

Optimizing Adjustments to Transboundary Water Sharing Plans: A Multi-Basin Approach

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Abstract Afghanistan contributes water supplies to Iran, Pakistan, Tajikistan, Turkmenistan, and Uzbekistan. However, with the exception of the Helmand Basin, Afghanistan has negotiated transboundary water sharing agreements with no downstream country. This paper describes a constrained optimization framework to minimize economic costs within each of nine Afghan transboundary basins of adapting to potential water sharing agreements. Model results show impacts of water agreements on farm income and food security for each Afghan basin. Our results show that unrestricted trading reduces the economic costs of adapting to water sharing treaties by two to 6 % compared to the conventional water sharing system. A higher scale of reservoir storage capacity as well as market trading of water among regions moderates costs of water shortages, both with and without water agreements in place.

Keywords Economic benefit · transboundary water resources · constrained optimization water treaties

1 Introduction

1.1 Background

Growing water scarcity and variability in supply coupled with increasing water demands worldwide have reinforced the need for equitable apportionment and sustainable use of shared

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water resources. The complexity of water allocation increases when dealing with transboundary rivers where stakeholders involved are countries (Mimi and Sawalhi 2003, Van der Zaag 2007). The need for improved transboundary water cooperation and agreements among riparian countries presents an ongoing global issue (Thomas et al. 2016, Wouters 2013). Yet some riparian countries that have successfully engaged in transboundary treaty agreements face roadblocks to implementing those agreements (McKinney 2011). The need for workable methods to implement signed treaty agreements comes partly from weak accounting for important forces such as climate variability and change, increasing water demand with rising populations, and environmental sustainability challenges (Ahmad 2010, UN Water 2008).

Afghanistan's irrigated agriculture uses about 85% of the nation's water. That sector's importance and its essential role in creating national wealth and providing income-earning opportunities are widely recognized. Nevertheless, according to a recent Afghan government report for donor partners, a critical assessment of the future of irrigated agriculture and its potential for improvement is essential. Afghan irrigated agriculture's challenges are complicated further by outdated agricultural practices and lack of modern inputs and weak access to greater mechanization; so water itself becomes an important on-farm resource to use wisely. This is especially important as there is little reservoir storage in the country to protect irrigated agriculture in drought periods (Government of Islamic Republic of Afghanistan Ministry of Agriculture 2016).

Afghanistan also faces numerous challenges regarding the management and use of its large water endowments shared with numerous downstream countries. As a headwater country to several major transboundary river basins, Afghanistan bears the responsibility of cooperating with downstream countries regarding equitable apportionment of supplies while protecting its own water users' economic welfare. Except for the Helmand Basin Treaty of 1973 agreement between Afghanistan and Iran, Afghanistan has entered into no treaty agreement with downstream countries regarding the regulation and use of its transboundary waters (Hanasz 2012). Although the Helmand Basin Treaty agreement of 1973 is in place, implementing that treaty faces challenges arising from high natural flow variability and unmeasured flows going into Iran (Government of the Islamic Republic of Afghanistan 2007).

Transboundary water treaty agreements have the potential to provide economic benefits to all riparian countries (Giordano and Wolf 2003, Grey and Sadoff 2003, Zeitoun and Mirumachi 2008, Zeitoun and Warner 2006). Treaty cooperation can promote regional economic growth, increased human well-being, enhanced environmental sustainability and improved political stability (Jalilov et al. 2013, United Nations Economic Commission for Europe 2015). In addition, regional water cooperation creates transparency among riparian countries concerning basin water use and management (Dinar and Wolf 1994). Drafting and enforcing a transboundary treaty agreement on Afghanistan's shared river basins could potentially eliminate over appropriation of water resources as well as encourage sustainable and efficient water use in the region (Libert and Lipponen 2012).

1.2 Previous Work

Water treaty negotiations between Afghanistan and downstream countries date to the nineteenth century. For example an 1873 agreement between Afghanistan and Russia as well as 1946 and 1958 agreements between Afghanistan and the former USSR all sought to promote water use and cooperation among Afghanistan and downstream countries (Horsman 2005).

Historically, water dialogue typically occurs to promote cooperation among water sharing riparians. A 2010 investigation on managing waters of the Kabul River Basin found key issues such as declining annual flow of the Kabul River into Pakistan due to climate variability and persistent drought. Other factors included some Afghan hydro-power developments as well as weak regional cooperation on water sharing among riparian countries (Ahmad 2010). An analysis of hydropower investigated the impact of climate change on water resources and found that hydropower production is largely vulnerable to long-run climate changes that can influence the distribution of runoff (Hurd et al. 2004).

A notable recent work investigated water flow, irrigation development and the impact of climate change in northern Afghanistan (Rycroft and Wegerich 2009). Those results found that forecast flows across the northern basin, which includes Amu Darya and Panj River Basins, are forecast 10–30% lower with climate change. Results also established that such shortages in water flows have negative impacts on irrigated agriculture in the region. (Thomas and Warner 2015) investigated the dynamics of hydro-politics in the Harirud River basin between Afghanistan, Iran and Turkmenistan. Results identified Afghanistan as a weak negotiator characterized by the absence of dialogue as well as resource capture impacts from the Salma Dam construction.

Afghanistan needs better information on its water supply and delivery capacity to better negotiate future water sharing arrangements with its neighbors (Thomas and Warner 2015). Plans by Iran and Turkmenistan to jointly construct the Dostluk Dam in the Harirud Basin takes on regional importance (King and Sturtewagen 2010). Nevertheless, some have suggested that several riparian communities continue engaging in strategies of unilateral resource capture, in which each individual country believes it can increase its own water demand without entering into formal transboundary negotiating agreements (Thomas and Warner 2015, Wegerich 2008).

This *Journal* alone has published numerous works on water demand management, water allocation, climate change, drought adjustment, and mitigation of irrigation water shortages, all of which provide insights to the goal of minimizing negative impacts of growing water scarcity. Two recent studies investigated integrated impacts of climate change mitigated by man-made interventions by upstream water users sharing waters of transboundary basins (Al-Faraj and Tigkas 2016, van Pelt and Swart 2011). A 2016 work on water demand management suggests that water cooperation among users can yield more benefits (Xiao et al. 2016). Analysis from 2008 used decision analysis to evaluate and compare four transboundary water treaties (Ma et al. 2008). Findings revealed limitations of international water treaty design in relation to conflict resolution and suggested cooperation from non-treaty methods as a possible pathway. The results also suggest that problems inherent described in four special cases studied are common to numerous current transboundary water treaties.

1.3 Research Gaps

While attempts at water treaty negotiations over the use of several transboundary basins in Afghanistan have occurred in the past, virtually none has led to a sustainable treaty agreement with its many downstream neighbors. There is an ongoing and urgent need for Afghan planners to have information on adjustment costs of various policy proposals that would share flows with downstream countries. Such information would put Afghan negotiators in a stronger position to negotiate transboundary water sharing agreements, for which this information is for the most part lacking.

Despite the need for analysis of water cooperation among riparian countries, to date we have seen no multi-basin peer reviewed study of the adjustment costs to Afghanistan from potential transboundary water agreements. For Afghans to benefit from a water agreement on any of its transboundary rivers, an investigation is needed to assess economic impacts of adapting to proposed agreements. Weak information on adjustment costs of transboundary water arrangements limits the capacity of Afghan policymakers to contribute to negotiated settlements.

1.4 Original Contribution

The novelty of this paper lies in its presentation of a nationwide multi-basin framework for assessing alternative water sharing systems combined with reservoir capacity expansion planning. Such a national scale analysis of water sharing systems combined with optimized reservoir capacity planning has the potential to reduce the internal economic cost of establishing transboundary water sharing arrangements with downstream countries.

