# Snowmelt runoff modeling in the Tamor River Basin in the eastern Nepalese Himalaya

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Abstract:

The recent IPCC (2007) report has confirmed, through observations and model-based studies, substantial hydrological changes in mountain watersheds where hydrology is dominated by cryospheric processes. The response of cryospheric processes to a warming climate in mountainous areas can be analyzed by examining the responses in the seasonal and annual hydrologic regimes of rivers where snow and ice contribute significantly to the runoff. This study utilizes a snowmelt runoff model in the Tamor River Basin in the eastern Nepalese Himalaya which is driven by remotely sensed snow cover from Moderate Resolution Imaging Spectroradiometer (MODIS). The Snowmelt Runoff Model (SRM) is calibrated using daily streamflow from 2002 to 2005 and the streamflow can be predicted with a high degree of accuracy. Although snowmelt hydrology has been examined at a large watershed scale in the Hindu Kush-Himalaya region, changes in hydrologic processes with climate change need to be examined and compared across finer basin scales for assessing water availability and vulnerability. Three climate change scenarios were used to drive the model in order to understand the impact of changing conditions. A scenario of a 4°C temperature increase and 20% precipitation increase results in a significantly increased runoff volume by ~23%, with streamflow exceeding present conditions in all months. A second scenario of a 4°C temperature shifts the snowmelt runoff but does not alter flow volume significantly. An increase in precipitation by 20% with temperatures unchanged results in a 15% increase in runoff volume, mainly during the summer months. These results show the importance of improved monitoring and modeling in the region to better understand the impact of climate change on hydrology.

Keywords: Snowmelt, hydrology, SRM, climate change, MODIS snow, Himalaya.

## Introduction

Growing evidence indicates that the low-latitude mountainous cryosphere is undergoing change due to recent warming (IPCC 2007). Geographic areas where the water cycle is dominated by snowmelt hydrology are expected to be more susceptible to climate change as it affects the seasonality of runoff (Adam et al. 2009). The Hindu Kush-Himalaya (HKH), regarded as the 'water towers' of Asia, is one such critical region as it nourishes several of the major Asian watersheds through perennial rivers such as the Ganges, Indus, and Brahmaputra (Messerli et al. 2009). Changes in seasonal snow cover and glaciated regions may alter the variability of streamflow and hence water availability which sustains a large population downstream. Despite its regional importance, there is uncertainty associated with the rates and magnitude of climate change impacts on snow cover and snowmelt hydrology. These climate-driven responses of mountainous river hydrology when combined with potential land cover changes, population growth, and already stressed water resources may pose significant challenges for this region. Since the negative impacts of climate change to water resources are expected to be greater than its benefits (Kundzewicz et al. 2007), it is important to understand the hydrologic variability particularly in mountain environments with respect to potential climatic changes.

Regional climate projections by the IPCC (2007) indicate Central Asia to be warmed by a median temperature of 3.7°C by the end of the 21$^{st}$ century, with largest warming over higher altitudes particularly the Tibetan Plateau and the Himalayas. According to the IPCC, the temperature increase in the Himalayan region has been greater than the global average of 0.74°C over the last 100 years. Most recent research analyzing tropospheric temperatures from the longest available record of microwave satellite measurements reveals widespread pre-monsoonal and mean annual warming over the HKH region at a rate of 0.21 ± 0.08 °C/decade (Gautam et al. 2010; Gautam et al. 2009). A recent international workshop on emerging issues in climate change in the Himalayas-Tibetan Plateau was inconclusive on the question of climatic impacts of river discharges, mainly due to lack of adequate scientific data and systematic research (UNEP 2009).

Several global scale and few local to regional scale hydrological studies have been conducted to assess impacts of a changing climate on snowmelt hydrology. Hydrological simulations of large, continental river basins to climate change in 2025 and 2045 assessed through global climate models showed that snow-dominated basins of mid to higher latitudes showed the largest changes in the hydrological cycle (Nijssen et al. 2001). In these scenarios, although the coldest snow dominated basins exhibit an increase in the spring streamflow peak, the basins with more transitional snow regimes exhibit a reduced snow melt peak and increased winter streamflow. Analytical studies representing temperature increases of 1-3˚C in the western Himalayan region suggest an increase in glacial melt runoff by 16-50% (Singh and Kumar 1997), regression of the annual maximum spring streamflow period by a month, and increased sensitivity of snow-fed basins in terms of reduction in water availability (Singh and Bengtsson 2005). A study by Immerzeel et al. (2008) indicates that the hydrology of the upper Indus basin will be affected due to accelerated glacial melting by regional warming by the end of the century. Similarly, other studies have examined potential discharge under changing glacier extent and climate scenarios in northern Pakistan (Akhtar et al. 2008), and Tien Shan mountains (Hagg et al. 2007). A recent study by Immerzeel et al. (2010) using hydrological modeling of present-day climate indicates that meltwater plays an important role in the Indus and Brahmaputra basins.

