimal (baseline) scenario (%)		
	Normal	90% of normal	80% of normal	Normal	90% of normal	80% of normal
Irrigation benefits (million USD)						
OPT	2776	2558	2213	0.0	0.0	0.0
OPT+ROG	2761	2574	2245	-0.5	0.7	1.5
OPT+ROG+KAM	2767	2583	2253	-0.3	1.0	1.8
OPT+TECH	3378	3283	3131	21.7	28.4	41.5
OPT+TECH+ROG+KAM	3367	3285	3134	21.3	28.4	41.7
Hydropower production benefits (million USD)						
OPT	395	349	320	0.0	0.0	0.0
OPT+ROG	414	362	331	4.9	3.9	3.3
OPT+ROG+KAM	503	444	411	27.2	27.1	28.4
OPT+TECH	413	366	323	4.6	5.0	0.9
OPT+TECH+ROG+KAM	526	452	408	33.1	29.6	27.3
Hydropower production (million KWh)						
OPT	21.5	19.1	17.1	0.0	0.0	0.0
OPT+ROG	29.9	26.2	23.5	39.0	37.1	37.0
OPT+ROG+KAM	35.5	31.6	28.6	65.1	65.2	66.9
OPT+TECH	22.0	19.5	17.2	2.1	2.1	0.5
OPT+TECH+ROG+KAM	36.3	31.7	28.3	68.8	65.7	65.3
Environmental benefits (million USD)						
OPT	39	30	27	0.0	0.0	0.0
OPT+ROG	40	30	27	2.2	-0.4	-0.6
OPT+ROG+KAM	40	30	27	2.1	-0.4	-0.6
OPT+TECH	47	36	27	20.8	21.7	2.0
OPT+TECH+ROG+KAM	43	37	34	9.4	22.7	25.9
Total benefit (million USD)						
OPT	3210	2937	2560	0.0	0.0	0.0
OPT+ROG	3215	2966	2603	0.2	1.0	1.7
OPT+ROG+KAM	3310	3056	2690	3.1	4.1	5.1
OPT+TECH	3839	3685	3481	19.6	25.5	36.0
OPT+TECH+ROG+KAM	3936	3774	3576	22.6	28.5	39.7

Notes: OPT - Optimal water allocation; ROG - Construction of the Rogun Dam; KAM - Construction of the Kambarata reservoir; TECH - Technological improvements by increasing irrigation and conveyance efficiencies

Source: Author's calculations

According to the simulation results, the construction of the Rogun dam does not influence much on water releases from the Nurek reservoir under normal water supply if optimal basin-wide gains are intended. Even when water supply in the source nodes is reduced, water releases from the Nurek may only slightly increase if all the riparian countries agree for basin-wide cooperation. The same is true to the case of constructing the Kambarata reservoir.

Impacts on the benefits of irrigation, electricity generation, and environmental systems of constructing the large dams were also analyzed (Table 5.8). Additionally these impacts were compared to the impacts of the irrigation and conveyance efficiency improvements. According to the model simulations, the construction of the dams under normal water supply does not influence much on irrigation benefits but might only slightly improve the irrigation benefits when water availability reduced to 80% of normal supply. Since most of the river flow can be already controlled by current reservoirs (Dukhovny and Schutter 2011:134; see also footnote in page 33 and Table 2.10 in this study), benefits of the newly constructed dams for balancing seasonal water variability and annual shortages for sustainable irrigation is infinitesimal.

In contrast to constructing dams, improving irrigation and conveyance efficiencies would substantially increase irrigation benefits. As the model simulations indicated, irrigation benefits may increase by 20% to 40% when irrigation and conveyance efficiency improvements take place throughout the ASB. This option is useful particularly when water supply in source nodes decreases.

Regarding the changes in electricity generation due to the newly build reservoirs, electricity generation benefits from constructing the Rogun dam are considerable but much lower than the power generation benefits of constructing the Kambarata reservoir because of differences in investment costs of the projects. The construction of the Kambarata reservoir in addition to the Rogun dam may increase power generation substantially (up to 38% under reduced water supply) since the investment costs of the Kambarta is lower than the costs of constructing the Rogun dam. Despite lower benefits from the Rogun dam, electricity generation can shift up to 37-39% after constructing the dam. Constructing the Kambarata reservoir additionally can increase electricity production by 65-67%. Therefore, constructing the dams can be recommendable for improving the regional energy security. However, the governments that are sharing the common resources in the ASB should cooperate in managing and planning strategically important infrastructural facilities in order to reduce their investment, operation, and transaction costs and thus increase their financial feasibility. Collaborations over the large constructions that has basin-wide significance is also important for creating mutual trust among the countries within the ASB and preventing selfish attitude of any user that may harm benefits of all users. Produced energy should be used for maintaining normal electricity supply to the domestic households and industrial enterprises at first place. Exporting the electricity outside the ASB can be discussed only after providing abundant electricity to the internal demands. Functioning of the regional market for the increased electricity supply also depends on the cooperation among the ASB countries since the establishment of the regional energy market requires normal functioning of the electricity grids located in the territories of all ASB countries.

5.4 Discussion of the water availability and benefit impacts of irrigation modernization and infrastructural developments and conclusions

According to the analyses, the development of hydro-infrastructural facilities improves energy security and the modernization of irrigation systems improve food/income security when the riparian water users cooperate with each other to attain basin-wide optimal gains. Substantial economic and food security benefits of irrigation and conveyance efficiency improvements can be realized if producers and governmental organizations have an incentive for that. For instance, liberalization of agricultural markets by abolishing state production targets for wheat and cotton production while allowing more freedom to agricultural producers in decision making processes, provision of secure land rights and improvement of market infrastructure for agricultural commodities may make crop production more profitable to farmers. Therefore, market liberalization creates incentives of efficient water use to enhance crop yields and profitability. Meanwhile, improving conveyance efficiency of irrigation canals depends on both collective actions of the farmers as well as the governmental support since canals serve for the entire community of farmers.

Potential benefits through increased hydropower production from the construction and operation of new hydro-infrastructural facilities depend on the cooperation of all riparian countries to gain mutual benefits rather than aiming at individualistic and opportunistic gains. At present, under the non-existence of new large dams (Kambarata and Rogun), upstream users changed the mode of the present dams for producing more hydropower during winter. This caused considerable losses to downstream irrigation especially in years with reduced basin-wide water supply. Additionally built large dams upstream may help to solve this problem under certain conditions. For instance, the newly constructed dams are recommendable if these dams store water during summer and release in winter for meeting hydropower demand in cold months while the dams next to them (e.g., Tokhtogul in the Syr Darya and Nurek in the Amu Darya) store upstream winter releases and discharge more water in summer for downstream needs. However, the risks using the dams for geopolitical purposes are extremely high when upstream countries choose different operations modes of the reservoirs. If, for instance, Rogun releases more water during summer that is stored by Nurek and is released in winter, energy production benefits may be still optimal to upstream but the downstream irrigation gets destroyed. Therefore, developing the trust is essential and upstream countries interested in hydropower production should initiate the cooperation of the stakeholders from downstream to take part in infrastructural developments and sharing the cooperative benefits fairly while guaranteeing non-use of the constructed reservoirs as a tool for geopolitical influence. Eliciting cooperation rather than following individualistic goals or trying to exploit the weaknesses of other parties is a solution for better performance and less conflicts (Axelrod 1984).

There are also other risks from the reservoir constructions that may eliminate potential gains from increased hydropower production. Reduced downstream water availability may occur during the period of filling the newly build reservoirs. For instance, frequent water shortages were observed in mid-1980s when the Nurek reservoir was being filled during and after construction (Dukhovny and Schutter 2011). However, due to the static nature of the model used in this study, a possible water scarcity downstream during the initial period for filling the new reservoirs was not analyzed. Thus the results of the modeling technical aspects of water management in the ASB are valid once after the accomplishment of upstream reservoirs. The impact of the constructions during the period of filling the reservoirs should be analyzed further based on a dynamic hydro-economic modeling framework.

There are also threats of flooding if the newly build reservoirs are destroyed accidentally as they were planned to build in highly active seismic zones and politically unstable countries. The model does not allow considering these effects but they should be analyzed in detail by determining the places of flooding and potential number of people who can be affected. Appropriate measures of evacuation under force-majeure situations should be planned before the constructions start. Sharing the costs of these force-majeure events among the riparian countries and responsibilities of each party should be mutually agreed and endorsed to prevent potential conflicts among the regions.

6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Summary and conclusions

Increasing water demands for irrigated agriculture, power generation, and environmental systems are the main reasons for aggravating conflicts over water sharing among the riparian countries of the ASB. Negative consequences of inefficient water distribution are reflected among others by the desiccation of the Aral Sea and frequent occurrence of water shortages in downstream regions of the basin, such as Khorezm.

The enormous expansion of irrigated cotton production since the 1960s in Central Asia was triggered by a combination of high costs of cotton imports to the SU and significant, available, suitable land and water resources in the ASB. Increased cotton production supported increased employment and social control in densely populated settings. However, the imposed, bureaucratic top-down management turned out to be ineffective for a rational use of the limited resources. After independence, investments in irrigation and conveyance systems declined sharply, further increasing water losses in the irrigation system. Ineffective coordination of basin water and infrastructural resources among riparian regions following the emergence of the five independent countries in Central Asia additionally complicated water sharing in the basin. The lack of experience in market-based management approaches combined with a reluctance to cooperate with respect to sharing common basin resources prevented more efficient water use. As a result, plans are now underway by upstream countries to build new reservoirs to regulate river flow for increased power production in winter against the will of downstream regions where agriculture heavily relies on water releases of the upstream reservoirs in summer.

The dominance of water intensive production activities, ineffective coordination of basin resources due to ineffective water management institutions, and a reliance on outdated irrigation and conveyance systems in the ASB, meantime, imply a huge potential for improvement options. This dissertation addressed these core water resource challenges in the ASB, using a step-by-step approach that extends the scope and details of the analysis in each additional step. The macroeconomic analysis, developed in chapters 3, concluded that a series of less water intensive production activities were feasible as comparisons of direct and indirect water uses by all economic sectors resulted in. Chapters 4 assessed the potential of efficient water allocation among irrigation zones and environmental sites in the ASB while considering market-based water management approaches. Additionally, chapter 5 discussed the crucial food, energy, environment, and water nexus in the ASB based on a more disaggregated hydro-economic model that considers seasonal water allocation, detailed crop production activities, basin infrastructure, and the availability of irrigation/conveyance technologies.

According to the comparison of the economic sectors based on their growth impact and total water consumption levels, the production of cotton, wheat, and rice turned out to be least attractive when their total (direct and indirect) water use requirements per economic output were considered. Despite the dominance and high forward linkage impact of cotton, food security relevance of wheat, and high profitability of rice for farmers, they are less recommendable crops under water scarce conditions since these crops are the most water intensive crops with total water use of 18.4 m^3/USD, 18.4 m^3/USD, and 36 m^3/USD respectively. On the other hand, food crops such as fruits and vegetables with total water use requirements of 9.1 m^3/USD are more recommendable than cotton, rice, or wheat when water scarcity is a key constraint for economic development. In contrast to the general perception of the higher water footprint of livestock commodities than crop commodities, the livestock sector is rather favorable in terms of water use when direct and indirect water uses are measured per economic output rather than per physical output. Development of agro-processing sectors was also identified as an important water use reduction option. Fostering the growth in non-agro-processing industries and services was shown to have even higher potential than agricultural and related industries in reducing water use. However, economic restructuring reform options suggested above, in turn, require infrastructural, institutional, and legal environmental improvements that may also entail substantial investment and operation costs. Furthermore, since water use is only one aspect of the environmental system other environmental factors such as impact on water quality and carbon emissions under the suggested options should be considered additionally for a more comprehensive analysis of sectoral transformation reforms. Extending the scope of the analysis by additionally considering institutional, financial, and environmental factors would improve the results and policy implications of the study.

In addition to the economic and water use reduction benefits through sectoral transformation, substantial economic gains can be achieved by inter-regional water reallocations. Voluntary water reallocation that fosters water flows from lower to higher valued uses and increases basin-wide benefits and water productivity can be achieved by allowing tradable water use rights in the ASB. According to the results, when the transaction costs of water rights trading are assumed to be zero, additional benefit from intercatchment water rights trading compared to the fixed water use rights is $370 million USD while this amount is $260 million USD for intra-catchment water rights trading, under normal water supply. Additional benefits from introducing tradable water use rights increases under growing water scarcity. Total basin-wide benefits under water rights trading, considering minimum water flow to the environmental needs (the Aral Sea), increased even with compensation of the reduced benefits of the irrigation water users. However, when the transaction costs are higher than $0.05 USD per m^3 of tradable water use right benefits of market-based water allocation are eliminated. Thus, effectiveness of the tradable water use rights strongly depends on transaction costs.

Considering the dominance of administrative management approaches that are deeply rooted in the governance systems in Central Asia, altering the current institutions to the more effective ones that are based on the market principles indeed requires time and the transaction costs of this reform are likely high. Nevertheless, the experiences of the developed countries such as the US and Australia in implementing market ideas for more efficient water allocation can be a good lesson also for Central Asian water users and managers to reduce unproductive use of scarce resources. Transaction costs of this institutional change can be lowered through improving institutional and legal frameworks, empowering water users in decision making processes, improving the necessary technical infrastructure, and raising the awareness of the users on economic and legal aspects of water use.

In addition to economic and institutional reforms, technical improvements of irrigation networks and basin infrastructure also would have positive impacts on water availability and benefits. Since irrigated agriculture is the dominant livelihood form in the ASB, but accompanied by enormous water losses, upgrading the irrigation networks and improving water application at field level are essential for reducing the pressure of water scarcity. The present lack of maintenance of the irrigation networks engraves the on-going deterioration as evidenced by the ever-growing number of silted up and damaged canals, broken gates, outdated pumps, lack of spare parts, and so on. Hence, modernizing the irrigation network bears a high potential to decrease overall water losses. Improving conveyance efficiency is even more beneficial under reduced water supply that may occur due to expected climate change. Substantial potential for wide adoption of conveyance efficiency improvement measures exists to attain basin-wide optimal gains, particularly in downstream irrigation sites. Furthermore, considering the dominance of furrow and basin irrigation techniques in the ASB and their excessive water losses, more advanced irrigation techniques such as drip irrigation in cotton production and laser guided land leveling in cotton, wheat and rice cultivation are also potential options for reducing water use and enhancing yields (Bekchanov et al. 2010). Scarcer water conditions necessitate wider adoption of advanced irrigation technologies. According to the results, total basin-wide benefits may increase by 20% under normal water supply and by 40% under 80% of normal water availability when optimal irrigation efficiencies are achieved in the ASB. The overall basin-wide optimal benefits under increased rates of technological adoptions are much higher than the potential benefits following the construction of additional reservoirs to regulate river flow in the upper reaches of the Amu and Syr Darya Rivers. However, wide adoption of water saving technologies is dependent not only on increased access for technologies but also on secure water and land use rights and consequent creation of incentives for more productive use of water.

The construction of the Rogun and Kambarata Dams as proposed by upstream countries can slightly decrease downstream water availability under normal water supply in the ASB and may only negligibly improve downstream water access even under dry years if the reservoirs are operated to maximize basin-wide benefits. Therefore, these hydro-infrastructural developments do not have considerable impact on agricultural revenues if the cooperation concurrently takes place. Since the capacity of current reservoirs is already sufficient to regulate and balance seasonal and annual variability of water supplies in the Amu Darya and Syr Darya basins, the construction of additional dams does not seem beneficial for downstream irrigation. However, electricity generation volumes would increase and bring substantial economic gains if the investment costs were sufficiently low as more vividly exemplified in the case of Kambarata reservoir. The results showed that total energy production in the ASB may increase by 65-67% with the construction of the proposed reservoirs. Increased energy production may enhance energy security in upstream countries where the dams are located and also may partially improve energy access in other ASB countries and some South Asian countries if a cooperation among these countries is achieved.

Downstream irrigation sites are not harmed by the operation of new reservoirs (The Kambarata and Rogun) when these reservoirs store water in summer and release water to the reservoirs next to them in winter while the latter store water in winter but release water to mid- and down-stream reaches in summer. This operation mode would also allow stabilizing electricity supply over all months of the year for upstream countries. However, cooperation, mutual agreement, and trust among the riparian countries are fundamental requirements for attaining this mutually beneficial reservoir operation mode that provides optimal basin-wide economic gains. Upstream countries that initiated the constructions should foster the involvement of downstream partners in the infrastructural development projects, and share the common benefits of the collaboration in order to reduce mistrust and make the efforts fruitful for all parties. However, seismic conditions in the current construction sites and the impact on downstream water availability of filling the new reservoirs at the initial stages of their operation need to be further examined before a final decision on the profitability of these gigantic infrastructural facilities can be pronounced. Indeed, the risks of using the reservoirs as a tool for geopolitical purposes are another serious threat that makes the constructions unacceptable by downstream regions. Guarantying the non-use of the reservoirs for political pressure through sharing the ownership rights and benefits of the massive projects among all riparian countries is also important if the gains from the hydro-infrastructural developments are still acceptable after considering the destruction risks related to natural calamities.

6.2 Recommendations for further research

The identification of economic sectors with higher growth potential and lower water use requirements using an environmentally extended IO modeling framework, and the analysis of tradable water use rights and technological/infrastructural improvement using aggregated and disaggregated hydro-economic models, provides important suggestions for improving water use efficiency and maintaining sustainable prosperity in the ASB. Comparing economic growth impact potentials and total (direct plus indirect) water requirements of different activities in different countries through estimating and analyzing input-output models with environmental accounts for each Central Asian country would additionally reveal the comparative advantages of each of the countries to specialize in particular sectors. Integration of CGE/IOT models with integrated hydro-economic models framework is another option for further research that would allow the simultaneous estimation of not only direct, but also indirect welfare effects of water management reforms. Furthermore, establishing dynamic models on the basis of aggregated and disaggregated hydro-economic models would allow a more realistic picture of long-term sustainable growth in the ASB. Long-term analysis of the possibilities of cooperation among the users based on a dynamic model is essential for attaining more stable agreements among the users. Gains from establishing a common agricultural market in Central Asia as an alternative to the self-reliance policy should be investigated further by incorporating an inter-state commodity trade component into the model. Methods of measuring transaction costs of institutional change and environmental flow benefits still need much improvement and should be investigated further based on a more precise conceptual framework.

REFERENCES

Abdullaev I., F. Nurmetova, F. Abdullaeva, J.P.A. Lamers, 2008. Socio- technical aspects of water management in Uzbekistan: emerging water governance issues at the grass root level. In Rahaman, M. and Varis, O. (eds.): Central Asian Water. Water & Development Publications - Helsinki University of Technology, Helsinki, Finland

Abdullaev I., C. de Fraiture, M. Giordano, M. Yakubov, and A. Rasulov, 2009. Agricultural Water Use and Trade in Uzbekistan: Situation and Potential Impacts of Market Liberalization. Water Resources Development, 25 (1), 47–63.

Addams L., G. Boccaletti, M. Kerlin, M. Stuchtey, 2009. Charting Our Water Future – Economic Frameworks to Inform Decision-making. McKinsey & Company, New York.

Aladin N., P. Micklin, D. Keyser, I. Plotnikov, R. Letolle, A. Smurov, and J-F. Crétaux, 2006. Results of Aral Sea studies. International Association of Theoretical and Applied Limnology, Vol. 29(5), 2271-2275.

Aldaya M.M. and M.R. Llamas, 2008. Water Footprint Analysis for the Guadiana River Basin. Research Report No. 35. Delft, the Netherlands: UNESCO-IHE Inst. for Water Education

Aldaya M.M., G. Muñoz, and A.Y. Hoekstra, 2010. Water footprint of cotton, wheat and rice production in Central Asia, Value of Water Research Report Series No.41, UNESCO-IHE.

Allen Consulting Group (ACG), 2006. Transaction Costs of Water Markets and Environmental Policy Instruments. Final Report to the Productivity Commission. Melbourne, Australia: Allen Consulting Group.

Anderson, R.C., 1997. Environmental damage assessment of the Aral Sea disaster. Issue Paper No. 1, Environmental Policies and Technology. EPT Project, Almaty, Kazakhstan. U.S. Agency for International Development.

Anderson K., and J. Swinnen, 2008. Distortions to Agricultural Incentives in Europe’s Transition Economies. World Bank, Washington D.C.

Antonov V.I., 2000. Water resources in Uzbekistan as a part of total water resources in the Aral Sea basin and their present and perspective use. In: Umarov U. and Karimov A.H. (eds.), Water Resources, Problems of the Aral Sea and Environment. Tashkent, Universitet, 19-39 (in Russian).

Antonov V.I., 1996. On program of further development of irrigation in Uzbekistan. Herald: 1, 7-10 (in Russian).

Archibald S.O. and M.E. Renwick, 1998. Expected transaction costs and incentivesfor water market development. In: K.W. Easter, M.W. Rosengrant, and A. Dinar (eds.), Markets for Water—Potential and Performance, Boston: Kluwer, pp. 94–117.

Ashirbekov U.A. and I.S. Zonn, 2003. Aral: The history of disappearing Sea. Dushnabe (in Russian)

Asian Development Bank (ADB), 2010. Central Asia Atlas of Natural Resources. Manila, Philippines. Available online at: http://www.adb.org/publications/central-asia-atlas-natural-resources (accessed on 09.02.2013)

Aus der Beek T., F. Voß, and M. Flörke, 2011. Modelling the impact of global change on the hydrological system of the Aral Sea basin. Physics and Chemistry of the Earth, 36, 684-694.

Australian National Water Commission (ANWC) (2008) Distilled (eNewsletter). http://www.nwc.gov.au/__data/assets/pdf_file/0005/11885/DistilledJuly2008.pdf (accessed on 21.05. 2011)

Axelrod R., 1984. The Evolution of Cooperation. New York: Basic Books.

Babaev A. and A.A. Babaev, 1994. Aerospace monitoring of dynamic of desert geosystems under watering. Problems of Desert Development, 1: p. 21-29.

Badescu V. and R.B. Cathcart, 2011. Aral Sea partial restoration. I. A Caspian water importation macroproject, Int. J. Environment and Waste Management, Vol. 7, Nos. 1/2, pp.142–163.

Baffes J., 2004. Cotton: Market Setting, Trade Policies, and Issues. Policy Research Working Paper No. 3218, World Bank, Washington D.C.

Baffes J., 2007. Cotton-Dependent Countries in the Global Context. In: Kandiyoti D. (ed.), The Cotton Sector in Central Asia. Economic Policy and Development Challenges, London: The School of Oriental and African Studies, p. 32.

Barbier E., 1994. Valuing environmental functions: tropical wetlands. Land Economics, 70(2), 155-73.

Barton D.N., T. Saloranta, S.J. Moe, H.O. Eggestad and S. Kuikka, 2008. Bayesian Belief Networks as a Meta-modelling Tool in Integrated River Basin Management; Pros and Cons in Evaluating Nutrient Abatement Decisions under Uncertainty in a Norwegian River Basin, Ecological Economics Special Issue Integrated Hydro-Economic Modelling: Approaches, Key Issues and Future Research Directions.

Bauer C.J., 2004. Results of Chilean water markets: Empirical research since 1990. Water Resources Research 40:1-11.

Bear J. and O. Levin, 1966. Optimal utilization of an aquifer as an element of a water resources system. P.N. 5/66, Hydraulic Lab., Technion – Israel Inst. Of Technology, Haifa.

Bear J. and O. Levin, 1967. The Optimal Yield of an Aquifer, Haifa Symposium. International Association of Hydrological Sciences, Haifa. pp. 401–412.

Bear J. and O. Levin, 1970. Optimal utilization of an aquifer as an element of a water resource system: research period 1967–68. In: Levin, O. (Ed.), Selected Works in Operations Research and Hydraulics. Israel Institute of Technology, Haifa, pp. 64–279.

Bear J., O. Levin, N. Buras, 1964. Optimal utilization of aquifers as elements of water-resources systems. Progress Report No. 1: Basic Concepts and Program of Research, Technion – Israel Institute of Technology, Hydraulic Laboratory, Haifa.