1.5 Objectives

This paper presents an empirical constrained optimization framework developed for each of nine transboundary Afghan basins. The goal served by this analysis is to discover combinations of infrastructure development and internal water shortage sharing methods. That discovery, if successful, can inform the design of complementary policy instruments to reduce economic costs of adapting to potential water sharing plans enacted with downstream neighbors. Our investigation summarizes impacts on farm income and food security for each of nine Afghan river basins for two possible methods to share water supplies internally under four reservoir development options, while meeting downstream water sharing agreements if enacted.

2 Materials and Methods

2.1 Study Area

Our study area consists of nine sub-basins within five major river basins. The five major basins are the Amu Darya, Northern, Harirud-Murghab, Helmand and Kabul (Indus) Basins. The Amu Darya River Basin forms much of the border between Afghanistan and Tajikistan, the entire border of Afghanistan and Uzbekistan and parts of the border of Afghanistan and Turkmenistan. Its main tributaries include the Panj, Kokcha, Kunduz, Khanabad and Ab-I Rustaq watersheds. Headwaters of the Amu Darya originate from the Pamir River and Chakmatin Lake in Badakhshan Province. It drains into the Aral Sea after travelling 2400 km. There is no formal Afghan treaty agreement with downstream countries that stipulate an allocation among countries of the waters in the Amu Darya Basin.

The Northern Basin consists of the Khulm, Balkh, Sari Pul and Shirin Tagab watersheds. It contributes 2 % of the total annual water flow in Afghanistan. During seasons of high precipitation, the Balkh River contributes flows to Turkmenistan. As is the case for the Amu Darya there is no transboundary water treaty agreement between Afghanistan and Turkmenistan.

The Helmand Basin covers several sub-watersheds in southern Afghanistan, including Adraskan Rod, Farah Rod, Upper and Lower Helmand. Despite the huge drainage area, it constitutes only 11% of the total annual water flow of supplies into the country. The Helmand Basin drains water from the western side of the Paghman Mountains northwest of Kabul and travels 1150 km to the border between Afghanistan and Iran. At the international border the Helmand River terminates into the Sistan wetlands and Lake Hamun in Iran. Afghanistan and Iran signed an international treaty in 1973 covering use of the waters of the Helmand Basin. The treaty describes a discharge of $22\text{m}^3/\text{s}$ to Iran and further permits Iran to purchase an additional quantity of $4\text{m}^3/\text{s}$ during normal and average years (Government of the Islamic Republic of Afghanistan 2007).

The Kabul Basin drains the Kabul River and its tributaries in Afghanistan into the Indus River. The Kabul Basin accounts for approximately 26% of the total annual water flow generated inside Afghanistan (Ahmad 2010). There is no transboundary treaty between Afghanistan and its downstream neighbor of Pakistan. The lack of treaty agreement between Afghanistan and Pakistan poses difficult hydrological, political, and economic challenges regarding sustainable and equitable use of the Kabul Basin (Figure 1). Other basin descriptions are available from the authors on request, but could not be included because of space limitations.

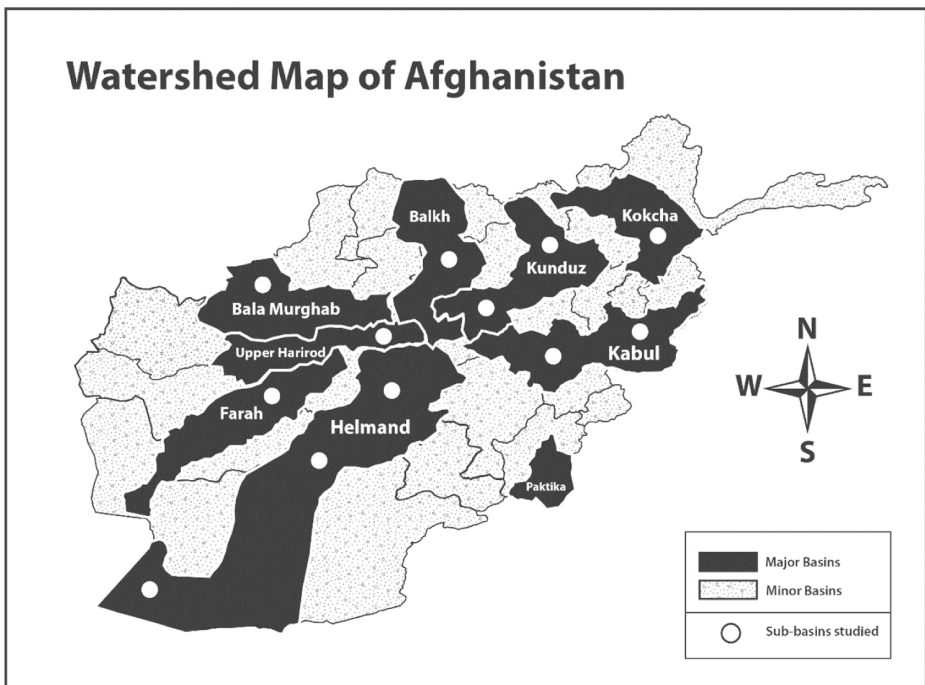


Illustration by Ana Henke, Marketing and Communications
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Fig. 1 Afghanistan’s Major River Basins Used for Present Study. Source: Adapted from Watershed Map of Afghanistan, Afghanistan Information Management Service (AIMS)

2.2 Model and Data

A constrained optimization framework was formulated to analyze economic benefits of water use in irrigated agriculture, combined with analysis of reservoir storage capacity expansion, water right systems and transboundary water treaty agreements. The model contains many moving parts, each of which requires connecting handles to the other parts as well as data to read. Irrigated land in production, crop yield, water use, crop prices and annual flows were some of the data secured. Data on irrigated in land production by province and basin was secured from the Food and Agriculture Organization (Food And Agricultural Organization 2012). Crop yield, evapotranspiration (ET) and price elasticity of demand data by crop were secured from (Gohar et al. 2013). Crops included wheat, alfalfa, rice, melon, cotton, potato, tomato and pulses. The research focused on these crops because of their importance to Afghan diets and/or farm earnings from crop production. Historical water use and supply by each basin was determined using estimates from crop water requirements (ET) and observed cropland in production. Future water supply scenarios defined by basin and year are stochastically distributed with historical mean and variance based on observed natural supply, shown in appendix eq. 1.

2.3 Hydrology

This work analyzed nine sub-basins: Kokcha, Kunduz, Balkh, Murghab, Upper Harrirud, Farah, Helmand, Kabul and Patika (Figure 1). The dynamics of surface water flows and uses in each sub-basin begin with natural supplies from snowmelt and other precipitation scenarios, moving downstream with consumptive use and sometimes spills from non-use. Each sub-basin was split into three agricultural regions (Upper, Middle and Lower) based on upstream-downstream location.

Crop water use (ET) per hectare is defined by sub-basin, region and crop. Total crop water use calculated by basin, water right system, region, crop, time, storage capacity and treaty agreements (mathematical appendix). The weak current capacity to store significant amount of natural supply in wet periods results in spills (unused water), runoff to downstream countries and subsequently shortages in the later hotter summer period.

In view of weak existing storage capacity, our study included four capacity expansion scenarios: no additional storage capacity, small (0.50 times annual average historical runoff), medium (0.75 times annual average historical runoff) and Large (2.50 times annual average historical runoff). Figure 2 shows the model framework for basin inflows, storage, use, and outflows.