Water resource management and the evaluation of impacts of climatic change require quantification of streamflow variability and hydrologic models provide a framework to

investigate these relationships (Leavesley 1994). The assessment of hydrological impacts to climate change is particularly challenging in mountain environments as they constitute sensitive hydrological systems due to extreme heterogeneity in vegetation, soils, topography, and spatially and temporally varying snow cover (Gurtz et al. 2005). Poor accessibility and adequate network of hydrometeorological station in high altitude regions is a major impediment to runoff modeling and as a result only a few studies have explored snowmelt runoff models in Himalayan subbasins (Akhtar et al. 2008; Braun et al. 1993; Shrestha et al. 2004). The impact of potential climate change on snowmelt hydrology in the Himalaya, therefore, remains an active area of research. The objective of this paper is to analyze and forecast the responses of snowmelt runoff in a catchment in the eastern Himalayan region. This paper also demonstrates the use of a simple snowmelt runoff model based on degree-day approach and few parameters to understand hydrological processes, thereby utilizing scarce data in a mountainous environment to assess the impact of potential warming on river discharge. Based on the future projected climatic scenarios for the Himalayan region, three climate scenarios where temperature and precipitation are increased were used to assess and quantify the potential changes and effects of a warmer climate on snowmelt runoff and total discharge.

## Methods

### Study area

The upstream of Tamor River Basin in the Eastern Himalayas of Nepal was selected for the snowmelt runoff modeling (Figure 1). Although a majority of the precipitation for this region is concentrated during the summer monsoon months (June to September), the upper reaches of the basin is snow covered and glaciated which contribute meltwater to the streamflow. The Tamor Basin covers an area of 4,274 $km^2$, with an elevation range of 422 to 8505 m. Tamor River, which is one of the major tributaries of the Sapta Koshi River, flows between high peaks such as the Kanchenjunga (8,586 m) and the Everest (8,848 m) on gorges reaching depth of 2,000 m (Dixit et al. 2009). The upper reaches of the Tamor River Basin fall within Taplejung district with an estimated population of 135,000 (CBS, 2002).

### Hydro-meteorological data

Hydro-meteorological measurements for Tamor River basin in the eastern Himalaya was acquired from the Department of Hydrology and Meteorology (DHM), Nepal. Daily temperature data at Taplejung station (27.35° latitude and 87.67° longitude at 1732 m elevation) and daily precipitation data measured at Lungthung station (27.55° latitude and 87.78° longitude at 1780 m elevation) in Taplejung district were used for the hydrological modeling (Figure 1). Discharge data measured daily for Tamor River at Majhitar station (27.15° latitude and 87.71° longitude at 533 m elevation) was used for validation purpose. Tamor Basin was delineated at the Majhitar station using Arc Hydro tool (Maidment 2002) along with 90 m digital elevation data acquired from the CGIAR Consortium for Spatial Information (CSI). The basin was divided into four zones and the zonal mean hypsometric elevation (Figure 2) was used as the elevation to which base station temperatures were extrapolated for the calculation of zonal degree days (Table 1) (Martinec et al. 2008).

### MODIS snow cover

Satellite-derived snow cover is the most efficient and readily available input for snowmelt runoff modeling. Snow cover was derived using MODIS/Terra global 8-day product (500 m spatial

