Economic performance of water storage capacity expansion for food security

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\textbf{Summary}

Continued climate variability, population growth, and rising food prices present ongoing challenges for achieving food and water security in poor countries that lack adequate water infrastructure. Undeveloped storage infrastructure presents a special challenge in northern Afghanistan, where food security is undermined by highly variable water supplies, inefficient water allocation rules, and a damaged irrigation system due three decades of war and conflict. Little peer-reviewed research to date has analyzed the economic benefits of water storage capacity expansions as a mechanism to sustain food security over long periods of variable climate and growing food demands needed to feed growing populations. This paper develops and applies an integrated water resources management framework that analyzes impacts of storage capacity expansions for sustaining farm income and food security in the face of highly fluctuating water supplies. Findings illustrate that in Afghanistan’s Balkh Basin, total farm income and food security from crop irrigation increase, but at a declining rate as water storage capacity increases from zero to an amount equal to six times the basin’s long term water supply. Total farm income increases by 21%, 41%, and 42% for small, medium, and large reservoir capacity, respectively, compared to the existing irrigation system unassisted by reservoir storage capacity. Results provide a framework to target water infrastructure investments that improve food security for river basins in the world’s dry regions with low existing storage capacity that face ongoing climate variability and increased demands for food security for growing populations.

1. Background

Continued climate variability, population growth, and rising food prices present ongoing challenges for achieving food and water security in poor countries that lack adequate water infrastructure. Undeveloped storage infrastructure presents a special challenge in northern Afghanistan, where food security is undermined by highly variable water supplies, inefficient water allocation rules, and a damaged irrigation system due three decades of war and conflict. Afghanistan is a developing Asian country with livelihoods heavily dependent on agriculture that has suffered ongoing consequences of military conflict since the late 1970s (Fig. 1). These conflicts have severely damaged the country’s irrigation infrastructure, institutions, and capacity to adapt to ongoing climate variability. Balkh Province is located in the northern part of the country with total population around 1.12 million (Torell and Ward, 2010). In that province, agricultural activities in the Balkh Basin (the basin) are a major source of income, livelihoods, and food security. That region is an important producer for the country’s most important grain and staple food crops, especially wheat (Reeling et al., 2012; Chabot and Dorosh, 2007). Runoff into the basin is the main source for fresh water for irrigation in the Balkh Province.

Farmers in this province face highly fluctuating water supplies with no significant reservoir storage capacity, which places heavy stress on food production in dry years, especially in the low part of the watershed. Reliable water availability is a major determinant of the recovery and expansion of irrigated agriculture activities in Balkh Basin to its former high levels of the mid 1970s (Kugbei et al., 2005; Walters et al., 2012). In the basin, weak water institutional capacity (e.g., rules for defining water rights) limits farmers’ ability to adapt to highly fluctuating flows supplied from runoff in the Balkh River and its tributaries. Average annual water supplies in the river are estimated at 1540 MCM per year (Torell and Ward, 2010). Moreover, the basin has a high fluctuation in yearly water supply that can undergo severe drought. This occurred in the period 1998–2002 (Chabot and Dorosh, 2007).

Weak water institutions combined with virtually no reservoir storage capacity limits irrigators’ capacity to earn a sustainable income and sustain adequate food security in drought periods, especially in downstream areas. These weak water-sharing
arrangements result in high fluctuations in food supply and production, and increasing the country’s dependence on national food aid and imports from neighboring countries like Pakistan. While foreign food aid and imports temporarily supplement grain needs in any given year, such aid causes reductions in domestic grain prices, reduces future production and more generally is not sustainable (Chabot and Dorosh, 2007). Furthermore, high variability in water supply negatively influences the net farm income and food production in downstream agricultural production.

Numerous previous studies have examined irrigation, water institution, agricultural systems, and food security in Afghanistan. Many national and international projects intend to examine ways to improve and rehabilitate the irrigation infrastructures and agricultural system. Example includes studies aimed at estimating crop water consumption (Senay et al., 2007), agricultural productivity (Sharp et al., 2002), impacts of the 2008 Afghan Water Law (Wege rich, 2010). However, few existing studies have aimed to improve the Balkh Basin’s water and irrigation institution capabilities. Torell and Ward (2010) investigated a water allocation framework that aimed to improve water use and food security in the Balkh Basin. Reeling et al. (2012) applied a linear programming approach to investigate impacts of a range of reservoir and water right allocation systems on the basin’s agricultural activities. However, no previous work to our knowledge has systematically integrated the hydrological, economic, and institutional characteristics of the basin as part of science-based policy assessment to improve food security and farm livelihoods.