2.4 Agronomy

Securing data on observed crop yield by sub-basin and region was quite a challenge to put it mildly. Observed yield data for wheat, alfalfa, potatoes, pulses, tomatoes, melon, cotton and rice were adapted from (Gohar et al. 2015). Despite its simplification, yield data for Balkh Basin were used with adjustment for each sub-basin, since no other reliable data were available to us. Future crop yield was calculated by the optimization model by basin, water right system, region, year, storage capacity, and transboundary water sharing arrangement.

Crop yield was specified as a linear function of land in production calibrated with an calibration approach known as “positive mathematical programming” (Howitt 1995), with our

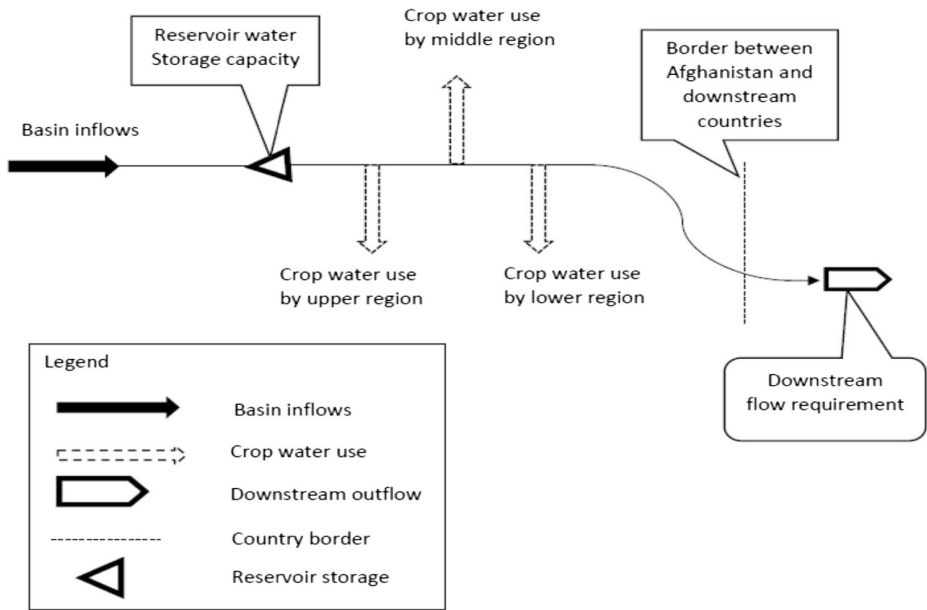


Fig. 2 Schematic of basin water inflows, use and outflows

implementation shown in appendix eq. 6. Declining yield with increased acreage for any given crop is caused by less suitable land brought into production (Gohar et al. 2015).

2.5 Economics

Several elements contribute to economic performance. These include farm income, consumer surplus as a proxy for food security, and total economic benefits. Crop price data for the Balkh Basin were secured from the Ministry of Agriculture, Irrigation and Livestock, Afghanistan as well as from selected donor organizations. Crop price plays an important role in determining farm income, consumer surplus, and total economic benefits. A linear demand function was specified based on observed production, observed price and estimated price elasticity (appendix eq. 9). Increased storage capacity for which added capacity is used for irrigation has the potential to bring more farmland into production, thus decreasing crop prices and raising consumer surplus. Appendix eq. 10 shows the equation used for consumer surplus.

Total discounted domestic water-related economic welfare is calculated as farm income and consumer surplus summed over agricultural regions and crops minus the total cost of reservoir development. Selection of a discount rate is significant because the choice of discount rate has a major influence on the discounted net present value of economic benefits. We selected a discount rate of 1 %, based on a low social rate of time preference assigning a high value of economic welfare of food security for future generations (Gohar et al. 2013, Marglin 1963).

In situations where price signals are misleading or distorted, shadow prices can provide additional information decision makers need to guide policy reform. For our constrained

optimization framework, the shadow price of water is calculated as the change in the objective function (discounted net present value) from relaxing the water constraint by one unit. We calculated the shadow price of domestic and transboundary water sharing method, basin and storage capacity expansion, shown in appendix eqs. 18 and 19.

2.6 Policies and Institutions

In Afghanistan, water infrastructure development and water sharing institutional adjustment are challenges facing water planners and the donor community. Years of civil war and other conflict have devastating irrigation infrastructure, water management systems, and irrigated land in production (Qureshi 2002). Proactive measures taken to analyze the optimization of infrastructure development and institutional adjustment offer the potential to contribute significantly towards both domestic food and water security.

The design of domestic water sharing arrangements and treaty structure are areas of fundamental concern in Afghanistan, as both affect food security. Upstream priority and free market (unrestricted) water trading were two water allocation systems considered. Upstream priority is the traditional long-practiced approach currently in use in Afghanistan where farmers closer to the watershed's source of runoff have increased access to the water resource while downstream farm water use is constrained more heavily in drought periods. Unrestricted trading of water motivated by growing demands for high valued crops with a low water use priority is rarely if ever formally practiced in Afghanistan (Goes et al. 2016).

The measured shadow price of water informs debates over potential gains from water markets for efficient allocation if such markets could be established (Hung and Shaw 2005). While Afghans rarely practice unrestricted trading, the need to analyze impacts of such trading in the constrained optimization framework was important for policy consideration.

Transboundary treaty agreements, in which each downstream country would receive 20% of native runoff in the watershed of origin, was included for the constrained optimization framework. The opportunity costs of such agreements are an important piece of information needed to guide the design of actual such treaties. Obviously, many other percentage delivery arrangements are possible, for which we hope to consider others in the future. Varying the percentage from zero to a range of higher levels would trace out opportunity cost (supply) schedule.

2.7 Optimization Framework

We analyzed the problem of maximizing domestic water use efficiency for increased water security and economic benefit while facing institutional and infrastructure constraints. The model applies a calibration approach that combines the hydrology, agronomy, economics and institutions. We used the Positive Mathematical Programming (PMP) approach to calibrate our model (Howitt 1995). It calibrates the model through the use of non-linear terms in the objective function which subsequently ensure that optimality conditions in relation to the decision variables are met while respecting the constraints (Gohar et al. 2013, Heckeley et al. 2012). As applied to our study, PMP calibrates the model using observed data and it generates baseline optimal solutions for modelling future water scenarios. An optimized solution is found for each of the nine river basins, two water right systems, four storage capacity development and two treaty agreements. In all, a total of 144 optimization models were run.

3 Results

3.1 Overview

Several important messages emerge from our results:

- Entry into transboundary water sharing agreement decreases overall economic benefits by an average of 2 % for any given river basin, producing an average of 6 % increase in domestic crop prices.
- Reservoir storage capacity up scaling can increase water use and food production in irrigated agriculture, and reduce the extent and economic cost of uncontrolled spills both with and without treaties in place.
- Increased water storage capacity increases water availability, reduces water scarcity, and reduces the shadow price of water, both with and without treaties.
- Grain and other crop prices are lower when unrestricted water trading takes advantage of financial incentives to move water to higher-valued uses. These prices are higher when water-sharing treaties effectively reduce domestic water available for domestic use.
- Reservoir up scaling increases consumer welfare as a consequence of reduced crop prices, under any water sharing system used. Overall, a policy of unrestricted water trading increases consumer surplus by 4 % without water sharing treaties and by 2 % with such treaties.
- Domestic food buyers are generally better off with unrestricted water trading but are worse off in the short term with treaties that require downstream deliveries.
- Farm income increases under unrestricted trading, but the increase is larger without than with water sharing treaties.
- Nationwide, irrigated farm income summed over all major crops is higher under unrestricted water trading, both with and without water treaties.
- Except for the Kabul Basin, all other basins in the country showed the highest discounted net present value of economic benefits when some reservoir storage capacity is expanded.