resolution) and updated every eight days using snow depletion curve. The MODIS snow cover is based on a snow mapping algorithm that uses at-satellite reflectance in MODIS bands 4 (0.545-0.565 µm) and 6 (1.628-1.652 µm) to compute the Normalized Snow Difference Index (NDSI) (Hall et al. 2002). A pixel will be mapped as snow if the NDSI ≥ 0.4 and MODIS band 2 (0.841–0.876 µm) > 11 %; however, if the MODIS band 4 reflectance is < 10%, then the pixel will not be mapped as snow even if the other criteria are met (Hall et al. 2002). MODIS 8-day maximum snow cover extent was preferred to daily snow product for cloud minimization. The MODIS product distributed through the National Snow and Ice Data Center (Hall et al. 2000) was acquired for the scene, h25v06, covering the study region from 2002 to 2006 which were then reprojected using MODIS Reprojection Tool (MRT 2003) to World Geodetic System 1984 (WGS84), Universal Transverse Mercator (UTM) zone 45 with a spatial resolution of 500 m. The conventional depletion curve was derived for each elevation zone using the 8-day snow cover data which provides the input as the decimal portion of snow covered area for each day.

**Snowmelt runoff modeling**

The modeling of the stream discharge was based on the Snowmelt Runoff Model (SRM) developed by Martinec (2007). SRM is a conceptual, deterministic, degree day hydrologic model that simulates and forecasts daily runoff resulting from snowmelt and precipitation from hydro-meteorological input data. This was designed for streamflow modeling in basins where snowmelt is a major contributor and more recently it has been applied for evaluation of impacts of climate change on seasonal snow cover and runoff (Immerzeel et al. 2010; Immerzeel et al. 2008). SRM has been applied to basins ranging from 0.76 to 917,444 $km^2$ and an elevation range from 0 to 8840 m above sea level (masl) in over 100 basins in 29 different countries (Martinec et al. 2008). This model was chosen to assess the climate change impacts on hydrology due to its minimal data requirements and transferability to a variety of geographic regions. Based on input of daily temperature, precipitation and snow-covered area values, SRM computes the daily streamflow as:

$$Q_{n+1} = [Csn\ a_n\ (T_n+\Delta T_n)\ Sn + CrnP_n]\ A\ (10000/86400)\ (1-k_{n+1}) + Q_n\ k_{n+1}$$

where Q ($m^3/s$) is discharge at day n+1, C is the runoff coefficient to snowmelt (Csn) and to rain (Crn), a is the degree day factor, T+ΔT (˚C) are the degree days, P (cm) is the precipitation per day, A ($km^2$) is area of the basin, S is fractional snow cover, and k is the discharge recession coefficient. The daily average streamflow on day n+1 is computed by addition of snowmelt and precipitation that contributes to runoff with the discharge on the preceding day. The snowmelt of the preceding day is a product of the degree day factor (a), zonal degree days (T+ΔT), and the snow-covered area percentage (S). The snowmelt runoff coefficient (Cs) and the zonal area (A) are further multiplied with the above product to compute the percentage that contributes to runoff. Similarly, the product of the rainfall runoff coefficient (Cr) and the zonal area (A) determines the precipitation contribution to runoff. The recession coefficient (k) is also an important parameter as it determines the proportion of daily meltwater production that appears immediately in the runoff.

The parameters for runoff coefficients, lapse rate, critical temperature, recession coefficient, and lag time are parameters characteristic for each basin and are determined where possible or are extracted from literature from studies conducted on other Himalayan basins. A temperature lapse rate of 0.65 °C/100 m is commonly assumed but can be altered by zone or season. The daily maximum and minimum temperatures at Lungthung station are extrapolated to the hypsometric mean elevations of the respective elevation zones. The critical temperature is

used to determine whether a precipitation event is rain or snow. The above equation is applied to each zone of the basin and the discharges are summed up. The seasonally variable degree-day factor was also selected in the range of 0.3 – 0.75 cm °C$^{-1}$d$^{-1}$ from previous studies conducted in Himalayan river basins (Seidel and Martinec 2002).

**Accuracy assessment**

The modeled streamflow is assessed for accuracy using the Nash-Sutcliffe statistic and the volume difference ($D_v$).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2}$$

where: $Q_i$ is the measure daily discharge
$Q_i'$ is the computed daily discharge
$\overline{Q}$ is the average measured discharge of the given year or snowmelt season
n is the number of daily discharge values

$$D_v[\%] = \frac{V_R - V_R'}{V_R}.100$$

where: $V_R$ is the measured yearly or seasonal runoff volume
$V_R'$ is the computed yearly or seasonal runoff volume

**Climate change scenarios**

SRM has been used in several studies for assessing the hydrological effects of climate change (Immerzeel et al. 2010; Rango et al. 2008; Seidel and Martinec 2002). The basis of runoff computation for climate scenarios is based on modified depletion curves (MDC) of the snow coverage which takes into account the amount of snowfalls changed by the new climate. The MDCs relate the snow covered area to the cumulative snowmelt depth computed each day. A formalized procedure described in detail in Martinec et al. (2008) is used to produce climate-affected conventional depletion curves which then serve as input variables for simulating climate-affected runoff. Alternatively, global climate model (GCM) future scenarios of temperature, precipitation, and snow cover can also be used to drive the SRM to assess hydrological impacts (Immerzeel et al. 2010).

