HYDROLOGIC MODELING OF GLACIATED WATERSHED IN CENTRAL ASIA

Timur Sabitov
sabitov.ty@gmail.com

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HYDROLOGIC MODELING OF GLACIATED WATERSHED IN CENTRAL ASIA

by

Timur Sabitov

A thesis
submitted in partial fulfillment
of the requirements for the
Master of Science Degree
State University of New York
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Department of Environmental Resources Engineering

Approved by:
Cornelius B. Murphy Jr., Major Professor
Lindi J. Quackenbush, Co-Major Professor
Alexander Weir, Chair, Examining Committee
Theodore A. Endreny, Department Chair
S. Scott Shannon, Dean, The Graduate School
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Abstract


This work utilizes four hydrologic models based on simple water balance and Soil Conservation Service (SCS) runoff curve number methods to analyze watershed characteristics for the Pskem River watershed in Central Asia. We collected comprehensive information about streamflow, temperature, and precipitation for the Pskem watershed, determined land cover features affecting streamflow conditions such as glaciers and analyzed climatic characteristics in the watershed. We compared four increasingly complex hydrologic models to estimate streamflow for water years 2013–2015 and to determine if the increased complexity provided accuracy or computational advantages. The coefficients of determination of the final hydrologic models (in order of increasing complexity) for monthly streamflow were 0.84, 0.77, 0.93 and 0.85, suggesting that there are moderate requirements of model adjustment needed. Parameters used for streamflow modeling were estimated using extensive calibration and remote sensing techniques and could also be applied to other watersheds that have similar characteristics.

Key Words: Hydrologic modeling, Central Asia, remote sensing, model calibration, hydrologic forecasting, glaciers, land cover classification, water balance, climate forecasting.

T.Y. Sabitov
Candidate for the degree of Master of Science, May 2018
Cornelius B. Murphy Jr., PhD
Lindi J. Quackenbush, PhD
Department of Environmental Resources Engineering
State University of New York College of Environmental Science and Forestry
Syracuse, NY
Chapter 1 : Thesis Introduction and Overview

Introduction

Scientific evidence suggests that humans have dramatically altered the environment around them. Such changes have impacted the world and caused changes in global climate conditions (Pachauri et al., 2014). These climatic condition changes have triggered disastrous environmental events including an increase in the frequency of meteorological anomalies, decreases in the ice balance (Mysak et al., 1990), and other singular events.

The World Health Organization (WHO) estimated that warming and precipitation anomalies due to climate change in the last 30 years of the last century was responsible for as many as 150,000 deaths annually and the rates will likely keep growing to reach 250,000 deaths per year in the next decades (Fig. 1-1) (WHO, 2002). Many human health consequences are linked to climate change, from cardiovascular mortality and respiratory illnesses due to heatwaves, to transmission of infectious diseases and malnutrition from crop failures due to catastrophic anomalies such as drought or flooding (Hales et al., 2003).

Climate change is also affecting water resources with high flows in some parts of the world (e.g. South America, North America) causing billions of dollars in damages, while other parts of the globe are experiencing the opposite with increased drought events and decreased runoff (e.g., parts of Europe, the Mediterranean, South Africa, and Central Asia) (Aizen et al., 2007; Bohner, 2006).

Adaptation to climate changes can be observed in both physical and ecological systems as well as in the adjustment of societies and organizations to manage resource availability and risks at different spatial and societal scales. Such adaptation requires accurate and reliable predictions achievable through modeling of the changes at regional and global scales. Millions
have been spent on improving data quality and developing models, yet we have serious
challenges due to the variance in the weather across the world and the limited number of
monitoring stations, which leads to data gaps.

Fig. 1-1. Infographic by World Health Organization: Impact of climate change on population health across
the world.
Several distinct fields of climate modeling have emerged over the past decades. This study focuses on one of these: hydrologic modeling. The aim of hydrologic modeling is to develop tools for analysis of water resources and prediction of future conditions based on existing and recorded parameters such as land cover, precipitation, air temperature, and evapotranspiration. The approaches used for modeling have changed in recent years; more and more scientists integrating locally developed models in a global framework are relying on accuracy achieved through the regional scale of the studies (David et al., 2013; Tharme, 2003). The complexity of such models varies and is dependent on project objectives. In some regions hydrologic modeling has not been applied, hence there is no reference for assessment of the appropriate level of model complexity required.

This project will explore water resource changes occurring in a region of Central Asia that is not well characterized. This will fulfill a missing gap in the hydrologic perspective for a watershed feeding a city with a population of about 4 million people that has been affected by climate change over the past decades. The remainder of this chapter will explore evidence of climate change including increasing air temperature, temperature anomalies, melting glaciers, water resource changes, and the trend of increasing population in the region of interest.

**Global and local temperature trends**

One of the best indicators of climate change is the Land-Ocean Temperature Index that the National Aeronautical and Space Administration (NASA) Goddard Institute for Space Studies uses to demonstrate global surface temperature change. Fig. 1-2 shows the difference in global temperatures relative to the 1951–1980 average.
Except for a leveling off between the 1940s and 1970s, Earth surface temperatures have increased since 1880 and the last decade has brought temperatures to the highest levels ever recorded. As shown by the red line in Fig. 1-2, long-term trends are more apparent when temperatures are averaged over a five-year period. The increase in air temperature is also apparent while looking at Fig. 1-3, which displays the distribution of temperature anomalies from the global average. We are living in an era of increased variability of climate parameters that not only includes air temperature, but also includes carbon dioxide emission, and precipitation.
Water resources worldwide and in arid regions

Climate change has not left the water ecosystem of our planet untouched. Most vulnerable to the changing climate is the glacial system and glacial water balance. Researchers across the world have reported a dramatic reduction in the cryosphere, including a decrease in the area of polar ice shelves, which have been adversely affected due to changes in air temperature. Fig. 1-4 indicates the reduction in the cumulative mass balance of glaciers across the globe. The decline in the glacial mass balance is apparent in regions of Patagonia, Alaska, northwestern USA, and southwestern Canada. Most of these regions have experienced a glacial decline in the past several decades.
Glacial decline impacts global sea levels, which rise each year and have threatened the populations of many cities. However, while some regions have an abundance of water and frequent flooding events, in other regions dramatic droughts are observed. These regions are often heavily dependent on water for supporting a range of population needs such as agriculture. One such region struggling to deal with changes in water availability is Central Asia.

Central Asia includes post-Soviet Union Republics such as Uzbekistan, Kazakhstan, Tajikistan, Kyrgyzstan. Poor management of water resources in the Soviet era has degraded the Aral Sea, a dominant water body in the region. After the collapse of the USSR, the separation of countries shifted control of natural resources from a centralized system to a decentralized system with management headquartered in each of the separate states. Such breaks caused countries lying downstream to be dependent on countries controlling the place of origin for major rivers for the management of watersheds. Streamflow patterns in Central Asia are strongly driven by seasonality and by available water from the snow and glacial melt in the spring and summer seasons. Fig. 1-5 depicts the location of the Central Asian region and some of the observed
precipitation patterns in winter (January) and summer (July). Fig. 1-5 also includes the location of six selected glaciers. Fig. 1-6 shows the drastic decline in the glacier mass balance of these glaciers over the past 130 years.

In recent decades, countries in Central Asia have experienced not only natural but political changes. The post-independence shift of water resources associated with irrigation use has increased tension between upstream and downstream countries. In such an environment, the proper management and accurate prediction of water resources for the countries lying downstream becomes even more important. Such changes have affected every country in the region, most notably Uzbekistan. Uzbekistan has the second largest population in the region after Afghanistan, but unlike Afghanistan, which includes some upstream waters, Uzbekistan is mainly located downstream of the main water resources. Such conditions led Uzbekistan to become one of the most politically sensitive countries regarding management of water resources.

![Map of Tien Shan mountains and seasonal distribution of precipitation in Central Asia](image)

**Fig. 1-5.** Map of Tien Shan mountains and seasonal distribution of precipitation in Central Asia. (a) Hydrologic network in Central Asia, including glaciers, main lakes, reservoirs, and rivers. Main monthly precipitation in January (c) and July (d). Based on SRTM (Sorg et al., 2012).
The productivity of the Central Asian region is highly dependent on water resources. The agriculture sector is a major employer in the region and produces a large percentage of the Gross Domestic Product of each country. The diversion of water for irrigation in the past has adversely affected the Aral Sea basin, causing salinization and droughts. There is an urgent requirement for proper management of water resources, improving water quality and meeting basic human needs. Flow coming from upstream countries Kyrgyzstan and Tajikistan contribute about 77% of the total water resources in the Aral Sea Basin, with Afghanistan adding around 10% of the basin water resources. Thus 87% of the total water resources originate outside of agriculture-oriented countries Kazakhstan and Uzbekistan. Recent economic development and stability in the region have increased demand for agriculture production and demand for water is growing rapidly.

Population growth in the Central Asian region over the past three decades has also placed a great strain on the region’s water resources. Since 1960, the population in the Aral Sea basin has
grown from 13 million to more than 50 million people (Fig. 1-7). As is shown in Fig. 1-7, Uzbekistan and Kazakhstan constitute more than half of the population in the region. Therefore, managing climate change and modifications to water availability are challenging. Analysis and modeling of existing water resources at the local scale can play an important role in water resource management and the adaptation to the climate change in the entire region.

![Graph showing population growth in Central Asia since 1960](https://data.worldbank.org)

This project focuses on one of the most important parts of the region: a watershed that provides water for Tashkent, the capital city of Uzbekistan, and the densely populated region around the capital. In this area, there is existing data that is sufficient to model and validate streamflow. The manuscript presented in the next chapter analyzes four applicable hydrologic models and provides perspective to the conditions of the water resources in the upper parts of the Tashkent region.
Chapter 2: Hydrologic Modeling in Central Asia

Introduction

Background

Scientists studying river watersheds have reported the impact of climate on hydrologic conditions in many parts of the world (Hannah et al., 2005; Wenger et al., 2011). Such results are due to a strong connection between hydrologic patterns of a watershed and local climatic conditions such as air temperature. Many have reported altered regimes of rivers and decreasing or increasing streamflow (Gan et al., 2015; Hannah et al., 2005; Olsson et al., 2010; Wenger et al., 2011). In addition, the increase in air temperature over the last few years in mountainous areas has decreased the area of glaciers and increased the number of mountain lakes (Petrov et al., 2017a; Semakova et al., 2015).