3.2 Water

Table 1 shows water use, storage, and spill are all influenced by the scale of storage capacity if developed. As expected, the quantity of water available for use in each basin uniformly increases across reservoir storage up scaling options. The increase in water available for use in each basin assigns significant motivation to investigate reservoir building. Because of the considerable cost of upscaling storage capacity, information on the optimal reservoir size is necessary for analysis of economic net efficiency (Potts and Ankras 2014).

The discussion below shows that the most economically efficient size of reservoir capacity varies widely by conditions. Results in the table show that accounting for all the dynamics of adjusted water use patterns, results typically suggest a medium or large size reservoir capacity as the optimal storage scale. That conclusion, though not known in advance, came from measured total economic welfare, defined as farm income plus consumer surplus. The presence or absence of a transboundary water treaty had a definite influence on basin water use, storage, and spill.

Table 1 Water Supply, Use, and Spill, by Capacity and Basin, Afghanistan (20 Years Average, Million Cubic Meters /Year)

Basin	Reservoir Storage Capacity															
	Basin Supply			1-None			2-Small			3-Medium			4-Large			
	Basin Supply	Storage	Spill	(0 * basin natural supply)	Basin Use	Storage	Spill	(0.5 * basin natural supply)	Basin Use	Storage	Spill	(0.75 * basin natural supply)	Basin Use	Storage	Spill	(2.5 * basin natural supply)
Balkh	1360	0	210	1268	206	54	1287	264	15	1302	293	0				
Farah	224	0	21	215	33	6	218	53	2	220	65	0				
Helmand	957	0	259	765	228	193	787	340	166	864	968	89				
Kabul	71	0	1	71	1	0	71	1	0	71	1	0				
Kokcha	200	0	41	181	47	19	189	68	11	200	176	0				
Kunduz	661	0	139	571	172	75	577	271	62	577	731	11				
Murghab	75	0	14	68	22	6	71	32	3	74	41	0				
Patika	250	0	54	208	43	36	214	67	27	229	206	0				
UpperHarirud	695	0	197	525	199	155	536	294	138	542	849	83				

3.3 Crop Prices

Table 2 shows modelled crop prices by water sharing arrangement, crop, and storage capacity, with and without a water treaty. As expected, crop prices are typically lower as reservoir up scaling occurs for all basins with or without a transboundary sharing water treaty. The pattern of decreases in crop price as reservoir up scaling occurs remains consistent across water sharing systems with or without a treaty in place. Nevertheless, the reduction in crop prices without a sharing treaty is much higher than with a treaty in place.

3.4 Food Security

Table 3 shows consumer surplus from the production of crops, by river basin, internal water sharing institutions, and storage capacity for all crops. Consumer surplus measures the welfare gained from consuming goods at a lower than maximum price (Adams et al. 1995). It is measured as the additional area beneath the crop demand function associated with increased production that reduces crop prices.

For most basins, with or without a treaty, the most economically efficient reservoir scale measured by consumer surplus was found to be ‘medium’ or ‘large’ size. Generally, there is additional economic benefit to build large size dams because consumer surplus increases as reservoir storage capacity is scaled from ‘medium’ to ‘large.’ Nevertheless, Kabul and Kunduz basins are the few exceptions where there was little to no economic motivation to expand reservoir storage beyond medium size, as added economic benefit is smaller than added up scaling costs (Gohar et al. 2013).

Table 2 :Crop prices defined by institutions, crop type and Storage Capacity summed over river basins (20 years average, \$US/ton)

Treaty	Crop	Water Right System							
		us_priority				free_market			
		1-None	2-Small	3-Medium	4-Large	1-None	2-Small	3-Medium	4-Large
Without_treaty	Alfalfa	656	625	613	603	603	583	581	578
	Cotton	3860	3581	3518	3397	4032	3701	3593	3434
	Melon	480	463	457	453	443	438	438	437
	Potato	359	344	338	334	328	322	322	321
	Pulses	1354	1285	1270	1241	1417	1333	1304	1262
	Rice	2222	2088	2036	1985	2078	1964	1940	1912
	Tomato	1028	954	934	916	844	842	841	841
	Wheat	594	563	553	540	579	547	540	531
With_treaty	Alfalfa	668	637	625	614	622	599	596	592
	Cotton	4581	4356	4304	4217	4810	4551	4451	4308
	Melon	482	465	459	455	447	441	440	440
	Potato	362	347	342	338	334	327	326	325
	Pulses	1551	1496	1483	1462	1619	1555	1529	1493
	Rice	2348	2216	2166	2113	2239	2124	2096	2060
	Tomato	1029	956	936	917	847	844	843	843
	Wheat	634	604	594	582	628	597	589	578

Table 3 Discounted Consumer Surplus by Treaty Arrangement, Basin, Water Sharing Institution, and Reservoir Storage Capacity, Afghanistan (\$US Million)

Treaty	Basin	Water Right System							
		us_priority				free_market			
		1- None	2- Small	3- Medium	4- Large	1- None	2- Small	3- Medium	4- Large
Without_treaty	Balkh	20,325	22,253	22,425	22,495	22,491	23,267	23,346	23,408
	Farah	1798	1910	1941	1950	2026	2080	2095	2107
	Helmand	5633	6284	6519	7261	6504	6918	7019	7407
	Kabul	645	649	649	649	893	896	896	896
	Kokcha	1050	1249	1334	1413	1187	1329	1371	1420
	Kunduz	3529	3971	4010	4010	3773	4055	4076	4076
	Murghab	617	662	710	741	681	749	761	768
	Patika	1256	1376	1450	1558	1449	1517	1555	1611
	UpperHarirud	4163	4477	4606	4652	4472	4670	4737	4761
	TOTAL	39,017	42,832	43,644	44,730	43,475	45,481	45,855	46,454
With_treaty	Balkh	19,096	20,912	21,061	21,118	21,182	21,895	21,956	22,006
	Farah	1607	1709	1736	1744	1808	1862	1873	1882
	Helmand	5085	5668	5888	6563	5814	6177	6291	6664
	Kabul	594	598	598	598	806	809	809	809
	Kokcha	937	1117	1192	1266	1044	1172	1216	1268
	Kunduz	3099	3497	3536	3536	3269	3548	3575	3575
	Murghab	597	643	689	720	649	713	729	741
	Patika	1116	1227	1293	1395	1255	1328	1365	1432
	UpperHarirud	3796	4079	4199	4241	4055	4218	4281	4312
	TOTAL	35,927	39,449	40,191	41,180	39,883	41,725	42,095	42,689

3.5 Farm Income

Table 4 shows that farm income is greatly influenced by wheat price, storage capacity expansion, transboundary water treaty and water right systems. For most basins, reservoir up scaling leads to higher farm income with or without a water treaty. Yet there were instances where farm income decreased as storage capacity increases. Specifically, estimated farm income for wheat production in Upper Harirud and Patika river basins decreased as reservoir storage size was scaled from medium to large. The decrease in farm income is explained by the large decrease in commercial wheat price from medium size to large size.

Farm income results also reveal significant insights for impacts of a water treaty. Although high crop prices shown with a treaty may constrain the purchasing power of some Afghans, they significantly increase wheat crop farmer's income. Hence having a transboundary water treaty does not only satisfy a political and arguably moral obligation to protect historical use patterns of downstream countries and the need to avoid possible future conflict over the use of shared water resources, but it can also translate into higher farm income. Table 4 summarizes the results on farm income produced by basins, institutions and storage capacity, summed over all crops for Afghanistan.