In this study we evaluate three hypothetical scenarios and the climate effects for these scenarios are evaluated by comparing present conditions against modeled conditions. These scenarios simulate the estimates of extreme changes in temperature over the study region and although precipitation changes are also taken in account, there are large uncertainties associated with projected changes in precipitation (Rango et al. 2008; Singh and Bengtsson 2005). Global Circulation Model (GCM) projections indicate that the average temperature in Nepal will increase within a range of 3.0 to 6.3°C, with a multi-modal mean of 4.7°C (Dixit et al. 2009). It is also expected that a warmer climate will prevail during both the snowmelt season and the winter accumulation season (Rango 1997). As in other reported studies, temperatures and precipitation changes were uniformly varied by the projected amount of changes over the simulation period (Martinec et al. 2008; Rango et al. 2008). The degree-day parameter and the runoff coefficients for snowmelt are shifted to earlier months to approximate the earlier advancement of snowmelt season and shift of the snow cover depletion curves with a temperature increase.

Scenario A: Temperature increase of 4°C, precipitation unchanged

Scenario B: Temperature increase of 4°C, precipitation increase by 20%
Scenario C: Temperature unchanged, precipitation increase by 20%

**Model application**

The monthly streamflow for the Tamor River basin at Majhitar station along with the total monthly precipitation (mm) at Lungthung station indicates a fingerprint of monsoonal precipitation in the eastern Himalayas from June to September (Figure 3). Rainfall seasonality based on a 12-year Tropical Rainfall Monitoring Mission (TRMM 2B31 product) time series from 1979-2008 for the Tamor Basin exhibits a similar monsoonal signal as indicated by the meteorological station (Figure 4) (Bookhagen 2010). The monthly average TRMM rainfall is shown for each elevation zone with highest rainfall in the lower elevations (zone 1 and 2). Results of the observed temperature measured at Taplejung station from 1970 to 2006 show a statistically-significant trend at the 95% confidence level of increasing annual average temperature at a rate of 0.18 °C per decade (Figure 5a). There is a decline in mean annual stream discharge between the 1996 to 2000 and 2001 to 2006 periods, particularly during the summer monsoon months (Figure 5b).

The SRM was run with all the possible input parameterizations for the hydrologic years 2002 to 2005. MODIS 8-day maximum snow cover product was used to derive the snow cover depletion curves for each zone in the basin (Figure 6). The best model for the 2002/03 hydrologic year has a $R^2$ value of 0.77 and runoff volume difference of 12.7%. The model accuracy for all hydrologic years from 2002 to 2006 was an average $R^2$ value of 0.64 and average volume difference of 10%. The simulated hydrograph matched well with the observed hydrograph; however, it was not able to simulate peak stream flows very well during the summer monsoon months (Figure 7). The runoff computations can also be proportioned into respective contributions of rainfall and snowmelt. The proportion of snowmelt in the runoff in the Tamor Basin for the 2002/03 hydrologic year is 19.4 %, which includes 13.5 % from new snow or temporary snowfalls, while around 80% is attributed to rainfall particularly during the summer monsoon months (Figure 8). The cumulative runoff indicates that most of the snowmelt contribution occurs between April and August.

After calibration, SRM was also used to examine the effect of any changes of meteorological parameters in changed climate scenarios. The computed runoff in the basin for Scenario A compared with the original runoff simulation for the hydrological year 2002/03 shows an increase in the runoff volume during the winter low flow period and spring melt period (Figure 9a). There is more melting during the winter flow period which results in the increased flow. The spring runoff in also greatly amplified while there is a decline in the summer monsoonal period. Scenario B with an temperature increase of 4°C and precipitation increase of 20% results in the highest runoff volume increase by ~23%, with streamflow exceeding present conditions in all months (Figure 9b). An increase in precipitation by 20% with temperatures unchanged in Scenario C results in a 15% increase in runoff volume, mainly during the summer months (Figure 9c).

