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Projected Hydrologic Changes Under Mid-21st Century Climatic Conditions in a Sub-arctic Watershed

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Abstract The potential effects of mid-21st century climate change on the hydrology of the Cook Inlet watershed in south-central Alaska was analyzed in this study. Climate datasets representing a set of potential change scenarios for the period 2041–2070 were developed from the North American Regional Climate Change Assessment Program (NARCCAP) archive of dynamically downscaled climate products. The NARCCAP 50-km scale regional climate output was converted to realistic daily weather time series using a “change factor” method in which observed meteorological time series used for model calibration are perturbed. The perturbations are based on statistical summaries of change for the different climate scenarios, by month, as calculated from the differences between the 1971–2000 and 2040–2070 climate model simulation periods. The downscaled climate datasets were then used to run the Soil and Water Assessment Tool (SWAT) for the Cook Inlet watershed. Generally, it was observed that increasing rainfall and warmer temperatures across the Cook Inlet watershed led to a predicted increase in the stream flow in the major rivers, increase in 7-day low flows, and considerable increase in 100-year peak flow. Furthermore, under future climatic conditions precipitation is expected to increase in the Cook Inlet watershed but the amount of snowfall is expected to decrease. Also, the amount of snowmelt is expected to increase due to warmer temperature thereby causing the average annual fraction of snowfall as precipitation to decrease leading to a reduction in the glacial mass balance in the watershed. Moreover, average annual water yield, runoff, baseflow, snowmelt across the basin is expected to increase. More specifically the different hydrologic components varied seasonally and monthly driven by the seasonal and monthly changes in precipitation and temperature. However, the overall hydrology of the watershed is projected to remain snowmelt dominated through the mid-21st century without a major shift in regime. These simulations provide a benchmark of hydrologic sensitivity to potential future climate change in this watershed useful for identifying vulnerabilities and informing the development of adaptation responses.

Keywords Hydrology · Climate change · SWAT · Cook inlet

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1 Introduction

Reports from the Intergovernmental Panel on Climate Change (IPCC) indicates an increase in the average temperatures in the arctic regions by almost twice the rate of global averages while the spatio-temporal changes predicted for precipitation have been highly variable (IPCC 2007). One of the responses to the changes in climate includes changes in the snow accumulation and melting processes in the arctic and sub-arctic regions of the world. Because water produced by snowmelt and glacial melt is an important part of the annual hydrologic cycle in these regions any change in the future climatic conditions may contribute significant changes in the annual water balance and streamflow in an arctic/sub-arctic watershed thereby affecting the livelihoods and well-being of Arctic ecosystems. Therefore, analyzing future hydrology in a sub-arctic basin will help to design water control projects under a changing climate in areas dominated by snow accumulation and melting processes. This can be done through physically based watershed simulation models such as the Soil and Water Assessment Tool (SWAT) which is commonly used to investigate the complex interactions of different components of the hydrologic cycle as well as climate change impacts on hydrology (Bekele et al. 2010; Mango et al. 2011; Wu et al. 2012; Faramarzi et al. 2013; Fiseha et al. 2014). SWAT has been extensively evaluated by researchers over different spatial and temporal scales for watersheds with many different characteristics, but mostly in areas where stream flows were dominantly generated from rainfall events, with negligible/limited contributions from snowmelt. Only a few studies have evaluated SWAT in areas with dominant snow hydrology. These includes the work by Fontaine et al. (2002) where the SWAT model's snowmelt hydrology subcomponent was used to predict annual stream flow using elevation bands to distribute temperature and precipitation. Wang and Melesse (2005) assessed the effectiveness of the SWAT model's snow melt algorithm to predict stream flows of the Wild Rice River watershed with low relief and mixed landcover located in northwestern Minnesota where melting snow is the dominant source for stream flows in spring but rainfall runoff is the dominant source for stream flows in summer and fall. Ahl et al. (2008) used SWAT to simulate the streamflow of a snow-dominated, forested mountainous watershed with snowmelt driven runoff located in central Montana, and represents biophysical characteristics that are representative of the high elevation, forested watersheds east of the Continental Divide in much of southwest Alberta, Montana and Wyoming. Abbaspour et al. (2007) used SWAT to calibrate several snow-related parameters and simulate all related processes affecting water quality, sediments and nutrient loads for the Thur watershed in Switzerland that is characterized by a pre-alpine/alpine climate. Rahman et al. (2013) modeled streamflow in a highly managed mountainous watershed in Switzerland. However, SWAT has not been evaluated in watersheds with sub-arctic conditions and therefore the objective of this paper is to describe the hydrology within the Cook Inlet watershed in South-Central Alaska (where snow typically covers the ground for more than 6 months in a year) and provide an understanding of the factors affecting the hydrology under future climate conditions. Even if most parts of the Cook Inlet Basin are only sparsely developed it has the majority of Alaska's population and related infrastructure. Therefore, results from this study will provide a benchmark for future hydrologic changes associated with changing climate in this region and will help natural-resources scientists, policy-makers and planners to design comprehensive plans for water management projects.

The work described in this paper was undertaken as part of a larger scale study of climate change impacts in 20 large watersheds across the US (Johnson et al. 2011; USEPA 2013). That study was designed to investigate a number of methodological issues regarding different watershed modeling and climate downscaling methods in addition to providing an ensemble of predictions of watershed response for the mid-21st century. A major focus of the study was on evaluating watershed response to climate scenarios using dynamically downscaled projections in which global circulation models (GCMs) provided boundary conditions for more detailed regional climate models (RCMs).

2 Materials and Methods

2.1 Study Area

Location and Physiography: Cook Inlet is a 290 km long estuary in south-central Alaska that stretches northeast from the Gulf of Alaska to Anchorage (Fig. 1). The Cook Inlet watershed covers 121,729 km^2 east of the Aleutian Range and south of the Alaska Range and includes the drainage area of Mount McKinley (Brabets et al. 1999; Glass 1999). General physiography in the Cook Inlet watershed is dominated by high rugged mountains, followed by low mountains, plateaus and highlands of rolling topography and gentle slopes, plains and lowlands with altitude ranging from sea level to the highest point in North America, Mount McKinley, at 6193.5 m (Brabets et al. 1999; Glass 1999). Major land use in the Cook Inlet basin comprises of water, permanent snow and ice, tall shrub, alpine tundra and some forested areas along with urban development limited around the City of Anchorage (Brabets et al. 1999; Glass 1999).