A multitude of studies has assessed the evolution of watersheds through modeling approaches (Can et al., 2012; Galelli and Castelletti, 2013; Shrestha et al., 2008). Prior studies have described the degree of degradation of glaciers by documenting the subsequent reduction in meltwater volume input into streamflow (Brown et al., 2007). Kormann (2015) reported that streamflow conditions are driving water supply for alpine regions through glacial melt, early snowmelt, and reduced snow accumulation in the wintertime. However, the study of mountain regions is complicated when these regions are natural borders between countries in regions of conflicts. This has led to some areas being excluded from scientific studies due to security precautions or political considerations.
Project focus

This study focuses on the watershed of the Pskem River, one of the major tributaries of the Syr-Darya River and an important source of water to the Aral Sea. The water from this river system serves as a supply for Tashkent, the capital city of Uzbekistan, and for irrigation of downstream watersheds. Three main tributaries contribute 98% of the water volume in the Pskem. Initial data assessment revealed a discrepancy between reported streamflow conditions at the tributaries and sites downstream, hence the desire to establish a hydrologic model that better captures flow in the region.

In this study, we explored the use of hydrologic models to determine streamflow conditions based on climatic parameters and watershed characteristics. Our study considers the impact of glacial melt, early snowmelt and reduced snow accumulation in the wintertime on streamflow conditions. We also considered the influence of land cover features other than glaciers in the watershed and assessed some of the input parameters for the hydrologic models. We developed and tested four hydrologic models to estimate monthly streamflow. The models start with a simplified method with each subsequent model adding complexity. The overall goal was to determine the best model to estimate monthly streamflow to understand better the factors affecting streamflow conditions. The study also explored streamflow data to determine if there are differences in streamflow conditions for 1965–1990 compared to 1991–2015 and if there are trends in flow that are associated with seasonality.

Study area

The Pskem River watershed in the northern part of the Tien Shan ridge (Fig. 2-1) is the primary source of water for the Tashkent region of Uzbekistan. The Pskem River is one of the
major tributaries of the Chirchik River that forms after the confluence of the Pskem and Chatkal rivers. The Chirchik watershed is one of the main sources of water for the Syr-Darya River that flows about 500 km through Uzbekistan into Kazakhstan and then into the northern part of the Aral Sea.

Fig. 2-1. The Aral Sea basin is comprised of two main rivers (Amu-Darya from the South and Syr-Darya from the North). The rectangle on the Kazakhstan/Kyrgyzstan/Uzbekistan border highlights the location of the Pskem River watershed, a major tributary of the Syr-Darya (https://earthexplorer.usgs.gov).

Topography in the Pskem watershed is highly variable with mountainous ridges at an average elevation of 2770 meters (m) above sea level (ASL). Since the average elevation of the watershed is 2770 m ASL, we suggest that variations in the streamflow are seasonal and driven
by snowmelt and glacial melt. The total area of the watershed is 2540 km$^2$. The basin is located in Uzbekistan and Kazakhstan and shares a border with Kyrgyzstan. The nearest urban city is Tashkent, the capital of Uzbekistan, which is located 70 km to the west and has a population of about 3.5 million people. The 62 km Oigaing River in Uzbekistan is the largest tributary of the Pskem River with a watershed area of 1005 km$^2$. The 43 km Maydantal River has a 450 km$^2$ watershed located in the territory of Kazakhstan. The 15 km Charalma River has the smallest watershed of 105 km$^2$ (in Uzbekistan). The last part of the Pskem watershed is the 980 km$^2$ valley where the Pskem River flows 47 km south after the confluence of the three tributaries. The highest point of the Pskem watershed is 4830 m ASL. The mountainous environment leads to a mean slope in the watershed of 28° (Fig. 2-2).

Fig. 2-2. The Pskem watershed stream network and watersheds of three primary tributaries river; (a) River network and watershed boundaries, (b) slope and aspect extracted from digital elevation model with 12.5-meter resolution (https://vertex.daac.asf.alaska.edu).
The Pskem-Mualala stream gage is situated at the Mualala village almost at the point of inflow into the Charvak reservoir, which serves as a water supply and a power source for the Tashkent region. The Maydantal, Oigaing, and Charalma stream gage stations are located at the downstream ends of the corresponding watersheds.

The region has a continental climate with cold winters (minimums around -20° C) and hot summers when the temperature can reach up to +45° C, with the temperature gradient primarily determined by the topography of the region. However, there are no studies that document the spatial distribution of temperature throughout the watershed. Precipitation in the region varies from averages of 40mm/year in the flat areas downstream up to 400 mm/year in the mountains (Gulyamov and Vaxobov, 2013). Observations from Northern Tien Shan showed that by the end of the 20th-century glacial runoff contributed 18–28% on average to annual runoff and 40–70% to summer runoff (Aizen et al., 1997). A recent study revealed that from 1960 to 2010 the Pskem watershed lost around 23% of glaciation area; the rate of shrinkage in the last decades decreased from 0.62–0.39 % per year. Such results reflect an increase in the extent of moraine and debris cover that prevents glaciers from intense melt. In 2015, (Semakova et al., 2015) estimated the area of the glaciation in the watershed was as 91 km². It is important to note that significant research has been completed that revealed changes in the landscape and an increase in the area of moraine and debris cover around the glaciers. Such processes are resulting in increasing numbers and area of mountain lakes (Petrov et al., 2017a).
Materials and Methods

Data used

We extracted average elevation, watershed boundaries, and river networks from ASTER/PALSAR digital elevation model (DEM) data with a spatial resolution of 12.5 m that were downloaded from the NASA web portal (https://vertex.daac.asf.alaska.edu/). We downloaded an orthorectified Landsat 8 image with calibrated at-sensor radiance acquired on August 26, 2016 (https://explorer.earthengine.google.com; path 153, row 31), which was used to generate land cover data for the region. Climate data are available from two data sources: (1) The National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (https://www.ncdc.noaa.gov/cdo-web/), which provides a worldwide collection of observed precipitation and daily temperatures; and (2) climate data for Central Asia available online from the National Snow and Ice Data Center (NSIDC; http://nsidc.org/) with observations from 1873–2003 for 298 hydro-meteorological stations across the region (Williams, 2008). Both of the climate databases are only partly filled. However, NSIDC contained more complete historical observations in the form of an Excel spreadsheet with missing data noted, while the NOAA database contains daily observations only since 1990. We used average monthly values of air temperature for the periods of observation that correspond to the available precipitation measurements from both datasets (1965–2015) for the Pskem watershed. Differences in average monthly air temperatures between the Oigaing and Pskem hydro-meteorological stations were used to obtain an environmental lapse rate (ELR).

Daily streamflow data for the stream gage at the Pskem River near village Mualala (41° 47' 00" N, 70° 13’ 00" E) was obtained for 2010–2015 directly from the Uzbekistan Centre of Hydrometeorological Service (Uzhydromet; http://www.meteo.uz/#/en ). Climate characteristics
came from the Pskem meteorological station located in the watershed that is under the World Meteorological Organization (WMO; https://www.wmo.int) listing. Monthly average streamflow data for the Pskem River at the Mualala village, located at the lower part of the watershed after the confluence of tributary rivers, and daily precipitation for 1965–2015 and 2010–2015, were obtained from the Department of Hydrology at the National University of Uzbekistan. This data was used previously in studies (Glazirin and Glazirina, 2012).

The streamflow modeling and analysis along with the construction of charts for flow duration curve and temperature analysis were conducted using a combination of open source software such as Google Earth Engine, and R. Commercial software, i.e., ArcGIS, was used for map generation and DEM analysis.

**Data uncertainty: Precipitation, Evapotranspiration and Water Balance**

The location of stations between mountain ridges and the high elevation of the watershed with an average slope of 28° can have a severe effect on measurement accuracy. Primarily this is reflected in capturing solid precipitation (Larson and Peck, 1974). This is a crucial parameter in this watershed; however, while visual observations of snow cover from helicopters in late winter and early spring are reported for agricultural purposes, unfortunately, daily snow measurements are not recorded away from the meteorological stations.

Multiple studies have investigated elements of water balance such as evapotranspiration. Since we do not have available measurements, the estimation of ET was a crucial requirement for understanding the water balance. We focused on studies that were conducted in mountainous regions (Ballinas et al., 2015; Carrillo-Rojas et al., 2016; Coners et al., 2016; Gurtz et al., 1999; Konzelmann et al., 1997; Minderlein and Menzel, 2015), and found that evapotranspiration for
watersheds having similar characteristics constitutes between 10 to 25% of the total balance. Multiple studies that estimated ET using Hamon’s method, which relies on solar radiation affecting rates of ET, provided more reliable results compared to ET models based on air temperature (Alkaeed et al., 2006; Hamon, 1960; Lu et al., 2005). In the current study, we utilized Hamon’s model (Hamon, 1960) to estimate potential evapotranspiration (E₀) from the surface as a function of N, the number of hours of daylight per day using average monthly values. If air temperature was below 0°C, then we assumed that there was no potential for evaporation.

\[
E₀(i) = 0.021 N^2 e_s / (T(i) + 273), \text{ (cm)}
\]  
(1)

Where \(e_s\) is saturated vapor pressure, which is a function of air temperature (\(T_i\)) on day i. At a given temperature, saturated vapor pressure is calculated using Eq. (2).

\[
e_s(i) = 0.6108 \times \exp \left(17.27 \times T(i) / (237.3 + T(i))\right), \text{ (cm)}
\]  
(2)

A crop coefficient was employed to estimate actual evapotranspiration to account for variation of vegetation during growing or dormant seasons. The estimated evapotranspiration cannot exceed the available water in the unsaturated zone storage on any day. Therefore, the smaller value of the water depth in the unsaturated zone or the estimated evapotranspiration was used to estimate actual evapotranspiration (ET).

For the region of interest (Narama et al., 2010) indicated annual precipitation around 800 mm, (Semakova et al., 2015) reported 730mm, and (Zhou et al., 2018) validated data accuracy and indicated values for mean total annual precipitation of 600 mm/year. These values are within the range of the annual amount of precipitation observed in the watershed.

It is important to mention that one of the limitations we addressed in our model was a restriction of the mean annual average sum of evapotranspiration at 250 mm/y. This value was
selected based on multiple observations across several watersheds and corresponds to approximately 1/3 of the total precipitation in the mountains, which is similar to the approach used by Gurtz et al. (1999) in the Swiss Alps and Minderlein and Menzel (2015) in semi-arid regions of Mongolia. These basins have similar characteristics as the basin of the Pskem River.

**Design of hydrologic models**

Four increasingly complicated hydrologic models (Table 2-1) were developed in this study. This section describes the fundamental assumptions and data inputs for the four models.