Increase in year-round temperature causes more precipitation in the form or rain as opposed to snow events during winter (low flow periods) thereby resulting in more immediate runoff, and less snow accumulation in addition to more snowmelt and runoff due to warmer temperatures (Rango 1997). SRM partitions precipitation to be rain or snow based on the critical temperature. If the temperature is less than the critical temperature, precipitation is considered to be snowfall. The seasonal snow cover of present climate depletes faster in a warmer climate

assuming no changes in precipitation. Therefore, warmer temperatures lead to a decline in precipitation as snowfall which leads to a redistribution of seasonally snowmelt runoff. A shift from the snow dominated precipitation during winter to a rainfall dominated precipitation leads to a change in the timing of the peaks of streamflow. On the other hand, increased precipitation slows down the seasonal snow cover depletion. However, the effect of a 10-20 % increase in precipitation on the snow cover is relatively insignificant compared to the temperature-related effect (Rango and Martinec 1994), but the effect on the total change in volume is greater as most of the precipitation changes are observed during the summer monsoonal months (Figure 9c).

The Eastern Himalayan hydrology is dominated by monsoonal precipitation and although snowmelt contribution is secondary, this study indicates significant changes particularly in winter runoff due to the advancement of snowmelt period and the conversion of snowfall to rainfall caused by warmer temperatures. Increase in temperature leads to decreases in flow during the summer months which may stress water resources. Increases in both temperature and precipitation, which may be expected from a climate change, leads to the exceedance of streamflow across all months. This is particularly of concern during summer months as extreme events such as flooding is prevalent in the Koshi River Basin, of which Tamor River is a primary tributary (Dixit et al. 2009).

**Conclusion**

This study has shown that a snowmelt runoff model based on degree-day factor can be used to simulate daily streamflow in a mountainous environment with limited coverage of hydrometeorological measurements. One of the limitations of the model was its failure to capture peak stream flows well. This is most likely due to the lack of precipitation coverage across the basin. Improvements on this type of study will be to incorporate the present and future role of glaciers in the runoff. Although this study using SRM does not explicitly incorporate glaciated regions, they are implicitly taken into account. The decline of snow cover depletion curves levels out during later part of the snowmelt season thereby indicating present of permanent snow or glaciers. This is observed from the snow depletion curves particularly for zone 4 (Figure 6). Despite its limitations, the SRM model was able to adequately simulate the hydrological balance in a Himalayan basin, separate relative contributions of rain and snow to streamflow, and evaluate impacts on runoff for hypothetical climate scenarios.

According to this analysis, climate change will impact hydrology in this region by altering the flow during certain times of the year, shifting of snowmelt runoff, and changing the streamflow volume. An increase in temperature leads to a temporal redistribution of runoff without significant changes in runoff volume; however, hypothetical changes of both temperature and precipitation may lead to significant changes in runoff volume. The direction and magnitude of hydroclimatic signal will vary from region to region and with climate change the greatest changes are expected to occur where warmer temperatures could shift a precipitation regime from snowmelt dominated to rain dominated (Stewart 2009). Climate change is expected to make wet seasons wetter and dry seasons drier in the eastern Nepalese basins (Dixit et al. 2009). Mountain river hydrology is critical for downstream drinking water, agricultural irrigation, power generation, and flood management in this region. The results from this study, although based on hypothetical climate scenarios, provide useful guides on implications of climate change on water resources, thereby highlighting the need for further hydrological research on snow and glacial melt for the HKH region.