3.6 Economic Benefits and Costs

Table 5 presents discounted net present value of economic benefit defined by domestic water sharing right institution and storage capacity for all river basins with and without a

Table 4 Discounted Farm Income by Treaty Arrangement, Basin, Water Sharing Institution, and Reservoir Storage Capacity, Wheat, Afghanistan (\$US Million)

Treaty	Basin	Water Right System							
		us_priority				free_market			
		1- None	2- Small	3- Medium	4- Large	1- None	2- Small	3- Medium	4- Large
Without_treaty	Balkh	25,958	26,529	26,700	26,705	26,679	27,065	27,135	27,131
	Farah	2766	2798	2881	2894	2839	2867	2911	2925
	Helmand	9768	10,199	10,196	10,518	10,360	10,440	10,478	10,493
	Kabul	1363	1366	1366	1366	1393	1393	1393	1393
	Kokcha	1680	1770	1768	1796	1789	1812	1789	1790
	Kunduz	5149	5145	5133	5133	5225	5131	5115	5115
	Murghab	1253	1333	1366	1379	1282	1387	1387	1384
	Patika	2210	2208	2216	2239	2306	2281	2267	2256
	UpperHarirud	5849	6088	6071	6059	5895	6080	6057	6041
	TOTAL	55,997	57,436	57,697	58,090	57,768	58,455	58,532	58,527
With_treaty	Balkh	26,148	26,844	27,040	27,074	26,762	27,314	27,411	27,440
	Farah	2827	2873	2952	2968	2884	2930	2972	2989
	Helmand	9948	10,457	10,496	10,929	10,462	10,695	10,756	10,936
	Kabul	1354	1357	1357	1357	1374	1375	1375	1375
	Kokcha	1715	1834	1845	1887	1813	1879	1871	1890
	Kunduz	5344	5425	5423	5423	5428	5433	5426	5426
	Murghab	1246	1339	1373	1387	1273	1388	1394	1395
	Patika	2251	2268	2285	2329	2345	2340	2341	2351
	UpperHarirud	6042	6300	6300	6298	6086	6302	6305	6296
	TOTAL	56,874	58,697	59,072	59,652	58,427	59,657	59,850	60,098

transboundary water treaty. Tabled entries reflect the monetary value of reservoir storage capacity expansion for the various water right systems considered with or without transboundary water treaty.

Careful examination of the Tabled results reveals several important patterns to guide policy makers in seeking an economically efficient policy. Generally, building medium size reservoir storage capacity leads to increased economic benefit for all basins, except the Helmand. Economic benefits were typically highest for medium storage reservoirs compared to none, small and large size reservoirs. The increased economic benefits associated with medium size reservoirs remains unchanged regardless of the domestic water sharing system in place.

Policy makers may wish to consider water trading among farmers, in which water moves, through market signals, from lower to higher valued uses, to encourage economic efficiency in water use. With or without a water treaty, medium sized reservoir storage capacity still emerged as the most economically efficient policy option for all basins except Helmand. Still, establishing a treaty will noticeably reduce overall national economic benefits from irrigation as more quantities of native runoff are assigned and delivered to downstream neighbors (Emadi 1995).

Economic costs imposed on Afghan farmers associated with adjustments brought on by treaties with downstream neighbors are important politically, culturally, and economically. We analyzed those adjustment costs, described by province, storage capacity enhancement, and domestic water allocation system. Results of those treaty adjustments revealed higher costs for Balkh, Helmand and Kunduz basins irrespective of the water right system in place (Figs. 3 and 4). The considerably higher economic value of domestically allocated water to irrigation

Table 5 Discounted Net Economic Benefit by Treaty Arrangement, Water Sharing Institution, Reservoir Storage Capacity, and Basin, Afghanistan (\$US Million)

Treaty	Basin	Water Right System							
		us_priority				free_market			
		1-None	2-Small	3-Medium	4-Large	1-None	2-Small	3-Medium	4-Large
Without_treaty	Balkh	46,283	48,644	48,918	48,511	49,170	50,195	50,274	49,850
	Farah	4564	4685	4787	4728	4864	4924	4971	4915
	Helmand	15,401	16,404	16,596	17,386	16,865	17,279	17,379	17,506
	Kabul	2008	2006	2001	1966	2285	2279	2274	2239
	Kokcha	2731	3001	3075	3119	2975	3123	3133	3120
	Kunduz	8678	9063	9065	8883	8999	9133	9112	8930
	Murghab	1870	1988	2065	2084	1963	2128	2137	2117
	Patika	3466	3563	3634	3690	3755	3776	3790	3759
	UpperHarirud	10,012	10,516	10,602	10,460	10,366	10,700	10,719	10,551
	TOTAL	95,013	99,869	100,742	100,826	101,243	103,537	103,789	102,987
With_treaty	Balkh	45,245	47,618	47,894	47,502	47,945	49,072	49,160	48,757
	Farah	4434	4559	4653	4595	4692	4768	4810	4755
	Helmand	15,033	16,046	16,266	17,098	16,277	16,793	16,929	17,206
	Kabul	1948	1946	1941	1906	2180	2175	2170	2135
	Kokcha	2652	2932	3009	3063	2857	3033	3060	3068
	Kunduz	8443	8869	8880	8698	8697	8930	8922	8740
	Murghab	1843	1975	2051	2071	1923	2094	2112	2099
	Patika	3367	3474	3546	3617	3600	3647	3674	3676
	UpperHarirud	9837	10,329	10,424	10,288	10,141	10,471	10,511	10,358
	TOTAL	92,802	97,748	98,665	98,838	98,310	100,983	101,348	100,794

associated with unrestricted water trading increases the (opportunity) cost of enacting treaties when that trading system is in place compared to an upstream priority system. This occurs for all basins. Kabul, Kokcha and Murghab basins showed the lowest economic cost of treaty enactment relative to other basins studied.

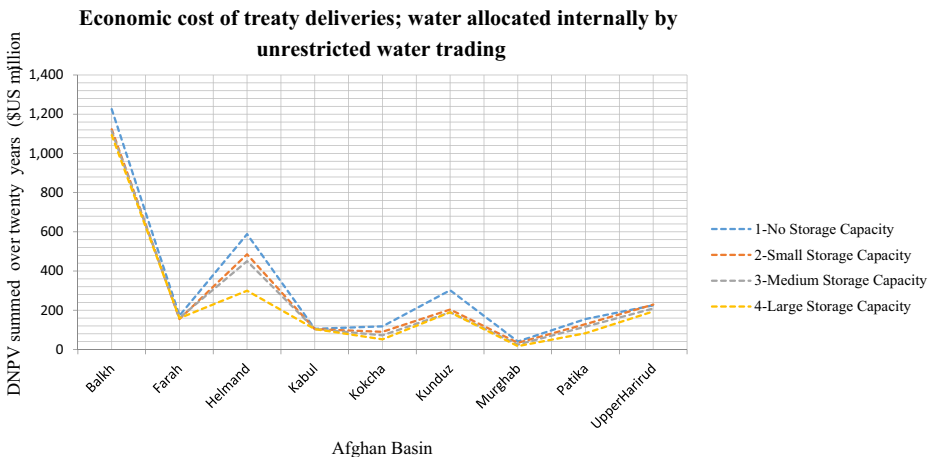


Fig. 3 Economic cost of treaty agreement by basin and storage capacity; unrestricted water trading system. (\$US millions, Discounted Net Present Value)