Parameters for the first hydrologic model were based on a general water balance and the required inputs were average air temperature and average precipitation measured at the Pskem hydro-meteorological station. This model assumes: (1) uniform distribution of precipitation across the entire watershed; (2) uniform average air temperature estimated at the average elevation of the watershed; (3) snow occurs at 0 °C air temperature; and (4) there is no impact of glacial melt.

The second model assumes that spatial variations in elevation impact streamflow conditions. We divided our watershed into three parts—lower (1251–2300 m), middle (2300–3300 m) and top (3300–4300 m)—and used seasonal variations in the lapse rates to adjust estimates of the average air temperatures at these elevations. This model accounted for evapotranspiration occurring in these zones by relating solar radiation and ET and used a crop coefficient to adjust ET estimates based on the state of vegetation (dormant or growing). We considered glaciation impact using an empirical relationship observed between air temperature and glacial melt. The relationship between the glacial melt and air temperature is considered to be uniform across the entire watershed. The ablation zone is assumed to be at an elevation of 3680 m ASL where glacial coverage exists.
The third model is a hybrid of Model 1 and Model 2 and improves them using elements of the Soil Conservation Service (SCS) curve number CN method from (Cronshey, 1986a). CNs depends on land cover type and impervious surface extent and utilize 5-day antecedent moisture conditions that provide potential retention of moisture by vegetation. Model 3 assumes consistent average air temperature and precipitation over the entire watershed and did not differentiate based on elevation; the rest of the parameters follow those in Model 2.

Model 4 extends the third model by running the model separately for the three elevation levels of the watershed defined in Model 2. In addition, Model 4 also assumes independent saturated and unsaturated layers and considers each part of the watershed independently. This model uses runoff computed from slope analysis to estimate ET from the surface of watershed. The final modeled flow is the sum of the flows from the parts of the watershed.

Model calibration was achieved by iteratively varying model parameters through multiple model runs. For each parameter, a certain step was chosen, and a threshold value identified below which we changed the parameter in incremental amounts. This approach sometimes required adjusting one parameter inside another. This can adversely affect computation time since each “nested” parameter increases computations time exponentially. While the R language utilizes only one-core (Ihaka and Gentleman, 1996) and does not take an advantage of multi-core processers that other packages use (Eddelbuettel, 2018; Gaujoux and Seoighe, 2010; Urbanek, 2011), the efficiency of the models was not our main purpose, and therefore we proceeded without changing the default computational style that R implements.
Assessment of existing hydrologic conditions in the watershed

We examined stream conditions for the years where daily streamflow at the Pskem River Q(Pd) was measured with corresponding measurements at the major tributaries (i.e., 2012 and 2014). We assumed that daily average runoff observed at the Pskem River stream gage comes from cumulative runoff from the tributaries along with the runoff from the remaining part of the watershed below the confluence:

\[
Q(P_d) = Q(O_d) + Q(C_d) + Q(M_d) + \triangle Q(P_d), \quad (m^3/s)
\]

where Q(O_d) is daily average discharge at Oigaing River, Q(C_d) is daily average discharge at Charalma River, Q(M_d) is daily average discharge at Maydantal River, and \(\triangle Q(P_d)\) is the remaining watershed after confluence.

The Pskem-Mualala stream gage is situated at the Mualala village almost at the point of inflow into the Charvak reservoir, which serves as a water supply and a power source for the Tashkent region. The Maydantal, Oigaing, and Charalma stream gage stations are located at the downstream ends of the corresponding watersheds.

Mean annual flow (MAF), low return flows Q1.5 and Q2 (floods with a recurrence interval of 1.5 and 2-years, respectively), and flows of different duration were compared for the tributaries. The mean annual flow (Q_{MAF}), based on average annual daily discharge, was estimated for each tributary. The water contribution per unit area was also estimated as \(Q/F\) where Q is the discharge and F is the watershed area; units are in \((m^3/s/km^2)\). We normalized the streamflow records by the catchment area (flow rate per unit area).
Land cover classification

We used a Landsat 8 image taken on August 26, 2016, to classify land cover within the study area. This scene was selected based on having the minimum cloud and snow coverage of the scenes available within the time period of interest. Minimizing snow cover helped to reduce potential confusion with the glacial surface. We used Google Earth Engine to classify the image in order to define existing land cover conditions in the watershed. Such analysis helped to approximate the range of values for the curve number (a function of land cover type), which is used in Models 3 and 4. The land cover map was generated using an unsupervised K-mean algorithm with 6 clusters. The K-means algorithm is a statistical way of grouping data that assigns each observation to the cluster with the shortest Euclidean distance (Lloyd, 1982). We chose the number of classes experimentally to best reflect the main features of the landscape.

Streamflow assessment

A two-tailed, student’s T-test was performed to determine if there was a difference between mean streamflow ($\mu_1$, $\mu_2$) for the periods 1965–1990 and 1991–2015. A large sample size of means ($12\times n_{\text{years}}$) introduced normality of data and unknown population variance ($\sigma^2$). Our null hypothesis ($H_0$) claims $\mu_1=\mu_2$, otherwise we accept our alternative hypothesis ($H_a$) $\mu_1\neq\mu_2$. The test statistics and rejection regions for the current test are:

$$t = \frac{\bar{x}-\mu}{S/\sqrt{N}} ; \; t \leq -t\alpha/2, \; N-1; \; t \geq -t\alpha/2, \; N-1$$

We set a value of significance for type 1 error ($\alpha$) at 0.05. Following our comparison of mean annual flow over the two periods of observations, we performed a non-parametric Mann-Kendall (Hirsch-Slack) test (Mann, 1945) of seasonality to detect any trends. This test does not assume that data is normally distributed and allows detection of significant trends in monotonic
movements that usually occur with streamflow annually. The trend test considers the change of a parameter over time in log space. In this study, the Kendalls-S statistic is estimated from the pairwise relationship of monthly flow across time and then we tested if the slope of that relationship was significantly different from zero. The Kendall-S statistic ($S_t$) for each season is summed to form the overall statistics ($S_k$):

$$S_k = \sum_{i=1}^{m} S_i$$

(5)

We conducted flow duration analysis based on mean annual flow calculations. The flow duration curve represents the exceedance probability of the streamflow conditions (Vogel and Fennessey, 1995, 1994). This analysis provided the information on the duration of time that specific flows were exceeded within a given period. To create a flow duration curve, we calculated frequencies by ranking flows from the highest to the lowest values.

**Environmental lapse rates assessment**

The temperature lapse rate is a measure of how air temperature changes as it rises in the atmosphere. Usually, ELR ($\lambda$) is assumed to be around $6.5^\circ C/1000$ m (Arnold et al., 2006; Prentice et al., 1992; Roe and O’Neal, 2009). However, this value may vary from (3 to 9° C/1000m) and is different for various regions in the world (Minder Justin R. et al., 2010). Rather than simply assume a value, for this work, the lapse rate was calculated as a function of the change in elevation and temperature at a ratio of 1000m Eq. (6) moreover, defined the lapse rate for each season separately.

$$\lambda = (\partial T_{up} - \partial T_{dow})/ 1000 \times \Delta H \ (^\circ C/m)$$

(6)

Where $\Delta H$ (895 m) is the elevation difference between the Oigaing MS (2151 m ASL) and Pskem MS (1254 m ASL); $\partial T_{up}$ and $\partial T_{dow}$ are air temperature at the upstream (Oigaing) and
downstream (Pskem) meteorological stations, respectively. Average monthly air temperatures were available for both meteorological stations for the period between 1963–2004.

We attempted to correlate changes in the air temperatures with changes in the measured river flow at the watershed. For each month, the average air temperatures were calculated across water years (ending on September 30), and then the average seasonal temperature was calculated as the arithmetic mean of the average monthly temperatures during the different seasons of the year. For both stations, the absolute difference in elevation and temperature was used to interpolate temperature values with the corresponding adiabatic lapse rates for each season. These lapse rates were used to estimate the average air temperature at the average watershed elevation $T(Z_w)$ for every day over the year of observations:

$$
T(Z_w) = (Z_w - H)/1000 \times \lambda + T_{air} \, (^\circ C)
$$

Where $Z_w$ is the average elevation of the watershed (2770 m ASL), $H$ is the elevation of the Pskem MS (1251 m ASL), $\lambda$ is the average air temperature lapse rate for the corresponding season, and $T_{air}$ is the daily average air temperature at the Pskem MS.

Calculations

*Hydrologic models*

This section describes the four models used to estimate streamflow at the glaciated watershed of the Pskem River. Table 2-1 provides a summary of the model inputs, which shows the increasing model complexity from the very simple (Model 1) to the most complicated (Model 4). Model 2 is a spatially adjusted (sa) adaptation of Model 1 that considers ET. Model 3 is a multilevel model that uses the SCS curve number method. Model 4 uses a multilevel and spatially adjusted SCS curve number method.
Table 2-1. Parameters involved in models to estimate and calibrate streamflow at Pskem River watershed

<table>
<thead>
<tr>
<th>Model #</th>
<th>Surface layer</th>
<th>Subsurface layer</th>
<th>Baseflow</th>
<th>CN</th>
<th>ET (overall)</th>
<th>ET (sa)</th>
<th>Air temp (sa)</th>
<th>Glacial runoff</th>
<th>Melt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
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<td>Y</td>
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<td>Y</td>
</tr>
</tbody>
</table>

1ET (sa) – spatially adjusted estimates of evapotranspiration from the surface,

2Air temp (sa) – spatially adjusted estimates of air temperature,

CN – curve number.

**Model 1: Simplified model**

The first model attempts to assess storage available in the watershed that would accumulate as snow during the fall and winter seasons and be released in the spring and summer (Fig. 2-3). Our model includes multiple parameters and is driven primarily by knowledge about daily air temperature and daily average precipitation.

![Simplified hydrologic model](image)

Fig. 2-3. A concept of the simplified hydrologic model showing runoff from the saturated layer over bedrock.

Our approach in Model 1 was to use the general water balance model and estimate daily streamflow ($Q_{(1)}$) using Eq. (8). This model does not account for spatial variation of air temperature across the entire watershed. Instead we computed an average air temperature over the watershed and assumed a uniform distribution of precipitation. We extrapolated air
temperature observed at the elevation of the Pskem MS (1251 m ASL) to the average elevation of the watershed (2770 m ASL) using the environmental lapse rate of 6.5°C/1000m.

\[ Q_{(i)} = P_{(i)} + MT_{(i)} - ET_{(i)} \text{ (m}^3\text{/s)} \]

(8)

Where \( P_{(i)} \) is precipitation, \( MT_{(i)} \) is snowmelt, and \( ET_{(i)} \) is evapotranspiration corresponding to day (i).