Due of its large size and range in altitude, the Cook Inlet Basin has three climate zones based on variations in precipitations and temperatures. The Continental Zone has greater range of temperatures than the other climate zones with an average annual temperature of −5.5 °C

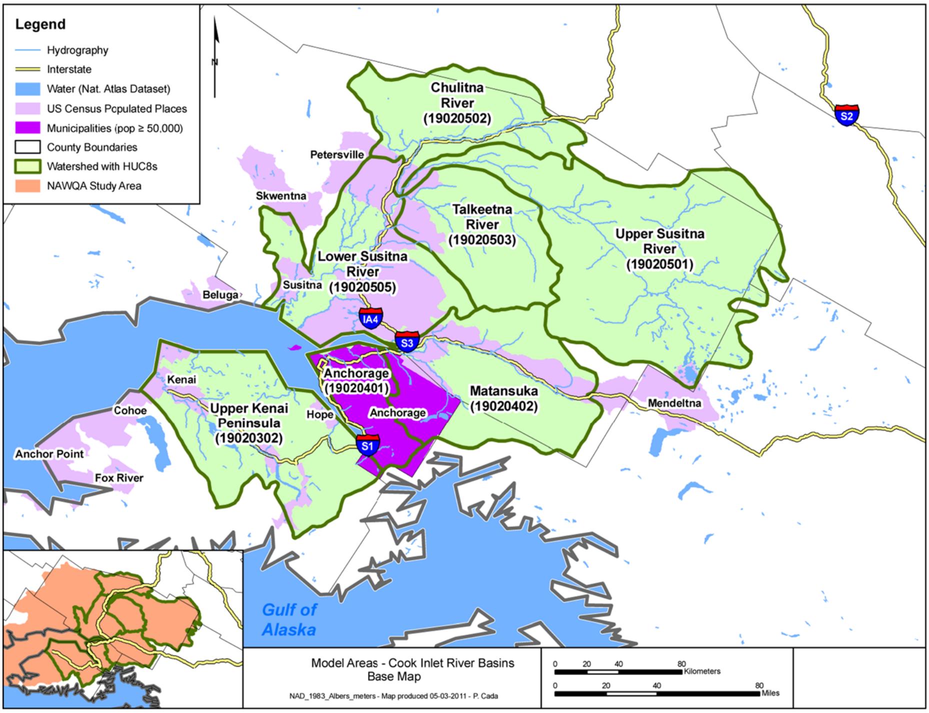

Fig. 1 Location of Cook Inlet watershed (USEPA, 2013)

and an average annual precipitation of about 500 mm. The average annual temperature in the Transitional Zone is about −5 °C and average annual precipitation is about 760 mm. The Maritime Zone is the wettest of the three zones, with an average annual temperature of about 8.3 °C and an average annual precipitation of about 1800 mm (Hartman and Johnson 1984). Precipitation in the Cook Inlet Basin ranges from 500 to 6000 mm annually with an annual average precipitation of about 1100 mm and generally falls as snow from November to March over most parts of the basin except for the extremely high mountains, where snow is deposited year-round on glaciers and ice fields (Brabets et al. 1999; Glass 1999). However, evaporation within the basin is low due to relatively cold climate, high humidity, and cloud cover that prevail over most of the basin and transpiration is negligible due to the short summer season that decreases the active growing time for vegetation (Brabets et al. 1999; Glass 1999).

The Cook Inlet watershed receives water from the melting snow and ice from Mount McKinley, the Chugach Mountains and the Aleutian Range through its tributaries the Kenai, the Susitna and Matanuska rivers (Brabets et al. 1999; Glass 1999). Most of the streams and rivers in the Cook Inlet Basin are perennial and originate in the mountainous areas. Flow from these streams and rivers are primarily from snowmelt and icemelt (from glaciers). Current seasonal streamflow characteristics of the Cook Inlet watershed are similar to other watersheds in Alaska where flows peak during late-spring/early-summer snowmelt and late-summer/early-fall rains, and slowly recede (several weeks to months) leading up to these periods. The rise in streamflow is relatively quick relative to its decline, which increasingly becomes dominated by groundwater baseflow. Despite the sub-freezing air temperatures and continuous snowpack during winter months that virtually eliminate surface runoff, warmer groundwater continuously discharges to streams. Streamflow is at the maximum during the summer months.

2.2 SWAT Model

SWAT is a physically based, semi-distributed, continuous time watershed model that is used to predict the impacts of land management practices on water, sediment, and agricultural chemical yields in complex watersheds over a range of scales with varying soils, land use, and management conditions over extended periods of time (Srinivasan and Arnold 1994; Rosenthal et al. 1995; Spruill et al. 2000; Weber et al. 2001; Santhi et al. 2001; Luzio et al. 2002; Jayakrishnan et al. 2005; Yen et al. 2014). Additionally, SWAT has been designed to model ungauged watersheds by using readily available data and also simulates the impact of alternative input data such as changes in land use, land management practices and climate (Arnold et al. 1998; Neitsch et al. 2005). SWAT is computationally efficient and therefore able to run simulations of very large basins or management practices without consuming large amounts of time or computational resources.

SWAT comprises three major components (Subbasin, Reservoir Routing, and Channel Routing) and each component and subcomponent is divided further into subcomponents. For example, the subbasin component consists of eight major subcomponents (hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, agricultural management, and pesticides) and the hydrology subcomponent is further subdivided into surface runoff, lateral subsurface flow, percolation, groundwater flow, snowmelt, evapotranspiration, transmission losses, and ponds. In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the subwatershed area and are not identified spatially within a SWAT simulation. Climatic inputs used in SWAT include daily precipitation, maximum and minimum temperature, solar radiation data, relative humidity, and wind speed data, which can be input from measured records and/or generated. Customized climatic input data options include: (1) simulation of up to ten elevation bands to account for orographic effects on precipitation and temperature and/or for snowmelt calculations, (2) adjustments to climate inputs to simulate climate change, and (3) forecasting of future weather patterns. SWAT simulates the overall hydrologic balance for each HRU, including canopy interception of precipitation, partitioning of precipitation, snowmelt water, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers. It uses a storage routing technique to calculate redistribution of water between layers in the soil profile. In addition, SWAT allows irrigation water to be transferred from any reach or reservoir to any other hydologically linked reach in the watershed (Santhi et. al. 2005; Zheng et al. 2010). Based on surface runoff calculated using the SCS runoff equation, excess surface runoff not lost to other functions makes its way to the channels where it is routed downstream. Detailed descriptions of the methods used in modeling these components and subcomponents can be found in Arnold et al. (1998), Srinivasan et al. (1998), and Neitsch et al. (2005).

2.3 Future Climate Data and Model Scenarios

Global climate models (GCMs) typically provide output on a 1-degree grid, which is too coarse for watershed simulation and does not capture many important orographic effects. Downscaling is required to resolve climate predictions to a finer scale. Two main approaches to downscaling are dynamical downscaling, in which the GCM is used to provide boundary conditions to a regional climate model (RCM) and statistical downscaling, in which the output from the GCM is corrected based on spatial statistical relationships between the GCM predictions and meteorological observations for current conditions. For this study we chose dynamical downscaling and used an ensemble of climate products to investigate the potential state of future climate to which adaptation may be needed. Datasets representing a set of potential climate change scenarios for the period 2040–2070 were obtained from the North American Regional Climate Change Assessment Program (NARCCAP). The NARCCAP archive contains dynamically downscaled climate products developed from the application of RCMs to the output from a set of the IPCC 4th Model Intercomparison Project GCMs. The NARCCAP products provide detailed scenarios of regional climate change over the continent, using different combinations of RCMs and GCMs, allowing examination of the uncertainties associated with using different climate projections. The three specific scenarios evaluated for Cook Inlet and their GCM downscaling combination is shown in Table 1.