In light of these gaps, this paper aims to investigate the economic returns associated with a range of storage capacity expansions that would benefit farm income and food security in the Balkh Basin, Afghanistan. Using available data, an integrated basin framework is developed and applied that addresses the basin’s hydrology, economics, culture, and institutions that uses a dynamic mathematical optimization framework. Based on our integrated framework, results are examined for three reservoir capacity expansions: small, medium, and large. Impacts are identified for several outcomes: regional farm income, land use, and irrigated crop production. These results are compared to the base condition in the basin, where no significant water storage currently exists.

2. Methodology

2.1. Data

With a history of more than three decades of military conflict, continuous research grade records of hydrological and agricultural data do not exist for our study area. This work employed the (very limited quality) available data on irrigated land, crop water use coefficients, and net revenue for fourteen canals in the basin (Fig. 2). Data used in this study, including average annual water inflow for the Balkh headwater were obtained from previous works of Torell and Ward (2010) and Reeling et al. (2012). Estimated available land for irrigation considered for this study, is 5762 paikals, where each pai kal is a local measure of water that is sufficient to irrigate 80 ha of land. Data on irrigated land, crop water use per ha, and net revenue show variability by sub-region (Fig. 2). In this paper, eight of the basin’s most important crops are included: wheat, alfalfa, rice, cotton, melon, potato, tomato, and pulses (legume crop).

The fourteen canals that take water from the Balkh River are divided into three regions that have similar water supply reliability.
and economic conditions. The first region is the Upper Region, which contains four main canals: Aman Sahib, NahrShahi, Siagard, and Balkha canals. The second region is the Middle Region, which includes Mushtag, Chemtal, Dawlatabad, and Abdullah canals. The third region is the Lower Region that contains six canals: Charbulak, Murdian, Faizabad, Mingajik, Aqcha, and Khanaqah canals at the bottom of the basin (Fig. 2). The future water supply is stochastically distributed around the average annual volume of 1540 MCM per year with historic variance in flows for the years 1964–1978, measured by USGS gauges that were working for that time period. These stochastic supplies were used to forecast future year-to-year variation in water supply in the basin.

2.2. Integrated water resources management

2.2.1. Overview

In recent years, integrated water resources management has emerged as the state-of-the-art approach for assessments of policy choices available at the basin scale. Integrated basin analysis has been used for policy design, implementation, and evaluation in the Rio Grande Basin in the USA; Maipo Basin in Chile; Mekong Basin; and Murray Basin in Australia (Ward and Pulido-Velazquez, 2008a,b; Rosegrant et al., 2000; Ringler, 2001; Mainuddin et al., 2007). Furthermore, integrated basin scale analysis provides a best management approach to assess alternative water allocation proposals (Wegerich, 2004; Gohar and Ward, 2011). Another advantage of the integrated basin framework methodology is its established record in tracking water supply and use patterns under a range of water supply variability and policy scenarios as well as investigating alternative water institutions and policies (Gohar and Ward, 2010).

The integrated basin framework is a comprehensive tool that encompasses agronomy, hydrology, economics, institutions, and environmental dimensions of the problem. Our study takes a first step to develop and apply an integrated basin framework that includes hydrology, agronomy, land use, culture, economics, and water institutions for Balkh Basin in Afghanistan. A brief mathematical framework is presented below. The complete mathematical framework and GAMS model code used for this research and study is available on the web at http://agecon.nmsu.edu/fward/water/.

2.2.2. Hydrology

The basin is an important watershed in Northern Afghanistan that includes 14 main canals (Fig. 1). The basin’s runoff feeds the water supply for all fourteen canals used to irrigate a range of crops in the catchment. Our framework treats the entire basin as one unit, which allows for a unified tracking for surface water from the headwater to a range of locations lower in the catchment. The hydrologic balance accounts for headwater flows, river flows, reservoir storage volume, water diverted, water use, and water return flows at different locations and time scale within the basin. To complete the hydrologic balance, four (virtual) gauges are specified. These gauges are used to track total water diverted, used, and returned to the river’s mainstem at the three main regions and at the tail end of the watershed (Fig. 2).

Total water use in any region is defined as the quantity of water lost through evaporation and evapotranspiration (ET), implemented by the use of crop water use coefficients. Total water use for any given region and period is the estimated ET by crop multiplied by the irrigated land observed during period in given region. Annual total (stochastic) water inflow is set at an equal trajectory for all reservoir capacity scenarios. The main motivation behind the hydrology model is a desire to reflect mass balance, both for surface flow interactions and reservoir levels. The hydrology model described below uses mass balance principles to account for headwater flows, river flows, reservoir levels, water from surface applied to various uses at different locations, and the impact of
surface flows and river diversions for land under irrigation by crop and region for both the current as well as for three alternative reservoir storage levels.