Becker N., 1995. Value of moving from central planning to a market system: lessons from the Israeli water sector. Agricultural Economics 12 (1), 11-21.

Bekchanov M., J.P.A. Lamers, C. Martius, 2010. Pros and Cons of Adopting Water-Wise Approaches in the Lower Reaches of the Amu Darya: A Socio-Economic View. Water, 2: 200-216. doi:10.3390/w2020200

Bekchanov M., A. Bhaduri, M. Lenzen, and J.P.A Lamers, 2012. The role of virtual water for sustainable economic restructuring: evidence from Uzbekistan, Central Asia. ZEF Discussion Paper, No. 167. Further Information: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2099172

Bekchanov M., M. Müller, and J.P.A. Lamers, 2012. A computable general equilibrium analysis of agricultural development reforms: national and regional perspective. In: Martius C, Rudenko I, Lamers JPA, Vlek PLG (eds) Cotton, water, salts and soums - economic and ecological restructuring in Khorezm, Uzbekistan. Springer: Dordrecht/Heidelberg/London/New York, pp 347-370

Bekchanov M. and A. Bhaduri, 2013. National tendencies and regional differences in small business development in Uzbekistan. Paper presented at IAMO Forum, 19-21 June, 2013, Halle, Germany.

Bekchanov M., A. Bhaduri, and C. Ringler, 2013a. How market-based water allocation can improve water use efficiency in the Aral Sea basin? ZEF Discussion Paper, No. 177.

Bekchanov M., A. Bhaduri, and C. Ringler, 2013b. Is Rogun a Silver bullet for water scarcity in Central Asia? In: Paswlowsky I. and M.N. Ahmad (Eds.), The Proceedings of the Young Researchers' Forum of the International Conference - Natural Resource Use in Central Asia: Institutional Challenges and the Contribution of Capacity Building, September 30 - October 1, 2013, Giessen, Germany, 33-36.

Bekchanov M., J. Lamers, and K. Beyjanov (forthcoming). Economic incentives for adopting irrigation innovations in arid environments. In: Lamers JPA, Khamzina A., Rudenko I, Vlek PLG (eds.): Restructuring land and water use in the lower Amudarya region: policies and practice.

Beyers W.B., 1976. Empirical identification of key sectors: some further evidence. Environ Planning A 8: 231-236. doi:10.1068/a080231

Bhaduri A., and E.B. Barbier, 2008. Linking Rivers in the Ganges-Brahmaputra River Basin Exploring the Transboundary Effects. In: Amarasinghe, U.A., Sharma, B.R. (eds.): Strategic analyses of the National River Linking Project Series 2. Intenational Water Management Institute, 373-395.

Bharadwaj K.R., 1966. A note on structural interdependence and the concept of a key sector. Kyklos 19: 315-319

Bobojonov I., J.P.A. Lamers, M. Bekchanov, N. Djanibekov, J. Franz-Vasdeki, , J. Ruzimov, and C. Martius, 2013. Options and constraints for crop diversification: A case study in sustainable agriculture in Uzbekistan. Agroecology and Sustainable Food Systems. doi: 10.1080/21683565.2013.775539

Bobojonov I., J.P.A. Lamers, N. Djanibekov, N. Ibragimov, T. Begdullaeva, A. Ergashev, K. Kienzler, R. Eshchanov, A. Rakhimov, J. Ruzimov, and C. Martius, 2012. Crop diversification in support of sustainable agriculture in Khorezm. In: Martius C, Rudenko I, Lamers JPA, Vlek PLG (eds) Cotton, water, salts and soums - economic and ecological restructuring in Khorezm, Uzbekistan. Springer, Dordrecht/Heidelberg/London/New York, pp 219-233

Bobojonov I. and J.P.A. Lamers, 2008. Analysis of agricultural markets in Khorezm, Uzbekistan. In: Wehrheim P, Shoeller-Schletter A, Martius C (eds) Continuity and Change: land and water use reforms in rural Uzbekistan. Socio-ecnomic and legal analyses for the region Khorezm. IAMO, Halle/Saale, pp 165-182

Bobojonov I., 2008. Modelling Crop and Water Allocation under Uncertainty in Irrigated Agriculture: A Case Study on the Khorezm Region, Uzbekistan. Dissertation, ZEF/Bonn University

Bobojonov I., J.P.A. Lamers, M. Bekchanov, N. Djanibekov, J. Franz-Vasdeki, J. Ruzimov, and C. Martius, 2013. Options and Constraints for Crop Diversification: A Case Study in Sustainable Agriculture in Uzbekistan. Agroecology and Sustainable Food Systems , 37(7), 788-811.

Booker J.F. and R.A. Young, 1994. Modeling intrastate and interstate markets for Colorado river water resources. Journal of Evironmental Economics and Management 26(1): 66-87.

Booker J.F., A.M. Michelsen, F.A. Ward, 2005. Economic impact of alternative policy responces to prolonged and severe drought in the Rio Grande Basin. Water Resources Research 41, W02026, doi:10.1029/2004WR003486.

Brander L.M., R.J.G. Florax, and J.E. Vermaat, 2006. The Empirics of Wetland Valuation: A Comprehensive Summary and a Meta-Analysis of the Literature. Environmental & Resource Economics, 33, 223–250. DOI 10.1007/s10640-005-3104-4

von Braun J., R.V. Hill, and R. Pandya-Lorch, 2009. The poorest and hungry: a synthesis of analyses and actions. In J. von Braun, R.V. Hill, R. Pandya Lorch (eds.). The Poorest and Hungry: Assessments, Analyses and Actions, Washington, D.C.: International Food Policy Research Institute, pp. 1-61.

von Braun J., 2009. Overcoming the World Food and Agriculture Crisis through Policy Change, Institutional Innovation, and Science. TAAS Foundation Day Lecture. New Delhi, March 6, 2009 http://www.taas.in/documents/fdl4_jvbraun.pdf

von Braun, J. 2008. The food crisis isn't over. Nature 456 (11 December): 701. http://dx.doi.org/10.1038/456701a

von Braun J. and E. Diaz-Bonilla (eds.), 2008. Globalization of Food and Agriculture and the Poor. New Delhi: Oxford University Press for IFPRI. http://www.ifpri.org/sites/default/files/publications/globalpoortoc.pdf

von Braun J., M.S. Swaminathan, and M.W. Rosegrant, 2003. Agriculture, Food Security, Nutrition and the Millennium Development Goals. New York: International Food Policy Research Institute (IFPRI).

von Braun J. and U. Grote. 2002. Does Decentralization Serve the Poor? In: Managing Fiscal Decentralization. Ed.: E. Ahmad, and V. Tanzi. London and New York: Routledge.

von Braun J., H. Bouis, and R. Pandya-Lorch, 1992. Improving Food Security of the Poor: Concept, Policy and Programmes. IFPRI, Washington.

Brooke, A., Kendrick, D., Meeruas, A., Raman, R., GAMS-User’s Guide. GAMS Development Corporation, Washington, D.C., 2006.

Brouwer R. and M. Hofkes, 2008. Integrated Hydro-Economic Modeling: Approaches, Key Issues and Future Research Directions, Ecological Economics 66, 16-22.

Brouwer R., M. Hofkes and V. Linderhof, 2008. General Equilibrium Modelling of the Direct and Indirect Economic Impacts of Water Quality Improvements in the Netherlands at National and River Basin Scale. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Brown T.C., 2006. Trends in Water Market Activity and Price in the Western United States. Water Resources Research, 42, 1-14.

Bryan J, Jones C, Munday M (2005) Investigating the potential of key sectors using multisectoral qualitative analysis: a Welsh case study. Environ Plann C 23(5): 633–656

Cai X. 1999. Modeling framework for sustainable water resources management. Unpublished Ph.D. dissertation, University of Texas at Austin.

Cai X., D. C. McKinney, and L. S. Lasdon (2002), A framework for sustainability analysis in water resources management and application to the Syr Darya Basin. Water Resources Resesarch, 38 , 6 , doi:10.1029/2001WR000214.

Cai X., McKinney, D., and Lasdon, L. (2003a). Integrated hydrologic-agronomic-economic model for river basin management. Journal of Water Resources Planning and Management 129 (1), pp. 4–17.

Cai X., D.C. McKinney, and M.W. Rosegrant (2003b). Sustainability analysis for irrigation water management in the Aral Sea region. Agricultural Systems, 76, 1043–1066

Cai X., C. Ringler, and M.W. Rosegrant, 2006. Modeling Water Resources Management at the Basin Level: Methodology and Application to the Maipo River Basin. IFPRI Research Report 146. IFPRI, Washington DC, US

Cai X., 2008. Implementation of Holistic Water Resources-Economic Optimization Models for River Basin Management – Reflective experiences, Environmental Modelling & Software, Vol. 23, 1, 2-18. doi:10.1016/j.envsoft.2007.03.005

Cai X., Y.E. Yang, J. Zhao, and C. Ringler, (2011), Can water allocation in the Yellow river basin be improved?: Insights from a multi-agent system model, No 1117, IFPRI discussion papers, International Food Policy Research Institute (IFPRI).

Cella G (1984) The Input-Output Measurement of Interindustry Linkages. Bull Oxford Univ Inst Econ Statist 46(1): 73-84

Center for Economic Research (CER), 2010. Addressing Urban Poverty in Uzbekistan in the Context of the Economic Crisis. Policy Brief. Tashkent, Uzbekistan.

Challen R., 2000. Institutions, Transaction Costs and Environmental Policy: Institutional Reform for Water Resources. Aldershot, UK: Edward Elgar, 2000, 233 pp.

Chapagain AK, Hoekstra AY, (2007) The water footprint of coffee and tea consumption in the Netherlands. Ecolog Econ 64(1): 109-118

Chapagain AK, Hoekstra AY (2004) Water footprints of nations. Value of Water Research Report Series No.16, Vol. 1, UNESCO-IHE, Delft, Netherlands

Chapagain AK, Hoekstra AY (2003) Virtual water flows between nations in relation to trade in livestock and livestock products. Value of Water Research Report Series No.13, UNESCO-IHE, Delft, Netherlands

Chembarisov E., 1996. Return flows of the Basin. Aral Herald: 1, 40-46 (in Russian).

Chenery H.B., Watanabe T (1958) Internatioinal comparisons of the structure of production. Econometrica 26: 487–521

Chenery H.B., 1960. Patterns of Industrial Growth. The American Economic Review, 50(4), 624-654

Chub V.E., 2000. Climate change and its impact on natural resources potential of the Republic of Uzbekistan. Main Administration on Hydrometeorology under the Cabinet of Ministers of the Republic of Uzbekistan/Central Asian Hydrometeorological Research Institute named after V.A. Bugayev, Tashkent, Uzbekistan

Chub V.E., 2002. Climate change and its influence on the natural resource potential of the republic of Uzbekistan. Glavgidromet, Tashkent (in Russian).

Chub V.E., 2007. Climate change and its impact on hydrometeorological processes, agro-climatic and water resources of the Republic of Uzbekistan. Center for Hydro-meteorological Service under the Cabinet of

Ministers of the Republic of Uzbekistan (Uzhydromet) / Scientific and Research Hydro-meteorological Institute (NIGMI), Tashkent, Uzbekistan

Clark C., 1940 (revised and reprinted in 1951). The Conditions of Economic Progress. MacMillan & Co. Ltd., London

CLG (Communities and local government), 2009. Multi-criteria analysis: a manual. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7612/1132618.pdf (accessed on 03.02.2013)

Coase R.H., 1937. The Nature of the Firm. Economica, , 4, 386-405.

Coase R.H., 1960. The Problem of Social Cost. Journal of Law and Economics, 3, 1-44.

Colby B.G., 1990a. Enhancing instream flow benefits in an era of water marketing. Water Resources Research 26 (6), 1113–1120.

Colby B.G., 1990b. Transaction costs and efficiency in western water allocation. American Journal of Agricultural Economics, 72, 1184-1192

CRIIWRM (Central Research Institute of Integrated Water Resources Management – Sentralniy Nauchno-Issledovatelskiy Institut Kompleksnogo Ispolzovaniya Vodnih Resursov), 1980. Aggregated norms of water use and discharge in animal husbandry and in rural settlements with centralized water sewage system. CRIIWRM, Minsk

Daniels P. L., M. Lenzen, and S. J. Kenway, 2011. The ins and outs of water use - a review of multi-region input-output analysis and water footprints for regional sustainability analysis and policy. Econ. Syst. Res., 23 (4), 353–370.

Demsetz H., 1967. Toward a theory of property rights. American Economic Review, 57, 347-359.

Diao X. and T. Roe, 2003. Can a water market avert the “double-whammy” of trade reform and lead to a “win-win” outcome? Journal of Environmental Economics and Management 45, 708–723.

Sehring J. and A. Diebold, 2012. Water Unites: From the Glaciers to the Aral Sea. Trescher Verlag, Berlin, 2012.

Dietzenbacher E., 1997. In vindication of the Ghosh model: a reinterpretation as a price model. J Reg Sci 37: 629–651

Dietzenbacher E. and E. Velázquez, 2007. Analysing Andalusian Virtual Water Trade in an Input-Output Framework. Regional Studies, 41 (2): 185-196

Dinar A., 2003. The Political Economy Context of Water Pricing Reforms. In: P. Koundouri, P. Pashardes, T.M. Swanson, A. Xepapadeas, The Economics of Water Management in Developing Countries (pp. 15- 40). UK: Edward Elgar Publishing, Inc.

Dinar A., M.W. Rosegrant, and R. Meinzen-Dick, 1997. Water allocation mechanisms. World Bank: Policy Research Working Paper No. 1779, Washington, DC.

Dinar A. and A. Wolf, 1994. International Markets for Water and the Potential for Regional Cooperation: Economic and Political Perspectives in the Western Middle East. Economic Development and Cultural Change.Vol.43 #1.

Djanibekov N. 2008. A Micro-Economic Analysis of Farm Restructuring in Khorezm Region (Uzbekistan). PhD Dissertation, Bonn University.

Doorenbos J. and A.H. Kassam, 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33. Rome, FAO.

Draper A.J., Jenkins, M.W., Kirby, K.W., Lund, J.R., Howitt, R.E., 2003. Economic Engineering Optimization for California Water Management. Journal of Water Resources Planning and Management, 129 (3), 155–164.

Duarte R. and H. Yang (eds), 2011. Special Issue: Input-Output and Water: Introduction to Special Issue. Economic Systems Research, 23(4): 341-351

Dublin Conference (DC), 1992. Dublin Statement on water and sustainable development. International conference on water and the Environment, Dublin.

Dudu H. and S. Chumi, 2008. Economics of Irrigation Water Management: A Literature Survey with Focus on Partial and General Equilibrium Models. Policy Research Working Paper 4556. World Bank, Washington D.C.

Dukhovny V. and V. Sokolov, 2000. Strategy of water resources management in Central Asia. In: Umarov U. and Karimov A.H. (eds.), Water Resources, Problems of the Aral Sea ad Environment. Tashkent, Universitet, 121-151 (in Russian).

Dukhovny V.A., 2007. Water and globalization: case study of Central Asia. Irrigation and Drainage, 56(5), 489–507. DOI: 10.1002/ird.327

Dukhovny V.A., A.G. Sorokin, and G.V. Stulina, 2008. Should we think about adaptation to climate change in Central Asia? Tashkent: CAREWIB, 2008. Available online at: www.cawater-info.net/library/eng/adaptation_climate_en.pdf (accessed on 20.07.2011)

Dukhovny V.A. and J.L.G. de Schutter , 2011. Water in Central Asia: Past, Present, Future. Taylor and Francis, London.

Dupuit J., 1844. De la mesure de l’utilité des travaux publics. Annales des Ponts et Chaussées, Memoirs et Documents 8 (2), 332–375.

Dziegielewska D., T. Tietenberg, S.S. Niggol , 2009. Total economic value. In: Encyclopedia of Earth. Eds. C.J. Cleveland. Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment. Available online at: January 7, 2013 http://www.eoearth.org/article/Total_economic_value (accessed on 07.01.2013)

Easter K.W., M.W. Rosegrant, and A. Dinar, (Eds.), 1998. Markets for water: Potential and performance. Boston: Kluwer.

Easter K.W., M.W Rosegrant, and A. Dinar. 1999. Formal and informal markets for water: Institutions, performance and constraints. World Bank Research Observer 14 (1): 99–116.

Easterly W., 2001. The Elusive Quest for Growth: Economists Adventures and Misadventures in the Tropics. Cambridge: MIT Press.

European Comission (EC), 2008. Guide to cost-benefit analysis of investment projects. Available online at: http://ec.europa.eu/regional_policy/sources/docgener/guides/cost/guide2008_en.pdf (accessed on 03.02.2012)

European Comission (EC), 2000. Directive of the European Parliament and of the Council 2000/60/EC establishing a framework for Community action in the field of water policy. Official Journal L 327, 22/12/2000. pp. 1-73.

Ekins P., 2000. Economic growth and environmental sustainability: the prospects for green growth. Routledge, Landon/New York

Eshchanov B.R., M.G.P. Stultjes, S.K. Salaev, R.A. Eshchanov, 2011. Rogun Dam—Path to Energy Independence or Security Threat? Sustainability 3(9): 1573-1592

Falkenmark M. and J.Rockström, 2004. Balancing water for humans and nature: The new approach in ecohydrology, Earthscan, London, UK.

FAO, 2013. AQUASTAT (online database). Irrigated lands across the countries grouped by income level. Available online at: http://www.fao.org/nr/water/aquastat/data/query/results.html (Last accessed on 02.03.2013)

Feng K., A. Chapagain, S. Suh, S.Pfister, K. Hubacek, 2011a. Comparison of Bottom-Up and Top-Down Approaches to Calculating the Water Footprints of Nations. Econ Systems Res 23 (4): 371-385. DOI: 10.1080/09535314.2011.638276

Feng K., K. Hubacek, J. Minx, Y.L. Siu, A. Chapagain, Y. Yu, D. Guan, and J. Barrett, 2011b. Spatially Explicit Analysis of Water Footprints in the UK. Water, 3(1): 47-63

Foran B., Lenzen M., Dey C., Bilek M., 2005. Integrating Sustainable Chain Management with Triple Bottom Line Reporting. Ecological Economics 52: 143-157

Fourastié J., 1949. Le Grand Espoir du XXe Siècle. Paris: Presses Universitaires de France. Reprinted as ‘Moderne Techniek en Economische Ontwikkeling’ (1965). Het Spectrum, Amsterdam

Gallego B. and M. Lenzen, 2005. A consistent input-output formulation of shared producer and consumer responsibility. Economic Systems Research, 17(4): 365-391

Garrick D., C. Lane-Miller and A.L. McCoy, 2011. Institutional Innovations for Governing Environmental Water in the Western U.S., Economic Papers, 30 (2), 167–84.

Ghosh A., 1958. Input-Output Approach in an Allocation System. Economica 25: 58-64

Gisser M. and A. Mercado, 1972. Integration of the agricultural demand function for water and the hydrologic model of the Pecos basin. Water Resources Research 8 (6), 1373–1384.

Glantz M.H. (ed), 1999. Creeping Environmental Problemsand Sustainable Development in the Aral Sea Basin. Cambridge University Press, Cambridge, UK

Glazovsky N.F., 1990. The Aral crisis: Causes and ways of solution. Moscow, Nauka, pp. 134 (in Russian).

Gleick P. H., 1996. Water resources. In Encyclopedia of Climate and Weather, ed. by S. H. Schneider, Oxford University Press, New York, vol. 2, pp. 817-823.

Gleick P. H., 2003. Global Freshwater Resources: Soft-Path Solutions for the 21st Century. Science, 302(5650), 1524-1528.

Global Environment Facility (GEF), 2002. Water and environmental management project: Subcomponent A1, Regional report No. 2. GEF Agency of the IFAS Aral Sea Basin Program, Tashkent, Uzbekistan.

Global Environment Facility (GEF), 2003. Water and Environmental Project. Regional report No 3. GEF Agency of the IFAS Aral Sea Basin Program, Tashkent, Uzbekistan.

Golan A., Judge G., and D. Miller, 1996. Maximum entropy econometrics: robust estimation with limiteddata. John Wiley & Sons, Chichester, UK

Grafton Q., C. Landry, G. Libecap, S. McGlennon, B. O’Brien, 2010. An Integrated Assessment of Water Markets: Australia, Chile, China, South Africa and the USA. CWEEP Research Paper 10-09.

Green G.P. and J.P. O'Connor, 2001. Water Banking and Restoration of Endangered Species Habitat: An Application to the Snake River. Contemporary Economic Policy, 19(2), 225-237.

Greene W.H., 2003. Econometric Analysis, fifth edition. New York.

Griffin R.C., 2006. Water Resource Economics: The Analysis of Scarcity, Policies and Projects. The MIT Press Cambridge, Massachusetts.

Griffin R.C., and S.-H. Hsu, 1993. The potential for water market efficiency when instream flows have value. American Journal of Agricultural Economics 75 (May 1993), 292–303.

Hardin G., 1968. The Tragedy of the Commons. Science, 162 (3859), 1243–1248. doi:10.1126/science.162.3859.1243

Harou J. J., M. Pulido-Velazquez, D.E. Rosenberg, J. Medellín-Azuara, J.R. Lund, and R.E. Howitt, 2009. Hydro-Economic Models: Concepts, Design, Applications, and Future Prospects. Journal of Hydrology 375 (2009) 627–643

Hartman L.M., and D. Seastone. 1970. Water Transfers: Economic Efficiency and Alternative Institutions. Baltimore, Maryland: Resources for the Future, Johns Hopkins Press.

Hazari B.R., 1970. Empirical Identification of Key Sectors in the Indian Economy. Rev Econ Statist 52 (3): 301-305

Hearne R. and K.W. Easter, 1995. Water Allocation and Water Markets: An Analysis of Gains-From-Trade in Chile. Technical Paper No. 315, World Bank, Washington, DC.

Heaven S., G. B. Koloskov, A.C. Lock, T.W. Tanton, 2002. Water Resources Management in the Aral Basin: A River Basin Management Model for the Syr Darya. Irrigation and Drainage, 51(2):109-118.

Heerden J.V., J. Blignaut, J.M. Horridge, 2008. Integrated water and economic modelling of the impacts of water market instruments on the South African economy. Ecological Economics, 66(1), 105-116.

Heidecke C. and T. Heckelei, 2010. The impact of water pricing in an arid river basin in Morocco considering the conjunctive use of ground- and surface water, water quality aspects and climate change. Paper presented at the Conference of the Global Catchment Initiative (GCI) on the Global Dimensions of Change in River Basins, 6-8 December 2010, Bonn, Germany. 85-89.

Heidecke C., A. Kuhn, and S.Klose, 2008. Water pricing options for the Middle Drâa River Basin in Morocco. African Journal of Agricultural and Resource Economics 2(2), 170-187.

Heinz I., M. Pulido-Velazquez, J.R. Lund, J. Andreu, 2007. Hydro-economic modeling in river basin management: implications and applications for the European water framework directive. Water Resources Management 21 (7), 1103–1125.

Hewings G.J.D., 1982. The Empirical Identification of Key Sectors in an Economy: A Regional Perspective, The Developing Economies 20: 173-195

Hirschman A.O., 1958. The Strategy of Economic Development. Yale University Press, New Haven, CT, USA

Hoekstra A.Y., H.H.G. Savenije, and A.K. Chapagain, 2001. An Integrated Approach towards Assessing the Value of Water: A Case Study on the Zambezi Basin. Integrated Assessment, 2, 199-208.

Holden P. and M. Thobani, 1995. Tradable Water Rights: A Property Rights Approach to Improving Water Use and Promoting Investment, Latin American Journal of Economics - formerly Cuadernos de Economía, Instituto de Economía. Pontificia Universidad Católica de Chile., 32(97), 263-290.

Howe C.W. and D.V. Orr, 1974. Effects of agricultural acreage reallocation on water availability and salinity in the upper Colorado river. Water Resources Research, 10(5):893–897.

Howe C.W., D.R Schurmeier., and W.D. Shaw, 1986. Innovative Approaches to Water Allocation: The Potential for Water Markets. Water Resources Research, 22(4), 439-445.