The NARCCAP downscaled climate scenarios are based on the IPCC's A2 greenhouse gas storyline, representing a continuously increasing global population, regionally oriented economic development, and relatively moderate and fragmented per capita economic growth and technological change with expected carbon-di-oxide

Table 1 Future climate scenarios for the cook inlet watershed

Scenario Name	GCM	Downscaling RCM
Baseline	1973–2003 Existing Conditions	
Scenario_01	HadCM3	HRM3
Scenario_02	GFDL	GFDL High Resolution
Scenario_03	CCSM	WRFP

concentrations on 575 ppm. However, the 50-km NARCCAP scale is still too coarse for watershed modeling and many GCMs display well-documented biases with regard to precipitation frequency and intensity (Dai 2006; Sun et al. 2006). Therefore meteorological time series for input into SWAT were created using a "change factor" method in which the alterations are based on monthly statistical summaries of change for the different climate scenarios, as calculated from the differences between the 1971–2000 and 2041–2070 climate model simulation periods. These change statistics were used to perturb the existing climate records of precipitation and temperature using the Climate Assessment Tool (CAT), developed for EPA's BASINS system (USEPA 2009). Changes in additional meteorological variables (e.g., solar radiation, relative humidity, wind) are represented by modifying the monthly parameters of the SWAT statistical weather generator.

2.4 Model Inputs

The SWAT model for the Cook Inlet watershed was built using a Digital Elevation Model with a resolution of 30 m and subwatershed boundaries and reach hydrography (with connectivity) defined using NHDPlus data. The NHDPlus data incorporates the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), the National Land Cover Dataset (NLCD), and the Watershed Boundary Dataset (WBD) and the NHDPlus catchments/reaches were aggregated into model subwatersheds and reaches (comparable to the HUC10 scale). Land use/cover input to the SWAT model was from the 2001 National Land Cover Database (NLCD) coverage (Fig. 2). Soils in the watershed are specified as represented in the STATSGO state soil coverage and fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and D (low infiltration capacity). SWAT used information drawn directly from the soils data layer to populate the model. Furthermore, 14 weather stations were identified for use in the Cook Inlet model with a common period of precipitation and temperature record from 10/1/1972-9/30/2002. These data have been processed to fill gaps and redistribute accumulated precipitation as part of the BASINS4 meteorological data set (USEPA 2008). The required meteorological time series for the SWAT simulations are precipitation and air temperature. The simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are also drawn from the BASINS4 Meteorological Database (USEPA 2008). Because the research plans for the USEPA 20 watersheds study (Johnson et al. 2011) required simulation over 30 years, stations with a common 30-year period of record that covers the year 2001 were considered. Additionally, two major reservoirs were considered within the SWAT model for the Cook Inlet basin. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of dams (NID) database. Keeping in view, the climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, target release approach was used in the SWAT model. Finally, only the major point source dischargers, with a design flow greater than 0.5 MGD were included in the simulation. There are only two major point source discharges in the watershed and they have been represented as long-term average flows, without accounting for changes over time or seasonal variations.

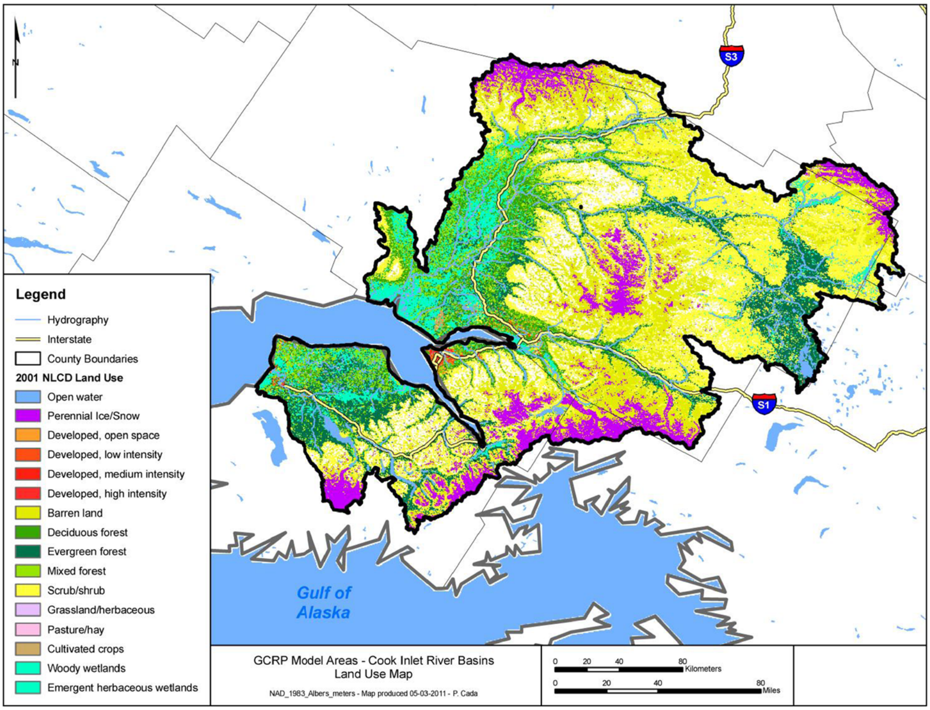

Fig. 2 Land use in the Cook Inlet watershed (USEPA, 2013)

2.5 Calibration Setup and Analysis

The Cook Inlet basin was divided into 116 subbasins and 2194 Hydrologic Response Units (HRUs) for the purposes of modeling. The watershed parameterization and model inputs were generated using ArcSWAT ver. 2.5.4. The basic datasets required to build the model are: topography, soil, landuse and weather data. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface to form HRUs from an intersection of land use, major soils and slopes. A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds. Elevation bands were created in the subbasins where elevation was above 500 m to account for variations in precipitation and temperature with elevation. Additionally regions of permafrost were identified within the basin and were accounted for by adding initial snow water content in the subbasins.

A spatial calibration approach was adopted for the SWAT modeling for Cook Inlet basin where parameters were adjusted manually within the practical range at the calibration focus area until the simulated results were acceptable according to the model evaluation criteria; some adjustments were applied throughout the basin while adjustments to specific subwatersheds were kept as minimal as possible.

2.6 Criteria Used to Compare the Measured and Simulated Discharges

During the calibration of the Cook Inlet Basin SWAT model we attempted to achieve a range of error statistics (Percent Bias) for total volume, seasonal flows, and high and low flows while also maximizing the Nash-Sutcliffe coefficient of model fit efficiency to assess the performance of the SWAT model. The Nash-Sutcliffe coefficient is defined as:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2},$$

where O_i and P_i represent members of a set of n paired time series observations and $\bar{O}$ is the mean of the observed values. *NSE* ranges from minus infinity to 1.0, with higher values indicating better agreement. A value of zero for *NSE* indicates that the observed mean is as good as the model mean, while negative values indicate that the observed mean is a better predictor than the model mean (Moriasi et al. 2007).

Percent bias (PBIAS) or Mean Percent Error measures the percent deviation of the simulated data (total flow, low flows, high flows, and seasonal flows) from their observed counterparts. The ideal value of PBIAS is 0.0, with low values indicating accurate model simulation. Positive values indicate that the model has a tendency to underestimate while negative values indicate that the model tend to overestimate. (Moriasi et al. 2007). Most of the calibration efforts aimed at getting a closer match between simulated and observed flows at one of the USGS gaging station of the basin.

3 Results and Discussion

3.1 Climate Variables

Monthly precipitation and temperature outputs from the NARCCAP scenarios were processed for the Cook Inlet Watershed. Figures 3a and b shows the change in precipitation (rainfall and snowfall) by month from the baseline scenario for each climate scenario. Generally, the climate scenarios indicate increased monthly precipitation for the Cook Inlet watershed during the mid-twenty-first century. The precipitation considered here is a combination of rain and snow and the fraction occurring as rain is projected to increase under future climate: rainfall may increase by as much as 20 % during the winter season and 40 % during the spring season and snowfall may decrease by as much as 42 % during the summer season and 17 % during the fall season under mid-21st century climatic condition. The seasonal changes in the projections can vary greatly across the climate models. Figures 4a and b show the maximum and minimum temperature by month for the baseline conditions (1972–2002) and for each climate scenario. The temperature changes for the scenarios indicate increasing temperatures in the Cook Inlet Watershed. The largest temperature changes are mostly during the winter months and early spring (>4 °C).