For Model 1 we neglected the impact of potential evapotranspiration and measurement errors and evaluated the effect of the input values. We also assumed that at any day when the air temperature is below 0°C, any precipitation falls as snow and accumulates to the next day since there is no snowmelt. Values of ET impact current snow cover and decrease available moisture for the surface runoff or infiltration. However, when we have a day with a positive air temperature, we look for the minimum value of either: a combination of snowmelt constant (K) and average air temperature that determines snowmelt at day (i), or the value of a snow layer that is still on the ground at day (i). K values vary, and observations of snowmelt should be conducted for the site. However, the US Army Corp of Engineers (1960) has derived K through laboratory experiments and obtained value of 0.45, which we used in this study.

As was shown in Fig. 2-3, snowmelt and rain percolate down to the unsaturated layer. Saturation occurs when the unsaturated layer reaches its field capacity. Evapotranspiration on any day occurs if and only if the value of the unsaturated layer exceeds 0 cm, which accounts for the existence of moisture in the soil. During a precipitation event, when the storage capacity of the unsaturated layer is reached, water percolates down to the subsurface level, which corresponds to the baseflow of the river. The final flow to the river is the fraction of the moisture released from the soil at the day of observations with the baseflow and any water that percolated down to the subsurface layer from precipitation and snowmelt.
**Model 2: Spatially adjusted simplified model.**

In Model 2, we assumed that consideration of spatial variation of the air temperature and empirically estimating glacial melt would improve model outputs. The entire watershed was split into three main parts as shown in Fig. 2-4. We defined three elevation zones—1251–2300 m, 2300–3300 m, and 3300–4300 m—and defined average air temperature for each zone using interpolation of the average air temperature from the Pskem meteorological station and the corresponding seasonal lapse rate. We defined average lapse rates for each month over the last 45 years and used the corresponding value for the adjustment. For each elevation zone we used a ratio of the zone area to the total area to estimate potential snow cover, while the remaining precipitation remains as rain. We considered estimates of potential evapotranspiration from the surface of the watershed. Eq. (9) depicts the concept driving estimation of the streamflow \( Q(i) \) for the day of observation \( (i) \).

\[
Q(i) = P(i) + Qgl(i) + MT(i) - ET(i), \text{ (m}^3/\text{s})
\]  \quad (9)
Observations of glaciers in Central Asia by Krenke and Hodakov (1966) revealed that the average ablation from the surface of glaciers is a third power function of the air temperature at the elevation of glacier accumulation zone. The average range in elevation of glacier boundaries in the study site was determined as 3300–4500 m. Following previous research by (Glazirin and
Glazirina, 2012), we considered that average elevation of the accumulation zone remained the same across the region and used Eq. (10) to estimate ablation \( (Ab_{(i)}) \) from the glaciers.

\[
Ab_{(i)} = (9.5 + T(ac))^3, \text{ (m}^3/\text{s}) \tag{10}
\]

Where \( T(ac) \) is the average air temperature at the average elevation of the glaciers accumulation \( (ac: 3643 \text{ m ASL}) \). Based on the assumption that all meltwater is in the river, then an average annual discharge from glaciers \( (Qg1) \) as calculated using Eq. (11):

\[
Qg1 = 1/(31.5 \cdot 10^3) \cdot Ab(Zf) \cdot Fg, \text{ (m}^3/\text{s}) \tag{11}
\]

Where \( Qg1 \) is a glacier runoff with a unit \( (m^3/s) \) if ablation \( (Ab) \) at the average elevation of the glacier accumulation zone \( (Zf) \) is in mm/year and area of glaciers \( (Fg) \) is in km\(^2\). Negative melt from glaciers represent favorable conditions for snow accumulation; however, in our study, we considered only positive values representing runoff from the glacier. This is because we already accounted for the precipitation and we assumed that there is no input to the glacial balance outside of the amount of precipitation that occurred.

According to the catalog of glaciers presented by Glazirin and Glazirina (2012), from 1960–1980 the average elevation of the lowest part of the glaciers increased from 3500–3540 m. Our observations between 2000 and 2015 in the Tian Shan range revealed an increase in the elevation of another 100 m (Fig. 2–5). Assessment of glacier ablation zones requires complex and stationary measurements; however, with our measurements, we assumed that this elevation changes linearly with the elevation of the lowest part of glaciers. Therefore, following our field measurements, the average elevation of the accumulation of glaciers was defined as 3643 m ASL.
Fig. 2-5. Examples of glaciers and glacial lakes in Pskem watershed, Tashkent, Uzbekistan: (a) Barkrak glacier, 3517 m ASL August 2013; (b) Tekeshsay glacier; 3630 m ASL August 2013, Credit: M.A Petrov; (c) Ozernoe upper, 3970 m ASL August 2002.; (d) Ozernoe upper, 3910 m ASL August 2002; Credit: G.E. Glazirin.

**Model 3: Multilevel model, SCS curve number method.**

Model 3 employed the SCS curve number method with further development to estimate surface runoff from rain, runoff from glaciers, baseflow, evapotranspiration and snowmelt runoff. The model is based on the water balance relationship shown in Eq. (12):

$$Q(i) = SD(i) + SR(i) + Q_{gl}(i) - ET(i), \ \text{(m}^3/\text{s})$$

(12)

Where $Q(i)$ is the discharge in the river, $SD(i)$ is the subsurface discharge to the river, $SR(i)$ is the surface runoff, and $Q_{gl}(i)$ is discharged from glaciers for the day (i).
The curve number is used to estimate surface runoff as it provides a simple estimate of the relationship between the retention of rainfall and runoff from a drainage area (Cronshey, 1986b). The estimation of this relationship requires knowledge about land cover, hydrologic soil group, and antecedent moisture content. We have not found prior research that examined these properties for this remote region. The curve number was estimated and calibrated based on the author’s field studies as a member of the Glacial Geology laboratory at the Institute of Geology and Geophysics in 2013, 2014 and 2015 (Fig. 2-6).

![Fig. 2-6.](a) Field trip to Barkrak glaciers, Pskem watershed, Tashkent, Uzbekistan, August 2015. (a) A view of the valley from the elevation of 2500 m ASL, Oigaing watershed; (b) Taking samples from the surface from the orographic right side of the Barkrak.

Farmers use these remote locations for grazing, due to mild summers and an abundance of natural resources. The upper part of the watershed has a high elevation gradient and significant slopes, which impacts infiltration capacity of soils. At lower elevations, there are forested regions with lower slopes that create favorable conditions for high infiltration. The higher part of the watershed has favorable conditions for surface runoff during precipitation events, which forms gullies and sheer flows with low infiltration. The hydrologic soils group along the river
was assumed to be group A, while the lands upstream are assumed to belong to group B. These estimated values were averaged to obtain the curve number value of 50.

Land cover was generated through unsupervised classification of Landsat 8 imagery using tools in Google Earth Engine. Interpretation of the classification was conducted in ArcMap using online high-resolution imagery from Bing Maps (https://www.bing.com/maps) and Digital Globe (https://www.digitalglobe.com/), to label and validate the cluster classes. Six classes were initially identified from the unsupervised classification: (1) water; (2) forest mixed with pasture; (3) debris cover and glaciers; (4) rocks; (5) bare soil with rocks; (6) alluvial fans mixed with pasture. The classification results and the high-resolution imagery were used to determine the area of glaciers for each watershed.

Population in the region is relatively low with only a few villages located downstream. Therefore, we neglected the impact of anthropogenic activity and applied an average curve number of 45 for model calibration. The curve number adjustment based on the assumption of antecedent moisture content over the five days prior to observations is equal to 0 (AM5 = 0). The retention rates of moisture vary seasonally based on vegetation abundance or scarcity. The boundary conditions for the curve number are unitless and were identified as in Eq. (13) or Eq. (14) (Cronshey, 1986a):

\[
CN(\text{low}) = \frac{CN}{(2.334 - 0.01334 \times CN)}
\]  
\[
CN(\text{up}) = \frac{CN}{(0.4036 + 0.0059 \times CN)}
\]

We defined the antecedent moisture boundaries for the dormant and growing season using the logical step function of the SCS method. For the dormant season the antecedent moisture (AM) boundaries were defined as AM (1) = 1.3 cm, AM (2) = 2.8 cm, for growing season as AM (1) = 3.6 cm, AM (2) = 5.3 cm. When 5-day antecedent moisture AM (5) was less than AM (1),
the curve number was equal to the curve number of the lower boundary (CN(low)). Where AM (5) fell between AM (1) and AM (2), the curve number remained unchanged. When AM (5) exceeds AM (2), the curve number changes to the value of upper boundary (CN(up)).

The curve number obtained was used to determine surface runoff and snowmelt with regards to the unsaturated and saturated zone mass balances. The surface runoff values were estimated using Eq. (15) (Cronshey, 1986b):

\[ SR_{(i)} = \frac{(P - 0.2S)^2}{P + 0.8S}, \text{ (m}^3\text{/s)} \]  \hspace{1cm} (15)

Where \( S \) is potential retention of precipitation, and \( P \) is rainfall depth. The boundary conditions for the rainfall were determined by the air temperature based on the assumption that precipitation below 0°C is converted into snow, otherwise, it falls as rain. The potential retention is unitless and estimated from the defined curve number as in Eq. (16) (Cronshey, 1986b):

\[ S = \frac{2540}{CN-25.4} \]  \hspace{1cm} (16)

The balance of unsaturated zone water storage was used to estimate infiltration and runoff (Eq. 17) (Cronshey, 1986b).

\[ UNSAT_{(i+1)} = UNSAT_{(i)} + I_{(i)} - ET_{(i)} - PERC_{(i)}, \text{ (mm)} \]  \hspace{1cm} (17)

Where \( UNSAT_{(i)} \) is the unsaturated zone storage at the beginning of day \( (i) \), \( I_{(i)} \) is the infiltration on day \( i \), \( ET_{(i)} \) is evapotranspiration on day \( i \), and \( PERC_{(i)} \) is percolation on day \( i \). We estimated infiltration on day \( i \) as the quantity of rain (\( R_{(i)} \)) and snowmelt (\( M_{(i)} \)) that is not surface runoff (\( SR_{(i)} \)) using Eq. (18) (Cronshey, 1986b).

\[ I_{(i)} = R_{(i)} + M_{(i)} - SR_{(i)}, \text{ (mm)} \]  \hspace{1cm} (18)

The infiltration includes interception of water, depression storage, and infiltrated waters. Final unsaturated zone estimates were adjusted based on the best correlation coefficient for the model estimates Eq. (19). The water from subsurface storage percolates only if the amount of
water exceeds unsaturated layer field capacity. Therefore the unsaturated layer is always in the range of field capacity (Cronshey, 1986b).