Howitt R.E., 1994. Empirical Analysis of Water Market Institutions: The 1991 California Water Market. Resource and Energy Economics, 16, 357-371.

ILA (International Law Association), 1966. The Helsinki Rules on the Uses of the Waters of International Rivers (Helsinki Rules), International Law Association.

International Fund for Saving the Aral Sea (IFAS), 2003. Program of concrete actions on improvement of environmental and socio-economic situation in the Aral Sea Basin for the period of 2003-2010. Dushanbe, Tadzhikistan.

INTAS, 2006. Final report: The rehabilitation of the ecosystem and bioproductivity of the Aral Sea under conditions of water scarcity. Tashkent, INTAS Project-0511 REBASOWS.

INTAS, 2001. Assessment of the Social-Economic Damage under the Influence of the Aral Sea Level Lowering for South Aral Sea Coast. INTAS Project-1733, Tashkent.

INTAS, 2004. Economical assessment of joint and local measures for the reduction of socio-economic damage in the coastal zone of Aral Sea. INTAS 1059, Tashkent.

IPCC (Intergovernmental Panel on Climate Change), 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones L.P., 1976. The Measurement of Hirschman Linkages. Quart J Econ 90(2): 323-333

Jonkman S.N., M. Bochkarjova, M. Kok and P. Bernardini, 2008. Integrated Hydrodynamic and Economic Modelling of Flood Damage in the Netherlands, Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Kadouri M.T., Y. Djebbar, M. Nehdi, 2001. Water rights and water trade: an Islamic perspective. In: Faruqui NI, Biswas AK, Bino MJ (eds), Water Management in Islam. United Nations University, Tokio/New York/Paris.

Karimov A., V. Smakhtin, A. Mavlonov, I. Gracheva, 2010. Water 'banking' in Fergana valley aquifers—A solution to water allocation in the Syrdarya river basin? Agricultural Water Management, 97, 1461-1468.

Keller A., J. Keller, D. Seckler, 1996. Integrated Water Resource Systems: Theory and Policy Implications.Research Report 3. Colombo, Sri Lanka: IIMI

Keller A., and J. Keller, 1995. Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources. Water Resources and Irrigation Division (Discussion Paper 22). Arlington, Virginia, USA: Winrock International

Kenney D.S., 2005, Prior appropriation and water rights reform in the western United States. In: Bruns, B.R., Ringler, C. and Meinzen-Dick, R. (eds) Water Rights Reform: Lessons for Institutional Design. International Food Policy Research Institute, Washington, DC, pp. 167‑182.

Kenzheguzin M.B. and B.K. Yessekina, 2004. Methodological Basis of Forecasting of Sustainable Development of Economic System. Mathematics and Computers in Simulation, 67 (2004), 343–349.

Khamraev N., 1996a. Water resources of Central and South Asia: scenarios for cooperative use. Tashkent, FAN (in Russian).

Khamraev N., 1996b. Water balance structure and its estimation. Aral Herald: 1, 2-4 (in Russian).

Khamraev N., 1998. Problems and perspectives of sustainable development of water management in the countries of the Aral Sea basin. Tashkent, UNDP (in Russian).

Kuhn A. and T. Britz, 2012. Can hydro-economic river basin models simulate water shadow prices under asymmetric access? Water Science & Technology, 66(4), 879-886. doi:10.2166/wst.2012.251

Kyle S. and P. Chabot, 1997. Agriculture in the Republic of Karakalpakstan and Khorezm Oblast of Uzbekistan. Working Paper No 97-13. Ithaca, N.Y.: Cornell University Department of Agricultural, Resource, and Managerial Economics.

Landsburg S.E., 1993. The armchair economist: economics and everyday life. New York, Free Press.

LC (The Library of Congress), 2012. Country studies. The profile of Kyrgyzstan. Available online at: http://lcweb2.loc.gov/frd/cs/profiles/Kyrgyzstan.pdf (accessed on 02.09.2012)

Lee D.J., and A. Dinar, 1996. Integrated Models of River Basin Planning, Development, and Management. Water International, 2, 4, 213-222.

Lee H.L., T.W. Hertel, S. Rose, and M. Avetisyan, 2009. An integrated global land use data base for CGE analysis of climate policy options. In: Hertel T.W., S. Rose, and R.S.J. Tol (Eds.), Economic Analysis of Land Use in Global Climate Change Policy. Abingdon: Routledge, 2009.

Lefkoff L.J., and S.M. Gorelick 1990. Benefits of an irrigation water rental market in a saline stream-aquifer system. Water Resources Research. vol. 26, no. 7, p. 1371-1381.

Lenzen M. and B. Foran, 2001. An input–output analysis of Australian water usage. Water Policy 3: 321-340

Lenzen M., 2003. Environmentally important paths, linkages and key sectors in the Australian economy. Struct Change Econ Dynam 14(1): 1–34

Lenzen M., 2009. Understanding virtual water flows: A multiregion input-output case study of Victoria. Water Resources Research 45, W09416, doi:10.1029/2008wr007649

Lenzen M., A. Bhaduri, D. Moran, K. Kanemoto, M. Bekchanov, A. Geschke, B.D. Foran, 2012. The role of scarcity in global virtual water flows. ZEF - Discussion Papers on Development Policy No. 169. Center for Development Research, Bonn, 24.
Further Information: www.zef.de/fileadmin/webfiles/downloads/zef_dp/zef_dp_169.pdf

Leontief W., 1951. The structure of the American economy. Second edition. University Press, New York / Oxford

Leontief W., 1936. Quantitative Input-output relations in Economic System of the United States. Input-output economics. Rev Econ Statist 18: 105-125

Levintanus A., 1992. Saving the Aral Sea. International Journal of Water Resources Development, 8 (1), pp. 60-64.

Lewis W. A., 1954. Economic Development with Unlimited Supplies of Labour. Manchester Sch. Econ. Soc. Stud., 22, 139- 91.

Libecap G.D., 2010. Water Rights and Markets in the U.S. Semi Arid West: Efficiency and Equity Issues, ICER Working Papers 30-2010, ICER - International Centre for Economic Research.

Lund J.R., R.E. Howitt, J. Medellin-Azuara, M.W. Jenkins, 2012. Statewide Economic-Engineering Water Model – CALVIN. Available online: http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/ (accessed on 12.12.2012)

Lund J.R., X. Cai, and G.W. Characklis, 2006. Economic engineering of environmental and water resource systems. Journal of Water Resources Planning and Management 132 (6), 399–402.

Maass A., M. Hufschmidt, R. Dorfman, H. Thomas, S. Marglin, and G. Fair, 1962. Design of Water-Resources Systems, Harvard University Press: Cambridge, Massachusetts.

Mainguet M. and L. Rene, 2001. Water Problems in Central Asia – Gigantomania Should be Replaced by Small Projects. In: Adeel Zafar ed., New Approaches to Water Management in Central Asia, United Nations University, Tokyo, 19-26.

Mansimov M., 1995. New data on lakes of Turkmenistan from the space surveys data. Problems of Desert Development, 3, 64-67.

Markard J., R. Raven, and B. Truffer, 2012. Sustainability transitions: an emerging field of research and its prospects. Research Policy, 41, 955–967.

Martius C., J. Froebrich, E.-A. Nuppenau, 2009. Water Resource Management for Improving Environmental Security and Rural Livelihoods in the Irrigated Amu Darya Lowlands. In: Hans Gunter Brauch, Ursula Oswald Spring, John Grin, Czeslaw Mesjasz, Patricia Kameri-Mbote, Navnita Chadha Behera, Bechir Chourou, Heinz Krummenacher (Eds.): Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts. Hexagon Series on Human and Environmental Security and Peace, Vol. 4 (Berlin – Heidelberg – New York: Springer-Verlag), 749-762.

Mayer A., and A. Muñoz-Hernandez, 2009.Integrated Water Resources Optimization Models: An Assessment of a Multidisciplinary Tool for Sustainable Water Resources Management Strategies. Geography Compass, Vol. 3, 3, 1176–1195. doi: 10.1111/j.1749-8198.2009.00239.x

McCann L. and K.W. Easter, 2004. A framework for estimating the transaction costs of alternative mechanisms for water exchange and allocation. Water Resources Research , 40 , W09S09, doi:10.1029/2003WR002830

McCann L., B. Colby, K.W. Easter, A. Kasterine, and K.V. Kuperan, 2005. Transaction cost measurement for evaluating environmental policies. Ecological Economics, 52(4), 527-542, doi: 10.1016/j.ecolecon.2004.08.002.

McKinley T., 2008. Uzbekistan: From Import Substitution to Export Boom. In: Development Digest: The Resource Curse. Centre for Development Policy and Research, pp 12-13.

McKinney D.C., and A. Karimov, 1997. Report on Model Development: Aral Sea Regional Allocation Model for the Amudarya. USAID.

McKinney D.C., X. Cai, M.W. Rosegrant, C. Ringler, and C.A. Scott, 1999. Modeling Water Resources Management at the Basin Level: Review and Future Directions. Colombo, Sri Lanka: IWMI. ix, 59p. (SWIM paper 6).

McKinney D.C., and A.G. Savitsky, 2001a. EPIC Modeling System Guided Water, Salt and Energy Management Problems. Available from: http://www.ce.utexas.edu/prof/mckinney/papers/aral/EPIC/EPICmodel.html (accessed on 10.08.2010)

McKinney D.C., and A.G. Savitsky, 2001b. EPIC Modeling Software. Available from: http://www.ce.utexas.edu/prof/mckinney/papers/aral/EPIC/EPICmodel.html (accessed on 10.08.2010)

McKinney D.C., 2004. Cooperative management of transboundary water resources in Central Asia. In: D. Burghart and T. Sabonis-Helf (eds), In the Tracks of Tamerlane: Central Asia's Path to the 21st Century. Washington, DC: National Defense University, 187‑220.

Medvedev A., no date. The history of transboundary water resources use problems in Central Asia and the role of international partners to solve them (in Russian). Available online at: http://ia-centr.ru/expert/8982/ (accessed on 28.07.2011)

Mekonnen M.M., A.Y. Hoekstra, 2010. The green, blue and grey water footprint of farm animals and animal products. Value of water research report series No. 48, UNESCO-IHE, Delft, Netherlands

de Mesnard L., 2009. Is the Ghosh model interesting? J Reg Sci 49 (2): 361-372

Micklin P., 1988. Desiccation of the Aral Sea: A water management disaster in the Soviet Union. Science, vol. 241, 1170-1176.

Micklin P., 1992. The Aral Crisis: Introduction to Special Issue. Post-Soviet Geography, 33(5), 269-282.

Micklin P., 2000. Managing Water in Central Asia. London, Royal Institute of International Affairs.

Micklin P., 2007. The Aral Sea Disaster. Annu. Rev. Earth Planet. Sci., 35, 47-72. Available online at: http://www.annualreviews.org/doi/pdf/10.1146/annurev.earth.35.031306.140120 (accessed on 28.07.2011)

Micklin P., 2010. The past, present, and future of the Aral Sea. Lakes & Reservoirs: Research & Management. 15(3), 193–213, Available online at: http://onlinelibrary.wiley.com/doi/10.1111/j.1440-1770.2010.00437.x/abstract (accessed on 29.07.2011).

Micklin P., 2011. The Siberian Water Transfer Scheme. In: Engineering Earth: The Impacts of Megaengineering Projects (ed S. D. Brunn), Springer Science+Business Media, Dordrecht. 1515-1530.

Midmore P., M. Munda, A. Roberts, 2006. Assessing Industry Linkages Using Regional Input-Output Tables. Regional Studies, 40(3): 329-343

Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Desertification synthesis. World Resources Institute, Washington DC, US

Miller R.E. and M.L. Lahr, 2001. A taxonomy of extractions. In: Lahr ML and Miller RE (eds), Regional Science Perspectives in Economics: A Festschrift in Memory of Benjamin H. Stevens. Amsterdam: Elsevier Science, pp 407–441

Mirchi A., D.W.Jr.Watkins, and K. Madani, 2010. Modeling for Watershed Planning, Management, and Decision Making. In: Vaughn J. C. (Ed.), Watersheds: Management, Restoration and Environmental Impact, Nova Science Publishers.

Mirzaev S.Sh., 2000. Main institutions of managing water resources in the Aral Sea basin (ASB). In: Umarov U. and Karimov A.H. (eds.), Water Resources, Problems of the Aral Sea ad Environment. Tashkent, Universitet, 308-331 (in Russian).

Mirzaev S.Sh. and H.I. Valiev, 2000. Main principles of saving the Aral Sea and restoring ecological balance in its basin. In: Umarov U. and Karimov A.H. (eds.), Water Resources, Problems of the Aral Sea ad Environment. Tashkent, Universitet, 99-120 (in Russian).

Mirzaev S.Sh. and N.R. Khamraev, 2000. The fate of the rivers and the water depressions of irrigation zones. In: Umarov U. and Karimov A.H. (eds.), Water Resources, Problems of the Aral Sea ad Environment. Tashkent, Universitet, 357-363 (in Russian).

Morozov A.N., no date. What are the reasons for that the Aral Sea problem have not been solved yet? (in Russian). Available online at: http://water-salt.narod.ru/site_en/prob_ca_en.htm (accessed on 10.07.2011)

Mukherjee N., 1996. Water and Land in South Africa: Economywide Impacts of Reform – A Case Study for the Olifants River. Trade and Macroeconomics Division (TMD) Discussion Paper No. 12. International Food Policy Research Institute, Washington, DC.

Müller M., 2006. A General Equilibrium Analysis of Water and Land Use in Uzbekitan. PhD Dissertation, Bonn University. Bonn, Germany.

Müller M., 2008. Cotton, agriculture and the Uzbek government. In: Wehrheim, P., Schoeller-Schletter, A., Martius, C. (eds.): Continuity and change: land and water use reforms in rural Uzbekistan. Studies on the agricultural and food sector in Central and Eastern Europe, 43. Halle/Saale, Germany: Leibniz-Institut für Agrarentwicklung in Mittel- und Osteuropa, 183-203.

Nanni M., 1996. The Aral Sea basin: legal and institutional issues. Review of European Community and International Environmental Law, 5(2), 130-137.

North D.C., 1989. Institutions and economic growth: An historical introduction, World Development, 17(9), 1319-1332.

North D.C., 1990. Institutions, institutional change and economic performance. Cambridge University Press, New York, U.S.A., 159 p.

NPC (National Research Council), 1992. Water Transfers in the West: Efficiency, Equity, and the Environment. Washington, DC: The National Academies Press.

OECD, 2011. Competitiveness and Private Sector Development: Central Asia 2011 – Competitiveness Outlook, OECD Publishing. Available online at: http://dx.doi.org/10.1787/9789264097285-en (accessed on 24.01.2013)

O’Hara S. and T. Hannan, 1999. Irrigation and water management in Turkenistan: Past systems, present problems and future scenarios. Euro-Asian Studies, Vol. 51, 1, 21-42.

O’Hara S. and M. Gentile, 2009. Household Incomes in Central Asia: The Case of Post-Soviet Kazakhstan. Eurasian Geography and Economics, 50(3), 327-347.

Oosterhaven J., 1988. On the plausibility of the supply-driven input-output model. J Reg Sci 28: 203–217

Oosterhaven J., 1989. The supply-driven input-output model: a new interpretation but still implausible. Journal of Regional Sciences, 29, 459–465.

Oosterhaven J., 1996. Leontief versus Ghoshian price and quantity models. Southern Econ Journal, 62, 750–759

Oosterhaven J. and D. Stelder, 2002. Net multipliers avoid exaggerating impacts: with a bi-regional illustration for the Dutch transportation sector. J Reg Sci 42: 533–543.

Ostrom E., L. Schroeder, and S. Wynne, 1993. Institutional Incentives and Sustainable Development. Boulder: Westview Press.

Pasific Institute, 2009.Water conflict chronology list (Online database). Available online at: http://www.worldwater.org/conflict/list/ (accessed on 18.06.2011)

PA Consortiom Group and PA Consulting (2002). Transboundary water and related energy cooperation for the Aral Sea basin region of Central Asia. Washington, DC: USAID Regional mission for Central Asia Office of Energy and Water.

Pandya-Lorch R., and M.W. Rosegrant, 2000.Prospects for food demand and supply in Central Asia.Food Policy, vol. 25, 6, 637-646. Available from: http://www.sciencedirect.com/science/article/B6VCB-41S4ST1-2/2/ab5e057d4f2d9f0240cec8db59759869

Pauw E. de, 2007. Principal biomes of Central Asia. p.3-24 In Climate change and terrestrial carbon sequestration in Central Asia (R. Lal, M.Suleimenov, B.A Stewart, D.O. Hansen and P. Doraiswamy. eds). Taylor and Francis Group, New York, NY, USA.

Petrov G.N. and H.M. Ahmedov, 2011. Integrated use of water and energy resources in transboundary river basins of Central Asia: Present, problems, and solutions. Dushnabe, Donish.

Pimental D., J. Houser, E. Preiss, O. White, H. Fang, L. Mesnick, T. Barsky, S. Tariche, J. Schreck, S. Alpert, 1997. Water resources: Agriculture, the environment, and society, BioScience 47(2), 97-106.

Pujol J., J. Berbel, F. Ramírez-de-Cartagena, D. Viaggi, M. Raggi, 2006a. Evaluation of markets for irrigation water in the internal river basins of Catalonia, Spain. Span J Agric Res 4(1), 3-16.

Pujol J., M. Raggi, D. Viaggi, 2006b. The potential impact of markets for irrigation water in Italy and Spain: a comparison of two study areas. The Australian Journal of Agricultural and Resource Economics, 50, 361-380.

Purcell J. and A. Currey, 2003. Gaining Acceptance of Water Use Efficiency: Framework, Terms and Definitions.National Program for Sustainable Irrigation (NPSI).

Quinn N.W.T., L.D. Brekke, N.L. Miller, T. Heinzer, H. Hidalgo, J.A. Dracup, 2004. Model integration for assessing future hydroclimatic impacts on water resources, agricultural production and environmental quality in the San Joaquin Basin, California. Environmental Modeling and Software 19, 305–316.

Qureshi M.E., J. Connor, M. Kirby, M. Mainuddin, 2007. Economic assessment of environmental flows in the Murray Basin, Australian Journal of Agricultural and Resource Economics. 513: 283-303

Raskin P., E. Hansen, Z. Zhu, and D. Stavisky, 1992, Simulation of Water Supply and Demand in the Aral Sea Basin, Water International, 17, 55-67.

Rasmussen P.N., 1956. Studies in Intersectorial Relations. North-Holland, Amsterdam

Ringler C., 2001. Optimal Allocation and Use of Water Resources in the Mekong River Basin: Multi-country and Intersectoral Analyses. PhD Thesis. Frankfurt, Germany, Peter Lang

Ringler C., J. von Braun, M.W. Rosegrant, 2004. Water Policy Analysis for the Mekong River Basin. Water International, Vol. 29, 1, 30-42.

Ringler C. and X. Cai. 2006. Addressing the value of fisheries and wetlands using integrated economic-hydrologic modeling–A case study of the Mekong River Basin. Journal of Water Resources Planning and Management, 132(6), 399-525.

Ringler, C., Huy, N.V., 2004. Water Allocation Policies for the Dong Nai River Basin in Vietnam: An Integrated Perspective. EPTD Discussion Paper No. 127. International Food Policy Research Institute, Washington DC.

Ringler, C., N.V. Huy, and S. Msangi, 2006. Water Allocation Policy Modeling for the Dong Nai River Basin: an Integrated Perspective. JAWRA Journal of the American Water Resources Association, 42, 1465–1482. doi: 10.1111/j.1752-1688.2006.tb06014.x

Rizk J. and B. Utemuratov, 2012. Balancing the use of water resources in the Amu Darya basin. Policy Brief. Available online at: www.amudaryabasin.net (accessed on 30.08.2013)

Rogers P. and D.V. Smith, 1970. Integrated use of ground and surface water in irrigation project planning. American Journal of Agricultural Economics 52 (1), 13.

Rose A.Z. and S.-Y. Liao, 2005. Modelling Regional Economic Resilience to Disasters: a Computable General Equilibrium Analysis of Water Service Disruptions, Journal of Regional Science, 45, 1, 75–112.

Rosegrant M.W. and H.P. Binswanger, 1994. Markets in tradable water rights: Potential for efficiency gains in developing country water resource allocation. World development, 22 (11), 1613-1625.

Rosegrant M.W. and R. Gazmuri, 1995. Reforming Water Allocation Policy Through Markets in Tradable Water Rights: Lessons from Chile, Mexico and California. Latin American Journal of Economics - formerly Cuadernos de Economía, Instituto de Economía. Pontificia Universidad Católica de Chile., 32(97), 291-316.

Rosegrant M.W., 1997. Water Resources in the Twenty-First Century: Challenges and Implications for Action. Food, Agriculture, and the Environment Discussion Paper 20. International Food Policy Research Institute, Washington, D.C.

Rosegrant M., C. Ringler, D.C. McKinney, X. Cai, A. Keller, G. Donoso, 2000. Integrated economic-hydrologic water modeling at the basin scale: the Maipo river basin. Agricultural Economics (IAEA), 24 (1), 33-46.

Rosegrant M.W., X. Cai, S.A. Cline, 2002. World Water and Food to 2025: Dealing with Scarcity. IFPRI, Washington, D.C.

Rosegrant, M.W., T.B. Sulser, C. Ringler, S.A. Cline, and S. Msangi, 2005. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Distributed Version 1.0. Washington DC: IFPRI.

Rosenberg, D.M., R.A. Bodaly, and P.J. Usher, 1995. Environmental and social impacts of large scale hydroelectric development: who is listening? Global Environmental Change 5:127–148.

Roy B., 1991. The outranking approach and the foundations of electre methods. Theory and Decision. 31(1), 49-73.

Rudenko I., 2008. Value Chains for Rural and Regional Development: The Case of Cotton, Wheat, Fruit and Vegetable Value Chains in the Lower Reaches of the Amu Darya River, Usbekistan. PhD Dissertation, Bonn University. Bonn, Germany.

Rudenko I., J.P.A. Lamers, and U. Grote, 2009. Could Uzbek farmers get more for their cotton? European Journal of Development Research, 21(2): 283-296.

Rudenko I., K. Nurmetov, J.P.A. Lamers, 2012. State order and policy strategies in the cotton and wheat value chains. In: Martius C, Rudenko I, Lamers JPA, Vlek PLG (eds) Cotton, water, salts and Soums: economic and ecological restructuring in Khorezm, Uzbekistan. Springer, Dordrech/Berlin/Heidelberg/New York, pp. 371-388.

Rudenko, I., M. Bekchanov, U. Djanibekov and J.P.A. Lamers, 2013. The added value of a water footprint approach: micro- and macroeconomic analysis of cotton production, processing and export in water bound Uzbekistan. Further information: http://dx.doi.org/10.1016/j.gloplacha.2013.09.007.

Ruziev M.T. and V.G. Pikhodko, 2007. Implementation of the Aral Sea basin socioeconomic model: An assessment of the opportunities to be gained through regional economic integration. In: Implementing Integrated Water Resources Management in Central Asia, Patricia Wouters, Victor Dukhovny and Andrew Allan (Eds.). NATO Sciece Series, Vol. 77, 2007, doi: 10.1007/978-1-4020-5732-8

Saaty T.L., 1980. Analytic Hierarchy Process. McGraw-Hill, New York.

Sachs J., 2005. The End of Poverty: How we can make it in our lifetime. Penguin Books, England, London.

Sala R., 2003. Historical Survey of Irrigation Practices in West Central Asia. Research report. Institute of Archaeology ACD KZ, Almaty, Kazakhstan. Available online at: http://www.lgakz.org/Texts/LiveTexts/7-CAsiaIrrigTextEn.pdf (accessed on 23.11.2012)

Saleth R.M., and Dinar, A., 2004. Water Institutions and Sector Performance: A Quantitative Analysis with Cross-Country Data. World Bank, Washington, DC.

SANIIRI (Central Asian Research Institute of Irrigation), 2004. Problems of integrated management, rational use, and protection of water resources in the Aral Sea basin. Project report. Tashkent, Uzbekistan, SANIIRI (in Russian).