3.2 Hydrological Model Calibration and Uncertainty Analysis

The hydrology calibration period was set to Water Years 1992–2001 (within the 30-year period of record for modeling) and validation was performed on Water Years 1982–1991. Calibration and validation of the SWAT model for the Cook Inlet watershed were pursued at two location: Kenai River at Soldotna (USGS ID: 15266300) with a drainage area of 5053 km^2 and Talkeetna River near Talkeetna (USGS ID: 15292700) with a drainage area of 5169.6 km^2. The parameters that were changed to calibrate the model at both the locations were snow

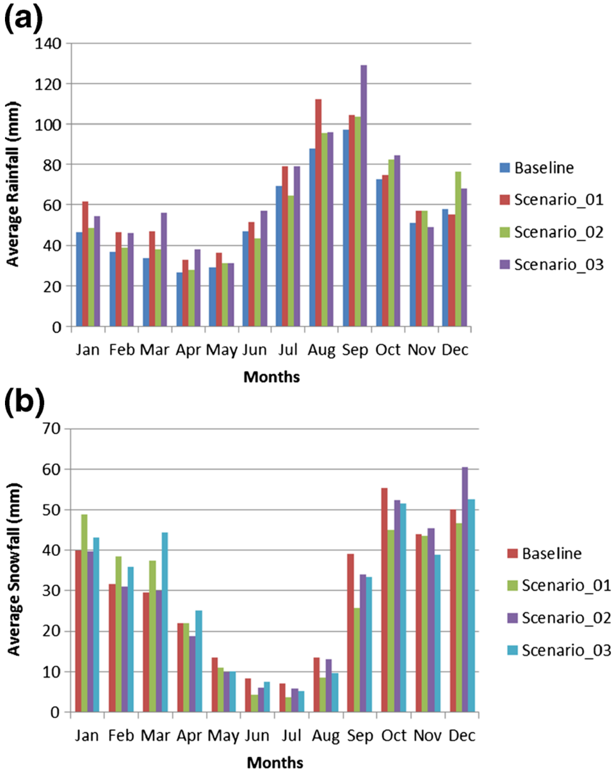

Fig. 3 **a:** Average monthly rainfall for the three climate change scenarios with respect to current conditions. **b:** Average monthly snowfall for the three climate change scenarios with respect to current conditions

parameters like the snowfall temperature (SFTMP), the snowmelt temperature (SMTMP), the maximum (SMFMX) and minimum (SMFMN) snowmelt rates, and the snow pack temperature lag factor (TIMP), groundwater parameters such as groundwater delay time (GW_DELAY), baseflow factor(ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (SHALLST), Initial depth of water in the shallow aquifer (GWQMN), threshold depth of water in the shallow aquifer required for “revap” or percolation to the deep aquifer to occur, recharge to deep aquifer (REVAPMN), and a few other parameters such as available water capacity of the soil layer (SOL_AWC), curve number (CN2), precipitation lapse rate (PLAPS), temperature lapse rate (TLAPS), and channel hydraulic conductivity (CH_K2). The model provides a good match to the total flow volume evaluated at a monthly time step (Fig. 5), as well as to the 10 % high flows, flows below the median (50th percentile), and the seasonal flow volumes for the calibration period. The validation also achieves a high coefficient of model fit efficiency. The monthly Nash-Sutcliffe coefficient for the calibration period (1992–2001) at the Kenai River at Soldotna (USGS ID: 15266300) was 0.88 and for the validation period (1982–1991) were 0.84. At the Talkeetna River near Talkeetna (USGS ID: 15292700) the monthly Nash Sutcliffe coefficient for the calibration period (1992–2001) was 0.84 and for the validation period (1982–1991) was 0.82. Moriasi et. al. (2007) recommends a *NSE* of 0.50 or better as an indicator of adequate hydrologic calibration when accompanied by a bias of 25 % or less. Therefore, the SWAT model performance for the Cook Inlet basin for both calibration and validation periods was very good, based on the performance criteria given by Moriasi et al. (2007).

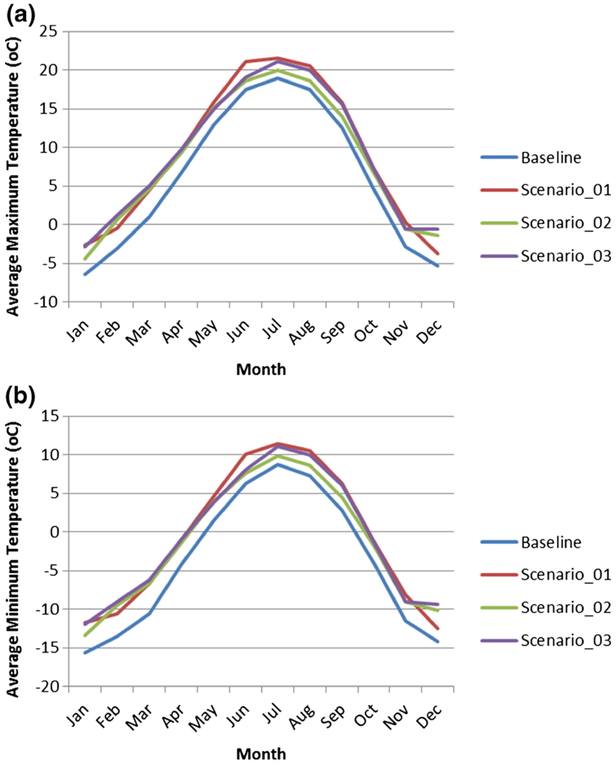

Fig. 4 **a**: Average monthly maximum temperature for the three climate change scenarios with respect to current conditions. **b**: Average monthly minimum temperature for the three climate change scenarios with respect to current conditions

3.3 Impact of Climate Change on the Water Resources of the Cook Inlet Watershed

Impact of future climate changes on the hydrology in the Cook Inlet watershed was evaluated by examining the water balance components in the basin and the streamflow in Talkeetna and Kenai Rivers at annual, seasonal and monthly time steps under the future climate conditions (as listed in Table 1) and compared with that under baseline/current climate conditions.

i) Annual and Seasonal Stream Flow changes: The model simulations for the different climate scenarios predicted varying streamflow volumes. However all the climate models predicted an increase in the flow volumes for both the Kenai River and Talkeetna River (Fig. 6). As shown in Table 2, under the different future climate scenarios, the flow from the Kenai River at Soldotna is projected to increase by 32 to 67 % with an average increase of 51 % whereas the river flow in the Talkeetna River near Talkeetna will increase by an average of 26 % but the variation in increase was less (20 to 31 %). This can be attributed to a general increase in precipitation and temperature across the watershed.