\[
\text{UNSAT}_{(i+1)} = \text{UNSAT}_{(i)} + I_{(i)} - ET_{(i)}, \text{ (mm)}
\]  

(19)

We suggest that water percolating from the saturated system enters the saturated zone storage and turns into groundwater. One of the assumptions of the model is that there is not any loss except baseflow, which applies to all previous models. The baseflow discharge \( (SD_{(i)}) \) is estimated as a function of groundwater (saturated zone) storage at the end of the previous day as shown in Eq. (20) (Cronshey, 1986b):

\[
SD_{(i)} = (1 - Kb) \text{SAT}_{(i)}, \text{ (m}^3\text{/s)}
\]  

(20)

Where \( Kb \) is a baseflow recession constant, and \( \text{SAT}_{(i)} \) is a saturated zone (groundwater) storage at the beginning of day \( i \). Thus, the mass balance of the saturated zone is estimated using Eq. (21) (Cronshey, 1986b):

\[
\text{SAT}_{(i+1)} = \text{SAT}_{(i)} + \text{PERC}_{(i)} - SD_{(i)}, \text{ (mm)}
\]  

(21)

We included runoff from the glaciers and snowmelt/snowpack discharge and accumulation over the period of observations. From this, final discharge from the watershed is estimated using Eq. (22):

\[
Q_{(i)} = Q_{gl_{(i)}} + SR_{(i)} + SD_{(i)} \text{ (m}^3\text{/s)}
\]  

(22)

Where \( Q_{(i)} \) is streamflow discharge in the river, \( Q_{gl_{(i)}} \) is the glacier runoff, \( SR_{(i)} \) is the surface runoff, and \( SD_{(i)} \) is the subsurface discharge at day \( i \).

**Model 4: Multilevel and spatially adjusted model, SCS curve number method.**

Model 4 combines the SCS curve number method from Model 3 with the spatially adjusted Model 2. For each of the three elevation zones of the watershed, Model 4 adjusts
available storage in saturated and unsaturated zones. The average air temperature is estimated separately at the average elevation for each part of the watershed—i.e., at 1800 m for the lower part of the watershed, 2800 m for the middle part of the watershed, and 3800 m for the upper part of the watershed.

The drainage area of the upper part of the watershed, with elevations above 3300 m, is around 660 km$^2$. According to the land cover classification, about $\frac{1}{6}$ of the upper part of the watershed is glaciers, while the rest is mostly bare soils and bedrock, which creates a zone that is almost impervious and prone to nearly complete surface runoff. Therefore, we used a curve number for the upper part of the watershed of 90, which is appropriate for hard surfaces.

According to our slope analysis, around 50% of the upper part of the watershed has slopes exceeding 30°, 25% has slope within 20–30°, 12 % is within 10–20° and the remaining 13% of the upper part of the watershed has slopes under 10°. We considered that the impact of evapotranspiration at such elevation with high slopes and low air temperatures decreases linearly. The empirical estimation of runoff from the glaciers is tied to the air temperature, which also affects evapotranspiration and therefore impact of ET is already included in our estimation of glacial runoff. The adjustment coefficient for actual ET is set to 0.5 since 50% of the watershed has slopes exceeding 30°.

The middle part of the watershed, with elevations 2300–3000 m, has a drainage area of 1200 km$^2$, with 49% of this area having slopes exceeding 30°. About 30% of the area has slopes from 20–30°, 16% of the zone is between 10–20°, and the rest is below 10° slope. For this elevation zone, we assumed that ET at slopes exceeding 30% is low; however, since the impact of air temperature is noticeable at these elevations instead of neglecting ET, we considered a
fraction equal to the drainage area with a slope less than 30°. The adjustment coefficient of ET for this part of the watershed was 0.49.

The third, and lowest, part of the watershed, which lies between the Pskem MS and elevations of 2300 m, is about 25% of the total area of the watershed. The slope analysis revealed that 44% of this zone of the watershed has slopes exceeding 30°, 10% is within 1–10°, 18% is within 10–20°, and 28% is within 20–30°. We followed the same steps applied to the middle zone and reduced potential ET by the fraction of the watershed lying within the slopes exceeding 30°. The adjustment coefficient of ET for this part of the watershed was 0.56.

Model assessment

The land cover classification was assessed by generating an error matrix, which was used to calculate user’s, producer’s and overall accuracy measures. User’s accuracy represents the ratio of the proportion of mapped pixels in a class that are correctly classified. The producer’s accuracy represents the proportion of reference pixels within a class that are correctly classified. The overall accuracy defines the total proportion of pixels that are correctly classified. We visually interpreted 110 polygons covering the 6 identified classes within high-resolution imagery to validate our results and generate a confusion matrix.

We assessed the performance of the models by computing the bias Eq. (23) and Nash–Sutcliffe efficiency (NSE) coefficient Eq. (24). The average residual corresponds to the bias of the predicted change in the volume of river flow:

\[
\text{Bias}(\hat{y}) = \frac{\sum_{i=1}^{N}(\hat{y}_i - y_i)}{N} \tag{23}
\]

Where \(y_i\) is the streamflow to be estimated, i.e., the output result of the model, \(\hat{y}_i\) is an estimator, i.e., the observed streamflow, and \(N\) is the number of observations. We typically want
our bias to be as close to zero as possible, meaning that there is no difference between estimates and observed values. The Nash–Sutcliffe model efficiency coefficient is defined in Eq. (24):

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Q_{im} - \hat{Q})^2}{\sum_{i=1}^{N}(Q_i - \bar{Q})^2}$$

(24)

Where: $\hat{Q}$ is the mean observed discharge and $Q_{i(m)}$ is the modeled discharge. An efficiency of 0 means that model predictions are as accurate as the mean of the observed data. If E<0, residuals are bigger than the variance of the model. The closer E is to 1, the better the fit of the model. Calibration of model estimates was performed to obtain balanced parameters that would estimate streamflow with bias close to 0 and NSE close to 1. The model needs to reach equilibrium, which occurs after one full cycle. Therefore, calibration was performed on the last two years of the observed data, since the first year was affected by the initial conditions of the model.

**Results**

**Watershed assessment**

Daily streamflow measurements at four gage stations were available from Uzhydromet. The 2540 km$^2$ Pskem watershed consists of three main tributaries: Oigaing (1005 km$^2$), Maydantal (450 km$^2$) and Charalma (105 km$^2$). Limited daily streamflow was also available for each of the tributaries. The input from these three tributaries for 2012 and 2014 shows a contribution into the Pskem River of 98% and 99% of the streamflow, respectively (Fig. 2-7). It is important to note that the 980 km$^2$ area of the watershed below the merging of tributaries contributes only about 2% of the annual flow. We treated such results as inconsistent with reasonable estimates.
Fig. 2-7. Streamflow conditions from Uzhydromet for Pskem, Charalma, Oigaing and Maydantal Rivers for 2010–2015.

Table 2-2 summarizes the physical properties of the watersheds along with the streamflow conditions defined by the flow duration curve analysis and the gage observations.
Table 2-2. Morphometric properties of watersheds under consideration

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Charalma</th>
<th>Oigaing</th>
<th>Maydantal</th>
<th>Pskem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, F (km²)</td>
<td>105</td>
<td>1005</td>
<td>450</td>
<td>2540</td>
</tr>
<tr>
<td>Length, L (km)</td>
<td>15</td>
<td>62</td>
<td>43</td>
<td>119</td>
</tr>
<tr>
<td>Years observed</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>MAF (m³/s)</td>
<td>4.30</td>
<td>34.93</td>
<td>21.51</td>
<td>70.04</td>
</tr>
<tr>
<td>MAF/F (L/s/km²)</td>
<td>40.98</td>
<td>34.75</td>
<td>47.80</td>
<td>27.57</td>
</tr>
<tr>
<td>Q50 (m³/s)</td>
<td>2.38</td>
<td>20.70</td>
<td>11.70</td>
<td>41.1</td>
</tr>
<tr>
<td>Q90 (m³/s)</td>
<td>0.78</td>
<td>7.69</td>
<td>4.83</td>
<td>18.47</td>
</tr>
<tr>
<td>Q95 (m³/s)</td>
<td>0.53</td>
<td>5.92</td>
<td>4.50</td>
<td>16.8</td>
</tr>
<tr>
<td>Q90/Q50</td>
<td>0.32</td>
<td>0.37</td>
<td>0.41</td>
<td>0.45</td>
</tr>
<tr>
<td>MAF on FDC (%)</td>
<td>32%</td>
<td>37%</td>
<td>39%</td>
<td>38%</td>
</tr>
<tr>
<td>Q1.5 (m³/s)</td>
<td>5.23</td>
<td>43.23</td>
<td>26.58</td>
<td>87.22</td>
</tr>
<tr>
<td>Q2 (m³/s)</td>
<td>2.67</td>
<td>22.92</td>
<td>14.41</td>
<td>51.51</td>
</tr>
<tr>
<td>Q1.5/Q2</td>
<td>0.51</td>
<td>0.53</td>
<td>0.54</td>
<td>0.58</td>
</tr>
<tr>
<td>Q2/MAF</td>
<td>1.21</td>
<td>1.23</td>
<td>1.23</td>
<td>1.24</td>
</tr>
</tbody>
</table>

MAF – mean annual streamflow; MAF/F – mean annual flow per unit of surface area; Q50, Q90, Q95 – streamflow that exceeds 50th, 90th and 95th percentile, respectively, on flow duration curve (FDC); Q90/Q50 – baseflow index; MAF on FDC – mean annual flow on flow duration curve; Q1.5, Q2 – 1.5 and 2-year low flows from log type II distribution; Q1.5/Q2 , Q2/MAF – ratio of 1.5-year over 2-year low flow, and ratio of 2-year low flow over mean annual flow.

We observed that the Oigaing River watershed is the largest contributor to the Pskem River, on average exceeding the Maydantal River flow by 13 m³/s and the Charalma River flow by 30 m³/s. However, the flow per unit area of the Maydantal River exceeds the value of the Oigaing, which means that on average the Maydantal watershed is contributing more water than the Oigaing would from the same area. DEM analysis shows that the Maydantal watershed has average elevation of 3016 m ASL with standard deviation (SD) of 501 m, while the average elevation of the Oigaing watershed is 3113 m ASL and SD of 551 m. The Charalma watershed has average elevation of 2645 m ASL and SD of 561 m, with the remaining area within the Pskem watershed averaging 2281 m ASL with SD of 689 m.