Sarbaev T., 1996. On further development of irrigation in Kyrgyzstan. Herald: 1, 10-14 (in Russian).

Savitsky A.G., M. Schlüter, R.V. Taryannikova, N.A. Agaltseva, V.E. Chub, 2007. Current and future impacts of climate change on river runoff in the Central Asian river basins. In: Pahl-Wostl C, Kabat P, Moeltgen J (eds) Adaptive and integrated water management—coping with complexity and uncertainty. Springer, Berlin

Savoskul O.S., E.V. Chevnina, F.I. Perziger, L.Yu. Vasilina, V.L. Baburin, A.I. Danshin, B. Matyakubov, R.R. Murakaev, 2003. Water, Climate, Food, and Environment in the Syr Darya Basin. Contribution to the project ADAPT - Adaptation strategies to changing environments.

Schlüter M., A.G. Savitsky, D.C. McKinney, H. Lieth, 2005. Optimizing long-term water allocation in the Amudarya River delta: a water management model for ecological impact assessment. Environmental Modelling & Software, 20, 529-545.

Schlüter M., N. Rüger, A. Savistky, N. Novikova, M. Matthies, and H. Lieth, 2006. An integrated simulation tool for ecological assessment of alternative water management strategies in a degraded river delta. Environmental Management, 38, 638-653.

Schlüter M. and N. Rüger, 2007. Application of a GIS-based simulation tool to illustrate implications of uncertainties for water management in the Amudarya River delta. Environmental Modelling & Software, 22 (2), 158–166.

de Schutter J., 2008. Communicating the Issues of the Aral Sea Basin: Long-term Vision for the Aral Sea Basin, The Aral Sea Basin Management Model (ASB-MM); in Moerlins J.E., Khankhasayev M.K., Leitman S.F., Makhmudov E.J. (Eds.), Transboundary Water Resources: A Foundation for Regional Stability in Central Asia; NATO Security through Science Series, Springer, 2008, 29-42, DOI: 10.1007/978-1-4020-6736-5_2

Shiklomanov A. 2009. Hydrological change in the mountainous and downstream regions of Central Asia. Proceedings of the International Workshop on the Northern Eurasia High Mountain Ecosystems, Bishkek, Kyrgyzstan, September 8-15, 2009. Available at: http://www.neespi.org/meetings/Bishkek_2009.htm (accesed on 05.10.2012)

Shodiev O., 1996. Water resources use and protection in Tajikistan. Herald: 1, 29-30(in Russian).

SIC-ICWC (Scientific-Information Center of Interstate Comission for Water Coordination in the Aral Sea Basin), 2010. Chronology of water conflicts from 3000 BC to 2010. Tashkent.

Simonovich S., 2009. Managing Water Resources: Methods and Tools for a Systems Approach. UNESCO.

Smajgl A. and L. Liagre, 2010. Analysing implications of limited water availability for Great Barrier Reef catchments. Economic Systems Research, 22(3), 263-277.

Smith D.R., 1995. Environmental security and shared water resources in post-Soviet Central Asia. Post-Soviet Geography, 36(6), 351-370.

Sokolov V. and V. Dukhovny, 2002. Lessons On Co-Operation Building To Manage Water Conflicts in The Aral Sea Basin. Paper submitted for the PC-CP Project report: Case Studies, UNESCO.

Sonis M., J.J.M. Guilhoto, G.J.D. Hewings, E.B. Martins, 1995. Linkages, key sectors, and structural change: some new perspectives. Developing Economies 33: 233-270

Spoor M., 1993. Transition to Market Economies in Former Soviet Central Asia: Dependency, Cotton and Water. Working paper No 160. Haage, Netherlands. Available online at: http://publishing.eur.nl/ir/repub/asset/18862/wp160.pdf (accessed on 23.06.2011)

StataCorp, 2009. Stata Statistical Software: Release 11. College Station, TX: StataCorp LP.

State Construction Bureau (SEV and VNI VODGEO Gosstroya SSSR), 1978. Aggregated norms of water consumption and sewage in various sectors of industry. Stroyizdat, Moscow

Strassert G., 1968. Zur bestimmung strategischer sektoren mit hilfe von von input-output modellen. Jahrbucher fur National okonomie und Statistik 182: 211–215

Strzepek K.M., G.W. Yohe, R.S.J. Tol and M.R. Rosegrant, 2008. General Equilibrium Modelling of the Value of the High Aswan Dam to the Egyptian Economy, Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Sutton W., P. Whitford, E.M. Stephens, S.P. Galinato, B. Nevel, B. Plonka, E. Karamete, 2008. Integrating Environment into Agriculture and Forestry: Progress and Prospects in Eastern Europe and Central Asia. The World Bank, Washington DC, US

TEEB in Business, 2011. The Economics of Ecosystems and Biodiversity in Business. Edited by Joshua Bishop. Earthscan, London.

The Telegraph, 2010. Aral Sea 'one of the planet's worst environmental disasters'. Issue on 5 April 2010. Available online at: http://www.telegraph.co.uk/earth/earthnews/7554679/Aral-Sea-one-of-the-planets-worst-environmental-disasters.html (accessed on 13.04.2012)

Thomas V., M. Dailami, A. Dhareshwar, D. Kaufmann, N. Kishor, R. Lopez, Y. Wang, 2000. The Quality of Growth. Oxford University Press & World Bank, Oxford & New York.

Timirkhanov S., B. Chaikin, Z. Makhambetova, A. Thorpe, R. van Anrooy, 2010. Fisheries and aquaculture in the Republic of Kazakhstan: a review. FAO Fisheries and Aquaculture Circular. No. 1030/2. FAO, Rome, pp. 76.

UN (United Nations General Assembly), 1997. United Nations Convention on the Law of the Non-navigational Uses of International Watercourses. UN General Assembly in Resolution 51/229.

UN (United Nations General Assembly), 2000. Resolution 2, Session 55, United Nations Millenium Declaration, on 18 September 2000.

UN, 2010. Shrinking Aral Sea underscores need for urgent action on environment – Ban. News report on visit of UN Secretary-General Ban Ki-moon to the Aral Sea. Available online at: http://www.un.org/apps/news/story.asp?NewsID=34276 (accessed on 22.03.2011)

UNDESA 2010. Progress to date and remaining gaps in the implementation of the outcomes of the major summits in the area of sustainable development, as well as an analysis of the themes of the Conference. Preparatory Committee for the UNCSD, 17-20 May 2010.

UNDP RBEC (UNDP Regional Bureau for Europe and the Commonwealth of Independent States), 2005. Central Asia Human Development Report. Bringing down barriers: Regional cooperation for human development and human security. Bratislava, Slovak Republic. Available online at: http://europeandcis.undp.org/home/show/300BDC00-F203-1EE9-BE944F24EDFC09CE (accessed on 05.07.2011)

UNECE (United National Economic Commission for Europe), 1992. Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Helsinki Convention).

UNECE, 2011. Launch of a regional project on the afforestation of the dry bed of the Aral Sea. Media report. Available online at: http://www.unece.org/index.php?id=26725 (accessed on 19.10.2013)

UNEP, 2005. Severskiy, I., Chervanyov, I., Ponomarenko, Y., Novikova, N.M., Miagkov, S.V., Rautalahti, E. and D. Daler. Aral Sea, GIWA Regional assessment 24. University of Kalmar, Kalmar, Sweden.UNEP and ENVSEC, 2011. Environment and security in the Amu Darya basin. UNEP, Bresson, France.

UNESCAP (United Nations Economic and Social Comission for Asia and the Pacific), 2009. Eco-efficiency Indicators: Measuring Resource-use Efficiency and the Impact of Economic Activities on the Environment. Bangkok, Thailand. http://www.greengrowth.org (accessed on 05.01.2012)

UNESCO, 2000. Water related vision for the Aral Sea basin. For the year 2025. Paris, France.

UNSD, 2011. System of Environmental-Economic Accounting for Water. United Nations Statistics Division, New York, US. http://unstats.un.org/unsd/envaccounting/water.asp (accessed on 05.01.2012

UN WATER, 2007. World Water Day 2007: Coping With Water Scarcity.

SredAzGiproVodKhlopok, 1984. Correcting the scheme of complex use and protection of water resources in Amu Darya basin (KIOVR Amu – Master Plan for River Basin Management). Tashkent, Uzbekistan.

Valentini K.L., E.E. Orolbaev, and K.K. Abylgazieva, 2004. Water problems of Central Asia. Bishkek, Kyrgyzstan, 142 p.

Van Oel P.R., M.M. Mekonnen, A.Y. Hoekstra, 2009. The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment. Ecological Economics, 69(1), 82-92.

Vardon M., M. Lenzen, S. Peevor, M. Creaser, 2006. Water accounting in Australia. Ecological Economics, 61: 650-659.

Varis O. and M.M. Rhamanan, 2008. The Aral Sea keeps Drying Out but is Central Asia Short of Water? In Central Asian Waters; Rahaman, M.M., Varis, O., Eds.; Helsinki University of Technology: Helsinki, Finland.

Vaux H.J. and R.E. Howitt, 1984. Managing water scarcity: An evaluation of interregional transfers. Water Resources Research, 20, 785–792.

Velazquez E., 2006. An input–output model of water consumption: Analysing intersectoral water relationships in Andalusia. Ecological Economics, 56, 226–240.

Vinogradov S. and V.P.E. Langford, 2001. Managing transboundary water resources in the Aral Sea basin: In search of a solution. International Journal of Global Environmental Issues, 1, 345-362.

Vörösmarty C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), 'Global Water Resources: Vulnerability from Climate Change and Population Growth', Science, 289(5477), 284-288.

Voyejkov A.I., 1882. Russia's Rivers, Presentation at the Society of Fans of Natural sciences, Anthropology, and Ethnography.

Walter T., 2010. Analysis of Sectoral Water Demands and Optimal Water Allocation in the Middle Olifants Sub-Basin of South Africa: The Case of Mining and Irrigation. (PhD Dissertaion). Culliver Verlag, Göttingen.

Wang J.J., Y.Y. Jing, C.F. Zhang, J.H. Zhao, 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews, 13 (9), 2263–2278.

Wang Y., 2012. A simulation of water markets with transaction costs. Agricultural Water Management, 103, 54-61, doi: 10.1016/j.agwat.2011.10.017.

Ward F.A. and M. Pulido-Velázquez, 2008. Efficiency, equity, and sustainability in a holistic water quantity — quality optimization model in the Rio Grande basin, Ecological Economics Special Issue Integrated Hydro-Economic Modeling.

WB (World Bank), 1992. World Development Report 1992: Development and the Environment. Washington D.C.: World Bank

WB (World Bank), 1995. Interview with Serageldin I., The Vice President of the World Bank, cited in New York Times, August 10, 1995

WBGU (German Advisory Council on Global Change) (1998) Worlds in transition: Ways towards sustainable management of fresh water resources. Springer-Verlag, Berlin

WCED (World Commission on Environment and Development), 1987. Our Common Future. Oxford University Press, Oxford.

Webb P. and M. Iskandarani (1998), Water Insecurity and the Poor: Issues and Research Needs. ZEF Discussion Paper, No. 2. Center for Development Research, Universitat Bonn, Bonn.

WEF (World Economic Forum), 2008. Annual Report 2007-2008. Available online at: http://www3.weforum.org/docs/WEF_AnnualReport_2007-08.pdf (accessed on 23.04.2012)

WEF (World Economic Forum), 2009. The Bubble Is Close to Bursting: A Forecast of the Main Economic and Geopolitical Water Issues Likely to Arise in the World during the Next Two Decades. Draft for Discussion at the World Economic Forum Annual Meeting 2009. Available online at: http://www3.weforum.org/docs/WEF_ManagingFutureWater%20Needs_DiscussionDocument_2009.pdf (accessed on 23.04.2012)

Wegerich K., 2010. Handing over the sunset: External factors influencing the establishment of water user associations in Uzbekistan: Evidence from Khorezm Province. Göttingen: CuvillierVerlag.

Wehrheim P., 2003. Modeling Russia's Economy in Transition. Ashgate Publishers, Aldershot, p. 200.

Weinthal E., 2002. State Making and Environmental Cooperation: Linking Domestic and International Politics in Central Asia. Cambridge, MA: MIT Press, 2002. pp. 274.

White D., F. Wester, A. Huber-Lee, C.T. Hoanh and F. Gichuki, 2008. Water Benefits Sharing for Poverty Alleviation and Conflict Management: Topic 3 Synthesis Paper. CGIAR Challenge Program on Water and Food, Colombo

Williamson O.E., 1996. The Mechanisms of Governance. Oxford University Press, UK.

Williamson O.E., 2000. The New Institutional Economics: Taking Stock, Looking Ahead. Journal of Economic Literature, 38(3), 595-613.

Wittwer G., 2009. The economic impacts of a new dam in South-east Queensland. Australian Economic Review, 42(1):12-23, March.

Wittwer G., 2012. Urban water supply: A Case Study of South-east Queensland. In: Wittwer G. (Ed.), Economic Modeling of Water: The Australian CGE Experience. Springer: Dordrecht/Heidelberg/London/New York, 143-162.

Wolf A.T., 1999. Criteria for Equitable Allocations: The Heart of International Water Conflict. Natural Resources Forum. 23 (1) 3-30.

WRI (World Resources Institute), 2005. World resources 2005: the wealth of the poor-managing ecosystems to fight poverty. World Resources Institute, Washington D.C.

WWF (World Water Forum), 2009. Bridging Divides for Water, 5th World Water Forum held on 16-22 March 2009, Istanbul, Turkey.

Yakubov M. and H. Manthrithilake, 2009. Water for Food as Food for Thought: Case Study of Applying the PODIUMSIM Model to Uzbekistan. Irrig. and Drain. 58: 17–37 doi: 10.1002/ird.451

Yang Y.E., J. Zhao, X. Cai, 2011 (in press). A Decentralized Optimization Method for Water Allocation Management in the Yellow River Basin. Journal of Water Resources Planning and Management.

Yoder R., 1981. Non-Agricultural uses of irrigation systems: Past experience and implications for planning and design. Paper prepared for Agricultural Development Council. Cornell University (mimeo).

Young R., 1996. Measuring economic benefits for water investment and policies. The World Bank. Technical Paper No. 338.

Zhao X., B. Chen, Z.F. Yang, 2009. National water footprint in an input-output framework - A case study of China 2002. Ecological Modeling, 220(2), 245-253.

Zilberman D., N. Macdougall, and F. Shah, 1994. Changes In Water Allocation Mechanisms For California Agriculture. Contemporary Economic Policy, Western Economic Association International, 12(1), 122-133.

Zonn I.S., 2010. Socio-Economic Conditions of the Aral Sea Region Before 1960. In: Kostianoy A.G. and A.N. Kosarev (Eds.): The Aral Sea Environment. Springer: Dordrecht/Heidelberg/London/New York, pp 65-73

Zonn I.S., M. Glantz, A.N. Kosarev, and A.G. Kostianoy, 2009. The Aral Sea Encyclopedia. Berlin-Heidelberg, Springer-Verlag, VIII, 290 p.

DATA SOURCES

ADB (Asian Development Bank), 2012. Turkmenistan. Factsheet. Available online at: http://www.adb.org/sites/default/files/pub/2012/TKM.pdf (accessed on 30.12.2012)

ADB (Asian Development Bank), 2011. Online database on socio-economic indicators of Asian countries. Available online at: www.adb.org (Accessed on 16.06.2011)

ADB (Asian Development Bank), 2008. Key economic indicators (Online database). http://www.adb.org (Accessed on 20.08.2008)

Arapov A., 2011. Russian cotton project in Turkestan at the beginning of 20th century (in Russian). Available online at: http://memoryoffuture.blogspot.com/ (accessed on 21.06.2011)

CEEP (Center for Efficient Economic Policy), 2000. Economy of Uzbekistan (Statistcial analytical review). CEEP, Tashkent, Uzbekistan

CER (Center for Economic Research), 2010. Addressing Urban Poverty in Uzbekistan in the Context of the Economic Crisis. Tashkent

Dukhovny V.A., 2010. Current problems in irrigated agriculture in Central Asia and future solutions. Paper presented at international scientific symposium titled "Water in Central Asia" held in November 24-26, 2010. SIC-ICWC, Tashkent, Uzbekistan.

Eurasian Development Bank (EADB), 2008. Water and energy resources in Central Asia: utilization and development issues. Industry Report. Almaty, Kazakhstan.

ECTACIS (European Commission TACIS Project), 1997. WARMAP Project: Formulation & Analysis of Regional Strategies on Land and Water Resources. Tashkent, Uzbekistan FAO 2000. Carbon sequestration options under the Clean Development Mechanism to address land degradation. World Soil Resources Reports No. 92, Food and Agriculture Organization of the United Nations, Rome

EC IFAS (Executive Committee of International Fund for Saving the Aral Sea), 2013. The Aral Sea basin economic allocation model BEAM. Report. Available online at: www.ec-ifas.org (Accessed on 20.08.2013)

FAO, 2012. AQUASTAT. Online database on irrigation and agriculture. Available online at: http://www.fao.org/nr/water/aquastat/data/query/results.html (accessed on 20.11.2012)

GEF (Global Environment Facility), 2002. Water and environmental management project: Subcomponent A1, Regional report No. 2. GEF Agency of the IFAS Aral Sea Basin Program, Tashkent, Uzbekistan.

IFPRI (International Food and Policy Research Institute), 2013. Data on crop evapotranspiration and effective rainfall across the main climatic zones of Central Asia based on IMPACT model database (Excel files delivered by Dr. Claudia Ringler and Dr. Tingju Zhu on 24.07.2013).

IMF (International Monetary Fund), 2012. World Economic Outlook. Online database. http://www.imf.org/external/ns/cs.aspx?id=28 (accessed on 04.06.2012)

INTAS, 1996. Final report: The rehabilitation of the ecosystem and bioproductivity of the Aral Sea under conditions of water scarcity. Tashkent, INTAS Project-0511 REBASOWS, 173-174.

Jigarev S., 2008. Water and energy issues and their solutions in Central Asia. Paper presented at the conference "Problems of Aral: Impact on the gene pool of Population, Flora, Fauna and international Cooperation for mitigating consequences", 11-12 March, 2008, Tashkent, Uzbekistan.

Kartenwerkstatt, 2008. Animated picture of the Aral Sea desiccation. Available online at: http://en.wikipedia.org/wiki/File:Aral_Sea.gif (Accessed on 15.02.2012)

KazStat (National Statistics Committee of Kazakhstan), 2011.Online database. Available online at: www.stat.kz (accessed on 30.05.2011)

KazStat (The Statistical Agency of Kazakhstan), 2010. Agriculture in Kazakhstan 2005-2008. KazStat, Almaty.

KazStat (National Statistics Committee of Kazakhstan), 2008. Statistical bulletin "National accounts of Kazakh Republic 2002-2006". Kazakhstan, Astana (in Russian).

KyrStat (National Statistics Committee of Kyrgyzstan), 2011. Online database. Available online at: www.stat.kg (accessed on 14.06.2011)

KyrStat (The Statistical Committee of Kyrgyzstan), 2010. Agriculture in Kyrgyzstan 2005-2008. KyrStat, Byshkek.

MA UzSSR (Ministry of Agriculture Uzbekistan SSR), 1973. 50 years of cotton cultivation in Uzbekistan. FAN, Tashkent, Uzbekistan (in Russian).

MA UzSSR (Ministry of Agriculture of Uzbekistan SSR), 1975. Production of cotton, ambary, and tobacco in 1974 in Uzbekistan. Uzbekistan, Tashkent, Uzbekistan (in Russian).

MA UzSSR (Ministry of Agriculture of Uzbekistan SSR), 1976. Production of cotton, ambary, and tobacco in 1975 in Uzbekistan. Uzbekistan,Tashkent, Uzbekistan (in Russian).

MA UzSSR (Ministry of Agriculture of Uzbekistan SSR), 1977. Production of cotton, ambary, and tobacco in 1976 in Uzbekistan.Uzbekistan,Tashkent, Uzbekistan (in Russian).

MA UzSSR (Ministry of Agriculture of Uzbekistan SSR), 1978. Production of cotton, ambary, and tobacco in 1977 in Uzbekistan. Uzbekistan, Tashkent, Uzbekistan (in Russian).

MAWR (Ministry of Agriculture and Water Resources of Uzbekistan), 2007. Conveyance costs of delivering one cubic m of water to the irrigation regions in 2006. Unpublished report. Tashkent, Uzbekistan.

McKinney D.C., 2004. Cooperative management of transboundary water resources in Central Asia. In: D. Burghart and T. Sabonis-Helf (eds), In the Tracks of Tamerlane: Central Asia's Path to the 21st Century. Washington, DC: National Defense University, 187–220.

NWC (National Water Commission), 2011. Water markets in Australia: short history. NWC: Canberra.

OblSelVodKhoz (Khorezm region branch of the Ministry of Water Resources and Agriculture), 2010. Revenues, costs, and profits of growing different agricultural commodities. Urgench, Uzbekistan.

Rakhmatullaev S., H. Frédéric, L.C. Philippe, M. Mikael and B. Masharif, 2010. Facts and Perspectives of Water Reservoirs in Central Asia: A Special Focus on Uzbekistan, Water 2010, 2, 307-320.

Shieder T., 2011. Analysis of water use and crop allocation for the Khorezm region in Uzbekistan using an integrated hydrologic-economic model. PhD Dissertation, Bonn University. Bonn, Germany.

SSU (Sentralnaya Statisticheskoye Upravleniye), 1990. Narodnoye hozyaystvo SSR za 1990 god. Moscow.

SIC-ICWC (Scientific-Information Center of Interstate Comission of Water Coordication in the Aral Sea Basin), 2003. The database of the Aral Sea Basin Optimization Model (ASBOM). Excel file. Tashkent, Uzbekistan.

SIC-ICWC, 2008. Crop production costs and revenues across the regions of Uzbekistan in 2006. Unpublished database. Tashkent, Uzbekistan.

SIC-ICWC, 2009. Water use by regions in Uzbekistan in 2000-2008. Unpublished report. SIC-ICWC, Tashkent, Uzbekistan.

SIC-ICWC, 2011. CAREWIB (Central Asian Regional Water Information Base). Available online at: www.cawater-info.net (Accessed on 27.01.2012)

SIC-ICWC, 2012. Website of SIC-ICWC. www.cawater-info.net (accessed on 14.04.2012)

TajStat (The Statistical Committee of Tajikistan), 2010. Agriculture in Tajikistan 2005-2008. TajStat, Dushanbe.

Tolstov S.P., 2005. Following the tracks of ancient Khorezmian civilization. UNESCO. First published in Russian language in 1948 by the Publishing House of the Academy of Sciences of the USSR, Moscow-Leningrad

TurkmenStat (The Statistical Committee of Turkmenistan), 2012. The Statistical Yearbook of Turkmenistan. TurkmenStat, Ashgabat.

United Nations Development Program (UNDP), 2010. National Human Development Report: Kyrgyzstan, successful youth – successful country. Byshkek, Kyrgyzstan.

UNEP (Prepared by Severskiy, I., Chervanyov, I., Ponomarenko, Y., Novikova, N.M., Miagkov, S.V., Rautalahti, E. and D. Daler), 2005. Aral Sea, GIWA Regional assessment 24. University of Kalmar, Kalmar, Sweden.

UzHydromet, 2009. The State Water Cadastre: Water Flows at Hydroposts (Kerki and Kishlak Kal) of the Amu Darya and Syr Darya in 1980-2008. Tashkent, Uzbekistan.

UzStat (Statitical Committee of Uzbekistan), 2010a. Agriculture in Uzbekistan 2007-2009. Tashkent, Uzbekistan.

UzStat (Statitical Committee of Uzbekistan), 2010b. Indicators of socio-economic development in the regions of Uzbekistan. Statistical Bulletin. UzStat, Tashkent

UzStat (National Statistical Committee), 2008. Statistical Yearbook, 1991-2007. Statistical buelletin. UzStat, Tashkent, Uzbekistan

UzStat (National Statistical Committee), 2006. Industry in Uzbekistan. Statistical buelletin. UzStat, Tashkent, Uzbekistan

UzStat (Statitical Committee of Uzbekistan), 2007. Agriculture in Uzbekistan 2003-2006. Tashkent, Uzbekistan.