The seasonal variation in the streamflow resulting from the predicted climate scenarios is depicted in the Fig. 7. In this analysis winter season includes the months of December, January and February, spring includes March, April and May, summer includes June, July and August and fall includes September, October and November. Average streamflow is

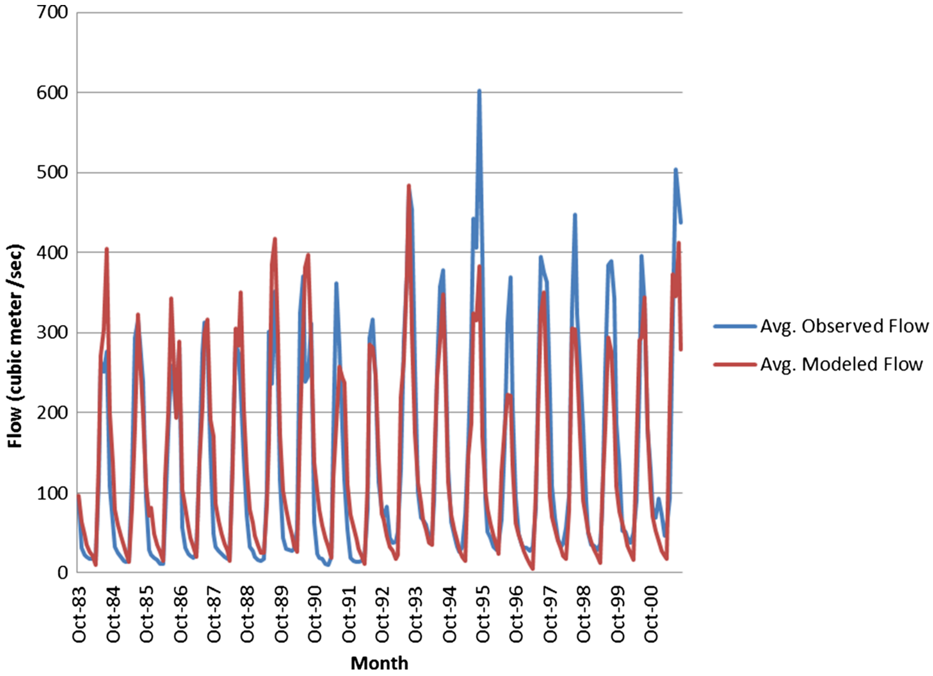

Fig. 5 Mean monthly flow for the Calibration Period (1992–2001) and Validation Period (1983–1992) for the Kenai R at Soldotna, AK

expected to be maximum during the summer season and minimum during the winter season but the predicted stream flow changed most during the winter season followed by

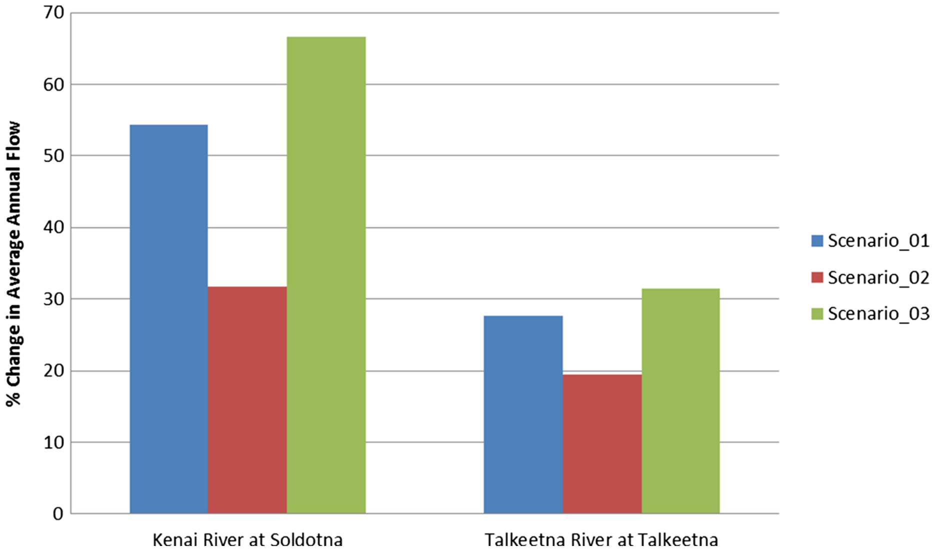

Fig. 6 Variations in % change in average annual streamflow for the Kenai and Talkeetna rivers under future climate conditions

Table 2 Change in future streamflow volumes relative to current streamflow volumes

	Change relative to Current			
	Min	Median	Mean	Max
Kenai River at Soldotna				
StreamFlow	31.74 %	54.35 %	50.89 %	66.56 %
Talkeetna River near Talkeetna				
StreamFlow	19.47 %	27.66 %	26.18 %	31.42 %

spring and fall seasons for both Kenai River and Talkeetna River. Winter streamflow may increase by an average of 85 % for the Kenai River and 57 % for the Talkeetna River across all climate change scenarios. This increase in winter streamflow is caused by greater winter precipitation and greater increase in winter temperatures resulting in earlier and greater snowmelt during winter. Average spring streamflow may increase by around 76 % for the Kenai River and 53 % for the Talkeetna River. This can be attributed to increases in spring precipitation and temperature that will cause snow melt to begin earlier in the spring. Average fall streamflow is also projected to increase by as much as 65 % for the Kenai River and 54 % for the Talkeetna River with respect to the current conditions due to increased precipitation that will compensate for temperature induced increases in evapotranspiration. Streamflow increases during the summer season were the smallest on a percentage basis, being within 14–33 % of the current conditions for both the rivers.

ii) Monthly Streamflow Changes: Fig. 8 shows the results of simulated change in the median monthly streamflow for all the three future climate scenarios. For both Kenai and

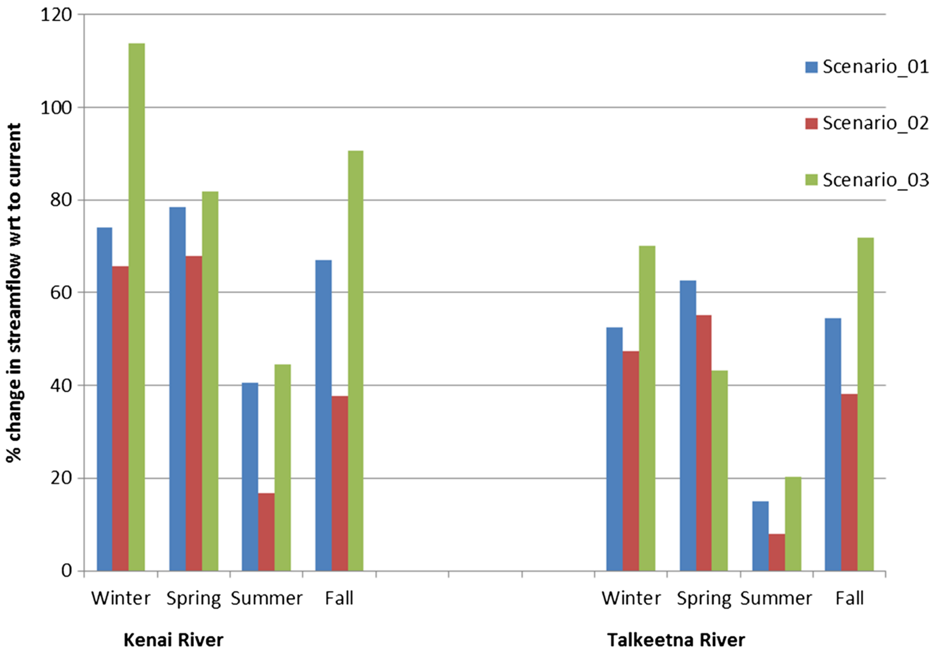

Fig. 7 % Change in seasonal streamflow for the Kenai and Talkeetna Rivers under future climate conditions