2.2.2.1. Headwater runoff. Annual average water flow is stochastically generated for 20 years around the long run mean measured water inflow. Water inflow at nth headwater gauge (n = 1 for this study) and year t, \( X_{int} \), equals total stochastically generated source supplies that preserved the historical mean and variance of annual supplies:

\[ X_{int} = N \sim source_{int} \]

2.2.2.2. Gauged streamflows. River flow at each nth river gauge, reservoir capacity c, in period t, \( X_{ct} \), equals the sum of flows over any upstream node whose activities directly influence that flow. These include: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; and (5) upstream reservoir releases. Total flows, required to be nonnegative, are defined for each of those five types of nodes, respectively, as:

\[ X_{ct} = \sum_{h} B_{th} X_{hct} + \sum_{v} B_{tv} X_{vct} + \sum_{d} B_{td} X_{dct} + \sum_{r} B_{tr} X_{rct} + \sum_{l} B_{tl} X_{lclt} \]

(1)

The set v defines all river gauges, and \( X_{vct} \) is the river flow at any river gauge node (element of the v set). Each of the five vectors of B coefficients takes on values of 0 for non-contributing upstream sources, 1 for sources that add flow, and -1 for sources that reduce flow. Thus, positive signs in an equation (+) require adding flows, and subtractions (-) occur whenever a B coefficient is negative. For example, the first term, \( \sum_{h} B_{th} X_{hct} \), sums contributions over the set (h) of headwater nodes. The vector \( B_{tv} \) contains 1 for all immediately upstream headwater gauges that contribute to a river's flow and 0 otherwise, where \( X_{vct} \) are flows at the one headwater gauge used for this study. The second right-hand side term, \( \sum_{v} B_{tv} X_{vct} \), sums contributions over the set (v) of relevant upstream river gauge elements. The vector \( B_{tv} \) typically contains a single 1, and the rest zeros. The third term, \( \sum_{d} B_{td} X_{dct} \), sums river flow reductions over the set (d) of upstream diversion nodes. By accounting for upstream diversions, the \( B_{td} \) coefficients are zero for non-diverting locations and for diversions that do not affect the given nodes flow. It is set at -1 where upstream diversions directly reduce that flow. The last two terms similarly account for; upstream surface return flows in the set (r), and upstream reservoir releases in the set (L) that affect river flows.

2.2.2.3. Water diverted. Agricultural water supply is used by direct stream diversions from the 14 canals that divert Balkh River water. Those canals are aggregated into three main regions: Upper, Middle, and Lower. The following equation, a wet water condition, requires that no diversion exceed available river flow at the point of diversion. Therefore, for the river to be wet, each diversion must be less than the sum of all five classes of upstream sources: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; and (5) upstream reservoir releases. A diversion (d subscript), which cannot be negative, is:

\[ X_{dct} \leq \sum_{h} B_{th} X_{hct} + \sum_{v} B_{tv} X_{vct} + \sum_{d} B_{td} X_{dct} + \sum_{r} B_{tr} X_{rct} + \sum_{l} B_{tl} X_{lclt} \]

(2)

The right hand side terms are the sum of all contributions to flow at the point of diversion from upstream sources. The various B terms, which indicate presence (1) or absence (0) of upstream flow sources for a given node, are used to configure the basin.

2.2.2.4. Water applied. Like diverted water, total water applied for use at any node in period t, \( X_{act} \), is a choice variable, where water applied come from stream diversion, \( X_{dct} \). Total water applied is:

\[ X_{act} = \sum_{d} B_{td} X_{dct} \]

(3)

The coefficient \( B_{td} \) is an identity matrix to conform like nodes in the basin. For each agricultural node in the basin, total water applied to farmlands is expressed as:

\[ X_{act} = \sum_{k} B_{tk} \sum_{u} B_{uk} l_{ukct} \]

(4)

Total irrigation water applied from surface flows at each nth water application node and nth reservoir capacity in the nth year equals total water demands. These demands are summed over crops (k) based on known water application amounts per hectares by crop, \( B_{uk} \). The result is multiplied by an identity matrix, \( B_{tk} \), that conforms nodes and the number of hectares irrigated at the nth use node by the kth crop by nth reservoir capacity in the nth year, \( l_{ukct} \). The optimal solution of a single model run determines the total quantity of irrigated land, \( l_{ukct} \), which determines the total demand for irrigation water applications, \( X_{act} \).

2.2.2.5. Water consumed. For any use node, consumptive use, \( X_{act} \), is an empirically determined proportion of total water applied, \( X_{act} \). For irrigation, consumptive use is the quantity of water lost through plant evapotranspiration (ET) to any future use in the system. That use, which cannot be negative, is measured as:

\[ X_{act} = \sum_{d} B_{td} X_{dct} \]

(5)

The parameters \( B_{td} \) are elements indicating the proportion of total water applied that is used consumptively. Setting \( B_{td} \) at 1.00 for the current model implementation achieved the best hydrologic balance when comparing model-predicted use against actual river flows and land under irrigation. For agricultural nodes, water use is measured as:

\[ X_{act} = \sum_{k} B_{tk} \sum_{u} B_{uk} l_{ukct} \]

(6)

Irrigation ET at the nth agricultural node under nth reservoir capacity in the nth year is derived from total hectares of land in production. That water use is measured as the sum over crops (k) of empirically estimated ET amounts per hectares by node, \( B_{uk} \) and \( B_{uk} \) times an identity matrix, \( B_{tk} \), that conforms nodes. The result is multiplied by the hectares irrigated. The quantity of land irrigated by use, crop, reservoir capacity, and time is determined by the model's optimal solution.