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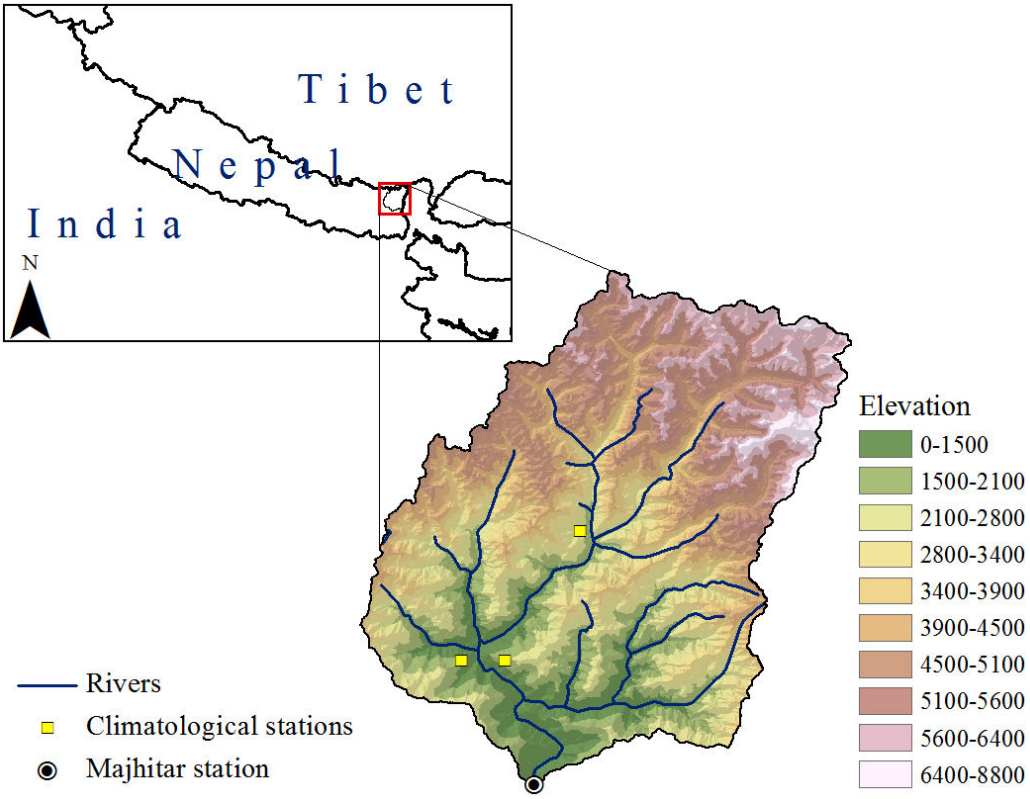



Figure 1. Tamor River Basin in the eastern Nepalese Himalayas

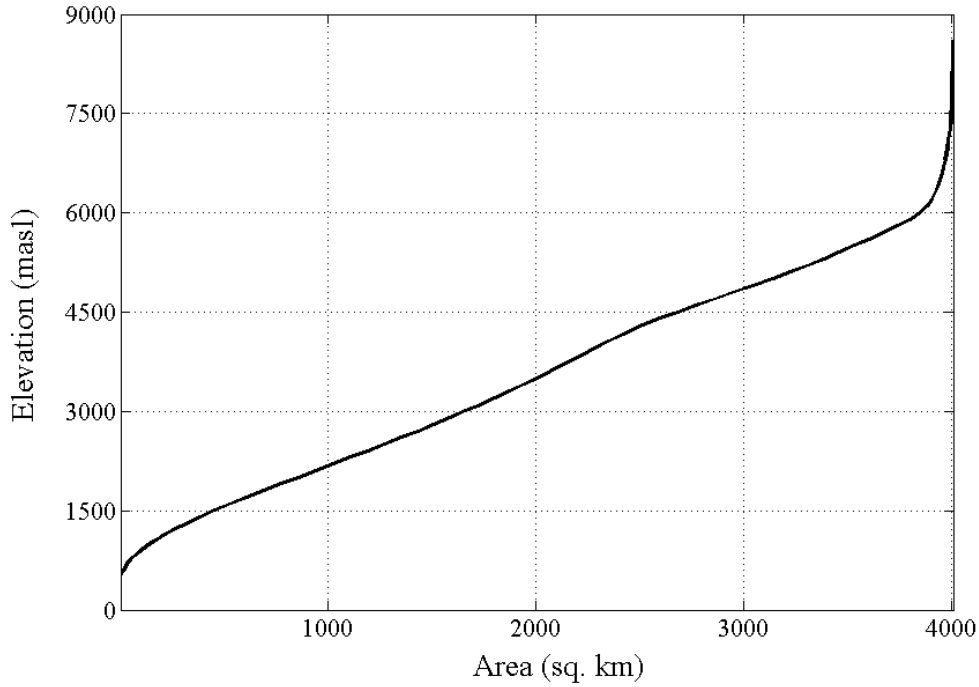



Figure 2. Area-elevation curve for the Tamor Basin.