Talkeetna rivers the streamflow changes across the summer months of June, July and August is very less ranging from 3 to 45 % while the spring months of March and April shows the most increase in streamflow as much as upto 326 % increase. The increase in streamflow is more during March for the Talkeetna River but more during April for the Kenai River. The fall and winter months also show significant increase in streamflow under future climate conditions by as much as 69 and 98 % respectively. For all the other months, the change in streamflow is more for the Kenari River than for the Talkeetna River. Figures 9 and 10 shows the predicted monthly streamflow changes for the current and the future climate scenarios for the Kenari River than for the Talkeetna River respectively. The shape of the hydrographs for the future scenarios is similar to the current baseline conditions, but with an increase in predicted streamflow for all months. The simulation shows greater melt and less ice accumulation in the future; however, unlike the Pacific Northwest (Hamlet and Lettenmaier 2007; Mantua et al. 2010), there is little projected change in average timing of flows by the mid-21st century: The system remains snow-dominated and is not projected to experience a regime shift to a more transient mixed snow-rain system.

In addition to the annual, seasonal and monthly streamflow changes we also analyzed percent changes in the 7-day low flows and 100-year peak flows under future climate scenarios (Table 3). Both the rivers in the Cook Inlet watershed exhibited a significant increase in 7-day low flows that points to an increase in the snow melting rate during the drier season under a warmer climate in Alaska. Furthermore the 100 year peak flow also increased considerably across all the scenarios being more for the Talkeetna River in the future. In addition to the flow volume the timing and intensity of flows are also important.

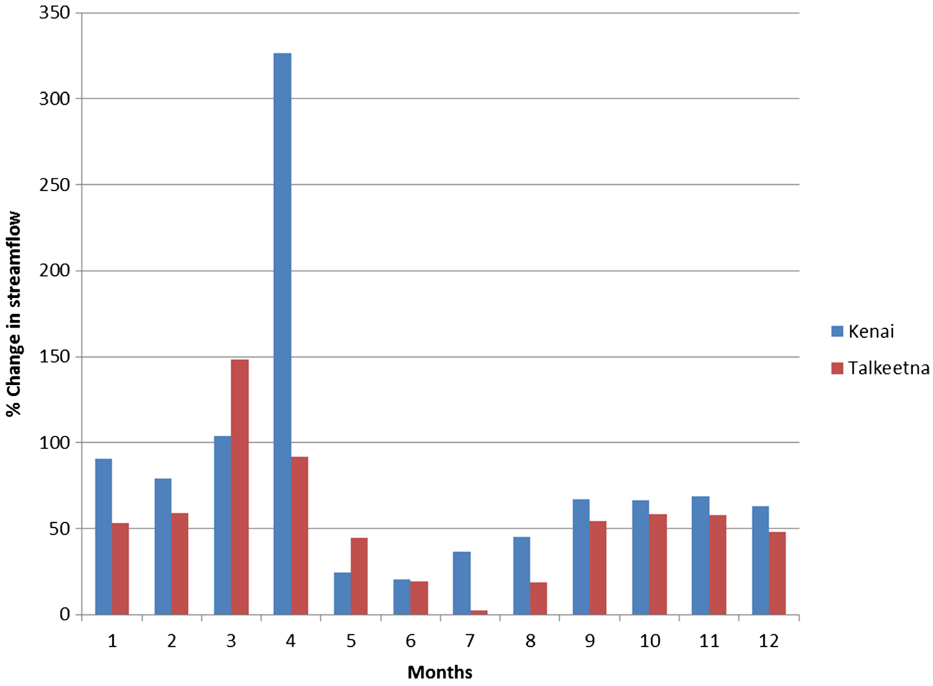

Fig. 8 % change in the median monthly streamflow for the Kenai and Talkeetna Rivers under future climate conditions

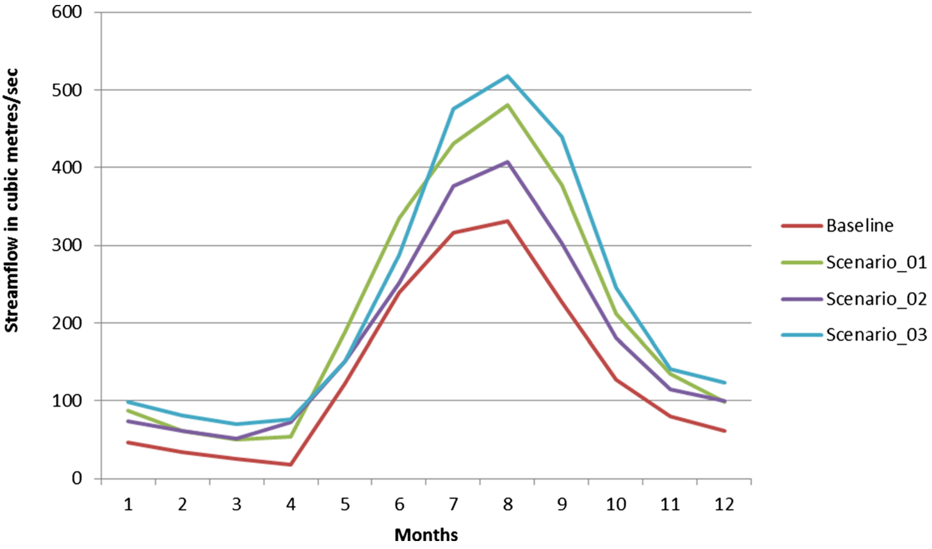

Fig. 9 Predicted monthly streamflow changes for the Kenai River at Soldotna for the current and the future climate scenarios

The number of days (since October 1, start of the water year) to the flow centroid—the point at which half the flow of an average year is achieved - is a useful summary measure of changes in seasonality. Table 3 shows that under the future climate scenarios the

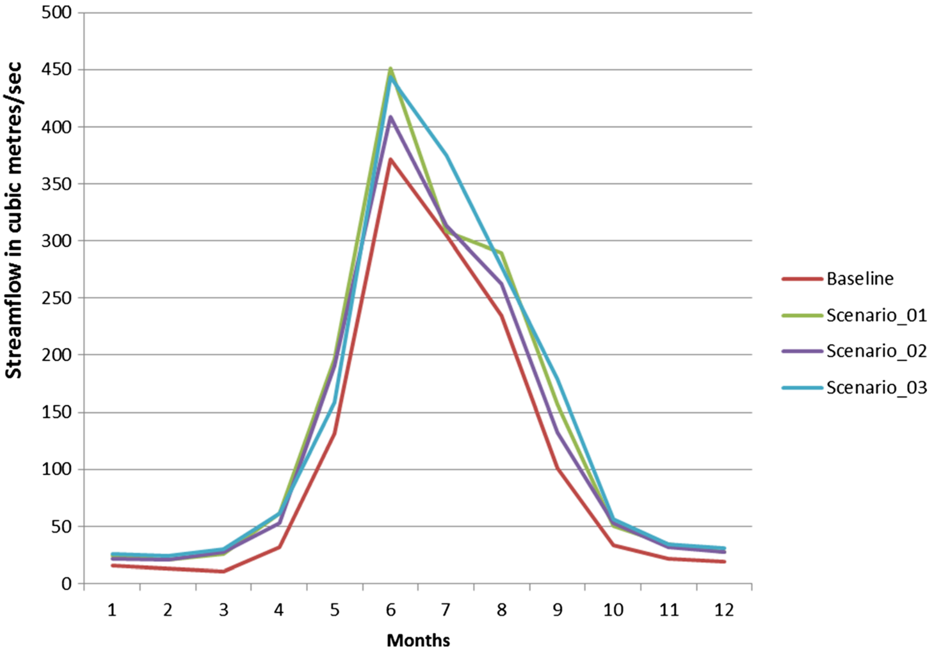

Fig. 10 Predicted monthly streamflow changes for the Talkeetna River at Talkeetna for the current and the future climate scenarios

centroid of flow on average comes earlier in the year in response to warmer temperatures for the snow-melt dominated Cook Inlet basin in Alaska, but the projected change is not large by the mid-2st century. This result reflects changes in snow melt timing due to warmer temperatures.