2.2.2.6. Return flows. For agricultural nodes, total surface returns to the river are measured as:

\[ X_{act} = \sum_{k} B_{tk} \sum_{u} B_{uk} l_{ukct} \]

(7)

In the case of the basin, there are little reliable data available for return water flow, so return flows were treated in this study as equal to zero. Our hope is to secure more data on these flows for future work.

2.2.3. Cultural characteristics: water rights

The Balkh Basin lacks a formal water right system that controls water allocation and use to adapt to shortages in periods of drought. The basin’s water allocation and distribution system relies on deep historical roots. Water allocation is organized by local communities for each canal service area. Important elements of these communities include Mirabs, Mirab Bashis, and Wakils.
mirab is a local farmer-elected leader at each canal who is responsible for water allocation and distribution within the canal service area. Each mirab attempts to resolve conflicts arising among the farmers regarding water allocation for his canal service area (Torell and Ward, 2010; Reeling et al., 2012). A mirab bashi is a less common version of a mirab, for which a single canal master is responsible for managing water disputes. A wakil is a water district representative responsible for water allocation in urban areas (Lee, 2006; Rout, 2008).

In the basin, the community-based water allocation system has many aims. Those aims include water distribution for of social justice, maintaining water flows, and addressing conflicts arising among farmers within any given canal service area. Despite the consistent aims of the mirab system throughout the basin, targeted water management practices are applied uniquely by canal service area and region. An important shortcoming of this community water allocation system has always been a weak capacity to resolve water conflicts that occur among mirabs, each of whom is responsible for maintaining peace for a given canal. As a result, during drought years, upstream canals, by virtue of their preferred location, have a default top priority to use water, for whatever water remains in the river's mainstream at that canal's location (Lee, 2006). Throughout this paper, the water right system of an "upstream priority" arrangement is maintained. For all water supply scenarios, upstream users have the top priority to use water.

2.2.4. Economics

Hydrologic data on water inflow, water diverted, and water use is combined with farm budget data that account for farm crop net revenue. A dynamic optimization framework that maximizes the discounted net present value of net farm income summed over crops and regions is developed. We apply that framework to assess consequences of alternative possible expansions of storage reservoir capacities. For any crop, net revenue per unit land is equal to crop yield multiplied by the crop price minus costs of production by period and region. Net revenue per ha is calculated by crop and region. Total net revenue (farm income) for each region in the basin is equal to the net revenue per ha for irrigated crops multiplied by the irrigated land from that crop at any period. For the water supply scenario used and storage capacity levels other than the baseline observed levels, irrigated land in production is an unknown and is solved by the model. Results show four combinations of water supply scenarios and reservoir storage levels.

2.2.5. Institutions and infrastructure

An important objective for this study is to investigate the economic value to irrigated agriculture in the basin of expanding storage reservoir capacity from the current level of zero to various alternative potential levels. The motivation for considering additional reservoir capacity rests with the well-known and ancient problem in this basin: farmers have limited ability to use water from previous wet years when the inevitable dry year occurs. Additional storage capacity could be used to support livelihoods, food security, and farm income in dry years when irrigators would otherwise suffer from the long-repeated historical pattern of little capacity to adapt to low supplies. In normal water years, total available land brought under irrigation is estimated at 461,000 ha. That quantity of land uses about 1540 MCM of water for all canal service areas in the basin. However, during drought years, farmers are unable to cultivate this amount of land without new storage capacity. Similarly, during flood years, there is no reservoir capacity available, so farmers cannot store otherwise unused water for future use.

2.2.5.1. Land use

Land use patterns assigned to irrigated crop affect the demand for water. For irrigated agriculture, total land in production is expressed as:

\[ L_{\text{irrig}} = L_{\text{net}} \times \text{RHS}_{\text{irrig}} \]  
\[ L_{\text{dry}} \leq 3.0 \times L_{\text{irrig}} \]  
\[ L_{\text{irrig}} \leq 461,000 \]  

Irrigated land for any given node and crop under any given reservoir storage capacity for the first year \( (p^{\text{first}}) \) is taken to be the same as the observed irrigated land in production for the base year. Similarly, irrigated land in production by node, crop, and reservoir capacity for later periods \( (p^{\text{later}}) \) cannot exceed three times the available land \( \text{RHS}_{\text{node}} \) by node, and period, a constraint that reflects limited land capacity expansion by crop compared to existing observed levels. We used the maximum current irrigated land capability for the Balkh Basin, estimated at 461,000 ha as the upper limit on total available land. However, more irrigated land could become available if greater long-term water supplies could be secured and if institutions could adjust to permit the extra water to be used by agriculture. The model keeps track of land use by node, crop, reservoir capacity available, if developed, by period.