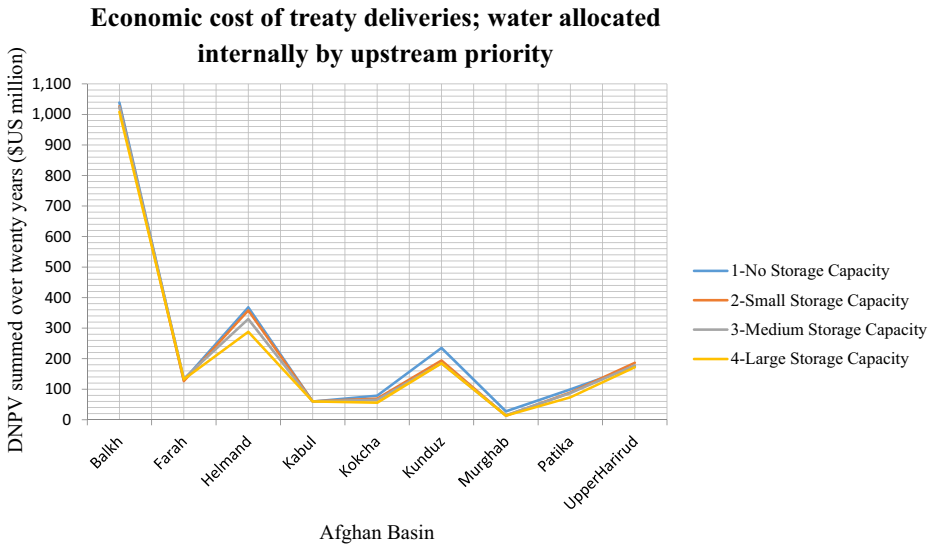


Fig. 4 Economic cost of treaty agreement defined by basin and storage capacity; upstream priority allocation system. (\$US millions, Discounted Net Present Value)

Water policy makers and deal negotiators are likely to take an active interest in the consequences of planning for water sharing treaties with a downstream country like Pakistan, for which the economic cost of treaty enactment is comparatively low. In relation to dam size, similar impacts of storage capacity on economic cost of treaty are shown in Figs. 3 and 4 across all basins regardless of the water right system in place. Having no storage capacity in place leads to high economic cost of treaty agreement compared to a lower economic cost when some form of reservoir storage capacity exists. This finding accords with common sense, because storage capacity offers greater flexibility for the timing and quantity of treaty deliveries. As expected, large storage capacity is associated with the lowest economic cost of treaty agreement in all basins. Yet, the economically best performing reservoir capacity was found to be either small or medium storage capacity because of the high incremental building costs of expansion, as shown in Figs. 3 and 4.

3.7 Shadow Price of Water

The shadow price of water is the discounted net present value of overall economic benefits gained through additional supplies of a resource like water. The shadow price, as used in this paper, reflects the additional economic value that can be secured through greater control of water use in the face of reservoir up-scaling with or without a transboundary water treaty (Doppler et al. 2002).

Table 6 summarizes our calculated shadow prices measured in US dollars per cubic meter for 144 possible conditions. The results reveals remarkable policy insights. When farmers are motivated and permitted to trade water for cash or other assets, the shadow price of water declines considerably compared to conditions when no trading is permitted, reflecting a greater overall economic abundance of water, even though physical quantities are unchanged.

Table 6 Shadow Price of Water by Treaty Arrangement, Storage Capacity, Water Right System, and Basin, Afghanistan (20 Years Average, \$US/m³)

Treaty	Basin	Water Right System							
		us_priority				free_market			
		1- None	2- Small	3- Medium	4- Large	1- None	2- Small	3- Medium	4- Large
Without_treaty	Balkh	2.75	0.81	0.78	0.78	0.38	0.21	0.20	0.19
	Farah	5.02	4.06	3.07	3.06	0.35	0.24	0.22	0.21
	Helmand	6.23	3.43	3.03	0.36	0.26	0.15	0.12	0.02
	Kabul	12.49	12.49	12.49	12.49	0.42	0.42	0.42	0.42
	Kokcha	4.27	0.65	0.56	0.01	0.25	0.09	0.06	0.00
	Kunduz	1.88	0.36	0.34	0.34	0.11	0.02	0.01	0.01
	Murghab	6.85	4.37	2.62	1.73	0.99	0.40	0.35	0.32
	Patika	3.18	2.30	1.43	0.89	0.18	0.13	0.11	0.05
	UpperHarirud	3.27	0.87	0.43	0.42	0.18	0.07	0.05	0.04
	AVERAGE	5.11	3.26	2.75	2.23	0.35	0.19	0.17	0.14
With_treaty	Balkh	2.90	0.96	0.93	0.93	0.56	0.36	0.35	0.34
	Farah	5.18	4.21	3.23	3.22	0.53	0.40	0.38	0.37
	Helmand	6.37	3.58	3.18	0.52	0.43	0.32	0.29	0.19
	Kabul	12.60	12.59	12.59	12.59	0.60	0.59	0.59	0.59
	Kokcha	4.40	0.80	0.70	0.15	0.40	0.25	0.21	0.15
	Kunduz	2.03	0.51	0.50	0.50	0.26	0.18	0.17	0.17
	Murghab	7.02	4.52	2.78	1.84	1.17	0.55	0.49	0.44
	Patika	3.33	2.44	1.57	1.03	0.35	0.29	0.26	0.20
	UpperHarirud	3.41	1.02	0.58	0.57	0.37	0.23	0.21	0.20
	AVERAGE	5.25	3.41	2.90	2.37	0.52	0.35	0.33	0.29

Storage capacity expansion has a noticeable impact on shadow price of water right systems. Generally, reservoir up-scaling comes with a decrease in shadow price, as expected. Thus, having large storage capacity eliminates or reduces possible water spills during seasons of high precipitation and permits water storage for future uses, especially valuable for future long dry spells. Increased water storage translates into increased availability of water and subsequent reduction in the shadow price of water.

4 Discussion

Afghans and their donor partners can more confidently engage in the design of a water planning with better information. Afghans especially need important information on average annual flows of all its transboundary rivers, estimated impacts of scenarios like drought on natural supply. They also need information on economic impacts of transboundary treaty agreements and reservoir storage expansion on available water resources. Afghans also need information on how a treaty agreement would affect other existing uses, especially in irrigated agriculture.

The contributions of this work come from its scope, methods of analysis, and significance. No peer reviewed study that we have seen has been conducted in this part of the world to assess the economic performance of treaty agreements in the face of alternative storage capacity expansions and alternative potential internal water sharing agreements. This paper uses a constrained optimization framework approach to investigate policy proposals in 9 sub-basins in Afghanistan.

Several important results emerge. Results are presented on water use associated with reservoir storage capacity expansion in the form of increased water availability for future use, reduced water spills and increased water use in irrigated agriculture. The increased availability of freshwater was associated with forecasted decrease in crop prices if reservoir up-scaling is developed. The economic impacts of including a transboundary water treaty are seen in an increase in crop prices, which for some would translate to falling farm income as well as reduced food security for Afghans.

Findings of the study address a crucial need to support water cooperation in the study area. It also provides a unique contribution for Afghanistan and downstream countries to negotiate over shares of a transboundary basin. Specifically, findings offer economic and hydrological incentives for water policy makers in Afghanistan to reach various treaty agreements with downstream countries. Generally, this study provides fundamental economic analysis for future transboundary water treaty dialogue among riparian countries. The nationwide multi-basin framework can easily be adapted to regions facing similar water sharing challenges as the case of Afghanistan, when in depth economic analysis is required to guide water treaty design and cooperation.