UzStat (Statitical Committee of Uzbekistan), 1999. Agriculture in Uzbekistan 1995-1998. Tashkent, Uzbekistan.

UzStat (Statitical Committee of Uzbekistan), 2003. Agriculture in Uzbekistan 1999-2002. Tashkent, Uzbekistan.

UNDP (United Nations Development Program), 2012. Human Development Report. Online database. hdr.undp.org/en/media/HDR_2010_EN_Tables_rev.xls

UNDP (United Nations Development Program), 2008. Decentrlaization in the Europe and CIS region. Discussion paper. Bratislava, Slovakia.

UNDP (United Nations Development Program), 2007. Water - critical resource for Uzbekistan's future. UNDP Energy and Environment Unit, Tashkent, Uzbekistan

UNDP (United Nations Development Program), 2006. Modeling the impact of changes in tax rates on key macroeconomic parameters. UNDP, Tashkent, Uzbekistan

WB (Word Bank), 2011. Indicators (Online database). Available online at: http://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG?page=2. (Accessed on 20.05.2011)

WB (World Bank*)*, 2008. World Development Report 2008: Agriculture for Development. WB, Washington D.C.

WB (World Bank), 2013. World Development Indicators. Online database. Available online at: http://databank.worldbank.org (accessed on 29.08.2013)

Zonn I.S., M. Glantz, A.N. Kosarev, and A.G. Kostianoy, 2009. The Aral Sea Encyclopedia. Berlin-Heidelberg, Springer-Verlag, VIII, 290 p.

Appendix A: Methods used to develop the regression models used in Chapter 2

Methods used for the analysis of labor and capital intensities of the Uzbekistan economy described in Box 2.2

After the collapse of the integrated economic system of the former SU, many structural transformations occurred in the economy of Uzbekistan and other Central Asian countries. Increased cereals production resulting from food self-sufficiency policies, expanded energy commodities production to increase export revenues, as well as the collapse of the large agro-processing enterprises are among the transformations that occurred during the post-Soviet transition. Despite these considerable structural changes, there are no recent econometric studies that analyzed the impacts of these changes, particularly considering the role of production factors in the economy, and of the capital and labor intensity of production. Therefore labor and capital elasticity values (intensities) of production across Uzbekistan are estimated using a cross-sectional regression analysis. Considering the similarity among the economies and transition paths of the ASB nations, the results are relevant not only to the case of Uzbekistan (the largest country in the region in terms of economy and population), but also for the other Central Asian countries.

A Cobb-Douglas function is commonly used for production elasticity analyses due to the ease of its operation. Here using data on annual investments for fixed capital (K), the number of employees (L), and output volumes ($Y_{R,r}$) across the districts (r) in each region (province, R) of Uzbekistan, the Cobb-Douglas function parameters for capital and labor elasticity values (α and β respectively) were estimated. Considering the assumption of constant returns of scale,

$$\alpha + \beta = 1 \qquad \text{(A.5)}$$

The Cobb-Douglas function takes the following form:

$$Y = TFP\ K^{\alpha}\ L^{1-\alpha} \qquad \text{(A.6)}$$

where, TFP is the total factor productivity.

Dividing both sides of the equation by L and taking logarithms, the following was derived:

$$\ln(\frac{Y}{L}) = \ln TFP + \alpha\ \ln(\frac{K}{L}) \qquad \text{(A.7)}$$

or

$$\ln y = \ln TFP + \alpha\ \ln k \qquad \text{(A.8)}$$

where, y is labor productivity and k is capital intensity.

Considering regional differences in the economy, separate capital elasticity values were assumed for each region. Therefore, dummy variables defined for each region (D_R) were introduced into the model. Consequently, the following model was derived as:

$$\ln y_{R,r} = \ln TFP + \sum_R \alpha_R D_R \ln k_{R,r} + \psi_{R,r} \qquad \text{(A.9)}$$

where, $\ln y_{R,r} = \ln Y_{R,r} - ln\, L_{R,r}$, $\ln k_{R,r} = \ln K_{R,r} - ln\, L_{R,r}$, and $\psi_{R,r}$ is residual error.

Model parameters were estimated using STATA (StataCorp 2009).

Appendix B: Datasets used in the aggregated hydro-economic model

Table B.1 Cropped land area (1000s ha)

	Initial (1999)	**Min**	**Max**
<u>Amu Darya basin:</u>			
GBAO	27.95	18	32
Khatlon	308	275	316
RRT	81	81	97
Surkhandarya	398	318	407
Mary	442	311	454
Ahal	405	201	424
Lebap	262	180	279
Kashkadarya	550	494	638
Samarkand	515	507	623
Navoi	147	128	151
Bukhara	239	217	255
Khorezm	217	204	246
Karakalpakstan	365	279	412
Dashauz	371	193	398
<u>Syr Darya basin:</u>			
Naryn	46	45	59
Osh	72	63	133
Jalalabad	61	57	73
Ferghana	395	287	399
Andizhan	244	207	271
Namangan	311	223	320
Sugd	266	233	274
Tashkent	439	338	446
Syrdarya	356	289	372
Jizzah	389	360	440
South Kazakhstan	336	315	394
Kyzylorda	131	131	249
Total:	**7377**	**5953**	**8161**

Source: SIC-ICWC (2011)

Table B.2 Water use per ha (1000s m^3/ha)

	Initial (1999)	**Min**	**Max**
Amu Darya basin:			
GBAO	12.9	11.4	20.8
Khatlon	16.6	14.7	17.7
RRT	8.2	6.0	8.2
Surkhandarya	7.7	5.6	10.6
Mary	10.0	9.0	13.2
Ahal	8.3	7.9	14.1
Lebap	12.0	10.3	21.5
Kashkadarya	6.8	5.6	7.5
Samarkand	5.4	3.1	5.7
Navoi	9.5	4.6	11.6
Bukhara	11.4	7.8	16.3
Khorezm	15.7	8.9	21.6
Karakalpakstan	16.3	6.9	25.7
Dashauz	14.0	9.2	25.3
Syr Darya basin:			
Naryn	13.9	10.9	16.0
Osh	21.3	10.0	21.8
Jalalabad	9.5	8.2	10.9
Ferghana	6.2	5.2	13.1
Andizhan	10.2	8.4	18.1
Namangan	5.9	5.0	13.7
Sugd	12.0	11.5	13.7
Tashkent	6.2	4.9	15.4
Syrdarya	6.0	4.7	7.5
Jizzah	4.5	3.3	5.7
South Kazakhstan	8.4	7.3	17.0
Kyzylorda	23.9	19.4	39.7

Source: based on SIC-ICWC (2011)

Table B.3 Total water use in growing season (mln m^3)

	Initial (1999)	Min	Max
Amu Darya basin:			
GBAO	362	347	379
Khatlon	5115	4535	5216
RRT	660	559	721
Surkhandarya	3075	2290	3568
Mary	4423	3339	5057
Ahal	3346	2695	3645
Lebap	3151	2338	4327
Kashkadarya	3747	2787	4170
Samarkand	2802	1705	2938
Navoi	1390	601	1489
Bukhara	2735	1858	3783
Khorezm	3408	1813	4581
Karakalpakstan	5956	2192	7445
Dashauz	5203	3419	5872
Syr Darya basin:			
Naryn	646	630	725
Osh	1539	939	1539
Jalalabad	585	585	704
Ferghana	2461	2078	3767
Andizhan	2490	2046	3747
Namangan	1837	1526	3098
Sugd	3185	3103	3342
Tashkent	2708	2074	5209
Syrdarya	2123	1667	2166
Jizzah	1765	1405	2059
South Kazakhstan	2813	2660	5675
Total:	**70655**	**52324**	**91706**

Source: SIC-ICWC (2011)

Table B.4 Conveyance costs (2006)

Amu Darya basin	Conveyance costs (in USD / m^3)	Syr Darya basin	Conveyance costs (in USD / m^3)
GBAO	0.00312	Naryn	0.00437
Khatlon	0.01302	Osh	0.00437
RRT	0.00312	Jalalabad	0.00725
Surkhandarya	0.00912	Ferghana	0.00437
Mary	0.00188	Andizhan	0.00725
Ahal	0.01222	Namangan	0.01302
Lebap	0.00188	Sugd	0.01302
Kashkadarya	0.01263	Tashkent	0.00187
Samarkand	0.00312	Syrdarya	0.00238
Navoi	0.00470	Jizzah	0.00536
Bukhara	0.01222	South Kazakhstan	0.00536
Khorezm	0.00188	Kyzylorda	0.00122
Karakalpakstan	0.00122		
Dashauz	0.00188		

Source: Author’s estimations based on MAWR (2007)

Table B.5 Water supply (mln m^3). Based on data of 1980-2000

River tributaries	Dry (1986)	Normal (1999)	Wet (1992)
Amu Darya basin:	43433	56720	82230
Atrek	44	40	222
Kafirnigan	4818	8688	11909
Kashkadarya	217	462	1291
Kunduz	2679	2679	2679
Murgab	585	724	2912
Pyandj	19710	26794	39786
Sherabad	72	100	356
Surhandarya	677	938	3356
Tedjen	444	740	1301
Vakhsh	11103	12130	15344
Yavansu	547	589	553
Zarafshan	2539	2836	3521
Syr Darya basin:	23316	24999	24187
Abshirsay	69	97	100
Aksu	63	92	149
Aris	484	274	313
Bugun	323	439	548
Chirchik	7102	4498	4824
Guzardarya	47	56	296
Isfara	315	385	398
Isfaramsay	348	526	715
Karadarya	2317	2453	3377
Kasansay	1217	149	254
Kuvasay	149	38	223
Naryn	8827	13106	9923
Shakimardan	153	220	196
Shaydansay	178	178	280
Sokh	1070	1317	1195
Akhangaran	330	617	732
Keles	145	258	308
Kattasay	29	37	33
Shirinsay	29	32	30
Khojabakirgan	120	229	294
Total:	**66749**	**84792**	**107417**

Source: SIC-ICWC (2011)

Table B.6 Return flow rates as a percentage of total water diversion

Amu Darya basin	Return flow rate, %	Syr Darya basin	Return flow rate, %
GBAO	0.50	Naryn	0.20
Khatlon	0.50	Osh	0.20
RRT	0.50	Jalalabad	0.20
Surkhandarya	0.24	Ferghana	0.39
Mary	0.07	Andizhan	0.50
Ahal	0.44	Namangan	0.25
Lebap	0.44	Sugd	0.06
Kashkadarya	0.05	Tashkent	0.25
Samarkand	0.11	Syrdarya	0.23
Navoi	0.13	Jizzah	0.01
Bukhara	0.00	South Kazakhstan	0.09
Khorezm	0.00	Kyzylorda	0.00
Karakalpakstan	0.04		
Dashauz	0.00		

Source: Author’s estimations based on EC TACIS (1997)