Examination of high-resolution imagery revealed that about 36% (33 km²) of all glaciers are located in the Maydantal watershed, while around 56% (51 km²) are in the Oigaing basin. Glaciers in the Pskem watershed after the confluence of the three tributaries comprise around 8% (7 km²) of total glaciation (91 km²). The ratio of the area of glaciation to the total area for the
Oigaing watershed is 5% while in Maydantal this ratio is equal to 8%. With the assumption of equal distribution of precipitation, temperature gradients, uniform subsurface layers and geological structure, an excess of 3% of glaciation along with other possible factors increase the amount of water contributed per unit area by 37%. In the Charalma watershed one glacier with an area of 0.34 km² was identified, which is less than 0.5 % of the total area of the Charalma watershed; however, the amount of water per unit area exceeds the amount of water per unit area from the Oigaing River watershed.

**Existing streamflow assessment**

Flow duration curve analysis (Fig. 2-8) revealed that the Maydantal River experiences relatively high low flows that affect the average area of the flood zone, while the Charalma and Oigaing experience relatively similar flows. The results displayed show that the Maydantal River flow is less than or equal to the mean flow (21.5 m³/s) or 47.80 l/s/km² 61% of the time, flow in the Oigaing River is less than the mean (34.9 m³/s) or 34.75 l/s/km² 63% of the time, and Charalma flows are below the 4.3 m³/s or 40.98 l/s/km² average 68% of the time.
Fig. 2-8. Flow duration curve analysis of Oigaing, Maydantal and Charalma tributaries at Pskem watershed, Uzbekistan.

Analysis of the average monthly streamflow at the Pskem gage for 1965–1990 and 1990–2015 using a two-sided t-test revealed no significant difference between the two periods (Fig. 2-9a). However, Fig. 2-9b shows that the seasonal Mann-Kendall trend test revealed a significant downward trend of streamflow for summer and fall seasons. The p-value for August is significant at 1% while in October and November at 5%. Such results suggest a significant decrease in the streamflow conditions occurring in August.
Fig. 2-9. (a) Average monthly streamflow conditions at Pskem River for 1965–1990 and 1990–2015; (b) Results of Mann-Kendall seasonal trend test.

**Environmental lapse rate assessment**

Analysis of the average monthly temperature observations revealed a correlation between temperatures at the Pskem and Oigaing MSs with the lapse rate fluctuating from 5–8°C over the past several decades (Fig. 2-10). A high variance was observed during the summer and spring
seasons when the lapse was as small as 5° C or as high as 8° C. Winter and Fall were relatively steady with lapse rates of 5–6° C. In Fig. 2-10 each point represents average air temperature lapse rate for the four seasons of each year. This figure shows that the variance of temperature lapse rates increased after 1980. Such an increase reflects the increased rates of ablation and snowmelt at higher elevations and impacts the intensity of snowmelt. The mean lapse rate during the summer is 6.5° C, fall 6° C, winter 6° C and spring is 6.7° C.

![Figure 2-10](image)

**Fig. 2-10.** Average air temperature lapse variation from 1963–2006 for the Pskem watershed during the four main seasons.

We also analyzed average monthly precipitation patterns. The available monthly average precipitation data enabled analysis of precipitation patterns over the watershed from 1963–2011 (Fig. 2-11). The analysis of average monthly precipitation revealed corresponding fluctuations in precipitation at the Oigaing and Pskem meteorological stations.
Fig. 2-11. Average monthly precipitation at Oigaing MS and Pskem MS from 1963–2011.

These fluctuations do not support assumption of a consistent precipitation rate over the watershed. A two-sided T-test revealed ($p < 0.05$) a significant difference ($\alpha = 5\%$) of mean average monthly precipitation values between the Oigaing and Pskem meteorological stations. It is interesting to note that precipitation at the lower elevation MS is greater than at the higher elevation MS. We suggest that this is because as the air temperature gets cooler with altitude, the maximum amount of precipitable moisture decreases, hence the rainfall-altitude curve reflects back upon itself. Such a trend suggests that we may have reached an elevation of maximum precipitation (Daly et al., 1994; Lloyd, 2005). Further data collection in the watershed to determine this elevation is required.
**Land cover classification**

The K-means unsupervised land cover classification (Fig. 2-12) had discrepancies in the glacier boundaries due to the relatively similar spectral response of surface water and the surface of the glaciers when covered with sheet flow during the melt. Hence, the classification resulted in relatively high uncertainty of the water and glacier classes. We assessed performance of classification using variety of classes (15, 9, 6, 4) and found that 6 represented most of the features of the landscape that played a key role in this study. A previous study aimed at identification of glacier boundaries and glacial lakes also revealed a high level of uncertainty (50%) for lakes and glaciers with area below 2000 m² (Semakova et al., 2015).

Fig. 2-12. Land cover map generated from K-mean clustering of 6 classes from Landsat 8 scene, August 26, 2016.
From the initial clustering, six major classes were identified: (1) forest cover mixed with pasture (298 km$^2$); (2) glaciers and debris around glaciers (108 km$^2$); (3) bare soils with rock formations (968 km$^2$); (4) clearly identified rocks (165 km$^2$); (5) alluvial fans with pasture (846 km$^2$); and (6) water surfaces (91 km$^2$). These land cover classes supported the identification of curve number values from the tables in TR-55 (USDA, 1986). However, there was a confusion of some classes due to similar spectral response. The error matrix representing user’s, producer’s, and overall accuracy is shown in Table 2-3. This shows relatively high classification accuracy for forests with pasture and alluvial fans with pasture, while water had the lowest producer accuracy. The validation set contained 110 polygons for six different classes that were determined based on visually interpretation of high-resolution imagery. The confusion matrix shown in Table 2-3 reports the proportion of pixels within each class.

<table>
<thead>
<tr>
<th>Predicted</th>
<th>Water</th>
<th>For/Past</th>
<th>Deb/Glac</th>
<th>Bare/Rock</th>
<th>Rocks</th>
<th>Fan/Past</th>
<th>User’s Acc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.96</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.96</td>
</tr>
<tr>
<td>For/Past</td>
<td>0.00</td>
<td>0.87</td>
<td>0.00</td>
<td>0.06</td>
<td>0.00</td>
<td>0.08</td>
<td>0.86</td>
</tr>
<tr>
<td>Deb/Glac</td>
<td>0.13</td>
<td>0.01</td>
<td>0.84</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>0.83</td>
</tr>
<tr>
<td>Bare/Rock</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.94</td>
<td>0.01</td>
<td>0.03</td>
<td>0.94</td>
</tr>
<tr>
<td>Rocks</td>
<td>0.21</td>
<td>0.01</td>
<td>0.01</td>
<td>0.11</td>
<td>0.66</td>
<td>0.01</td>
<td>0.65</td>
</tr>
<tr>
<td>Fan/Past</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>0.05</td>
<td>0.00</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Prod. Acc.</td>
<td>0.03</td>
<td>0.93</td>
<td>0.98</td>
<td>0.79</td>
<td>0.97</td>
<td>0.86</td>
<td>OVERALL 0.82</td>
</tr>
</tbody>
</table>

**Table 2-3. Computed confusion matrix from unsupervised land cover classification**

*Hydrologic modeling*

**Daily data overview**

The average daily precipitation patterns revealed common diurnal variations with maximum precipitation of 50 mm per day (Fig. 2-13a). The average air temperature at the average elevation over the period of observations (October 1, 2013 to September 30, 2015) shows variations from -20 to +20 C (Fig. 2-13b).
Fig. 2-13. (a) Average daily precipitation at the Pskem watershed. (b) Daily air temperatures at an average elevation of the Pskem watershed using 10 and 30-day moving means from 2013–2015;

*Model 1: Simplified model*

The simplified model results depicted the best correlation at the subsurface soil saturation on day one at 6.4 cm, when field capacity (FCAP) and moisture content in the existing unsaturated soil (UNSAT) were at 0. Surprisingly the best performance of the model occurred when the evapotranspiration from the surface was at 0. Fig. 2-14 depicts the results of the modeling on (a) daily and (b) monthly frequency. The Nash-Sutcliffe Efficiency is 0.70 and Bias is 0.01 for the daily frequency, while for the monthly average has NSE of 0.90 and Bias of 0.36. The total runoff on average overestimated by 1%. The correlation coefficient for the model is 0.83 for the daily modeled streamflow, and 0.84 for the monthly average streamflow values.
Fig. 2-14. Model 1 results. (a) Daily streamflow modeling results for the Pskem watershed; (b) Monthly average streamflow modeling results for the Pskem watershed.

Missing actual evapotranspiration in the model indicates that a significant amount of water input is missing, and we should carefully analyze additional sources of input. Not accounting for ET violates water balance and does not consider any loss of water from the system. In addition, we should consider uncertainty related to the measurement of precipitation from point locations.

**Model 2: Spatially adjusted simplified model with ET**

The results of Model 2, which considered ET, indicate a correlation coefficient of the daily estimates (Fig. 2-15a) of 0.73, and monthly estimates (Fig. 2-15b) of 0.76. As was mentioned before, this model incorporates an assumption of average annual actual evapotranspiration at a level of 250 mm. With Model 2, the NSE of daily estimates is 0.22 and Bias is -25; for the
monthly averages NSE is 0.23 while Bias is -25. Moisture content for the best-correlated model in the saturated zone reported at 0 cm. The field capacity for the watershed is at 3.9 mm. The model underestimates total surface runoff by 10% over the period of observation.

Fig. 2-15. Model 2 - adjusted simplified hydrologic model with ET. (a) Daily streamflow modeling results for the Pskem watershed; (b) Monthly average streamflow modeling results for the Pskem watershed. Glacial runoff estimated from the relationship between the glacial melt and average air temperature.

**Model 3: Multilevel model, SCS curve number method**

Model 3 showed the best performance with the initial unsaturated zone (UNSAT) storage defined as 0 cm, field capacity of the unsaturated zone was at 81.5 mm. The baseflow recession constant was 0.99, the average curve number was 50, the initial snow accumulation (S) and antecedent moisture content (AM5) was at 0, and the crop coefficient (K) was 0.45. The results of modeling on a daily step revealed a correlation between the modeled and measured daily
streamflow of 0.90 (Fig. 2-16a), while on a monthly time step this correlation increased up to 0.92 (Fig. 2-16b).

![Graph showing measured and modeled streamflow conditions at Pskem River watershed between 2013 and 2015 water years.]

**Fig. 2-16.** Model 3 - Multilevel model, SCS curve number method. The average monthly (a) and average daily (b) measured and modeled streamflow conditions at Pskem River watershed between 2013 and 2015 water years.