is, each region produces what we describe as use-related benefits, a benefit for crop irrigation that requires water use. For each irrigated agricultural region, the economic benefits are measured as net farm income. For any given agricultural use node under any reservoir capacity, benefits for the entire region are obtained by summing net farm income over all crops in production:

\[ X_{\text{Balt}} = \sum_{t} X_{\text{Bet}} \]  

The term \( X_{\text{Balt}} \) is the total economic benefit for nodes, reservoir capacity, and time periods summed over crops. Discounted net present value for each reservoir capacity over nodes and time-periods is expressed in its standard algebraic form:

\[ \text{NPV} = \sum_{t} \sum_{k} X_{\text{Balt}} \frac{1}{(1+r)^t} + \sum_{t} X_{\text{Bet}} \frac{1}{(1+r)^s} \]
2.2.5.2. Reservoir capacity. For the current work, we consider and evaluate the consequences of three different potential reservoir scales: small, medium, and large. A small reservoir is defined to hold 50% of the total average annual water inflows, estimated at 770 MCM. The second reservoir scale is the medium reservoir, assigned to hold 150% of average annual inflow, 2310 MCM. The third reservoir capacity is large, for which storage capacity is 600% of average annual water inflow. The three alternative potential reservoir capacities are specified as:

\[ Z_{ac} = \beta \times \text{Source}_a \]  

where the maximum reservoir capacity \((Z_{ac})\) for any storage volume \((s)\), and reservoir scale \((c)\), is each parameter described above \((\beta)\), multiplied by the average annual water inflow. The scale parameter takes the value of 0.5, 1.5, and 6.0 for small, medium, and large reservoir capacity, respectively.

2.2.5.3. Reservoir development costs. Storage reservoirs are built for hydropower generation, flood control, urban uses, irrigation, and various combinations of these. The cost of reservoir construction can be high, especially in a country with weakly-developed engineering infrastructure expertise. The cost of establishing storage reservoirs are affected by the type, purpose, size, design, geographical, and geological characteristics of the basin (Gaudette and Bultota, 2003; Mwea and Ngware, 1996). For these reservoirs, the reservoir site plays an important role in determining the construction cost in which earthwork can contribute 80% or more of the construction, operation, and maintenance cost (Aqueera et al., 2007).

While smaller reservoirs are more financially attractive because of their modest size, larger reservoirs hold more water, so large reservoirs can be a better method to adapt to long periods of drought (Chiquito, 2012; Yazdi and Neyshabouri, 2012; Mushtaq et al., 2007). Important negative externalities can be produced by reservoir construction such as costs of degraded environments and damaged key ecological assets. By contrast, large multiple use reservoirs can provide economic development and create employment in addition to securing water for irrigation in a series of dry years (Tundisi et al., 2008).

For this work, average estimated construction cost per unit of stored water of existing or planned dams and reservoirs were identified at similar regions to our study area. Information on these costs were transferred to our region. These other places were areas of similar geographical relief and geological conditions. Construction, operation, and maintenance costs were transferred from these places to our target site. This method provides a rough estimate of the construction, operation, and maintenance cost (Cost) of alternative potential reservoir storage capacities scaled from none to large. Available data from both Rogun and Dashtijum reservoirs in the Amu Darya Basin show that these planned reservoirs have storage capacities of 13.3 and 17.4 billion cubic meters and cost of $2.2 and $3.5 billion USD respectively. From these two existing storage sites, average construction cost is estimated at $0.186 USD per cubic meters of storage capacity. Total costs of different reservoir capacities were incorporated in the model to reflect the COM costs of the Afghan storage capacity expansions in the Balkh Basin considered for this study. The following equation describes the relationship we used between the reservoir capacity and construction cost.

\[ \text{ConCost}_{uc} = B_{uc} \times Z_{uc} \]  

where ConCost associated with different proposed reservoir scale \((c)\) is equal to the construction cost per unit of stored water multiplied by the maximum storage volume of the reservoir \((z)\).

2.2.6. Water supply scenarios

Data on annual stream flow for the period 1964–1979 were used to characterize mean annual long run water supply for our 20 year analysis. The estimated average annual snow runoff is 1540 million cubic meters. Still, this annual average water supply may be subject to impacts of climate change that could reduce this annual average inflow by different levels in future years. A base and three alternative climate water supply scenarios are used to investigate the impact of proposed reservoir capacities on the total regional farm income for the Balkh Basin. Those scenarios are compared to the base condition. Annual inflow is stochastically distributed for the base and for each of the three alternative climate scenarios. The first water supply climate scenario is set for mean flows to fall linearly after 20 years from the long term average flow to 90% of that average flow. The second scenario represents a moderate reduction in water supply from climate, for which long term average inflow is set to fall to 20% of the historical mean after 20 years. For the severe climate scenario, average inflows after 20 years are set to fall to 70% of the historical average. Under all water supply reduction scenarios, the annual inflow is stochastically generated and it is normally distributed. For all climate scenarios, reservoir storage capacity is set the same level.