iii) Annual, Seasonal and Monthly water balance: The SWAT model also computes the water balance of the watershed based on precipitation, surface runoff, evapotranspiration, and baseflow. In this section we will report the impact of future climate conditions on the different hydrologic components of the Cook Inlet watershed at different temporal scales.

The average annual hydrologic budget components simulated by SWAT for the Cook Inlet watershed's baseline and the three climate change scenarios are shown in Table 4. The precipitation changes across the watershed indicate an increased precipitation over a range of 10–22.5 % for the three climate change scenarios. A larger fraction of this precipitation will be as rainfall in the future compared to the baseline climatic conditions. The ratio of snowfall to total precipitation will decrease by as much as 13.5 %. As a result runoff is expected to increase by 14–35 %. In addition, the annual average baseflow over the entire watershed will also increase by 21–30 % and changes in Evapo-Transpiration (ET) are significantly less compared to the other hydrologic components, increasing by 2–8 %. Overall, the models predict that the total water yield in the Cook Inlet watershed will increase by 15–27 % under future climate conditions. In addition, several other summary measures of the water balance, largely drawn from the work of Hurd et al. (1999), are summarized as averages at the whole-watershed scale in Table 5. These are measures are computed from the hydrologic components: 1) Dryness Ratio, defined here as the fraction of precipitation that is lost to evapotranspiration (ET) as reported by the SWAT model. Hurd et al. (1999) calculated a dryness ratio by computing ET as the difference between precipitation and basin outflow. Results are generally similar, but the latter approach does not account for additional factors such as channel loss and is affected by reservoir management and boundary conditions. 2) Low Flow Sensitivity, expressed as the rate of baseflow generation by shallow groundwater, tile drainage, and lateral subsurface flow pathways. 3) Surface Runoff Fraction - the fraction of total flow from the uplands that is predicted to proceed through overland flow pathways. 4) Snowmelt Fraction – the fraction of total flow from the uplands that is generated by melting snow. These metrics were calculated from the hydrologic budget components and therefore follow a similar pattern corresponding to the hydrologic budget components. The dryness ratio is projected to decrease, low flow sensitivity is projected to increase, surface runoff fraction is projected to increase while snowmelt fraction is projected to decrease

Furthermore, seasonal water balance components simulated by SWAT for the entire Cook Inlet watershed under baseline and the three climate change scenarios were also analyzed. Water yield is expected to increase across all the seasons for the future climate scenarios as seen in Fig. 11a. However, the relative magnitude of the increase is at a maximum during the

Table 3 % change in 7- Day low flows, 100 year Peak Flows and centroid of flow for the Kenai and Talkeetna Rivers under future climate conditions

	Kenai River at Soldotna			Talkeetna River near Talkeetna		
	Scenario_01	Scenario_02	Scenario_03	Scenario_01	Scenario_02	Scenario_03
7d low flow	166.67	180.41	300.46	69.92	59.90	85.59
100 year Flow	31.75	24.60	32.12	100.75	54.10	57.84
Centroid	−1.08	−1.80	−0.36	−2.20	−1.83	−0.73

Table 4 % changes in the average annual hydrologic budget components under the three future climate scenarios

% change	Scenario_01	Scenario_02	Scenario_03
Precipitation	17.83	10.29	22.58
Snowfall	1.90	3.54	7.47
Snowmelt	8.14	5.97	11.49
Surface Runoff	28.24	14.65	35.34
Baseflow	24.74	21.20	29.87
Evapo-Transpiration	8.18	2.19	7.38
Water Yield	22.82	15.03	27.13
Snow/Pcp	−13.52	−6.12	−12.33

winter season ranging from 30 to 45 % followed by the spring season with an increase of about 40 %. Water yield during the fall season is predicted to increase by 20–40 %, while in summer it is predicted to increase by up to 15 %. This increase in the water yield across all the seasons can again be explained by the increasing temperature and precipitation across all the scenarios. Similar to the pattern of water yield, evapotranspiration is also expected to be at its peak during the summer season followed by the spring season (Fig. 11b). Under future climate conditions the percentage change in evapotranspiration in the Cook Inlet watershed will likely be largest during the winter months, with increases ranging from 20 to 40 % under different climate scenarios. Relative changes in ET during spring and fall is smaller, ranging between 9 and 10 % in spring and 3–8 % in fall. During summer season, ET across the watershed is expected to increase by 1–5 % under scenario_01 and scenario_03 but decrease by as much as 3 % under scenario_02. The decrease in ET during the summer months under Scenario_02 scenario can be explained by the decrease in summer precipitation and less increase in summer temperatures compared to the other two scenarios. In addition, runoff in the Cook Inlet watershed occurs mostly during the spring and summer seasons as seen in Fig. 11c. However under future climate conditions runoff is projected to increase during the winter and fall seasons. Winter runoff may increase by as much as 3000 % due to warmer temperatures and more precipitation in the form of rain instead of snow. Furthermore, runoff during the fall season may increase by as much as 100 % while spring runoff may increase by as much as 25 %. Runoff during the summer months is expected to decrease by 5 % under Scenario_02 and increase by 13–16 % under Scenario_01 and Scenario_03 scenarios. Likewise, recharge to shallow groundwater is expected to increase across all the seasons under all the climate scenarios. Similar to the baseline conditions recharge to shallow groundwater will be maximum during the winter and fall seasons and minimum during summer and spring. However, under future climate conditions recharge to shallow groundwater is expected to increase by as

Table 5 Measures of the water balance summarized as averages at the whole-watershed scale

	Baseline	Scenario_01	Scenario_02	Scenario_03
Dryness Index	0.029	−0.012	−0.013	−0.007
Low Flow Sensitivity	1.551	1.889	1.785	1.948
Fractional Surface Runoff	0.156	0.163	0.156	0.306
Fractional Snow Melt	0.538	0.465	0.505	0.472