Appendix C: GAMS code of the hydro-economic model for analyzing the scenarios of increasing transaction costs of water rights trading

```
$offsymxref
$offlisting
option limcol = 0;
option limrow = 0;

SETS

agdm Agricultural demand sites
/
***********Amudarya demand sites
GBAO, Khatlon, RRT, Surkhnadarya, Mary, Ahal, Lebap, Kashkadarya,Samarkand, Navoi, Bukhara
Khorezm, Karakalpakstan, Dashauz

*****Syrdarya demand sites
Narin, Osh, Jalalabad, Ferghana, Andizhan, Namangan, Sugd, Tashkent, Syrdarya, Jizzah
South_Kazakhstan, Kyzylorda
/

agdm_amu(agdm)
/
***********Amudarya demand sites
GBAO, Khatlon, RRT, Surkhnadarya, Mary, Ahal, Lebap, Kashkadarya,Samarkand, Navoi, Bukhara
Khorezm, Karakalpakstan, Dashauz
/

agdm_syr(agdm)
/
*****Syrdarya demand sites
Narin, Osh, Jalalabad, Ferghana, Andizhan, Namangan, Sugd, Tashkent, Syrdarya, Jizzah
South_Kazakhstan, Kyzylorda
/

rn River nodes
/
*******Simple nodes ***********
Amu1*Amu5
Syr1*Syr4

*******Supply nodes ***********
Atrek, Kafirnigan, Kashkadariya, Kunduz, Murgab, Pyandj, Sherabad, Surhandarya, Tedjen, Vakhsh
Yavansu, Zarafshan, Abshirsay, Aksu, Aris, Bugun, Chirchik, Guzardarya, Isfara, Isfaramsay, Karadarya
Kasansay, Kuvasay, Naryn, Shakimardan, Shaydansay, Sokh, Akhangaran, Keles, Kattasay, Shirinsay
Khojabakirgan

*****Outlet******************
Aral_Sea/

rns(rn) supply nodes
```

```
/
*****Amudarya river tributaries (12)*************
Atrek, Kafirnigan, Kashkadariya, Kunduz, Murgab, Pyandj, Sherabad, Surhandarya, Tedjen, Vakhsh,
Yavansu, Zarafshan

*****Syrdarya river tributaries (20) *************
Abshirsay, Aksu, Aris, Bugun, Chirchik, Guzardarya, Isfara, Isfaramsay, Karadarya, Kasansay, Kuvasay
Naryn, Shakimardan, Shaydansay, Sokh, Akhangaran, Keles, Kattasay, Shirinsay, Khojabakirgan
/

rna(rn) Aral Sea
/Aral_Sea/

rns_amu(rn)
/
*****Amudarya river tributaries (12)*************
Atrek, Kafirnigan, Kashkadariya, Kunduz, Murgab, Pyandj, Sherabad, Surhandarya, Tedjen, Vakhsh
Yavansu, Zarafshan
/



rns_syr(rn)
/
*****Syrdarya river tributaries (20) *************
Abshirsay, Aksu, Aris, Bugun, Chirchik, Guzardarya, Isfara, Isfaramsay, Karadarya, Kasansay, Kuvasay
Naryn, Shakimardan, Shaydansay, Sokh, Akhangaran, Keles, Kattasay, Shirinsay, Khojabakirgan
/;

alias(agdm, agdma,agdmb);
alias(rn_up, rn);
alias(rn, rn_lo);


SET RVLINK(rn_up,rn) node rn releases water to node rn_lo (any node)
/
*****Amu Darya nodes*******
Vakhsh.Amu1, Pyandj.Amu1, Kafirnigan.Amu1, YavanFSU.Amu1, Amu1.Amu2, Kunduz.Amu2
Sherabad.Amu2, Surhandarya.Amu2, Amu2.Amu3, Atrek.Amu3, Murgab.Amu3, Tedjen.Amu3
Amu3.Amu4, Kashkadariya.Amu4, Guzardarya.Amu4, Zarafshan.Amu4, Amu4.Amu5, Amu5.Aral_Sea


*****Syr Darya nodes*******
Naryn.Syr1, Shaydansay.Syr1, Syr1.Syr2, Karadarya.Syr2, Abshirsay.Syr2, Kuvasay.Syr2, Isfara.Syr2
Sokh.Syr2, Shakimardan.Syr2, Isfaramsay.Syr2, Kasansay.Syr2, Syr2.Syr3, AkFSU.Syr3
Khojabakirgan.Syr3, Kattasay.Syr3, Keles.Syr3, Chirchik.Syr3, Akhangaran.Syr3, Shirinsay.Syr3
Aris.Syr3, Bugun.Syr3, Syr3.Syr4, Syr4.Aral_Sea
/;


SET NDLINK(rn,agdm) node n diverts water to agricultural water user site agdm
/
```

```
*****Amu Darya sites*******
Amu1.GBAO, Amu1.Khatlon, Amu1.RRT, Amu2.Surkhnadarya, Amu3.Mary, Amu3.Ahal, Amu4.Lebap
Amu4.Kashkadarya, Amu4.Samarkand, Amu4.Navoi, Amu4.Bukhara, Amu5.Khorezm
Amu5.Karakalpakstan, Amu5.Dashauz

*****Syr Darya sites*******
Syr1.Narin, Syr1.Osh, Syr1.Jalalabad, Syr2.Ferghana, Syr2.Andizhan, Syr2.Namangan, Syr2.Sugd,
Syr3.Tashkent, Syr3.Syrdarya, Syr3.Jizzah, Syr3.South_Kazakhstan, Syr4.Kyzylorda
/;

SET DNLINK(agdm, rn) agricultural water user site agdm returns water to river node rn
/
*****Amu Darya sites*******
GBAO.Amu1, Khatlon.Amu1, RRT.Amu1, Surkhnadarya.Amu2, Mary.Amu3, Ahal.Amu3, Lebap.Amu4,
Kashkadarya.Amu4, Samarkand.Amu4, Navoi.Amu4, Bukhara.Amu4, Khorezm.Amu5
Karakalpakstan.Amu5,  Dashauz.Amu5

*****Syr Darya sites*******
Narin.Syr1, Osh.Syr1, Jalalabad.Syr1, Ferghana.Syr2,Andizhan.Syr2,Namangan.Syr2,Sugd.Syr2,
Tashkent.Syr3, Syrdarya.Syr3, Jizzah.Syr3, South_Kazakhstan.Syr3, Kyzylorda.Syr4
/;

SET lev levels of parameters
/
INITIAL, MIN, MAX
/;

SET coef profit function coefficinets
/
a0, a1, a2
/;

PARAMETERS
Source0(rn, lev) annual water supply (10^6 m^3)
Reg_Cons0(agdm,lev) overall irrigation zone water consumption (10^6 m^3)
Per_ha_Water0(agdm,lev) Water use per ha   (1000 m^3 per ha)
Tot_Land0(agdm,lev) total cropland area 1000 ha
COEF_PROF_FUNC(agdm,coef) profit function coefficients
FLOW_TO_ARAL0(lev) flow to the Aral Sea (10^6 m^3)
ENV_PROF_FUNC_COEF(coef) coefficients of environmental profit function
Conveyance_cost(agdm) conveyance costs (USD per m^3)
Ret(agdm, rn) return flow coefficients


****************Importing data from excel**********************
$libinclude xlimport Source0 ASB_Irrigation_profit_functions_4.xls SUPPLY
$libinclude xlimport Reg_Cons0 ASB_Irrigation_profit_functions_4.xls CONSUMPTION
$libinclude xlimport Per_ha_Water0 ASB_Irrigation_profit_functions_4.xls Per_ha_Water
$libinclude xlimport Tot_Land0 ASB_Irrigation_profit_functions_4.xls LAND
$libinclude xlimport COEF_PROF_FUNC ASB_Irrigation_profit_functions_4.xls COEF_PROF_FUNC
$libinclude xlimport FLOW_TO_ARAL0 ASB_Irrigation_profit_functions_4.xls FLOW_TO_ARAL
```

```
$libinclude xlimport ENV_PROF_FUNC_COEF ASB_Irrigation_profit_functions_4.xls
ENV_PROF_FUNC_COEF
$libinclude xlimport Conveyance_cost ASB_Irrigation_profit_functions_4.xls Conveyance_cost
$libinclude xlimport Ret ASB_Irrigation_profit_functions_4.xls Return_flow_rate
;

********Initial values estimation - calibration of the model to the water use level in 1999****
Parameter Ind_Mun_Wat0(agdm) industrial and municipial water use (assumed as 10 % of total water
consumption_ S.: SANIIRI 2004);
Ind_Mun_Wat0(agdm)= (1/9) * Reg_Cons0(agdm,"initial")   ;

Parameter Tot_Ind_Mun_Wat Total industrial and municipial water use
        Tot_Ind_Mun_Wat_Amu Total industrial and municipial water use  in the Amudarya river basin
        Tot_Ind_Mun_Wat_Syr Total industrial and municipial water use  in the Syrdarya river basin
;

Tot_Ind_Mun_Wat  = sum(agdm,Ind_Mun_Wat0(agdm)) ;
Tot_Ind_Mun_Wat_Amu  = sum(agdm$(ord(agdm) lt 15), Ind_Mun_Wat0(agdm)) ;
Tot_Ind_Mun_Wat_Syr  = sum(agdm$(ord(agdm) gt 14), Ind_Mun_Wat0(agdm)) ;

Parameter retn (agdm);
retn(agdm) = sum(rn, Ret(agdm, rn)$DNLINK(agdm, rn)) ;

Parameter  Tot_Agr_Ret_Wat   Total return flow
         Tot_Agr_Ret_Wat_Amu  Total return flow  in the Amudarya river basin
         Tot_Agr_Ret_Wat_Syr   Total return flow in the Syrdarya river basin
 ;
Tot_Agr_Ret_Wat  =  sum(agdm, retn(agdm) *  Reg_Cons0(agdm,"initial") )      ;
Tot_Agr_Ret_Wat_Amu  =  sum(agdm$(ord(agdm) lt 15), retn(agdm) *  Reg_Cons0(agdm,"initial") )      ;
Tot_Agr_Ret_Wat_Syr  =  sum(agdm$(ord(agdm) gt 14), retn(agdm) *  Reg_Cons0(agdm,"initial") )      ;

Parameter  Agric_Withdr   Total agricultural withdarawal
         Agric_Withdr_Amu   Total agricultural withdarawal  in the Amudarya river basin
         Agric_Withdr_Syr   Total agricultural withdarawal  in the Syrdarya river basin
 ;
Agric_Withdr   = sum(  agdm, Reg_Cons0(agdm,"initial") )        ;
Agric_Withdr_Amu   = sum(  agdm$(ord(agdm) lt 15), Reg_Cons0(agdm,"initial") )        ;
Agric_Withdr_Syr   = sum(  agdm$(ord(agdm) gt 14), Reg_Cons0(agdm,"initial") )        ;

Parameters  Supply       Total supply
          Supply_Amu   Total supply in the Amudarya river basin
          Supply_Syr   Total supply in the Syrdarya river basin
;
Supply = sum(rn, Source0(rn, "initial"));
Supply_Amu = sum(rn$(ord(rn) gt 9 and ord(rn) lt 22), Source0(rn, "initial"));
Supply_Syr = sum(rn$(ord(rn) gt 21 and ord(rn) lt 42), Source0(rn, "initial"));


****Environmental flow value **********
Parameters Aral_Flow0     initial flow to the Aral Sea
         Aral_Flow_Amu0 initial flow to the Aral Sea from Amudarya
         Aral_Flow_Syr0 initial flow to the Aral Sea from Syrdarya
```

```
;
Aral_Flow0 = Supply  - Agric_Withdr - Tot_Ind_Mun_Wat  +  Tot_Agr_Ret_Wat  ;
Aral_Flow_Amu0 = Supply_Amu  - Agric_Withdr_Amu - Tot_Ind_Mun_Wat_Amu  +
Tot_Agr_Ret_Wat_Amu  ;
Aral_Flow_Syr0 = Supply_Syr  - Agric_Withdr_Syr - Tot_Ind_Mun_Wat_Syr  +  Tot_Agr_Ret_Wat_Syr
;

Parameter Env_prof0 initial total environmental profit;
Env_prof0 =  ENV_PROF_FUNC_COEF("a0") + ENV_PROF_FUNC_COEF("a1")*Aral_Flow0 ;

Parameter Per_ha_Water0_max(agdm) water use in optimal point of the water-profit function;
Per_ha_Water0_max(agdm) =  - COEF_PROF_FUNC(agdm,"a1")/(2*COEF_PROF_FUNC(agdm,"a2"));

Parameter Max_Wat_Capacity0(agdm) maximum water intake capacity of the irrigation region;
Max_Wat_Capacity0(agdm) =  Per_ha_Water0_max(agdm)* Tot_Land0(agdm, "max");

Parameter Profit_per_ha0(agdm,lev) profit level per ha in USD;

Profit_per_ha0(agdm,"min") = COEF_PROF_FUNC(agdm,"a0") +
COEF_PROF_FUNC(agdm,"a1")*0.5*Per_ha_Water0(agdm,"min") + COEF_PROF_FUNC(agdm,"a2")
*0.25*Per_ha_Water0(agdm,"min")*Per_ha_Water0(agdm,"min");
Profit_per_ha0(agdm,"initial") = COEF_PROF_FUNC(agdm,"a0") +
COEF_PROF_FUNC(agdm,"a1")*Per_ha_Water0(agdm,"initial") + COEF_PROF_FUNC(agdm,"a2")
*Per_ha_Water0(agdm,"initial")*Per_ha_Water0(agdm,"initial");
Profit_per_ha0(agdm,"max") = COEF_PROF_FUNC(agdm,"a0") +
COEF_PROF_FUNC(agdm,"a1")*Per_ha_Water0_max(agdm) + COEF_PROF_FUNC(agdm,"a2")
*Per_ha_Water0_max(agdm)*Per_ha_Water0_max(agdm);

Parameter Total_prof0(agdm,lev) Total profit in million USD (based on initial level of areas);
Total_prof0(agdm,lev) = (1/1000)*Profit_per_ha0(agdm,lev)* Tot_Land0(agdm,"initial");

**************Water rights options ******************************
Parameter Water_right_shr1(agdm) water rights share due to "historical water use";
Water_right_shr1(agdm)$agdm_amu(agdm) = (1-retn(agdm))*Reg_Cons0(agdm,"initial") / (
Supply_Amu  - Tot_Ind_Mun_Wat_Amu -3500)     ;
Water_right_shr1(agdm)$agdm_syr(agdm) = (1-retn(agdm))*Reg_Cons0(agdm,"initial") / (  Supply_Syr -
Tot_Ind_Mun_Wat_Syr -1500)     ;

Parameter
*Water_right_shr1_Aral water rights share due to "historical water use" to the Aral Sea (the share of
historical minus minimum flow)
        Water_right_shr1_Aral_Amu    Aral Amu part share
        Water_right_shr1_Aral_Syr    Aral Syr part share
;
*Water_right_shr1_Aral = (Aral_Flow0 -FLOW_TO_ARAL0("min"))  / (  Supply + Tot_Agr_Ret_Wat -
Tot_Ind_Mun_Wat -FLOW_TO_ARAL0("min"))     ;
Water_right_shr1_Aral_Amu = (Aral_Flow_Amu0 - 3500)  / (  Supply_Amu  - Tot_Ind_Mun_Wat_Amu
- 3500)     ;
Water_right_shr1_Aral_Syr = (Aral_Flow_Syr0 - 1500)  / (  Supply_Syr  - Tot_Ind_Mun_Wat_Syr -
1500)     ;

Parameter TOT_INTAKE0(rn) initial levels of water intake from river node rn;
```

```
TOT_INTAKE0(rn) =  sum(agdm, Reg_Cons0(agdm,"initial")$NDLINK(rn,agdm) );

Parameter  Water_right1_0(agdm)    initial water right according to the share without considering
maximum water use capacity;

Water_right1_0(agdm)$agdm_amu(agdm) =  (Water_right_shr1(agdm)/(1-retn(agdm))) * (  sum(rn,
Source0(rn, "initial")$rns_amu(rn)) - Tot_Ind_Mun_Wat_Amu - 3500 )       ;
Water_right1_0(agdm)$agdm_syr(agdm) =  (Water_right_shr1(agdm)/(1-retn(agdm))) * (  sum(rn,
Source0(rn, "initial")$rns_syr(rn)) - Tot_Ind_Mun_Wat_Syr - 1500 )      ;

Parameters
Tot_shareable_wat_Amu total shareable water in the Amudarya
Tot_shareable_wat_Syr total shareable water in the Syrdarya;

Tot_shareable_wat_Amu = sum(rn, Source0(rn, "initial")$rns_amu(rn)) - Tot_Ind_Mun_Wat_Amu - 3500
;
Tot_shareable_wat_Syr = sum(rn, Source0(rn, "initial")$rns_syr(rn)) - Tot_Ind_Mun_Wat_Syr - 1500
;

Parameter trans_c transaction cots USD per m^3;
trans_c = 0.0;

POSITIVE VARIABLES
WITHDRAW(rn,agdm)   Water withdrawal from river node rn to agricultural demand site agdm  (10^6
m^3)
FLOW(rn,rn_lo) Water flow through river nodes   (10^6 m^3)
Aral_Flow  Flow to the Aral Sea and its delta  (10^6 m^3)
TOT_INTAKE(rn)  Total water withdrawal to agriculture from river node rn (10^6 m^3)
Tot_land(agdm)   Total land area cropped (1000 ha)
Per_ha_water(agdm) water use per ha (1000 m^3 per ha)
Profit_per_ha(agdm) Profit per ha (USD)
Tot_profit(agdm) total profit in agricultural demand site (10^6 usd)
Envir_profit environmental profit from water flow to the Aral Sea and its delta (10^6 usd)

*Variables related to water markets
WTP(agdm) water trading price (usd per m^3)
wsold(agdm) water sold volume  (10^6 m^3)
wbolt(agdm) water bought volume   (10^6 m^3)
Water_right1(agdm) water use right of the irrigation site  (10^6 m^3)

Water_right1_Aral_Amu water use right of the Aral Sea (Amudarya part) (10^6 m^3)
Water_right1_Aral_Syr water use right of the Aral Sea (Syrdarya part)  (10^6 m^3)
;

VARIABLE
obj   objective function value;
EQUATIONS
N_BAL(rn) river node water balance (10^6 m3)
Env_flow environmental flow  (10^6 m3)
Max_Land(agdm) maximum avaiable land  (1000 ha)
Min_Land(agdm) minimum allowable land  (1000 ha)
Max_Water(agdm) water use maximum    (1000 m3)
```

```
Min_Water(agdm) water use minimum  (1000 m3)
Reg_wat_bal(agdm) Regional water balance  (10^6 m3)
Prof_ha_wm(agdm)   Profit per ha   (USD)
Prof_wm(agdm)   Total regional profit   (10^6 USD)
Env_prof   Environmental profit    (10^6 USD)
Tot_prof    objective function     (10^6 USD)

*equations related to water trade
Wat_right_def_Amu(agdm) water rights calculation for the Amudarya   (10^6 m3)
Wat_right_def_Syr(agdm) water rights calculation for the Syrdarya   (10^6 m3)
Wat_right_def_Aral1_Amu  water rights of Aral Amu (10^6 m3)
Wat_right_def_Aral1_Syr  water rights of Aral Syr (10^6 m3)

Wat_right_bal(agdm) water withdrawal under water tading opportunities  (10^6 m3)
Water_sell_lim(agdm) limit to the amout of water for selling
Wat_trd_bal_Amu   balance of traded water
Wat_trd_bal_Syr
Wat_trd_cond(agdm) water trading conditions
Wat_trd_prc(agdm)  water trading price - willingness to pay to water
*Node_rights(rn) intercatchment water trading conditions I
*Node_lim(rn) intercatchment water trading conditions II
Water_trd_rev_bal_Amu all revenue from selling water is less than overall revenue from buying in the
Amu Darya basin
Water_trd_rev_bal_Syr all revenue from selling water is less than overall revenue from buying in the Syr
Darya basin
Profit_lim(agdm)      water users agree for selling water only if it increases their benefit
;


*River node flow balance
N_BAL(rn)$(ord(rn) ne 42) ..
*   "river node with an order of 42 should be the Aral Sea"

 SUM(rn_lo$RVLINK(rn,rn_lo), FLOW(rn,rn_lo))+
    SUM(agdm$NDLINK(rn,agdm), WITHDRAW(rn,agdm)) +
SUM(agdm$NDLINK(rn,agdm),Ind_Mun_Wat0(agdm))
   =e=
    SUM(rn_up$RVLINK(rn_up,rn),FLOW(rn_up,rn))  + Source0 (rn, "initial")
  + SUM(agdm$DNLINK(agdm, rn), Ret(agdm, rn)*WITHDRAW(rn, agdm) )
 ;

*Flow to the Aral Sea and its delta
Env_flow..
   Aral_Flow =e= SUM(rn_up$RVLINK(rn_up,"Aral_Sea"), FLOW(rn_up, "Aral_Sea"))  ;

*Environmental flow restriction
FLOW.lo("Amu5", "Aral_Sea") = 3500    ;
FLOW.lo("Syr4", "Aral_Sea") = 1500   ;
Aral_Flow.up = FLOW_TO_ARAL0("max") ;

**********************
*Land restriction
```

```
Max_Land(agdm)..
Tot_land(agdm) =l= Tot_Land0(agdm,"max");

Min_Land(agdm)..
Tot_land(agdm) =g= Tot_Land0(agdm,"min");

*Water use per ha restriction
Max_Water(agdm)..
Per_ha_water(agdm) =l= Per_ha_Water0_max(agdm);

*Regional water balance
Reg_wat_bal(agdm)..
SUM(rn$NDLINK(rn,agdm), WITHDRAW(rn,agdm)) =e=  Tot_land(agdm) * Per_ha_water(agdm)   ;

*Total regional profit without markets
*Prof_wm(agdm).. Tot_profit(agdm) =e= (1/1000)*Tot_land(agdm)*Profit_per_ha(agdm);

*Total regional profit with markets
Prof_wm(agdm)..
Tot_profit(agdm) =e= (1/1000)*(Profit_per_ha(agdm)-Conveyance_cost(agdm) *
Per_ha_water(agdm)*1000) *Tot_land(agdm) +
                    WTP(agdm)* wsold(agdm)  - WTP(agdm)*wbolt(agdm) -
trans_c*(wsold(agdm)+wbolt(agdm)) ;


*Profit-water function
Prof_ha_wm(agdm)..
Profit_per_ha(agdm) =e= COEF_PROF_FUNC(agdm,"a0") +
COEF_PROF_FUNC(agdm,"a1")*Per_ha_Water(agdm) + COEF_PROF_FUNC(agdm,"a2")
*Per_ha_Water(agdm)*Per_ha_Water(agdm);


*Environmental flow benefit with water trade
Env_prof..
Envir_Profit =e=  ENV_PROF_FUNC_COEF("a0") + ENV_PROF_FUNC_COEF("a1")*Aral_Flow
;

*objective function
Tot_prof..
obj =e= sum(agdm, Tot_profit(agdm)) + Envir_Profit;
*****Equations related to water trading

*Water rights calculation
Wat_right_def_Amu(agdm)$agdm_amu(agdm)..
Water_right1(agdm)$agdm_amu(agdm) =e= Water_right1_0(agdm)$(Water_right1_0(agdm) le
Max_Wat_Capacity0(agdm))  +  Max_Wat_Capacity0(agdm)$(Water_right1_0(agdm) gt
Max_Wat_Capacity0(agdm))
 ;

Wat_right_def_Syr(agdm)$agdm_syr(agdm)..
```

```
Water_right1(agdm)$agdm_syr(agdm) =e= Water_right1_0(agdm)$(Water_right1_0(agdm) le
Max_Wat_Capacity0(agdm))  +  Max_Wat_Capacity0(agdm)$(Water_right1_0(agdm) gt
Max_Wat_Capacity0(agdm))
;



Wat_right_def_Aral1_Amu..
Water_right1_Aral_Amu  =e= 3500 + Water_right_shr1_Aral_Amu * Tot_shareable_wat_Amu +
sum(agdm$(Water_right1_0(agdm)$agdm_amu(agdm) gt
Max_Wat_Capacity0(agdm)$agdm_amu(agdm)), (1-retn(agdm))*(Water_right1_0(agdm)-
Max_Wat_Capacity0(agdm)) )
 ;
Wat_right_def_Aral1_Syr..
Water_right1_Aral_Syr  =e= 1500 + Water_right_shr1_Aral_Syr * Tot_shareable_wat_Syr +
sum(agdm$(Water_right1_0(agdm)$agdm_syr(agdm) gt Max_Wat_Capacity0(agdm)$agdm_syr(agdm)),
(1-retn(agdm))*(Water_right1_0(agdm)-Max_Wat_Capacity0(agdm)) )
;



Profit_lim(agdm)..

Tot_profit(agdm) =g= (1/1000)*(    COEF_PROF_FUNC(agdm,"a0") +
COEF_PROF_FUNC(agdm,"a1")* Water_right1(agdm)/Tot_Land0(agdm,"initial") +
                      COEF_PROF_FUNC(agdm,"a2") *  (Water_right1(agdm)/Tot_Land0(agdm,"initial")) *
(Water_right1(agdm)/Tot_Land0(agdm,"initial"))   ) *  Tot_Land0(agdm,"initial")
                              -Conveyance_cost(agdm) * Water_right1(agdm)     ;

*Water balance considering water rights
Wat_right_bal(agdm)..
SUM(rn$NDLINK(rn,agdm), WITHDRAW(rn,agdm)) =l= Water_right1(agdm) -  wsold(agdm) +
wbolt(agdm) ;



*Environmental flow restriction
FLOW.lo("Amu5", "Aral_Sea") = 3500   ;
FLOW.lo("Syr4", "Aral_Sea") = 1500   ;

*No user is allowed to sell more water than their water right
Water_sell_lim(agdm)..
Water_right1(agdm) =g= wsold(agdm);



*Water trading balance - the total volume of water bought equal to the total volume of water sold
Wat_trd_bal_Amu..
sum(agdm, wsold(agdm)$agdm_amu(agdm) )  =e= sum(agdm, wbolt(agdm)$agdm_amu(agdm)) ;

Wat_trd_bal_Syr..
sum(agdm, wsold(agdm)$agdm_syr(agdm) )  =e= sum(agdm, wbolt(agdm)$agdm_syr(agdm));

*Water trading conditions - water user either buys from or sells to another water user
Wat_trd_cond(agdm)..
wsold(agdm) * wbolt(agdm) =e= 0;
```

```
*Water trading price (in USD/m^3)- marginal water productivity for the whole region - derivation of Total
regional profit by Total regional water use
Wat_trd_prc(agdm)..
WTP(agdm) *(wsold(agdm) + wbolt(agdm) +0.000000001)    =e= (1/1000) * (
COEF_PROF_FUNC(agdm,"a1") + 2*COEF_PROF_FUNC(agdm,"a2") * Per_ha_Water(agdm)
 - Conveyance_cost(agdm)*1000 ) *(wsold(agdm) + wbolt(agdm) +0.000000001)
+ trans_c * (wsold(agdm) - wbolt(agdm))  ;


Water_trd_rev_bal_Amu..
sum(agdm, WTP(agdm)$agdm_amu(agdm)* wsold(agdm))  =e= sum(agdm,
WTP(agdm)$agdm_amu(agdm)*wbolt(agdm)) ;

Water_trd_rev_bal_Syr..
sum(agdm, WTP(agdm)$agdm_syr(agdm)* wsold(agdm))  =e= sum(agdm,
WTP(agdm)$agdm_syr(agdm)*wbolt(agdm)) ;

*Restrictions related to intracatchment water trade

*Total water withdrawal rights from river node
*Node_rights(rn)..
*sum(agdm$NDLINK(rn,agdm), WITHDRAW(rn,agdm)) =l=   sum(agdm,
Water_right1(agdm)$NDLINK(rn,agdm) );


*Total sales and purchases are equal within the subcatchment
*Node_lim(rn)..
*sum(agdm$NDLINK(rn,agdm), wsold(agdm))  =e= sum(agdm$NDLINK(rn,agdm), wbolt(agdm))  ;


*Initial values for solving the model
Tot_land.l(agdm) = (Tot_Land0(agdm,"min") + Tot_Land0(agdm,"max"))*0.5;
Per_ha_Water.l(agdm) = 0.8*Per_ha_Water0(agdm,"initial");

wsold.l(agdm) = 2 ;
wbolt.l(agdm) = 1;
wtp.l(agdm) = 0.01;

MODEL Ann_HEM /all/;
Ann_HEM.holdfixed=1;
Ann_HEM.iterlim=100000;
Ann_HEM.reslim=100000;

*Solving model
option nlp=conopt3;

************For scenario reporting**************
Set
Scenario /Sc0*Sc20/;

Set source_lev
```

```
/normal, normal_90, normal_80
/;

Parameters
trans_cost(scenario) transaction cost per unit of water transaction USD per cubic m;

trans_cost(scenario) = (ord(scenario)-1)/400;
Display trans_cost;

parameters sav_trans_cost saving trans cost

Sc_Tot_withdraw_Amu(scenario, source_lev) total water withdrawal under scenario (million m^3)
Sc_Env_flow_Amu(scenario, source_lev) environmental flow (km^3)
Sc_wat_bolt_Amu(scenario, source_lev) water bought (million m^3)
Sc_wat_sold_Amu(scenario, source_lev) water sold (million m^3)
Sc_tot_net_ben_Amu(scenario, source_lev) total benefit (million USD)
Sc_WTP_Amu(scenario, source_lev) shadow price  USD per m^3

Sc_Tot_withdraw_Syr(scenario, source_lev)
*Sc_Env_flow_Syr(scenario, source_lev)
Sc_wat_bolt_Syr(scenario, source_lev)
Sc_wat_sold_Syr(scenario, source_lev)
Sc_tot_net_ben_Syr(scenario, source_lev)
Sc_WTP_Syr(scenario, source_lev)
;

sav_trans_cost = trans_c;

loop(Scenario,
trans_c = sav_trans_cost;
trans_c = trans_cost(scenario);



SOLVE Ann_HEM USING NLP MAXIMIZING obj;
Sc_Tot_withdraw_Amu(scenario, "normal")  = sum(agdm$agdm_amu(agdm), sum(rn,
WITHDRAW.l(rn,agdm)) ) ;
Sc_Env_flow_Amu(scenario, "normal")  =   Aral_Flow.l     ;
Sc_wat_bolt_Amu(scenario, "normal")  =  sum(agdm$agdm_amu(agdm), wbolt.l(agdm) );
Sc_wat_sold_Amu(scenario, "normal")  =  sum(agdm$agdm_amu(agdm), wsold.l(agdm) );
Sc_tot_net_ben_Amu(scenario, "normal")  = sum(agdm$agdm_amu(agdm), Tot_profit.l(agdm)) ;
Sc_WTP_Amu(scenario, "normal")   =      (sum(agdm$agdm_amu(agdm), wtp.l(agdm)*Tot_land.l(agdm))
) /(sum(agdm, Tot_land.l(agdm)));

Sc_Tot_withdraw_Syr(scenario, "normal")  = sum(agdm$agdm_syr(agdm), sum(rn,
WITHDRAW.l(rn,agdm)) ) ;
*Sc_Env_flow_Amu(scenario, "normal")  =   Aral_Flow.l     ;
Sc_wat_bolt_Syr(scenario, "normal")  =  sum(agdm$agdm_syr(agdm), wbolt.l(agdm) );
Sc_wat_sold_Syr(scenario, "normal")  =  sum(agdm$agdm_syr(agdm), wsold.l(agdm) );
Sc_tot_net_ben_Syr(scenario, "normal")  = sum(agdm$agdm_syr(agdm), Tot_profit.l(agdm)) ;
Sc_WTP_Syr(scenario, "normal")   =    (sum(agdm$agdm_syr(agdm), wtp.l(agdm)*Tot_land.l(agdm)))
/(sum(agdm, Tot_land.l(agdm)))    ;
);
```

```
Source0 (rn, "initial") = 0.9*Source0 (rn, "initial") ;
Water_right1_0(agdm)$agdm_amu(agdm) =  (Water_right_shr1(agdm)/(1-retn(agdm))) * (  sum(rn,
Source0(rn, "initial")$rns_amu(rn)) - Tot_Ind_Mun_Wat_Amu - 3500 )       ;
Water_right1_0(agdm)$agdm_syr(agdm) =  (Water_right_shr1(agdm)/(1-retn(agdm))) * (  sum(rn,
Source0(rn, "initial")$rns_syr(rn)) - Tot_Ind_Mun_Wat_Syr - 1500 )      ;

Tot_shareable_wat_Amu= sum(rn, Source0(rn, "initial")$rns_amu(rn)) - Tot_Ind_Mun_Wat_Amu - 3500
;
Tot_shareable_wat_Syr= sum(rn, Source0(rn, "initial")$rns_syr(rn)) - Tot_Ind_Mun_Wat_Syr - 1500       ;

loop(Scenario,
trans_c = sav_trans_cost;
trans_c = trans_cost(scenario);

SOLVE Ann_HEM USING NLP MAXIMIZING obj;

Sc_Tot_withdraw_Amu(scenario, "normal_90")  = sum(agdm$agdm_amu(agdm), sum(rn,
WITHDRAW.l(rn,agdm)) ) ;
Sc_Env_flow_Amu(scenario, "normal_90")  =   Aral_Flow.l     ;
Sc_wat_bolt_Amu(scenario, "normal_90")  =  sum(agdm$agdm_amu(agdm), wbolt.l(agdm) );
Sc_wat_sold_Amu(scenario, "normal_90")  =  sum(agdm$agdm_amu(agdm), wsold.l(agdm) );
Sc_tot_net_ben_Amu(scenario, "normal_90")  = sum(agdm$agdm_amu(agdm), Tot_profit.l(agdm)) ;
Sc_WTP_Amu(scenario, "normal_90")   =    (sum(agdm$agdm_amu(agdm),
wtp.l(agdm)*Tot_land.l(agdm)) ) /(sum(agdm, Tot_land.l(agdm)));

Sc_Tot_withdraw_Syr(scenario, "normal_90")  = sum(agdm$agdm_syr(agdm), sum(rn,
WITHDRAW.l(rn,agdm)) ) ;
*Sc_Env_flow_Amu(scenario, "normal_90")  =   Aral_Flow.l     ;
Sc_wat_bolt_Syr(scenario, "normal_90")  =  sum(agdm$agdm_syr(agdm), wbolt.l(agdm) );
Sc_wat_sold_Syr(scenario, "normal_90")  =  sum(agdm$agdm_syr(agdm), wsold.l(agdm) );
Sc_tot_net_ben_Syr(scenario, "normal_90")  = sum(agdm$agdm_syr(agdm), Tot_profit.l(agdm)) ;
Sc_WTP_Syr(scenario, "normal_90")   =    (sum(agdm$agdm_syr(agdm),
wtp.l(agdm)*Tot_land.l(agdm))) /(sum(agdm, Tot_land.l(agdm)))    ;
);


Source0 (rn, "initial") = (0.8/0.9)*Source0 (rn, "initial") ;
Water_right1_0(agdm)$agdm_amu(agdm) =  (Water_right_shr1(agdm)/(1-retn(agdm))) * (  sum(rn,
Source0(rn, "initial")$rns_amu(rn)) - Tot_Ind_Mun_Wat_Amu - 3500 )       ;
Water_right1_0(agdm)$agdm_syr(agdm) =  (Water_right_shr1(agdm)/(1-retn(agdm))) * (  sum(rn,
Source0(rn, "initial")$rns_syr(rn)) - Tot_Ind_Mun_Wat_Syr - 1500 )      ;

Tot_shareable_wat_Amu= sum(rn, Source0(rn, "initial")$rns_amu(rn)) - Tot_Ind_Mun_Wat_Amu - 3500
;
Tot_shareable_wat_Syr= sum(rn, Source0(rn, "initial")$rns_syr(rn)) - Tot_Ind_Mun_Wat_Syr - 1500       ;


loop(Scenario,
trans_c = sav_trans_cost;
trans_c = trans_cost(scenario);
```

```
SOLVE Ann_HEM USING NLP MAXIMIZING obj;
Sc_Tot_withdraw_Amu(scenario, "normal_80")  = sum(agdm$agdm_amu(agdm), sum(rn,
WITHDRAW.l(rn,agdm)) ) ;
Sc_Env_flow_Amu(scenario, "normal_80")  =   Aral_Flow.l     ;
Sc_wat_bolt_Amu(scenario, "normal_80")  =  sum(agdm$agdm_amu(agdm), wbolt.l(agdm) );
Sc_wat_sold_Amu(scenario, "normal_80")  =  sum(agdm$agdm_amu(agdm), wsold.l(agdm) );
Sc_tot_net_ben_Amu(scenario, "normal_80")  = sum(agdm$agdm_amu(agdm), Tot_profit.l(agdm)) ;
Sc_WTP_Amu(scenario, "normal_80")   =     (sum(agdm$agdm_amu(agdm),
wtp.l(agdm)*Tot_land.l(agdm)) ) /(sum(agdm, Tot_land.l(agdm)));

Sc_Tot_withdraw_Syr(scenario, "normal_80")  = sum(agdm$agdm_syr(agdm), sum(rn,
WITHDRAW.l(rn,agdm)) ) ;
*Sc_Env_flow_Amu(scenario, "normal_80")  =   Aral_Flow.l     ;
Sc_wat_bolt_Syr(scenario, "normal_80")  =  sum(agdm$agdm_syr(agdm), wbolt.l(agdm) );
Sc_wat_sold_Syr(scenario, "normal_80")  =  sum(agdm$agdm_syr(agdm), wsold.l(agdm) );
Sc_tot_net_ben_Syr(scenario, "normal_80")  = sum(agdm$agdm_syr(agdm), Tot_profit.l(agdm)) ;
Sc_WTP_Syr(scenario, "normal_80")   =     (sum(agdm$agdm_syr(agdm),
wtp.l(agdm)*Tot_land.l(agdm))) /(sum(agdm, Tot_land.l(agdm)))    ;
);

***Exporting the results to Excel*****************
$libinclude xlexport     Sc_Env_flow_Amu         ASB_Irrigation_profit_functions_4.xls
Env_flow_Amu_transac
$libinclude xlexport     Sc_Tot_withdraw_Amu     ASB_Irrigation_profit_functions_4.xls
Tot_withdraw_Amu_transac
$libinclude xlexport     Sc_wat_bolt_Amu         ASB_Irrigation_profit_functions_4.xls
wat_bolt_Amu_transac
$libinclude xlexport     Sc_wat_sold_Amu         ASB_Irrigation_profit_functions_4.xls
wat_sold_Amu_transac
$libinclude xlexport     Sc_tot_net_ben_Amu      ASB_Irrigation_profit_functions_4.xls
tot_net_ben_Amu_transac
$libinclude xlexport     Sc_WTP_Amu              ASB_Irrigation_profit_functions_4.xls
WTP_Amu_transac
$libinclude xlexport     Sc_Tot_withdraw_Syr     ASB_Irrigation_profit_functions_4.xls
Tot_withdraw_Syr_transac
$libinclude xlexport     Sc_wat_bolt_Syr         ASB_Irrigation_profit_functions_4.xls
wat_bolt_Syr_transac
$libinclude xlexport     Sc_wat_sold_Syr         ASB_Irrigation_profit_functions_4.xls
wat_sold_Syr_transac
$libinclude xlexport     Sc_tot_net_ben_Syr      ASB_Irrigation_profit_functions_4.xls
tot_net_ben_Syr_transac
$libinclude xlexport     Sc_WTP_Syr              ASB_Irrigation_profit_functions_4.xls      WTP_Syr_transac
;
```