Table 1. Elevation zone, elevation range, mean elevation, and zonal area for the four zones of the Tamor River Basin.

| Elevation zone | Elevation range / m a.s.l | Mean elevation of zone / m a.s.l. | Zonal area / sq. km |
|---|---|---|---|
| 1 | 0-2500 | 1685.9 | 1355.5 |
| 2 | 2500-4000 | 3208.1 | 1111.3 |
| 3 | 4000-5500 | 4764.3 | 1297.9 |
| 4 | 5500-8505 | 5988.8 | 509.2 |
| Total basin | - | - | 4273.8 |

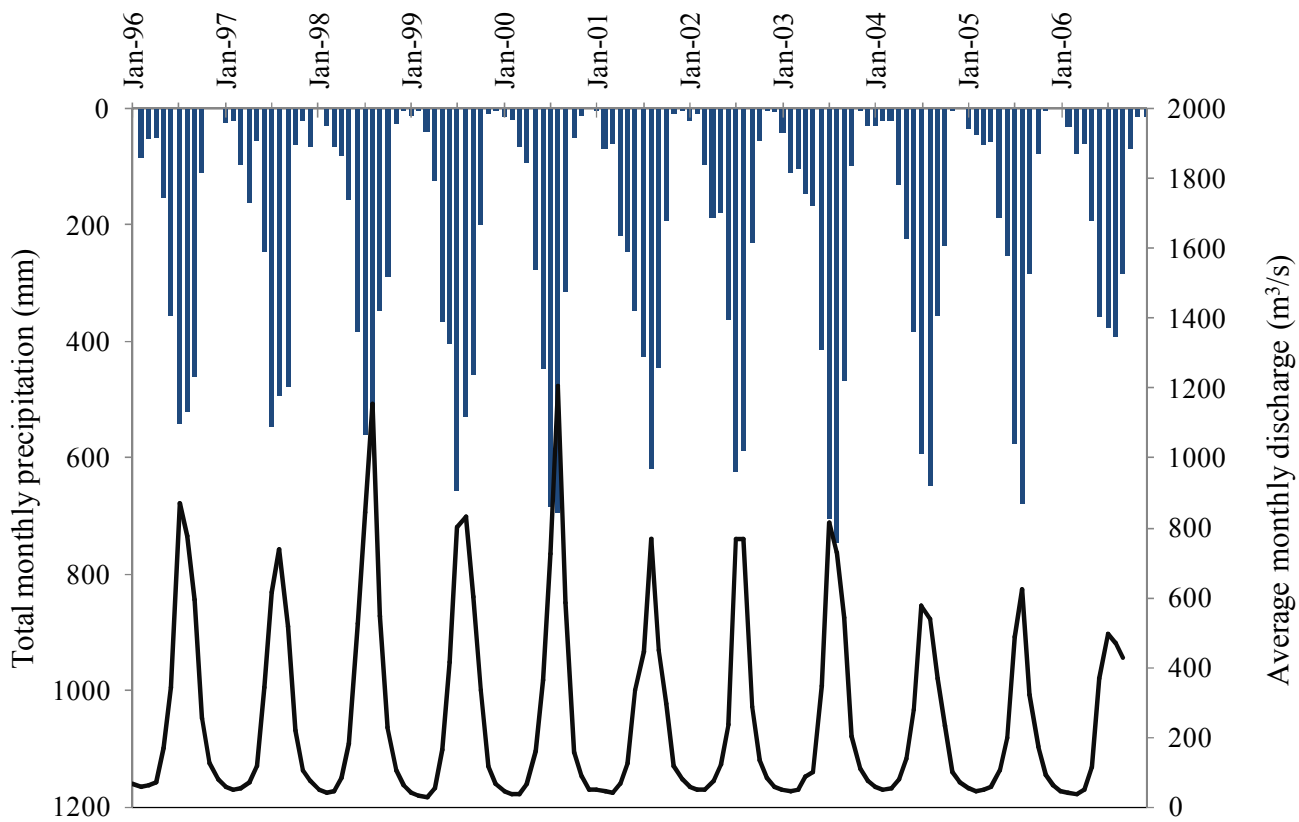



Figure 3. Average monthly streamflow ($m^3/s$) and total monthly precipitation (mm) from 1996 to 2006 at Majhitar station outlet.