3. Results

3.1. Overview

Results are shown for the base and for three alternative potential reservoir capacities. The impact of alternative reservoir capacities on basin water use, water storage, and water not used (existing the basin at the lower end) – are described for 20 years the time span for this analysis. In addition, impacts of reservoir capacity on irrigated land, water consumption, net farm income, and different water supply scenarios are shown. The tables show average values for the analyzed time scale.

3.2. Water supply, storage, use, and nonuse

Table 1 illustrates the basin’s annual water supply generated by the stochastic inflow, storage water, water use, and water nonuse by year and reservoir scenario, in MCM, for the basin. The stochastic water supply is set at the same amount for all reservoir capacities considered. Results show high variability in annual water supply. Furthermore, reservoirs under different capacities allowed storing the maximum storage capacity at the end of analysis period to sustain supplies for future generations that receive benefits after the end of the 20-year scenario considered here. Annual water supply ranges from a high of 4485 MCM, such as shown for year 15 to as low of 295 MCM in year four. The basin has a history of producing flashy supplies, in which supplies from 1 year to another show considerable fluctuation. This high variation in water supply reflects the natural of flood and drought pattern associated with the basin.

Over all reservoir capacities, maximum average water use for irrigation is 1465 MCM yearly, which is enough to irrigate the total historically irrigable land in the basin. In the case of no reservoir storage at all, which represents the current situation, farmers use the maximum amount of available water in an average year’s inflow. However, where inflow exceeds 1465 MCM, excess water has no use in the current year due to zero storage capacity. Table 1 shows that with no storage developed, 3020 MCM of supply has no use in year 15 for example, which equals more than twice average inflows, an amount that could be used for irrigation in future dry years.
Developing a small reservoir storage capacity, with 770 MCM of capacity, is equivalent to 50% of average annual inflow. Table 1 shows that the availability of small reservoir allows water users to benefit from stored 770 MCM in the third year and reallocate this amount of water for the subsequent drought years. The small reservoir storage also increases average water use from 885 MCM without any reservoir storage capacity, since larger reservoirs can trap more wet-year inflows. This situation repeatedly occurs in year 2, 3, 8, 15, 19, and 20. The average yearly amount of nonuse declines with expanded storage capacity, since larger reservoirs can trap more wet-year flows for release in dry years. For example, in year 15, nonuse, measured in million cubic meters per year, declines from 3020 (no storage) to 2250 (small storage) to 710 (medium storage) to 0 (large storage) in year 15, following several sequential wet years’ natural supply.

If a medium storage capacity is developed, reservoir storage increases up to 2310 MCM, 1.5 times the level of historical average annual flows. Increasing the reservoir capacity to that level considerably enhances the ability to reallocate stored water from wet to dry years. Table 1 shows that average annual water use for irrigation increases under this reservoir scale increases to 1209 MCM, an increase of 37% from the long run average water use level of 885 MCM without any reservoir storage capacity. Medium storage capacity increases average water use by making more available for dry years that would have otherwise gone unused. Unused water (nonuse) decreases to zero for all years except years 15 and 19, where the water inflow is very high and exceeds irrigated land capacity. In contrast, the average nonuse water decreases to be 1209 MCM under medium reservoir capacity.

Finally, large-scale reservoir capacity can capture up to six times average estimated inflow, an amount of water equal to 9240 MCM. This large capacity increases the ability to store for later use all water inflows even in very wet years in which some water would otherwise be lost to future nonuse if only smaller scale storage capacity are built. The high reservoir capacity of 9240 MCM reduces nonuse (spills) to zero for all 20 years. Results in Table 1 show that water stored and released for later years increases the ability of putting all water to beneficial use in irrigated agriculture and reduces the level and economic damages with the attendant tragic consequences for food security suffered by shortfalls in series of very dry years. Moreover, a large reservoir stores 2525 MCM that can be used in the future. Nevertheless, for 20 years analyzed and considering those sequential years of drought, even a large reservoir cannot hold enough amount of water to use when water users face a sequence of extremely dry years, such as could occur under a future climate change scenario. The large reservoir, however, provides more sustainability on the long run due to the reservoir’s capacity to store larger volume of water in very wet years for use in extreme drought years.

### 3.3. Water use

Average water use by crop, region, and reservoir storage capacity is shown in Table 2 for the basin. In Afghanistan as with many irrigated basins outside the western world, water users at the high end of watersheds typically default to the highest priority of water use when there is no water rights administration assigned and enforced by the central government. Average water use, especially in the lower parts of the watershed, increases as the reservoir capacity increases. Total average water use increases from 885 MCM in base condition of zero storage to 1036, 1209, and 1244 MCM for Small, Medium, and Large reservoir capacity respectively.