Appendix D: Database of the disaggregated hydro-economic model

Table D.1 Distribution efficiency across the demand sites

Demand sites	Distribution efficiency
Amy Darya basin:	
GBAO	0.64
Khatlon	0.64
RRT	0.64
Surkhandarya	0.64
Mary	0.70
Ahal	0.70
Lebap	0.70
Kashkadarya	0.64
Samarkand	0.64
Navoi	0.65
Bukhara	0.65
Khorezm	0.65
Karakalpakstan	0.70
Dashauz	0.70
Narin	0.73
Syr Darya basin:	
Osh	0.73
Jalalabad	0.73
Ferghana	0.73
Andizhan	0.73
Namangan	0.62
Sugd	0.73
Tashkent	0.73
Syrdarya	0.71
Jizzah	0.70
South Kazakhstan	0.70
Kyzylorda	0.70

Source: Based on GEF (2002)

Table D.2 Municipal water use (million m^3)

Demand sites	**Municipial water use by months**												**Total**
	m01	**m02**	**m03**	**m04**	**m05**	**m06**	**m07**	**m08**	**m09**	**m10**	**m11**	**m12**	
<u>Amu Darya basin:</u>													
GBAO	2	2	2	2	2	2	2	2	2	2	2	2	**24**
Khatlon	20	18	20	20	20	20	21	21	20	20	19	20	**238**
RRT	12	11	13	12	13	12	13	13	13	13	12	12	**150**
Surkhandarya	12	11	12	12	12	12	13	12	12	11	12	11	**142**
Mary	6	6	6	6	6	6	6	6	6	6	6	6	**72**
Ahal	9	9	9	9	9	9	9	9	9	9	9	9	**102**
Lebap	6	6	6	6	6	6	6	6	6	6	6	6	**70**
Kashkadarya	10	11	12	12	12	12	13	13	12	12	11	11	**142**
Samarkand	26	28	29	30	30	31	32	32	30	30	28	28	**353**
Navoi	3	2	3	2	3	2	3	3	2	3	2	3	**30**
Bukhara	3	3	3	3	3	3	3	3	3	3	3	3	**34**
Khorezm	6	5	6	6	6	6	6	6	6	6	6	6	**71**
Karakalpakstan	4	4	4	4	4	4	4	4	4	4	4	4	**47**
Dashauz	1	0	0	0	0	0	0	0	0	0	0	0	**6**
<u>Syr Darya basin:</u>													
Narin	0	0	0	0	0	0	0	0	0	0	0	0	**1**
Osh	8	8	8	8	8	8	8	8	8	8	8	8	**94**
Jalalabad	4	4	4	4	4	4	4	4	4	4	4	4	**52**
Ferghana	39	41	43	45	46	47	48	48	45	42	43	43	**528**
Andizhan	12	12	13	13	13	13	13	13	14	14	13	13	**156**
Namangan	9	8	9	8	9	8	9	9	8	9	8	9	**103**
Sugd	14	13	14	14	15	15	15	15	15	14	14	14	**172**
Tashkent	82	84	91	93	95	98	101	99	93	92	88	85	**1100**
Syrdarya	9	10	10	11	11	11	12	12	12	11	10	10	**128**
Jizzah	8	9	9	9	10	10	10	10	9	9	9	9	**112**
South Kazakhstan	4	4	4	4	4	4	4	4	4	4	4	4	**42**
Kyzylorda	1	1	2	2	2	3	3	3	3	2	1	1	**23**

Source: SIC-ICWC (2011)

Table D.3 Industrial water use (million m^3)

Demand sites	Industrial water use by months												Total
	m01	m02	m03	m04	m05	m06	m07	m08	m09	m10	m11	m12	
GBAO	0	0	0	0	0	0	0	0	0	0	0	0	**2**
Khatlon	6	5	6	6	8	7	8	7	6	6	6	6	**75**
RRT	13	12	13	12	13	12	12	12	12	12	12	13	**150**
Surkhandarya	2	2	2	2	2	2	2	2	2	2	2	2	**26**
Mary	98	98	98	98	98	98	98	98	98	98	98	98	**1173**
Ahal	9	9	9	9	9	9	9	9	9	9	9	9	**104**
Lebap	11	11	11	11	11	11	11	11	11	11	11	11	**126**
Kashkadarya	4	4	5	4	5	4	5	4	4	4	4	4	**51**
Samarkand	2	1	1	2	2	2	2	2	2	2	2	2	**19**
Navoi	60	56	65	63	67	66	70	70	67	67	33	63	**747**
Bukhara	2	2	2	2	2	2	2	2	2	2	2	2	**25**
Khorezm	0	0	0	0	0	0	0	0	0	0	0	0	**2**
Karakalpakstan	16	20	35	24	29	31	39	46	45	33	22	27	**369**
Dashauz	1	1	1	1	1	1	1	1	1	1	1	1	**6**
Narin	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Osh	0	0	0	0	0	0	0	0	0	0	0	0	**4**
Jalalabad	2	2	2	2	2	2	2	2	2	2	2	2	**19**
Ferghana	23	23	24	24	25	26	26	26	24	24	23	23	**292**
Andizhan	3	4	4	4	4	4	4	4	4	4	4	4	**45**
Namangan	1	1	1	1	2	2	1	2	2	2	2	2	**18**
Sugd	10	8	9	10	11	11	12	11	8	9	8	9	**116**
Tashkent	168	153	169	169	170	170	171	171	171	171	170	170	**2022**
Syrdarya	50	46	51	140	145	140	145	145	140	51	49	51	**1152**
Jizzah	0	0	0	0	0	0	0	0	0	0	0	0	**5**
South Kazakhstan	3	3	3	3	3	3	3	3	3	3	3	3	**42**
Kyzylorda	2	2	2	2	4	5	6	3	2	3	3	2	**35**

Source: SIC-ICWC (2011)

Table D.4 Irrigation water use in normal year (million m^3)

Demand sites	Irrigation water use by months												Total
	m01	**m02**	**m03**	**m04**	**m05**	**m06**	**m07**	**m08**	**m09**	**m10**	**m11**	**m12**	
GBAO	0	0	0	12	28	112	140	52	19	0	0	0	**362**
Khatlon	27	93	128	582	595	825	1184	1197	732	155	67	27	**5611**
RRT	0	0	0	12	46	130	233	183	57	14	0	0	**674**
Surkhandarya	4	51	230	306	570	563	707	632	298	99	196	112	**3768**
Mary	520	520	455	390	520	911	976	1041	585	260	325	7	**6510**
Ahal	394	394	344	295	394	689	738	787	443	197	246	5	**4925**
Lebap	371	371	324	278	371	649	695	742	417	185	232	5	**4639**
Kashkadarya	2	71	499	594	540	648	980	891	94	142	321	147	**4929**
Samarkand	12	32	197	221	396	423	800	621	342	197	76	0	**3316**
Navoi	101	109	176	166	218	221	296	298	191	113	81	34	**2004**
Bukhara	465	229	176	276	324	391	673	705	364	238	110	31	**3984**
Khorezm	231	357	263	273	602	718	839	709	267	274	30	0	**4563**
Karakalpakstan	124	455	352	256	1041	1264	1643	1491	260	34	143	646	**7711**
Dashauz	0	263	856	461	922	1120	1185	1185	329	198	66	0	**6586**
Narin	0	0	4	26	96	164	199	122	39	32	25	0	**707**
Osh	0	0	48	88	307	363	346	270	164	129	72	0	**1787**
Jalalabad	0	0	97	97	97	97	97	97	97	97	0	0	**779**
Ferghana	75	170	233	211	355	427	599	584	285	239	148	41	**3367**
Andizhan	56	51	152	152	379	492	623	576	269	271	160	14	**3194**
Namangan	58	41	111	200	265	318	408	407	239	181	83	17	**2329**
Sugd	18	45	54	382	386	459	769	737	452	75	34	9	**3420**
Tashkent	6	20	23	213	511	614	681	572	117	80	13	0	**2850**
Syrdarya	174	86	123	202	418	362	502	486	153	224	132	38	**2900**
Jizzah	128	49	182	202	327	319	412	360	143	205	75	22	**2425**
South Kazakhstan	44	107	55	275	499	645	775	443	176	22	9	6	**3056**
Kyzylorda	0	0	0	154	721	861	857	534	6	0	0	0	**3133**

Source: SIC-ICWC (2011)

Table D.5 Water supply by source nodes over the months in normal year (million m^3)

Supply nodes	**Water supply by months**												**Total**
	m01	**m02**	**m03**	**m04**	**m05**	**m06**	**m07**	**m08**	**m09**	**m10**	**m11**	**m12**	
Amu Darya basin:													
Atrek	26	27	30	21	0	10	9	0	0	14	31	17	**184**
Guzardarya	8	10	12	25	9	8	5	4	4	6	10	11	**112**
Kafirnigan	273	287	635	1481	2259	2139	1576	814	419	321	304	297	**10805**
Kashkadariya	83	87	149	172	86	88	63	21	33	37	74	75	**968**
Kunduz	122	127	149	272	350	638	616	513	290	193	140	125	**3535**
Murgab	92	109	194	233	196	108	72	54	61	82	88	89	**1379**
Pyandj	1153	1090	1466	2357	3675	5464	6734	5653	2911	1879	1439	1323	**35144**
Sherabad	15	14	17	26	37	24	9	1	3	8	13	8	**175**
Surhandarya	143	128	156	245	349	223	84	7	31	76	125	80	**1647**
Tedjen	60	86	198	341	327	66	5	0	0	1	4	21	**1109**
Vakhsh	1713	1386	1157	1012	1940	1886	2748	2988	1557	942	837	917	**19082**
Yavansu	46	39	49	49	78	83	94	192	92	78	77	45	**923**
Zarafshan	200	176	178	180	371	814	103	876	492	254	208	201	**4054**
Syr Darya basin:													
Abshirsay	3	3	4	6	11	10	10	8	6	5	3	3	**71**
Aksu	6	5	5	5	8	17	25	22	15	11	9	7	**136**
Aris	26	62	96	63	43	23	41	16	88	81	21	20	**580**
Bugun	1	1	47	81	110	72	125	45	5	57	89	3	**637**
Chirchik	435	298	411	353	745	903	1022	963	512	440	267	242	**6591**
Isfara	14	12	11	11	24	61	120	116	53	27	19	15	**484**
Isfaramsay	28	24	23	20	43	104	189	110	61	38	28	29	**695**
Karadarya	105	109	163	327	685	597	463	240	139	134	145	147	**3256**
Kasansay	5	5	6	8	59	30	37	9	5	5	4	5	**179**
Kuvasay	0	0	0	8	0	0	4	22	4	0	0	0	**38**
Naryn	540	506	588	854	2133	2892	3470	2472	1284	821	640	1165	**17366**
Shakimardan	16	14	15	15	30	35	59	44	37	28	24	16	**333**
Shaydansay	9	9	9	13	34	54	55	17	6	10	7	6	**228**
Sokh	50	54	54	77	86	207	437	331	179	129	90	58	**1752**
Akhangaran	15	27	38	124	282	111	60	26	14	9	11	20	**737**
Keles	70	69	86	91	61	25	27	19	35	60	85	75	**703**
Kattasay	2	2	1	1	7	10	11	6	1	5	1	1	**49**
Shirinsay	5	4	5	5	6	5	6	4	6	5	6	5	**62**
Khojabakirgan	14	12	13	14	23	47	63	52	30	21	17	16	**322**
The Aral Sea basin	**5277**	**4784**	**5966**	**8488**	**14069**	**16754**	**18343**	**15646**	**8372**	**5778**	**4817**	**5042**	113335

Source: SIC-ICWC (2011)

Table D.6 Irrigation efficiency by crops and across the demand sites

Demand sites	**Irrigation efficiency by crops**										
	Cotton	**Fodder**	**Fruit**	**Wheat**	**Maize**	**Cords**	**Potato**	**Rice**	**Beet**	**Vegetables**	**Grapes**
GBAO	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.62	0.62	0.62
Khatlon	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.62	0.62	0.62
RRT	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.62	0.62	0.62
Surkhandarya	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.62	0.62	0.62
Mary	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.18	0.58	0.58	0.58
Ahal	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.18	0.58	0.58	0.58
Lebap	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.18	0.58	0.58	0.58
Kashkadarya	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.62	0.62	0.62
Samarkand	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.62	0.62	0.62
Navoi	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.52	0.52	0.52
Bukhara	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.52	0.52	0.52
Khorezm	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.52	0.52	0.52
Karakalpakstan	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.15	0.48	0.48	0.48
Dashauz	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.16	0.53	0.53	0.53
Narin	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.17	0.55	0.55	0.55
Osh	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.17	0.55	0.55	0.55
Jalalabad	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.17	0.55	0.55	0.55
Ferghana	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.17	0.55	0.55	0.55
Andizhan	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.17	0.55	0.55	0.55
Namangan	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.23	0.63	0.63	0.63
Sugd	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.18	0.55	0.55	0.55
Tashkent	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.18	0.55	0.55	0.55
Syrdarya	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.24	0.73	0.73	0.73
Jizzah	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.23	0.63	0.63	0.63
South Kazakhstan	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.23	0.63	0.63	0.63
Kyzylorda	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.15	0.48	0.48	0.48

Source: Based on GEF (2002)

Table D.7 Cropland area by crops and across the irrigation sites (1000s ha)

Demand sites	**Cropland areas**											**Total**
	Cotton	**Fodder**	**Fruit**	**Wheat**	**Maize**	**Cords**	**Potato**	**Rice**	**Beet**	**Vegetables**	**Grapes**	
GBAO	0	8	2	9	0	8	1	0	0	0	0	**28**
Khatlon	86	32	5	142	7	4	9	9	0	10	5	**308**
RRT	16	12	3	35	0	0	4	3	0	4	1	**79**
Surkhandarya	119	21	103	113	3	3	5	5	0	9	16	**398**
Mary	168	16	5	234	7	2	1	0	0	5	3	**442**
Ahal	103	21	6	249	3	2	0	0	0	5	17	**405**
Lebap	120	15	5	105	4	2	2	2	0	4	2	**262**
Kashkadarya	174	52	14	275	2	4	4	0	1	13	11	**549**
Samarkand	99	46	101	197	6	2	9	2	0	20	33	**514**
Navoi	44	12	36	43	2	1	1	0	0	3	5	**146**
Bukhara	129	4	4	79	0	2	3	0	0	8	9	**238**
Khorezm	100	40	6	16	2	2	2	40	0	6	2	**217**
Karakalpakstan	145	72	5	28	9	8	2	86	0	8	0	**364**
Dashauz	200	16	4	93	3	4	4	42	0	5	0	**371**
Narin	0	38	0	2	0	0	4	0	0	1	0	**46**
Osh	11	10	14	7	12	2	3	2	0	8	2	**72**
Jalalabad	24	0	6	7	14	0	0	2	0	7	1	**60**
Ferghana	127	30	111	92	5	2	5	2	0	13	6	**394**
Andizhan	110	15	19	70	4	0	5	2	0	13	5	**243**
Namangan	100	15	79	79	5	2	4	4	0	10	13	**310**
Sugd	54	36	16	111	6	5	10	3	0	11	13	**266**
Tashkent	113	40	101	113	9	3	8	14	0	24	14	**439**
Syrdarya	141	12	90	90	4	3	1	8	0	5	2	**356**
Jizzah	113	22	10	221	4	5	1	0	0	7	6	**388**
South Kazakhstan	134	82	21	37	11	18	8	3	2	0	20	**336**
Kyzylorda	0	38	0	11	0	9	6	59	0	7	0	**129**
The Aral Sea basin	**2434**	**706**	**767**	**2456**	**122**	**93**	**103**	**288**	**4**	**205**	**184**	**7361**

Source: SIC-ICWC (2011)

Table D.8 Maximum crop evapotranspiration by crops and across the demand sites (average of 1980-2000, in mm)

Demand sites	Maximum crop evapotranspiration										
	Cotton	Fodder	Fruit	Wheat	Maize	Cords	Potato	Rice	Beet	Vegetables	Grapes
GBAO	0	732	671	384	0	742	663	0	0	0	0
Khatlon	687	732	671	384	514	742	663	738	0	742	671
RRT	687	732	671	384	0	0	663	738	0	742	671
Surkhandarya	895	952	870	473	686	964	877	978	0	964	870
Mary	915	976	892	500	693	988	891	0	0	988	892
Ahal	915	976	892	500	693	988	0	0	0	988	892
Lebap	915	976	892	500	693	988	891	992	0	988	892
Kashkadarya	895	952	870	473	686	964	877	0	964	964	870
Samarkand	895	952	870	473	686	964	877	978	0	964	870
Navoi	895	952	870	473	686	964	877	0	0	964	870
Bukhara	895	952	870	473	0	964	877	0	0	964	870
Khorezm	895	952	870	473	686	964	877	978	0	964	870
Karakalpakstan	895	952	870	473	686	964	877	978	0	964	0
Dashauz	915	976	892	500	693	988	891	992	0	988	0
Narin	0	704	0	349	0	0	646	0	0	713	0
Osh	664	704	643	349	504	713	646	719	0	713	643
Jalalabad	664	0	643	349	504	0	0	719	0	713	643
Ferghana	895	950	869	472	684	962	875	975	0	962	869
Andizhan	895	950	869	472	684	0	875	975	0	962	869
Namangan	895	950	869	472	684	962	875	975	0	962	869
Sugd	687	732	671	384	514	742	663	738	0	742	671
Tashkent	895	950	869	472	684	962	875	975	0	962	869
Syrdarya	895	950	869	472	684	962	875	975	0	962	869
Jizzah	895	950	869	472	684	962	875	0	0	962	869
South Kazakhstan	856	906	827	431	663	918	844	942	918	0	827
Kyzylorda	0	923	0	433	0	935	863	964	0	935	0

Source: Based on IFPRI (2013)

Table D.9 Effective rainfall by crops and across the demand sites (average of 1980-2000, in mm)

Demand sites	Effective rainfall by crops										
	Cotton	Fodder	Fruit	Wheat	Maize	Cords	Potato	Rice	Beet	Vegetables	Grapes
GBAO	0	118	122	138	0	99	90	0	0	0	0
Khatlon	81	122	123	140	43	102	84	43	0	102	123
RRT	116	162	163	176	0	0	124	83	0	142	163
Surkhandarya	42	64	68	92	17	42	38	17	0	42	68
Mary	26	45	45	71	11	26	23	0	0	26	45
Ahal	26	46	46	71	12	26	0	0	0	26	46
Lebap	25	45	45	71	11	25	23	11	0	25	45
Kashkadarya	40	61	65	90	16	40	36	0	40	40	65
Samarkand	43	64	68	92	18	43	38	18	0	43	68
Navoi	43	64	69	92	18	43	39	0	0	43	69
Bukhara	36	58	62	87	0	36	33	0	0	36	62
Khorezm	32	51	51	75	17	32	28	17	0	32	51
Karakalpakstan	37	59	59	83	18	37	33	18	0	37	0
Dashauz	25	44	44	69	12	25	23	12	0	25	0
Narin	0	180	0	140	0	0	157	0	0	169	0
Osh	145	172	172	138	103	161	145	106	0	161	172
Jalalabad	143	0	180	174	100	0	0	112	0	178	180
Ferghana	70	92	97	125	35	70	59	35	0	70	97
Andizhan	75	97	101	135	36	0	64	36	0	75	101
Namangan	62	84	85	113	31	62	51	31	0	62	85
Sugd	77	99	103	115	40	79	71	40	0	79	103
Tashkent	84	108	112	149	39	85	75	39	0	85	112
Syrdarya	83	107	111	149	38	85	74	38	0	85	111
Jizzah	84	108	112	149	39	86	75	0	0	86	112
South Kazakhstan	73	91	95	110	34	73	64	34	73	0	95
Kyzylorda	0	55	0	55	0	41	36	18	0	41	0

Source: Based on IFPRI (2013)

Table D.10 Kc - crop coefficients

Crops	Crop coefficients by months											
	m01	**m02**	**m03**	**m04**	**m05**	**m06**	**m07**	**m08**	**m09**	**m10**	**m11**	**m12**
Cotton	0.00	0.00	0.00	0.35	0.40	0.87	1.20	1.20	0.99	0.71	0.00	0.00
Fodder	0.00	0.00	0.41	0.72	0.95	0.95	0.95	0.95	0.94	0.63	0.00	0.00
Fruit	0.00	0.00	0.50	0.58	0.76	0.90	0.90	0.90	0.80	0.70	0.00	0.00
Wheat	0.80	0.87	1.05	1.15	0.97	0.40	0.00	0.00	0.00	0.35	0.40	0.60
Maize	0.00	0.00	0.00	0.00	0.36	0.95	1.10	0.86	0.38	0.00	0.00	0.00
Cords	0.00	0.00	0.00	0.70	0.76	0.96	1.05	1.05	1.01	0.97	0.00	0.00
Potato	0.00	0.00	0.00	0.50	0.55	1.15	1.15	0.96	0.75	0.00	0.00	0.00
Rice	0.00	0.00	0.00	0.00	1.05	1.13	1.20	1.20	0.95	0.00	0.00	0.00
Beet	0.00	0.00	0.00	0.70	0.76	0.96	1.05	1.05	1.01	0.97	0.00	0.00
Vegetables	0.00	0.00	0.00	0.70	0.76	0.96	1.05	1.05	1.01	0.97	0.00	0.00
Grapes	0.00	0.00	0.50	0.58	0.76	0.90	0.90	0.90	0.80	0.70	0.00	0.00

Source: Shieder (2011)