5 Scope, Limits, and Extensions

The scope of the study was limited to economically efficient use of Afghanistan's water resources by irrigated agriculture, with three policy instruments: reservoir storage capacity expansion, water trading, and establishment of downstream water treaty obligations. Many transboundary water treaty agreements fail to perform at top levels partly because negotiators do not take into account the impact of unexpected future climate possibilities, including drought and high variability in precipitation. We anticipate that our study's scope could be expanded to include the assessment of climate change impact and river basin protection to avoid long run depletion of water resources.

Economic benefits and costs from the view of countries downstream of Afghanistan could focus on estimating the economic impacts of water sharing agreements on transboundary water resources. Analyzing the effect of a formal transboundary treaty agreement on economic development of downstream countries is a vital research area that could guide the establishment of treaty cooperation among riparian countries in our study area and beyond.

Analysis of non-agricultural water uses such as urban and domestic water use protection is an important area for further research work. Meeting the millennium development goals for household water consumption is relevant since so many households in the world lack safe piped in water and sanitation. Therefore, water policy design should focus on the analyzing the impact of including urban and domestic water use protection, possibly also using a constrained optimization framework.

The need to protect aquifers connected to shared water resources cannot be ignored because viability of any water treaty agreement is contingent on the availability of water in the shared basins. Analyzing the design of transboundary aquifer treaties is also another area of productive research. Few if any published studies to date have provided guidance for informing debates on transboundary aquifer water sharing arrangements. The impacts of drought and high variability in precipitation have led to extensive dependence on groundwater resources in many arid and semi-arid regions. Nevertheless, the challenges facing optimal use of transboundary river basins are especially important for the use of shared aquifers. Assessing

impacts of treaty agreements on shared aquifers in the study area is important to support sustainable use of groundwater resources to promote economic development among riparian countries.

In recent years, environmental sustainability is increasingly gaining traction among stakeholders. In view of this, it is crucial for decision makers to design water policies that address environmental concerns. One possible pathway is to assess the economic benefit of allocating water for environmental purposes. A constrained optimization framework including environmental use protection among other competing water uses will give relevant results that could inform environmental policy decisions.

In addition, our research findings revealed unrestricted water trading right system as a more productive policy choice for low cost adjustment measures to transboundary water sharing agreements. Currently, Afghanistan uses upstream priority system, a traditional means of allocating water to farmers, except for well-recognized limited scope trading activity within limited regions where farmers know each other personally. An upstream priority water right system favors farmers closer to the top of the watershed and constrains downstream users securing an equitable share of the water resource. Unrestricted water trading at a regional scale could effectively allocate water to higher valued uses, yet at a regional and national scale, it requires a legal framework that establishes formal water rights to farmers engaged in the water market. In view of this, future research could focus on examining formal water right establishment as part of legal systems in Afghanistan (Gohar et al. 2015, Wegerich 2010).

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Appendix

Overview.

The appendix summarizes relevant mathematical documentation of the multi-basin hydro-economic model design to inform water policy decisions in Afghanistan. It outlines the mathematical framework of the optimization model built using General Algebraic Modeling Systems to include sets, parameters, variables, equations and the objective function specification. The complete model show hydrological, economic and institutional constraints. The code for the hydro-economic model and spreadsheet results are available at the New Mexico State University web page at <https://water-research.nmsu.edu/>

Sets. Sets characterize the foundation of the multi-basin framework. Each set constitute elements as described below. In our model, sets and corresponding elements are defined for all studied transboundary river basins in Afghanistan.

sets	set name	description	set elements
k	crop	Crop selection is an important choice variable for farm income, food security, and policy assessment that influences both.	/ Alfalfa, Cotton, Melon, Potato, Pulses, Rice, Tomato, Wheat/
t	Year	Year reflect a 20-year horizon	/year1 * year 20/
i			/upper, middle, lower/

sets	set name	description	set elements
	Region by basin	Each basin divided into 3 regions	
j	Water right priority	Priority among regions inside each basin	/j1, j2, j3/
r	Water allocation rule	Water right systems for sharing water shortages when they occur	/Upstream priority, free market/
s	Storage reservoir capacity scale	Scale at which new reservoirs could be built. None reflects base condition and has no storage.	/none, small, medium, large/
b	River Basin	Lists of all river basins studied in the country	/Balkh, Patika, Helmand, Farah, Kabul, Kokcha Kunduz, Murghab, Upper_Harirud
y	Treaty	Treaty agreement on transboundary river basins.	/Without treaty, With treaty/
tji(r,j,i)	Mapping set	Assigns priorities to regions in a basin to vary water right regime	us_priority.j1.upper,us_priority.j2.middle,us_priority.j3.lower free_mkt.j1.upper,free_mkt.j1.middle,free_mkt.j1.lower
rwa(r)	Upstream priority	Upstream users receive priority when shortages occur	upstream priority
rfm(r)	free_market	No restrictions on water reallocations from baseline	free market

Parameters.

Terms ending in p refer to parameters, data read by the model. They are:

Parameter	sets	Label	units
Nat_supp_p	(b)	Natural runoff inflow to basin	MCM / year
Nat_suppl_p	(b,t)	Stochastic water supply by year with set mean and standard deviation	MCM / Year
Nat_supply_p	(b,t,y)	Natural water supply adjusted by downstream delivery treaty requirement	MCM / Year
Pop_p	(b,t)	Forecast population by basin and years	thousands
Popratio_p	(b,t)	Ratio of given year population to base year	1 and above
Rho_p		Discount rate (1%)	unitless
Capacity_p	(b,s)	Maximum reservoir storage capacity	MCM
Com_cost_mcm	(b,s)	Construction cost per million cubic meters storage capacity	\$US/MCM
Prop_right_p	(b,i)	Proportion of right to water compared by region within basin	0–1
Right_p	(b,i)	Customary absolute right to water supply by region	MCM / year
Shortage_p	(b,r,i,t,s,y)	Water storage relative to full supply right	0–1
Basin_use_p	(b,r, t,s,y)	Total water use in the basin	MCM / year
Change_store_p	(b,r, t,s,y)	Total change in storage	MCM / year
Bc_p	(b,i,k)	Water use per unit land (irrigation depth)	M / year
Land_p	(b,i,k)	Observed land in production	Ha / year
Price_p	(k,b)	Observed crop prices	\$US per metric ton
Price_elast_p	(k,b)	Price elasticity of demand	unitless
Yield_p	(b,i,k)	Observed crop yield	Metric tons/ha
Cost_p	(b,i,k)	Production costs	\$US per ha
A0_p	(b,k,t)	Intercept in price-dependent demand function	\$US per metric ton
A1_p	(b,k,t)	Slope of price-dependent demand function	\$US per metric ton

Parameter	sets	Label	units
B0_p	(b,k,t)	Intercept in crop water production function (PMP)	Metric tons/ha
B1_p	(b,k,t)	Slope in crop water production function (PMP)	Metric tons/ha

Variables.