The bias of the modeled daily streamflow values using Model 3 is -11, with daily streamflow modeling results underestimating total discharge by 18%. The charts of the modeled and actual streamflow shown in Fig. 2-16 reveal model underestimation for the first part of the snow melting season (the end of the spring and beginning of the summer seasons) and underestimation for the last part of the summer (glacial melt). At the same time, the coefficient used to estimate glacial melt might be outdated, and new observations should be conducted to define a new
relationship between the glacial melt and air temperature. The value of actual evapotranspiration was assumed to be 250 mm/yr as was mentioned in methods.

**Model 4: Multilevel and spatially adjusted model, SCS curve number method**

Model 4 results had the best results with a field capacity of the watershed at 1.25 mm, while the baseflow constant was 0.956 in the upper, 0.96 in the middle part and 0.96 in the lowest part of the watershed Fig. 2-17 (a). Results of modeling indicate NSE for the daily observed values at 0.29, while bias is -5. The monthly NSE is equal to 0.69, with a bias of 5. The coefficient of correlation for daily model estimates is 0.83, while for monthly it is equal to 0.85 Fig. 2-17 (b).

![Graph of discharge over time and discharge over months](image)

**Fig. 2-17.** Model 4 – Multilevel and spatially adjusted model, SCS curve number method. (a) Daily streamflow modeling results for the Pskem watershed; (b) Monthly average streamflow modeling results for the Pskem watershed.
Discussion

Watershed assessment

The results of daily streamflow measurements revealed high water contribution from the surface area of the Maydantal watershed. This might be due to the increased water contribution from the glaciers located in the watershed. There is a limited number of reasons to explain these findings other than the impact of glaciation in the region although there is a possibility of inconsistent measurements in a post-Soviet era in Central Asia (Glazirin, 2015). More data is necessary to confirm this conclusion. Differences in topography may also explain differences in surface runoff for the different watersheds.

Streamflow assessment

This study revealed that there are no significant differences in the streamflow conditions for the two different periods examined (1965–1990 and 1990–2015). However, the trend test showed decreasing flow for August, October, and November. Current conditions could correlate with decreasing glacial area since the main water contribution in August is from glaciers. We suggest this highlights the need to study affected low flows in the autumn season in more detail to confirm this pattern.

Precipitation shows no significant differences between the two periods of time. This suggests that the steady streamflow results from a restored area of ablation by retreating area of accumulation of glaciers, due to the increase in the elevation of a mean annual snow line. The flow duration curve results are consistent with runoff from the unit surface area where the Maydantal River has higher flows compared to the Oigaing. These flows might result in higher rates of erosion of the watershed, which would lead to decreasing soils available for agriculture.
Environmental lapse rate assessment

The introduction of the seasonal lapse rate did not improve model accuracy; however, larger temperature variance has been observed in the last two decades, increasing the uncertainty of the model predictions. Even with significantly different precipitation values and the higher variance of temperature lapse rates at different elevations, it is still possible to model streamflow conditions with relatively high accuracy using the curve number method as it reflects major influencing parameters.

Land cover classification

A land cover classification based on unsupervised clustering helps to define major classes of land cover. However, for water and glacier detection, high-resolution imagery from ArcGIS and Google Earth Pro increases the accuracy of defined objects and supports object validation. We suggest the use of sustainability analysis along with more sophisticated classification methods, like machine learning, decision trees, and random forest techniques, to acquire the best estimate of land cover classes. In the current study, one of the major inputs of the SCS hydrologic model, the curve number, was defined based on the defined land cover classes, which may lead to model inaccuracy if the land cover class is incorrect.

Hydrologic modeling

We performed a streamflow modeling using simplified, adjusted simplified, SCS curve number, and adjusted SCS curve number methods for the Pskem watershed. Table 2-4 provides a summary of the results from the four models.
The models provided reliable results with $R^2$ from 0.77–0.93, giving model parameters that could be used for further streamflow modeling based on available meteorological data. The introduction of glacial runoff to the models (starting from the second model), slightly increased the adjusted coefficient of determination of monthly average flows by around 0.3% and contributed around 10% of the total runoff.

The results presented in this study demonstrate that performance of a simplified model is not satisfactory when a main element of a water balance, i.e., evapotranspiration is not considered. However, the assumption of ET at 250 mm in Model 2 did not improve model outputs. The best performance was demonstrated by Model 3, which utilizes the SCS curve number method. Adjustment for elevation (in Model 2 and Model 4) did affect model efficiency, as can be observed by the decrease in NSE. Unfortunately, this also increased the variance, introducing uncertainty to the model. Estimates of evapotranspiration from the watershed did not provide any useful results and all models performed better when evapotranspiration from the surface was at 0. Such results suggest that records of precipitation from one gage are not satisfactory for streamflow modeling, possibly due to mistakes in the measurements at the station. It is also important to note that there is uncertainty in the relationship between glacial runoff and air temperature since the equation applied may be outdated. Therefore, more current data from the glaciers should be acquired. The sensitivity of results to the average air temperature requires reliable climate data, and there is a possibility that an empirical relationship between air

### Table 2-4. Summary of modeling results

<table>
<thead>
<tr>
<th>Model#</th>
<th>NSE$_{(d)}$</th>
<th>NSE$_{(m)}$</th>
<th>Bias$_{(d)}$</th>
<th>Bias$_{(m)}$</th>
<th>Var$_{(d)}$</th>
<th>Var$_{(m)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.70</td>
<td>0.90</td>
<td>0.01</td>
<td>0.36</td>
<td>691</td>
<td>666</td>
</tr>
<tr>
<td>2</td>
<td>0.23</td>
<td>0.24</td>
<td>-24.90</td>
<td>-24.90</td>
<td>2630</td>
<td>2367</td>
</tr>
<tr>
<td>3</td>
<td>0.76</td>
<td>0.77</td>
<td>-10.90</td>
<td>-11.03</td>
<td>2275</td>
<td>2183</td>
</tr>
<tr>
<td>4</td>
<td>0.29</td>
<td>0.69</td>
<td>-5.03</td>
<td>-5.06</td>
<td>5575</td>
<td>5222</td>
</tr>
</tbody>
</table>
temperature and glacial melt does not hold for our region. We suggest improving environmental data acquisition in the region. The streamflow underestimation could be due to the neglected impact of energy coming from precipitation on the surface of snow and glaciers in the spring, which our model does not account for, as well as heat exchange between the surface and the atmosphere (Walter et al., 2005).

One of the options to adjust glacial melt is using the existing ratio between drainage from the watershed and the percent coverage of the total area by glaciers. A relativity analysis indicates that a 1% increase in glaciation increases total runoff by 12% (Table 2-2). Therefore, future work could be focused on assessing model behavior if we change the way of estimating glacial melt from the watershed. Another interesting aspect will be to assess actual change in ET with an increase in elevation and slopes over the watershed and incorporate this step for Model 3 by introducing the ET coefficient that was utilized in Model 4.

From the current results, we can conclude that the baseflow constant, curve number and field capacity of the watershed are the major parameters affecting model results. For further model improvement, field measurements should be conducted to define baseflow, glacial melt and temperature gradients over the watershed. However, the results generated by Model 3, suggest that the methods used are reliable for modeling other watersheds with similar streamflow conditions and physical properties in the region.

Conclusion

Through this study, we observe that physical conditions of the watershed can be used to support modeling streamflow conditions from climatic variables like precipitation and air temperatures for a selected watershed. Moreover, it is likely that these models will also apply to
other watersheds that have relatively similar basin characteristics. However, one should carefully examine existing data collection for possible errors in the measurements. In addition, it is clear that ET is one of the main elements affecting storage in the watershed and should not be neglected.

The results presented in this study illustrate that complexity of the models is not necessarily associated with better results, especially in this semi-arid region where streamflow in the rivers is primarily driven by snow and glacial melt. In addition, the increased complexity can be associated with decreased efficiency.

A decrease of glaciation and the associated disruption of the balance between the area of ablation and available area of accumulation over the next two decades will affect streamflow and will eventually lead to a decrease of overall average streamflow. Observed variations in the streamflow are related to the climatic conditions and trends such as the increase in air temperature and a decrease in precipitation in the region. Efficient management of water resources will require continued attention to understand the implications of climate change on the Central Asian region.
Chapter 3 Climate change, hydrology, and forecasting

This chapter provides a broader perspective to the application of the developed model. Here we discuss potential implications, available resources, and future research directions. We also illustrate the utility of the models developed in the prior chapter by applying Model 3, which showed the best results, to forecast future streamflow conditions for the year 2050 using various climatic scenarios developed for the region.

Climate change and forecasting

Climate change is strongly supported by evidence across multiple scopes and is most comprehensive for natural systems. The impact of climate change on precipitation or melting snow and ice is altering hydrologic systems and affecting water resources in terms of both quality and quantity across a range of different systems and scales. While many regions have significant levels of analysis that show a substantial increase in the impact attributed to the climate change, the absence of some regions from the literature does not necessarily imply that impacts have not occurred. While interest from the scientific community continues to expand the existing knowledge base, some regions around the world still lack comprehensive research into the impact of climate change on hydrologic systems.

Emission of greenhouse gases will impact mean surface temperature for the late 21st century and beyond. Acceleration in rates of greenhouse gas emissions will inevitably cause further climate change and increase the likelihood of severe and irreversible impacts for a range of ecosystems. However, projections of greenhouse gas emissions vary widely and depend on socio-economic development and policy decisions. The Intergovernmental Panel on Climate Change (IPCC) has developed emission scenarios forecasting future climatic conditions.
It is possible to use these to interpret climate changes that might occur. Four different scenarios were developed that indicated an increase in air temperature (Fig. 3-1). Using 1986–2005 as a baseline, the increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 under these scenarios varied from 0.3°C to 1.7°C under the RCP2.6 scenario, up to 2.6°C to 4.8°C under the RCP8.59 scenarios. In all the scenarios, the Arctic region will continue to warm more rapidly than the global mean (Edenhofer et al., 2014).

Fig. 3-1 Change in average surface temperature (a) and change in average precipitation (b) based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios (Edenhofer et al., 2014).

Climate change scenarios and hydrologic forecasting in Central Asia

Agal’tseva et al. (2010) conducted a robust study of the Central Asian region using in-situ observations from meteorological stations located in the region. Statistical downscaling was
performed by multivariate linear regression and was based on observational data from 22 stations in the case of air temperature, and 21 stations in the case of precipitation (Agal’tseva et al., 2010). For mid-century, the mean warming in the mountain region ranged from 2.2 °C (“moderate scenario”) to 3.1 °C (“hot scenario”) and is evenly distributed over the year. While our exploration of average air temperature and precipitation values at the Pskem station indicate no statistically significant differences between mean values of periods 1965–1990 and 1991–2015, Agal’tseva et al. (2010) found that precipitation patterns showed an increasing trend when assessed relative to 1990.