Table D.11 Ky crop yield response coefficients

Crops	**Cop yield response coefficients by months**											
	m01	**m02**	**m03**	**m04**	**m05**	**m06**	**m07**	**m08**	**m09**	**m10**	**m11**	**m12**
Cotton	0.00	0.00	0.00	0.20	0.40	0.40	0.50	0.50	0.40	0.20	0.00	0.00
Fodder	0.00	0.00	0.70	0.73	0.92	1.00	1.00	0.90	0.80	0.70	0.00	0.00
Fruit	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
Wheat	0.60	0.60	0.60	0.50	0.45	0.40	0.00	0.00	0.00	0.20	0.40	0.60
Maize	0.00	0.00	0.00	0.00	0.45	0.70	1.30	0.90	0.50	0.00	0.00	0.00
Cords	0.00	0.00	0.00	0.80	0.80	0.40	0.60	1.20	1.00	0.80	0.00	0.00
Potato	0.00	0.00	0.00	0.45	0.45	0.60	0.80	0.80	0.70	0.00	0.00	0.00
Rice	0.00	0.00	0.00	0.00	0.60	1.00	1.20	0.50	1.20	0.00	0.00	0.00
Beet	0.00	0.00	0.00	0.80	0.80	0.40	0.60	1.20	1.00	0.80	0.00	0.00
Vegetables	0.00	0.00	0.00	0.80	0.80	0.40	0.60	1.20	1.00	0.80	0.00	0.00
Grapes	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00

Source: Shieder (2011)

Table D.12 Seasonal crop yield response coefficients

Crops	Crop yield response coefficient
Cotton	0.85
Fodder	0.90
Fruit	1.10
Wheat	1.25
Maize	1.25
Cords	1.25
Potato	1.10
Rice	1.00
Beet	1.25
Vegetables	1.00
Grapes	1.00

Source: Based on Cai (1999) and Shieder (2011, p.206)

Table D.13 Observed yield levels by crops and across the irrigation sites (average of 1990-2000, in tons per ha)

Demand sites	Observed yield levels by crops										
	Cotton	Fodder	Fruit	Wheat	Maize	Cords	Potato	Rice	Beet	Vegetables	Grapes
GBAO	0.0	4.5	1.8	2.0	0.0	9.7	8.8	0.0	0.0	0.0	0.0
Khatlon	2.9	25.9	5.0	6.9	5.5	11.5	14.0	3.7	0.0	23.8	3.4
RRT	2.8	19.5	5.5	2.7	0.0	0.0	8.5	2.8	0.0	18.8	4.8
Surkhandarya	2.0	5.5	1.0	2.0	4.6	10.4	7.0	1.7	0.0	13.8	4.5
Mary	2.8	18.6	2.2	4.2	3.5	19.3	12.8	0.0	0.0	19.2	4.1
Ahal	2.0	2.5	5.4	1.2	3.3	7.1	0.0	0.0	0.0	19.2	4.0
Lebap	1.6	4.5	3.5	1.1	3.1	7.6	9.1	2.6	0.0	9.4	6.1
Kashkadarya	2.8	3.0	7.4	4.9	3.5	16.0	10.2	0.0	31.1	18.8	6.4
Samarkand	2.2	7.4	2.1	11.9	6.5	6.8	6.0	2.8	0.0	6.0	2.9
Navoi	1.7	2.2	2.4	1.0	2.0	10.5	8.3	0.0	0.0	14.6	1.7
Bukhara	1.6	0.6	2.5	1.3	0.0	5.3	12.5	0.0	0.0	17.8	9.5
Khorezm	2.3	1.8	3.4	1.4	2.1	8.7	8.3	1.7	0.0	13.9	2.8
Karakalpakstan	2.0	8.8	2.9	2.0	2.1	10.6	5.1	3.3	0.0	6.0	0.0
Dashauz	2.4	8.9	1.8	2.2	3.1	11.7	4.9	1.8	0.0	15.8	0.0
Narin	0.0	4.8	0.0	1.8	0.0	0.0	6.6	0.0	0.0	11.4	0.0
Osh	2.7	15.5	2.4	3.3	4.6	17.4	14.9	2.2	0.0	23.0	4.0
Jalalabad	2.0	0.0	10.9	9.9	3.3	0.0	0.0	2.1	0.0	13.2	4.0
Ferghana	2.7	12.1	0.5	1.5	2.5	11.7	9.4	1.8	0.0	13.6	2.4
Andizhan	2.4	5.0	2.7	13.6	11.6	0.0	5.1	3.2	0.0	7.0	4.0
Namangan	2.1	3.4	6.3	1.2	2.5	4.4	13.7	2.7	0.0	12.2	8.5
Sugd	2.4	6.7	0.8	1.5	2.9	14.9	12.3	1.8	0.0	22.6	3.5
Tashkent	1.9	2.8	3.5	1.1	2.6	10.0	12.6	3.5	0.0	16.5	4.0
Syrdarya	2.9	9.6	0.6	2.4	6.2	24.2	11.1	2.5	0.0	15.4	4.0
Jizzah	1.7	4.8	0.1	1.8	3.4	18.3	8.2	0.0	0.0	11.8	1.4
South Kazakhstan	2.4	8.2	1.7	2.7	3.1	15.9	11.1	3.3	29.0	0.0	4.0
Kyzylorda	0.0	8.5	0.0	9.7	0.0	5.8	5.1	2.7	0.0	17.4	0.0

Source: SIC-ICWC (2011)

Table D.14 Maximum yield levels by crops and across the irrigation sites (average of 1990-2000, in tons per ha)

Demand sites	Maximum yield levels by crops										
	Cotton	Fodder	Fruit	Wheat	Maize	Cords	Potato	Rice	Beet	Vegetables	Grapes
GBAO	0.0	7.4	2.8	2.4	0.0	22.1	15.1	0.0	0.0	0.0	0.0
Khatlon	3.2	34.3	9.1	11.3	5.7	14.8	19.5	5.1	0.0	28.7	4.6
RRT	3.1	26.2	12.5	4.0	0.0	0.0	14.5	7.0	0.0	21.6	7.0
Surkhandarya	2.3	6.7	1.4	2.4	6.6	18.5	16.9	3.1	0.0	17.4	10.0
Mary	3.1	23.8	7.4	6.8	4.2	22.6	16.3	0.0	0.0	21.6	5.7
Ahal	2.4	3.3	11.8	1.6	4.7	11.6	0.0	0.0	0.0	26.4	5.9
Lebap	2.7	5.6	4.7	1.3	3.5	9.0	11.7	3.3	0.0	13.9	8.2
Kashkadarya	3.3	3.9	8.5	10.2	4.3	21.6	13.8	0.0	96.7	28.4	8.3
Samarkand	2.5	9.6	2.1	13.6	6.6	7.0	6.1	3.3	0.0	6.3	3.1
Navoi	2.4	2.6	3.2	1.5	3.7	11.3	9.5	0.0	0.0	18.2	2.8
Bukhara	2.1	0.8	3.1	3.2	0.0	7.5	18.4	0.0	0.0	21.2	12.9
Khorezm	2.4	2.2	4.8	1.7	2.6	10.1	11.6	3.0	0.0	15.8	4.2
Karakalpakstan	2.4	13.8	4.9	3.6	2.6	14.6	6.7	4.4	0.0	12.6	0.0
Dashauz	2.8	13.6	2.3	2.6	4.2	14.0	6.8	2.5	0.0	22.9	0.0
Narin	0.0	7.7	0.0	2.5	0.0	0.0	10.8	0.0	0.0	17.4	0.0
Osh	3.1	18.6	7.3	4.0	5.6	20.3	18.9	2.8	0.0	27.3	5.3
Jalalabad	2.4	0.0	14.1	10.7	4.7	0.0	0.0	3.3	0.0	26.0	5.9
Ferghana	2.8	12.8	0.6	2.6	3.9	13.7	16.7	2.7	0.0	18.0	4.0
Andizhan	3.5	8.0	3.5	19.3	13.8	0.0	7.5	9.4	0.0	10.4	5.9
Namangan	2.5	3.9	12.4	1.8	3.7	7.0	20.3	3.6	0.0	15.1	12.2
Sugd	2.7	7.7	1.1	2.5	3.6	18.0	18.4	4.8	0.0	25.0	4.7
Tashkent	2.7	3.3	4.0	1.4	3.0	12.0	15.7	4.0	0.0	19.1	4.2
Syrdarya	3.3	11.0	1.2	3.4	13.8	28.2	16.8	3.8	0.0	19.6	4.6
Jizzah	2.3	5.7	0.4	2.4	4.8	21.9	11.2	0.0	0.0	19.6	2.4
South Kazakhstan	2.7	8.9	5.4	3.6	3.9	18.0	15.5	4.2	46.0	0.0	7.6
Kyzylorda	0.0	10.3	0.0	19.1	0.0	13.2	10.0	3.3	0.0	20.4	0.0

Source: SIC-ICWC (2011)

Table D.15 Crop prices across the irrigation sites (2006, in USD per ton)

Demand sites	Crop prices										
	Cotton	**Fodder**	**Fruit**	**Wheat**	**Maize**	**Cords**	**Potato**	**Rice**	**Beet**	**Vegetables**	**Grapes**
GBAO	494	49	151	98	98	202	226	478	49	201	224
Khatlon	453	45	136	90	90	169	210	478	45	158	424
RRT	494	49	151	98	98	202	226	478	49	201	224
Surkhandarya	439	65	240	130	130	193	244	478	65	155	319
Mary	425	52	237	103	103	307	168	478	52	203	203
Ahal	479	55	146	109	109	212	161	478	55	208	242
Lebap	479	55	146	109	109	212	161	478	55	208	242
Kashkadarya	439	65	240	130	130	193	244	478	65	155	319
Samarkand	425	52	237	103	103	307	168	478	52	203	203
Navoi	454	46	228	92	92	220	253	478	46	212	408
Bukhara	439	65	240	130	130	193	244	478	65	155	319
Khorezm	462	49	339	98	98	297	212	478	49	169	424
Karakalpakstan	439	65	240	130	130	193	244	478	65	155	319
Dashauz	494	49	151	98	98	202	226	478	49	201	224
Narin	494	49	151	98	98	202	226	478	49	201	224
Osh	468	48	229	96	96	132	285	478	48	117	287
Jalalabad	425	52	237	103	103	307	168	478	52	203	203
Ferghana	431	45	228	89	89	180	337	478	45	201	177
Andizhan	453	45	136	90	90	169	210	478	45	158	424
Namangan	479	55	146	109	109	212	161	478	55	208	242
Sugd	479	55	146	109	109	212	161	478	55	208	242
Tashkent	425	52	237	103	103	307	168	478	52	203	203
Syrdarya	466	45	304	91	91	127	297	478	45	176	184
Jizzah	379	45	151	89	89	168	144	478	45	169	347
South Kazakhstan	447	42	169	83	83	212	254	478	42	221	275
Kyzylorda	454	46	228	92	92	220	253	478	46	212	408

Source: Based on CIS-ICWC (2008)

Table D.16 Crop production costs across the irrigation sites (2006, in USD per ha)

Demand sites	Crop production costs										
	Cotton	Fodder	Fruit	Wheat	Maize	Cords	Potato	Rice	Beet	Vegetables	Grapes
GBAO	371	169	192	148	121	1341	1387	796	478	2975	887
Khatlon	797	894	519	478	380	1631	2473	1400	1819	3130	1242
RRT	691	738	593	203	351	2152	1346	1047	828	2904	743
Surkhandarya	534	284	213	205	470	1576	1531	658	647	1702	1155
Mary	688	715	303	326	266	3795	1479	1226	1536	2533	455
Ahal	495	123	631	122	330	1231	1717	796	624	3262	772
Lebap	406	224	416	112	306	1326	1201	994	624	1600	1190
Kashkadarya	725	156	1525	497	362	2425	2216	1240	1591	2305	1644
Samarkand	550	285	283	915	497	1329	690	1052	485	800	318
Navoi	445	92	444	83	163	1895	1714	204	385	2532	544
Bukhara	427	33	525	132	124	796	2730	505	821	2182	2443
Khorezm	443	70	628	107	163	1926	1489	633	234	2058	885
Karakalpakstan	523	450	607	203	214	1608	1114	1245	142	742	363
Dashauz	586	336	188	168	232	1627	777	665	478	2441	761
Narin	530	183	321	140	164	1087	1046	796	478	1768	1140
Osh	676	566	422	245	334	1808	3503	831	1914	2119	937
Jalalabad	495	203	1491	762	256	2170	1521	796	485	1751	441
Ferghana	584	425	109	108	173	1678	2498	673	130	2143	331
Andizhan	661	174	283	941	800	877	900	1229	437	929	1453
Namangan	517	166	737	120	246	757	1801	1017	624	2063	1645
Sugd	590	331	98	147	284	2593	1618	677	586	3845	674
Tashkent	463	109	485	86	202	1968	1462	1344	485	2185	449
Syrdarya	680	348	128	171	444	2178	2442	953	911	1974	526
Jizzah	378	163	13	124	233	1659	766	832	599	1378	295
South Kazakhstan	634	263	183	171	200	1824	1828	1244	924	3254	692
Kyzylorda	488	350	539	803	170	1053	1061	1029	380	3017	1894

Source: Based on CIS-ICWC (2008)

Table D.17 Crop production profits across the irrigation sites (2006, in USD per ha)

Demand sites	Crop production profits										
	Cotton	**Fodder**	**Fruit**	**Wheat**	**Maize**	**Cords**	**Potato**	**Rice**	**Beet**	**Vegetables**	**Grapes**
GBAO	381	50	79	43	36	615	601	207	141	889	411
Khatlon	519	268	154	143	114	326	475	364	546	635	196
RRT	710	217	244	60	103	988	583	272	243	868	344
Surkhandarya	360	77	35	56	128	427	181	171	176	437	275
Mary	491	246	221	112	91	2140	664	319	529	1363	378
Ahal	459	13	153	13	36	270	393	207	67	727	188
Lebap	376	24	101	12	33	290	275	259	67	357	290
Kashkadarya	488	42	250	135	98	657	262	323	433	592	391
Samarkand	393	98	206	315	171	750	310	274	167	430	265
Navoi	320	10	108	9	18	415	392	53	42	565	133
Bukhara	288	9	86	36	34	216	322	132	223	561	582
Khorezm	599	17	514	26	40	641	262	165	57	307	295
Karakalpakstan	352	122	99	55	58	436	131	324	39	191	86
Dashauz	602	99	77	49	68	747	337	173	141	730	353
Narin	545	54	132	41	48	499	453	207	141	529	528
Osh	591	174	119	75	103	481	750	216	588	568	215
Jalalabad	353	70	1085	262	88	1224	683	207	167	942	366
Ferghana	559	115	6	29	47	426	667	175	35	600	88
Andizhan	430	52	84	282	240	175	173	320	131	188	230
Namangan	479	18	179	13	27	166	412	265	67	460	401
Sugd	547	36	24	16	31	568	370	176	63	857	165
Tashkent	330	38	353	30	70	1110	656	350	167	1175	373
Syrdarya	682	88	46	43	112	900	852	248	231	728	215
Jizzah	268	51	7	38	72	1414	412	217	186	605	178
South Kazakhstan	440	81	98	53	62	1554	983	324	284	1429	417
Kyzylorda	351	38	131	87	18	231	243	268	41	673	462

Source: Based on CIS-ICWC (2008)

Table D.18 Costs of improving irrigation efficiency (2006, in USD per m^3)

Demand sites	Costs of improving crop irrigation efficiency										
	Cotton	**Fodder**	**Fruit**	**Wheat**	**Maize**	**Cords**	**Potato**	**Rice**	**Beet**	**Vegetables**	**Grapes**
GBAO	0.031	0.031	0.028	0.031	0.031	0.028	0.028	0.028	0.028	0.028	0.028
Khatlon	0.031	0.031	0.028	0.031	0.031	0.028	0.028	0.028	0.028	0.028	0.028
RRT	0.031	0.031	0.028	0.031	0.031	0.028	0.028	0.028	0.028	0.028	0.028
Surkhandarya	0.037	0.037	0.025	0.037	0.037	0.025	0.025	0.025	0.025	0.025	0.025
Mary	0.037	0.037	0.025	0.037	0.037	0.025	0.025	0.025	0.025	0.025	0.025
Ahal	0.037	0.037	0.025	0.037	0.037	0.025	0.025	0.025	0.025	0.025	0.025
Lebap	0.049	0.049	0.025	0.049	0.049	0.025	0.025	0.025	0.025	0.025	0.025
Kashkadarya	0.037	0.037	0.025	0.037	0.037	0.025	0.025	0.025	0.025	0.025	0.025
Samarkand	0.031	0.031	0.028	0.031	0.031	0.028	0.028	0.028	0.028	0.028	0.028
Navoi	0.049	0.049	0.025	0.049	0.049	0.025	0.025	0.025	0.025	0.025	0.025
Bukhara	0.049	0.049	0.025	0.049	0.049	0.025	0.025	0.025	0.025	0.025	0.025
Khorezm	0.056	0.056	0.027	0.056	0.056	0.027	0.027	0.027	0.027	0.027	0.027
Karakalpakstan	0.056	0.056	0.027	0.056	0.056	0.027	0.027	0.027	0.027	0.027	0.027
Dashauz	0.056	0.056	0.027	0.056	0.056	0.027	0.027	0.027	0.027	0.027	0.027
Narin	0.031	0.031	0.028	0.031	0.031	0.028	0.028	0.028	0.028	0.028	0.028
Osh	0.031	0.031	0.028	0.031	0.031	0.028	0.028	0.028	0.028	0.028	0.028
Jalalabad	0.031	0.031	0.028	0.031	0.031	0.028	0.028	0.028	0.028	0.028	0.028
Ferghana	0.037	0.037	0.025	0.037	0.037	0.025	0.025	0.025	0.025	0.025	0.025
Andizhan	0.037	0.037	0.025	0.037	0.037	0.025	0.025	0.025	0.025	0.025	0.025
Namangan	0.037	0.037	0.025	0.037	0.037	0.025	0.025	0.025	0.025	0.025	0.025
Sugd	0.043	0.043	0.027	0.043	0.043	0.027	0.027	0.027	0.027	0.027	0.027
Tashkent	0.043	0.043	0.027	0.043	0.043	0.027	0.027	0.027	0.027	0.027	0.027
Syrdarya	0.049	0.049	0.025	0.049	0.049	0.025	0.025	0.025	0.025	0.025	0.025
Jizzah	0.049	0.049	0.025	0.049	0.049	0.025	0.025	0.025	0.025	0.025	0.025
South Kazakhstan	0.056	0.056	0.027	0.056	0.056	0.027	0.027	0.027	0.027	0.027	0.027
Kyzylorda	0.056	0.056	0.027	0.056	0.056	0.027	0.027	0.027	0.027	0.027	0.027

Source: Based on Cai (1999) and considering inflation rates between 1998 and 2006

Table D.19 Irrigation water conveyance costs (2006, in USD per m^3)

Demand sites	**Conveyance cost[a] (USD per m^3)**	**Costs of improving conveyance efficiency[b] (USD per m^3)**	**Costs of groundwater use[b] (USD per m^3)**	**Costs of re-using return flows[b] (USD per m^3)**
GBAO	0.0031	0.015	0.0062	0.049
Khatlon	0.0130	0.015	0.0062	0.049
RRT	0.0031	0.015	0.0062	0.049
Surkhandarya	0.0091	0.017	0.0049	0.079
Mary	0.0019	0.020	0.0087	0.080
Ahal	0.0122	0.020	0.0087	0.080
Lebap	0.0019	0.020	0.0087	0.080
Kashkadarya	0.0126	0.017	0.0087	0.080
Samarkand	0.0031	0.015	0.0049	0.069
Navoi	0.0047	0.021	0.0087	0.080
Bukhara	0.0122	0.021	0.0087	0.080
Khorezm	0.0019	0.002	0.0074	0.074
Karakalpakstan	0.0012	0.002	0.0074	0.074
Dashauz	0.0019	0.002	0.0074	0.074
Narin	0.0044	0.015	0.0062	0.049
Osh	0.0044	0.015	0.0062	0.049
Jalalabad	0.0073	0.015	0.0062	0.049
Ferghana	0.0044	0.017	0.0049	0.079
Andizhan	0.0073	0.017	0.0049	0.079
Namangan	0.0130	0.017	0.0049	0.079
Sugd	0.0130	0.020	0.0037	0.069
Tashkent	0.0019	0.020	0.0037	0.069
Syrdarya	0.0024	0.021	0.0087	0.080
Jizzah	0.0054	0.021	0.0087	0.080
South Kazakhstan	0.0054	0.002	0.0037	0.074
Kyzylorda	0.0012	0.002	0.0074	0.074

Source: [a]Based on MAWR (2007); [b]Based on Cai (1999) and considering inflation rates between 1998 and 2006

Table D.20 Evaporation from the reservoirs (in mm)

Reservoirs	**Evaporation from the reservoirs by months**											
	m01	**m02**	**m03**	**m04**	**m05**	**m06**	**m07**	**m08**	**m09**	**m10**	**m11**	**m12**
*Rogun	12	20	47	102	157	169	171	143	100	38	27	14
Nurek	12	20	47	102	157	169	171	143	100	38	27	14
Tuyamuyun	24	40	94	204	314	338	342	286	200	76	54	28
*Kambarata	12	20	47	102	157	169	171	143	100	38	27	14
Tokhtogul	12	20	47	102	157	169	171	143	100	38	27	14
Andizhan res	12	20	94	204	314	338	342	286	200	76	54	28
Kayrakum	24	40	94	204	314	338	342	286	200	76	54	28
Farkhad	24	40	40	100	150	170	170	140	100	38	27	14
Shardara	24	40	94	204	314	338	342	286	200	76	54	28
Charvak	24	40	94	204	314	338	342	286	200	76	54	28

Notes: *Reservoirs planned to build in recent future

Source: Based on Cai (1999)

Table D.21 Reservoir level-storage and area-storage parameters

	Minimum reservoir storage (million m3)	Maximum reservoir storage (million m3)	Reservoir area and storage volume relationship parameters				Reservoir level and storage volume relationship parameters			Reservoir construction costs (million USD per month)
			c0	c1	c2	c3	d0	d1	d2	
*Rogun	3040	13300	1	0.021	-0.000001426	0.00000000006	86	0.020	-0.00000064	13
Nurek	2500	7130	14	0.021	-0.000002850	0.00000000018	10	0.056	-0.00000370	0
Tuyamuyun	2308	7800	0	0.100	0.000000000	0.00000000000	2	0.002	-0.00000007	0
*Kambarata	1220	4650	1	0.022	-0.000004581	0.00000000052	85	0.027	0.00000000	7
Tokhtogul	5500	19500	9	0.038	-0.000002355	0.00000000006	87	0.006	-0.00000008	0
Andizhan res	150	1900	0	0.036	0.000005769	-0.00000000202	31	0.077	-0.00002169	0
Kayrakum	750	3350	10	0.375	-0.000118702	0.00000001608	11	0.005	-0.00000043	0
Farkhad	45	595	0	0.000	0.000000000	0.00000000000	0	0.000	0.00000000	0
Shardara	970	5200	31	0.326	-0.000065024	0.00000000588	11	0.004	-0.00000027	0
Charvak	430	2010	1	0.042	-0.000017810	0.00000000324	72	0.055	-0.00000870	0

Notes: Reservoir surface area (S) and storage volume (V) are related to each other through the following equation: $S=c0+c1\ V+c2\ V^2+c3\ V^3$;
Reservoir level (H-Htail) and storage volume (V) are related to each other through the following equation: $H-H_{tail}=d0+d1\ V+d2\ V^2$
Source: EC IFAS (2013)

Table D.22 Maximum production capacity and efficiency of the power stations

Power stations	Maximum power generation capacity (in MW)	Power station efficiency
*Rogun	3600	0.90
Nurek	3000	0.80
Tuyamuyun	150	0.80
*Kambarata	1900	0.90
Tokhtogul	1200	0.85
Kurupsay	800	0.85
Tashkumir	450	0.85
Shamaldisay	240	0.85
Uchkurgan	180	0.85
Andizhan	140	0.85
Kayrakum	126	0.80
Farhad	126	0.85
Shardara	100	0.85
Chirchik	621	0.80

Notes: *Reservoirs planned to build in recent future
Source: SIC-ICWC (2003) and EC IFAS (2013)