As characterized in the multi-basin model, variables are endogenous (unknown) and end in v to distinguish the unknown data from parameters. These variables are optimized by the model, while respecting all important bounds. The most important variables are:

Variables	sets	label	units
Hectares_v	(b,r,i,k,t,s,y)	Land use	1000 ha
T_hectares_v	(b,r,i, t,s,y)	Total land use	1000 ha
Uses_v	(b,r,i, t,s,y)	Water use	MCM/year
Sum_uses_v	(b,r, t,s,y)	Summed water use	MCM/year
Production_v	(b,r,i,k,t,s,y)	Land in production details	1000 ha
Yield_v	(b,r,i,k,t,s,y)	Crop yields	Tons/ha
Crop_price_v	(b,r, k,t,s,y)	Crop price	\$US/ton
Netrev_v	(b,r,i,k,t,s,y)	Net revenue per unit land	\$US/ha
Con_surp_v	(b,r, k,t,s,y)	Consumer surplus (willingness to pay in excess of price)	\$US 1000 / year
Tgrossrev_v	(b,r,i,k,t,s,y)	Total gross revenue over all lands	\$US 1000 / year
Ag_ben_j_v	(b,r,i,k,t,s,y)	Discounted ag benefits with details	\$US 1000 / year
Tot_wel_v	(b,r, t,s,y)	Discounted total welfare	\$US 1000 / year
Wel_wo_cd_v	(b,r, s,y)	Discounted total welfare without reservoir capacity expansion	\$US 1000 / year
Ttot_wel_v	(b,r, s,y)	Discounted total welfare with reservoir capacity expansion	\$US 1000 / year

Equations

Mathematical expressions connecting the relationship between variables and parameters used in the optimization frame to characterize the most important indicators such as hydrology, land in production, crop production, and economic policy choices.

Hydrology Block

$$X(t) \sim N(\mu, \sigma^2). \tag{1}$$

Basin headwater supply for the year t, X(t)

$$X_v(b, r, i, k, t, s, y) = Bc_p(b, i, k) * hectares_v(b, r, i, k, t, s, y) \tag{2}$$

Crop water use equation calculated based on land in production

$$Uses_v(b, r, i, t, s, y) = \text{sum}(k, X_v(b, r, i, k, t, s, y)) \tag{3}$$

Water use summed over crops

$$\text{sum_uses}_v(b, r, t, s, y) = \text{sum}(i, Uses_v(b, r, i, t, s, y)) \tag{4}$$

It calculates water use summed over canals

Agronomy Block

$$T_{hectares_v}(b, r, i, k, t, s, y) = \text{sum}(k, hectares_v(b, r, i, k, t, s, y)) \tag{5}$$

Land in production summed over crops

$$Yield_v(b, r, i, k, t, s, y) = B0_p(b, i, k) + B1_p(b, i, k) * hectares_v(b, r, i, k, t, s, y) \tag{6}$$

Crop yields declines as acreage in production increases

$$Production_v(b, r, i, k, t, s, y) = Yield_v(b, r, i, k, t, s, y) * hectares_v(b, r, i, k, t, s, y) \tag{7}$$

It calculates crop production based on crop yield and acreage in production.

$$Tot_prod_v(b, r, k, t, s, y) = \text{sum}(i, production_v(b, r, i, k, t, s, y)) \tag{8}$$

Total crop production summed over regions.

Economics Block

$$crop_price_v(b, r, k, t, s, y) = BB0_p(b, k, t) + [BB1_p(b, k, t) * Tot_prod_v(b, r, k, t, s, y)] \tag{9}$$

Linear demand function of crop price for each basin as influence by water right systems, region, time, storage capacity and treaty

$$con_surp_v(b, r, k, t, s, y) = 0.5 * [BB0_p(b, k, t) - crop_price_v(b, r, k, t, s, y)] * Tot_prod_v(b, r, k, t, s, y) \tag{10}$$

Consumer surplus representing gains in economic benefits to the Afghan people as water right systems, treaty agreement and storage capacities are varied.

$$Netrev_v(b, r, i, k, t, s, y) = crop_price_v(b, r, k, t, s, y) * Yield_v(b, r, i, k, t, s, y) - Cost_p(b, i, k) \tag{11}$$

Net revenue per unit land is price times yield minus costs per unit land

$$Ag_Ben_j_v(b, r, i, k, t, s, y) = Netrev_v(b, r, i, k, t, s, y) * hectares_v(b, r, i, k, t, s, y) \tag{12}$$

Agricultural benefits by river basin, water right systems, agricultural region, crop, time period, storage capacity and treaty.

$$To_wel_v(b, r, k, t, s, y) = \text{sum}[i, ag_ben_j_v(b, r, i, k, t, s, y)] + con_surp_v(b, r, k, t, s, y) \tag{13}$$

Discounted net present value of total economic welfare

$$Tot_wel_v(b, r, t, s, y) = \text{sum}(k, To_wel_v(b, r, k, t, s, y)) \tag{14}$$

Summed total welfare over crops

$$Wel_wo_cd_v(b, r, s, y) = \sum (t, DF(t) * Tot_wel_v(b, r, t, s, y)) \tag{15}$$

Net present value of farm income plus consumer surplus

$$Ttot_wel_v(b, r, s, y) = Wel_wo_cd_v(b, r, s, y) - Tot_COM_cost_p(b, s) \tag{16}$$

Total net benefits after subtracting dam construction cost

$$Tot_b_v = \sum ((b, r, s, y), Ttot_wel_v(b, r, s, y)) \tag{17}$$

Total benefits looped over all changeable indices

$$shad_price_p(b, r, i, t, s, y) = uses_v.m(b, r, i, t, s, y) \tag{18}$$

Shadow prices for all water allocation rules except unrestricted trading

$$shad_price_p(b, rfm, i, t, s, y) = \sum uses_v.m(b, rfm, t, s, y) \tag{19}$$

Shadow prices for unrestricted trading

$$Storage_Capacity_p = scale_p * natural_supply_p. \tag{20}$$

Water storage capacity is defined by natural supply at various values of the scale parameter (scale_p)

$$Tot_Com_cost_p(b, s) = Cost_Per_Unit_Storage_p * Storage_Capacity_p. \tag{21}$$

$$Ttot_wel_v(b, r, s, y) = Wel_wo_cd_v(b, r, s, y) - Tot_Com_cost_p(b, s). \tag{22}$$

Total net benefits obtained after dam cost.

Bounds.

Bounds characterize constraints on institutions, technology, and water user behavior, while also producing realistic responses to future climate or policy adaptations to climate. A lower bound (.lo) on each water flows and land used assures no crop production or water supplies have negative values. An upper bound (.up) guards against a variable exceeding that set level.

$$hectares_v.lo(b, r, i, k, t, s, y) = 0. \tag{23}$$

Agricultural land in production cannot be negative.

$$\begin{aligned} uses_v.up(b, rwa, i, t, s, 'Without_treaty') \\ = 1.0 * wet_wat_use(b, rwa, i, t, s, 'Without_treaty') \end{aligned} \tag{24}$$

$$uses_v.up(b, rwa, i, t, s, 'With_treaty') = 0.8 * wet_wat_use(b, rwa, i, t, s, 'With_treaty') \tag{25}$$

Bounds water use in production, with use in the face of a treaty set to 80% of without treaty level

$$\begin{aligned} \text{sum_uses_v.up}(b, \text{rfm}, t, s, 'Without_treaty') \\ = 1.0 * \text{basin_use_p}(b, \text{rfm}, t, s, 'Without_treaty') \end{aligned} \quad (26)$$

$$\text{sum_uses_v.up}(b, \text{rfm}, t, s, 'With_treaty') = 0.8 * \text{basin_use_p}(b, \text{rfm}, t, s, 'With_treaty') \quad (27)$$

When water trading is allowed among regions in each basin, only total water use is bounded.

Objective.

The objective of the model is to maximize discounted net present value subject to the hydrologic and institutional constraints described above.

The objective function $Ttot_wel_v(b,r,s,y)$ specified above is maximized for each basin, water shortage sharing rule, treaty agreement and storage capacity level. A total of 144 model runs are optimized.

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