We used the results of Model 3 to explore the impact of various climate change predictions, since we concluded that this was the best of the models to estimate and model streamflow presented in Chapter 2. We calibrated best fit parameters, as presented in Chapter 2, and implemented several strategies from the study presented by Hagg et al. (2013) who assessed an upper part of Rukh River basin in Central Asia. The results of executing Model 3 under the current scenario are shown in Table 3-1. We also modeled the moderate and extreme weather scenarios presented by Agal’tseva et al. (2010).

Table 3-1. Results of modeled streamflow under current climatic and future scenarios in the region.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>N</th>
<th>Mean</th>
<th>St. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm/d)</td>
<td>1,095</td>
<td>2.25</td>
<td>5.77</td>
<td>0.00</td>
<td>52.00</td>
</tr>
<tr>
<td>Average air temperature (°C)</td>
<td>1,095</td>
<td>0.43</td>
<td>9.71</td>
<td>-25.98</td>
<td>20.40</td>
</tr>
<tr>
<td>Actual evapotranspiration (mm/d)</td>
<td>1,095</td>
<td>0.58</td>
<td>0.80</td>
<td>0.00</td>
<td>3.40</td>
</tr>
<tr>
<td>Modeled streamflow (m³/s)</td>
<td>1,095</td>
<td>51.44</td>
<td>46.09</td>
<td>3.40</td>
<td>221.0</td>
</tr>
<tr>
<td>Glacial runoff (m³/s)</td>
<td>1,095</td>
<td>3.82</td>
<td>6.05</td>
<td>0.00</td>
<td>40.49</td>
</tr>
<tr>
<td>Actual streamflow – observed (m³/s)</td>
<td>1,095</td>
<td>62.90</td>
<td>48.81</td>
<td>14.39</td>
<td>220.84</td>
</tr>
</tbody>
</table>
**Moderate scenario**

<table>
<thead>
<tr>
<th>Statistic</th>
<th>N</th>
<th>Mean</th>
<th>St. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm/d)</td>
<td>1,095</td>
<td>2.36</td>
<td>6.04</td>
<td>0.00</td>
<td>54.44</td>
</tr>
<tr>
<td>Average air temperature (C)</td>
<td>1,095</td>
<td>2.63</td>
<td>9.71</td>
<td>-23.78</td>
<td>22.60</td>
</tr>
<tr>
<td>Actual evapotranspiration (mm/d)</td>
<td>1,095</td>
<td>0.65</td>
<td>0.88</td>
<td>0.00</td>
<td>3.86</td>
</tr>
<tr>
<td>Modeled streamflow (m³/s)</td>
<td>1,095</td>
<td>54.88</td>
<td>48.51</td>
<td>3.57</td>
<td>249.3</td>
</tr>
<tr>
<td>Glacial runoff (m³/s)</td>
<td>1,095</td>
<td>5.81</td>
<td>8.47</td>
<td>0.00</td>
<td>52.61</td>
</tr>
</tbody>
</table>

**Extreme scenario**

<table>
<thead>
<tr>
<th>Statistic</th>
<th>N</th>
<th>Mean</th>
<th>St. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm/d)</td>
<td>1,095</td>
<td>2.40</td>
<td>6.15</td>
<td>0.00</td>
<td>55.43</td>
</tr>
<tr>
<td>Average air temperature (C)</td>
<td>1,095</td>
<td>3.53</td>
<td>9.71</td>
<td>-22.88</td>
<td>23.50</td>
</tr>
<tr>
<td>Actual evapotranspiration (mm/d)</td>
<td>1,095</td>
<td>0.68</td>
<td>0.91</td>
<td>0.00</td>
<td>4.07</td>
</tr>
<tr>
<td>Modeled streamflow (m³/s)</td>
<td>1,095</td>
<td>56.46</td>
<td>48.24</td>
<td>3.73</td>
<td>245.89</td>
</tr>
<tr>
<td>Glacial runoff (m³/s)</td>
<td>1,095</td>
<td>6.80</td>
<td>9.63</td>
<td>0.00</td>
<td>58.20</td>
</tr>
</tbody>
</table>

Fig. 3-2 represents the estimates generated from the daily streamflow modeling. This figure shows that the increase in the average air temperature will likely shift the regime of the streamflow towards an early release of water in Spring season. However, such shift will cause a decrease in the available water resources in the summer months when the need for irrigation is at the peak. Moreover, the results presented in table 3-1 show that contribution from glacial runoff will likely increase in the summer, which will lead to increasing rates of glacial runoff.
As it was mentioned before, multiple studies have indicated a worldwide decrease in glaciation. In the mountain range of Uzbekistan, the Pskem River watershed is characterized by a large number of small to medium sized glaciers (Semakova et al., 2015) and small glaciers are particularly sensitive to climate change (Kuzmichenok, 2009). The region has already experienced a drastic reduction in glaciation with up to 30% of the glaciers lost from 1990–2015 (Semakova et al., 2015). Such decrease in the glacial area has increased the potential for formation of glacial lakes (Petrov et al., 2017b), which can be a source of danger for the densely populated regions.

Considering the likely environmental changes around the Pskem watershed and expected changes of climate, policymakers need to identify measures to reduce the impact of climate change in the region. Currently, the government of Uzbekistan has made several steps towards...
hydrologic management with several dam projects introduced and more under development (Chellaney, 2014).

**Project summary**

The Aral Sea Basin is an important water resource in Central Asia. This thesis focused on developing hydrologic models for the Pskem watershed, which is the source of water for Tashkent and part of the Aral Sea basin. We showed that such models could be used to forecast possible hydrologic changes that might occur in the watershed, which has not previously been explored. To our knowledge, this is the first local scale research developed for this watershed that is validated with in-situ measurements.

Hydrologic modeling contains a variety of uncertainty; however, together with in-situ observations these models can become a powerful tool for forecasting possible changes due to climate impact. It is possible to model future conditions and assess them using parameters defined in this study not only for the watershed under study, but also for other watersheds with similar characteristics. Policy planning should be adjusted to consider such models since they provide a unique perspective about possible future changes in the watershed. Through the use of such tools an adaptation to climate change is in our hands.
References


Eddelbuettel, D., 2018. CRAN task view: High-performance and parallel computing with R.


Urbanek, S., 2011. multicore: Parallel processing of R code on machines with multiple cores or CPUs. R Package V 01-7 URL Httpscran R-Proj. Orgpackage Multicore.


Vita: Sabitov Timur

EDUCATION:

State University of New York: College of Environmental Science and Forestry (SUNY – ESF)
Master of Science: Geospatial Engineering
CURRENT GPA: 3.615 (Magna cum laude)
Expected date of graduation: May 2018

The National University of Uzbekistan named after Mirzo Ulug’bek
Master of Science: Hydrology of lakes and reservoirs (2014 – 2016)
Bachelor of Science: Hydrometeorology of arid regions (2010 – 2014)

GEOSPATIAL ENGINEERING AND HYDROLOGY QUALIFICATIONS:

- Experienced in modeling tools as HEC-RAS, HYDRUS, HYDROCAD, RETC, FLOW-2D, RAMMS
- Proficient in R, ArcGIS, Matlab, C++, Python, Photoshop and basic Microsoft Office products
- Highly qualified to work with numerical models with preferred languages as: C++, R, ArcGIS;

Languages: English, Russian

RELATED EXPERIENCE:

Hydrology Summer Intern

USGS MD-DE-DC Water Science Center, Baltimore, MD, USA

- Spatial analysis of sediment sources based on load data and mapped geological unit databases
- Geospatial analysis and statistical effort with stream and river flow and sediment erosion and transport
- Gaining an experience in aerial and terrestrial digital photogrammetry (structure from motion)

Junior Engineer

Academy of Science of Uzbekistan, Institute of Geology and Geophysics, Tashkent, Uzbekistan

- Assisting in the field trips to the mountain region for water sample collection from glacial lakes, bathymetric measurements, streamflow measurements with salinity and currency meters
- Post collection analysis of the data and writing drafts of papers along with poster presentations
- Represent institute at National level as member of community and promoting science among young people under United Nations Development Program (UNDP)
- Visits to Kyrgyzstan, Moscow, Switzerland to support meeting of scientific project leaders

Remote sensing project intern

Aerospace research lab, Faculty of Geography, Moscow State University in Lomonosov, Moscow, Russia

- Developing a project under European Science Foundation joint project to cope with Natural Hazards in Central Asia
- Performing analysis of remote sensing data from high-resolution imagery of GeoEye, SPOTS, RapidEye, BirdEye satellites
- Writing a project report draft from the side of IGG, Uzbekistan

Geology and hydrology project intern

October 1, 2015 – November 30, 2015
Dendrochronology lab, Institute of Geology, University of Bern, Bern, Switzerland

- Performed statistical analysis of data acquainted during the field trips and internship at MSU
- Wrote a report and presented results for joint project under ESF funding
- Provided further directions and the vision of the projected future from the side of Uzbekistan
- Training with UAV, monitoring of landslides and mudflows in Tasch, Switzerland

Workshop on Satellite Remote Sensing, Water Cycle and Climate Change  
July 20, 2014 – August 1, 2014

- Tver State University, Tver, Russia. Organized by Committee on Space Research (COSPAR) and the World Meteorological Organization (WMO)

RESEARCH INTERESTS:

- Outburst of glacial lakes in Central Asia, SCOPES project funded by NSF, application of remote sensing for natural hazard assessment. MS thesis in Hydrology, Uzbekistan
- Hydrology of glaciated watersheds in Central Asia and application of decision tree approach for classification and hazard detection. MS thesis Geospatial Science, SUNY ESF, Syracuse, NY, US.

CONFERENCES AND POSTER PRESENTATIONS:

- Annual spotlight, SUNY ESF & Syracuse University, Syracuse Center of Excellency Symposium, a poster presentation of current research projects findings.

AWARDS:

- World bank project winner to study ways of adaptation to changing climate, 2015
- Fulbright foreign exchange student fellowship under State Department of United of States and Institute of International Education at State University of New York, College of Environmental Science and Forestry (SUNY – ESF), 2016
- 17 annual Syracuse Symposium at Center of Excellency, Syracuse University. Winner of 2nd place at poster competition between Master Students at Syracuse University, 2017. Topic: Hydrology and landcover conditions of the high mountain watershed in the basin of Aral Sea in past half of century

MEMBERSHIPS:

- Edmund Muskie scholarship alumni;
- Fulbright international scholarship alumni;
- Member of Central Asia and the Caucasus research group at the Maxwell School of Citizenship and Public Affairs at Syracuse University;
- Mentor for international students at the State University of New York;

PUBLICATION(S):