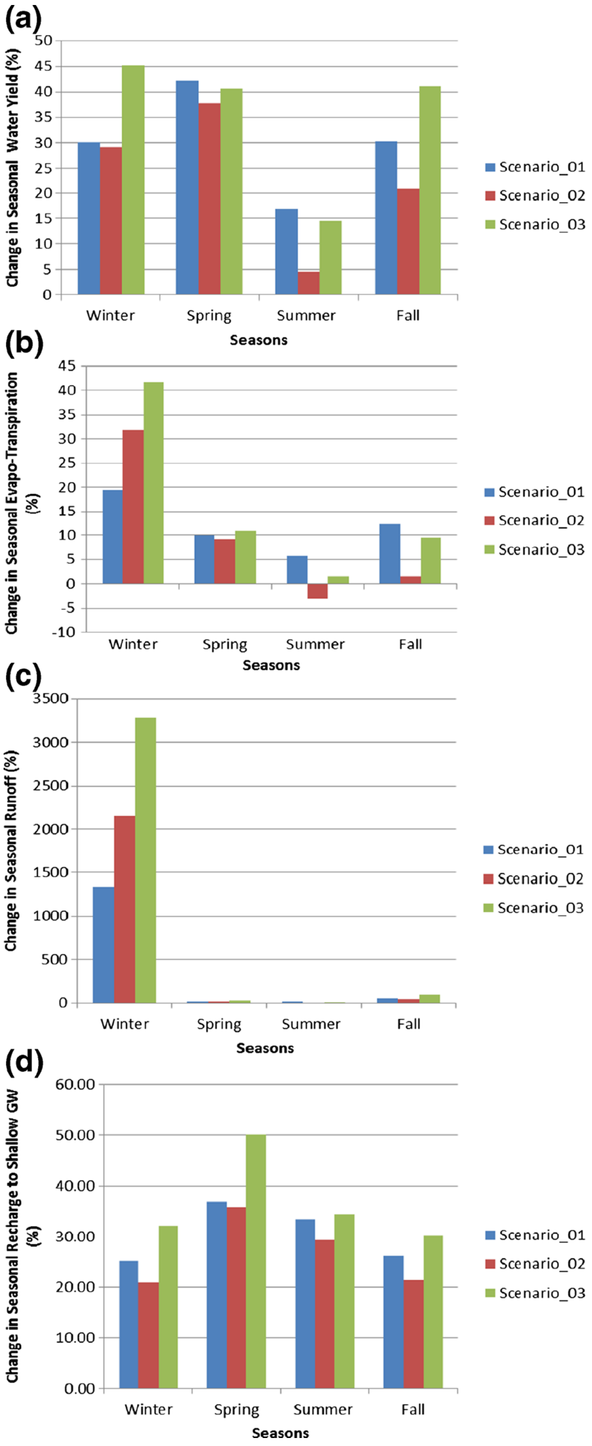

Fig. 11 a-d: Seasonal Variation in Water Yield (**a**), Evapotranspiration (**b**), Runoff (**c**) and Recharge to shallow GW (**d**) under future climate scenarios

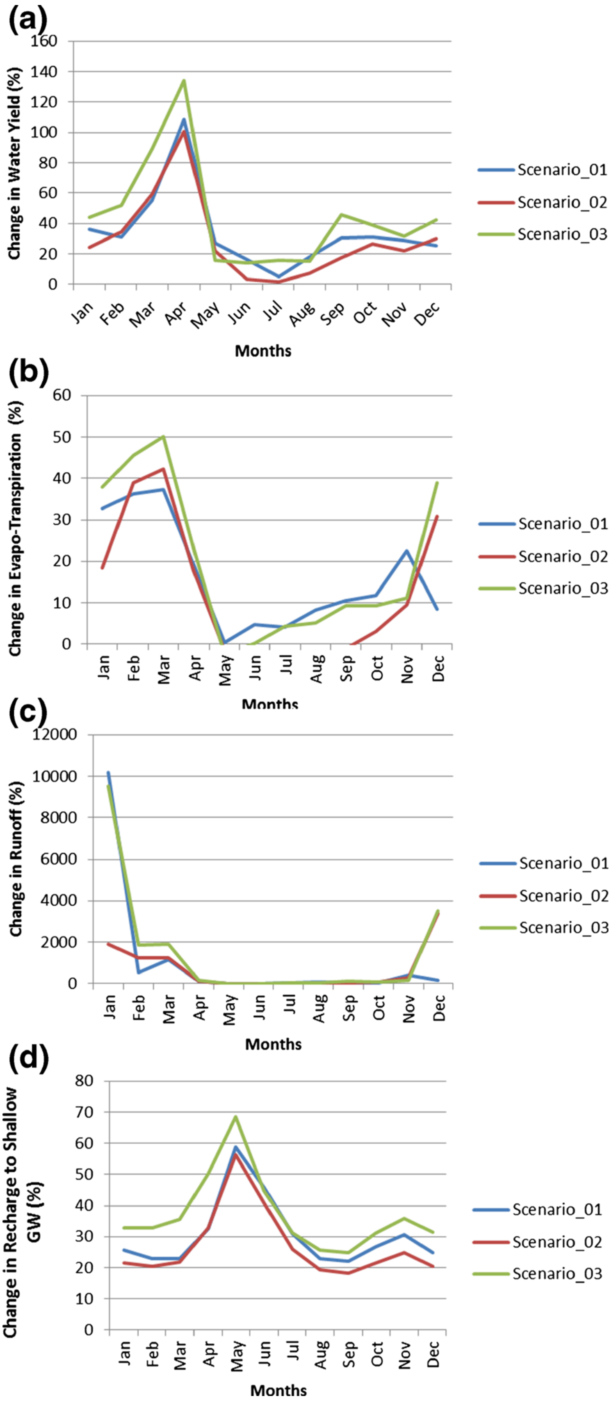

Fig. 12 **a-d**: Monthly Variation in Water Yield (**a**), Evapotranspiration (**b**), Runoff (**c**) and Recharge to shallow GW (**d**) under future climate scenarios

much as 50 % during spring and 35 % during summer and mostly by 20–30 % during spring and winter months (Fig. 11d).

Analyses of monthly water balance components (Fig. 12a-d) under future climatic conditions points to an increase in water yield during all the months with maximum during June, July, and August. Average water yield will increase by around 7 % in July to 114 % in April. Increase in Evapotranspiration will be more from December to March due to the climate getting warmer and wetter and less over May, June, and July. Average increase will be most during February by as much as 41 % while remaining almost unchanged during May, June and July. Runoff will increase manifolds during the months of December, January, February and March due to increase in rainfall ranging from 18 to 41 %. Groundwater recharge also increases over all the months across all the scenarios ranging from an average of 20 % in September to 60 % in May. In addition, average snowfall across all the climate scenarios will decrease by as much as 34 % between May to October while average rainfall will increase by 8–41 % across all the months.

4 Summary: Implications of Climate Change Impact

The ensemble of potential mid-21st climatic conditions suggests increasing precipitation and air temperature over the Cook Inlet watershed. Dynamically downscaled NARCCAP scenarios from three GCM/RCM model combinations were used to provide meteorological data for the period 2041–2070 to the watershed model SWAT. Results from SWAT simulations of future climate scenarios indicate an increasing precipitation that will result in an increase in water yield across the whole basin as increases in the runoff and baseflow. Additionally, the watershed response to climate change scenarios indicates increases in total streamflow, 7-day low flows and 100-year peak flows. Projected increases in temperature, which can be as much as 4 °C over the winter months, will result in less snowfall and more rainfall. Consequently, increases in winter streamflow are caused by greater winter precipitation and greater increase in winter temperatures resulting in earlier and greater snowmelt. Although calibration of the SWAT model to available data was reasonable in this study, uncertainties in climate data, model structure and parameter values are significant and affect the accuracy of the calibration and future predictions.

These simulations reflect only changes in climate drivers and do not represent interannual changes in storage associated with glaciers which can be an interesting future direction of research using newer version of the Soil and Water Assessment Tool.

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