Results illustrate that under the current zero reservoir capacity, total average water use is 885 MCM allocated among the subsbasins as 211, 299, and 374 MCM for the Upper, Middle, and Lower region respectively. Melon consumes a higher amount of water compared to other cultivated crops. In general, the Lower Region farmers consume large amount of water when available given the fact that this region contains large number of canals and irrigated land, and high agronomic productivity of water. Under small reservoir capacity, Middle Region farmers could increase their water use for melon crop almost by 55% comparing to base condition, while no increase occurred for other crops. Respectively, additional reservoir storage retrieves more water to Lower Region cultivators of wheat, melon, tomato, and pulses. Moreover, the average available water for rice irrigation falls in series of very dry years. Moreover, a large reservoir stores 2525 MCM that can be used in the future. Nevertheless, for 20 years analyzed and considering those sequential years of drought, even a large reservoir cannot hold enough amount of water to use when water users face a sequence of extremely dry years, such as could occur under a future climate change scenario. The large reservoir, however, provides more sustainability on the long run due to the reservoir’s capacity to store larger volume of water in very wet years for use in extreme drought years.
Under small reservoir comparing to no reservoir capacity. 

Under a medium reservoir development plan, melons in the Middle Region shows an increase of irrigated land from wheat, melon, tomato, and pulses with considerable decrease from cultivated land of rice crop.
place in Lower region for rice crop, while the irrigated land from pulses crops practice a small decline.

3.5. Farm income

The major advantage of up-scaling reservoir storage capacity is allowing more irrigation water for farming more cropland in drought years that would otherwise cause considerable hardship in food security and farm livelihoods. The net farm income by crop, region, and reservoir capacity in the basin is presented in Table 4. Results show that farmers in the three regions can gain in average around $US 144 million per year. Gains from wheat, melon, and tomato contribute the main source of income in the basin compared to incomes produced without any reservoir capacity available. Farmers increase their income by having access to the fruits of a small reservoir, seeing returns increase by 21%. The growing net income occurs in both the Middle and Lower Regions, regions that would otherwise shoulder the greatest burden of adapting to dry year shortages. The highest increase in net farm income takes place in the Middle Region for melon cultivators, where the net income rises by 55% comparing to no reservoir situation. In Lower Region, the income for the irrigators of wheat, melon, tomato, and pulses increases by 16%, 41%, 32%, and 23% respectively, while rice cultivators sustain negative gains of 19%. These same cultivators gain more income than they lose by switching from rice to alternative crops.

Development of medium reservoir storage adds more farm income for the basin. Under this reservoir scale, farmers enhance their overall net income by 16% comparing to the small-scale capacity reservoir. The added income occurs in Middle region for cultivators of wheat, melon, tomato, and pulses. As the farmers secure required water for irrigation by medium reservoir capacity, large reservoir adds slight increase in the regional farm income. The net farm income for the basin rises by one percent in comparison to the medium scale reservoir. The only increase in the net farm income is observed in Lower Region for the rice cultivators, while the net farm income for the irrigator of pulses crops decrease slightly by 5% comparing to medium reservoir capacity. Absolute increase in the net farm income generated by the reservoir capacities is shown in Table 5 in millions of US dollars by crop and region. Alternative additional storage capacities improve the net farm income for the Middle and Lower Regions mostly, since the Upper Regions secure their full supply even in most severe drought years.

3.6. Net farm income by climate scenario

Average total net farm income produced by different reservoir capacities under three alternative climate water supply scenarios are shown in Table 6 in addition to the estimated construction cost of those capacities. Climate impacts shown for the other five results tables are available from the authors on request. The data illustrate that under the historical water supply condition, average total net farm income increases net of construction costs rises then falls as reservoir scaling increases from none to a large scale. The reason for this is the high construction cost associated with the large reservoir is subtracted from total benefits of net farm income. The estimated cost for large reservoir that can hold up to 9.2 billion cubic meter is $1.7 billion US, which is considered economically inefficient. Under the small reduction of the snow runoff supply, 10% over a 20-year period, considerable decline in the total net farm income occurred with all reservoir scales. That decline in farm income is 4%, 6%, and 11% respectively for small, medium, and large scale reservoir development.

By contrast, a medium climate reduction of water supply, shown by the 20% decreases in snow runoff, could decrease net farm income under small, medium, and large scaled reservoirs by 8%, 15%, and 29% correspondingly. Under the highest reduction of the water supply, 30% after 20 years, the reduction will sharply decrease the net farm income under all reservoir capacity levels. However, the reduction in farm income will be the highest at the large reservoir capacities, estimated at about 50% of total average annual farm income. The severe impact of snow runoff reduction under the large reservoir capacity is explained by the high construction cost of large reservoirs and the much smaller inflows of snowmelt available for storage. In general, while the small reservoir capacity is relatively more beneficial under large reduction of water supply, the medium

Table 5
Net farm income produced by additional storage capacity, by crop, region, and reservoir capacity for Balkh Basin, Afghanistan (20 years average, millions of $ US/year).

<table>
<thead>
<tr>
<th>Crops</th>
<th>Base: no reservoir capacity</th>
<th>Small reservoir capacity</th>
<th>Medium reservoir capacity</th>
<th>Large reservoir capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Middle</td>
<td>Lower</td>
<td>Total</td>
</tr>
<tr>
<td>Wheat</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rice</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cotton</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Melon</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>19.95</td>
</tr>
<tr>
<td>Potato</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tomato</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pulses</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>19.95</td>
</tr>
</tbody>
</table>

Table 6
Discounted net present value of economic benefits: net farm income minus reservoir development costs of construction, operation, and maintenance, Balkh Basin, Afghanistan (20 years time horizon, millions $ US).

<table>
<thead>
<tr>
<th>Water supply scenario</th>
<th>Reservoir storage capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
</tr>
<tr>
<td>Base condition</td>
<td>2608</td>
</tr>
<tr>
<td>10% Reduction</td>
<td>2538</td>
</tr>
<tr>
<td>20% Reduction</td>
<td>2463</td>
</tr>
<tr>
<td>30% Reduction</td>
<td>2382</td>
</tr>
<tr>
<td>Construction, operation, and maintenance cost (discounted NPV)</td>
<td>0</td>
</tr>
</tbody>
</table>
reservoir size is more efficient under more modest declines in the basin's water supply.

4. Conclusions

Afghanistan's agricultural and water institutions as well as its irrigation infrastructure have suffered from decades of war and unrest. The essentially zero current water storage infrastructure capacity, places a large burden of farm income, food security, and livelihoods. These burdens are more painful in the face of ongoing climate variability that produces high fluctuations in water supplies from year-to-year. Without additional storage developed to adapt to climate variability, current and future water supply fluctuates constrain the country's sustainability for irrigated agriculture and its attendant capacity to secure and sustain staple food requirements. In Afghanistan, the Balkh Basin is an important source for the regional and national grain production, essential for food security. The annual water inflow for the Balkh Basin that comes mainly from snowmelt runoff is highly variable from year-to-year. Estimated annual long run supplies are 1540 million cubic meters based on data secured from the admittedly short period 1964–1978. However, given the certainty of water supply variability coming from future years of droughts and flooding, farmers are poorly positioned to take advantage of surplus water from wet years due to the current absence of significant water storage capacity. Therefore, in drought years, farmers are unable to find water for their irrigated land in the lower reach of the basin because of unavailable releases from previous wet years' storage.

In the Balkh Basin, weakly developed water institutions result in low capacity for growers in the lower parts of the basin to bring land into production, especially in dry years if additional developed storage capacity is not developed. In that basin, as in most of Afghanistan, local water managers called mirabs regulate water allocation and distribution. As a default water allocation system, the highest priority is assigned for upstream users. This default institution causes major hardship to downstream users' farm income without additional water storage capacity made available. Limited numbers of projects have been addressed the water allocation efficiency and institution policies that could be used to optimize net return of irrigation water in this country that relies so heavily on agriculture.

In summary, this work has attempted to shed light on the importance of considering the hydrologic characteristics of the basin. We evaluated three reservoir capacities on the Balkh Basin irrigation water use, allocation, and farm income. Using available farm budget data, this research has taken a preliminary step to develop an integrated basin scale framework that encompasses hydrology, institutional, cultural, and economic characteristics of the Balkh Basin. A dynamic empirical optimization model has accounted for irrigation water users in the basin, with the intent of optimizing net agricultural benefits under the three proposed alternative reservoir capacity developments. The three reservoir scales are assigned as small reservoir that could save half of the average long term annual flow, medium reservoir that stores 150% of total average inflow, and large reservoir that store six times average annual inflow. With respect to upstream water right priority, a stochastic water inflow for 20 years' time period analysis is implemented to characterize the variation in water inflow that are perceived by the basin's water users as the ongoing pattern of droughts and floods.

The integrated basin framework described for this study is the state-of-the-art analytic method for assessing policy alternatives at the river basin scale. This framework has the advantage of explicitly including a balanced hydrology that interacts with institutions, cultural, and economic characteristics of the basin. However, investigating more policies such as water pricing, more flexible water rights systems, and irrigation technologies are beyond the scope of this research and must be left for future work. Furthermore, other benefits such as hydropower generation in addition to urban water supply and environmental impact are excluded from the current work. Nevertheless, a central advantage of our framework is to provide to water policymakers, managers, mirabs, and farmers, the information needed to formulate science-based water policy designs.

Acknowledgments

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References