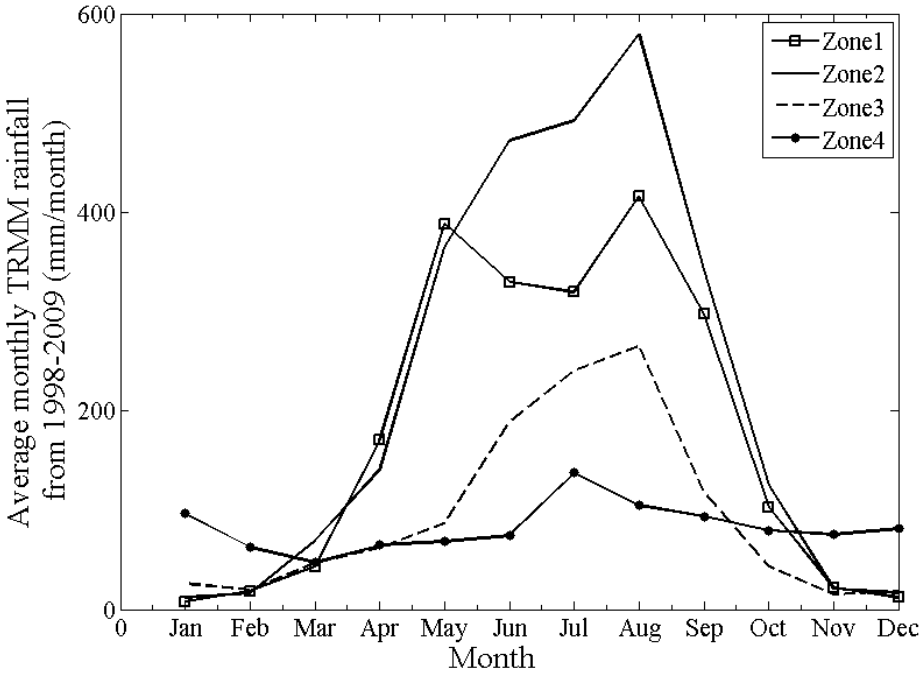
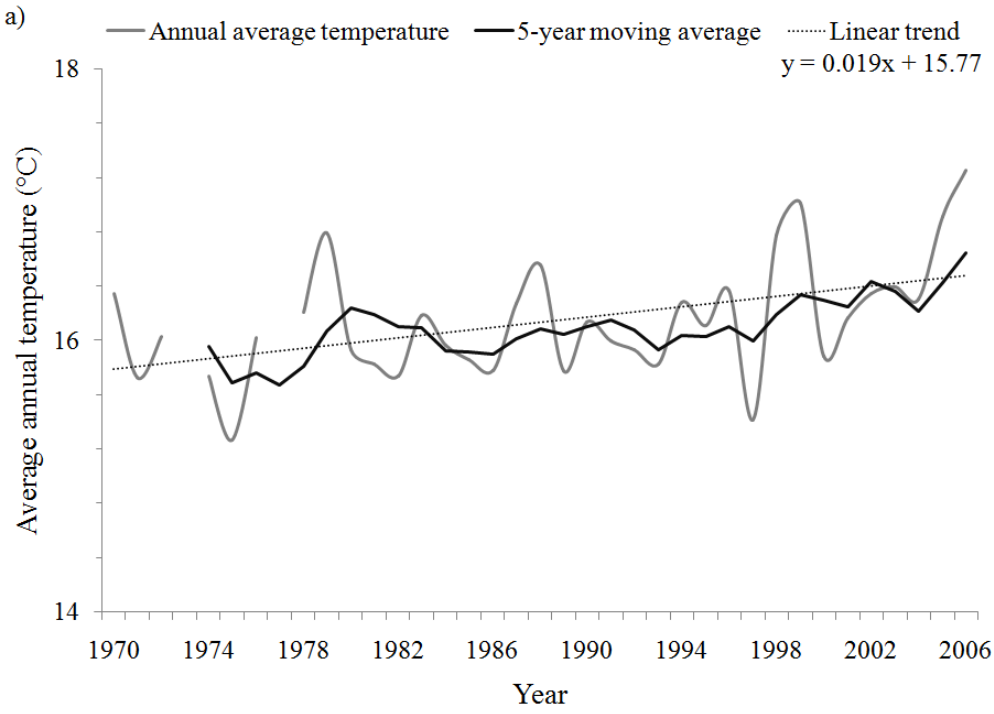



Figure 4. Average monthly TRMM rainfall from 1998-2009 for the four zones in the Tamor Basin.



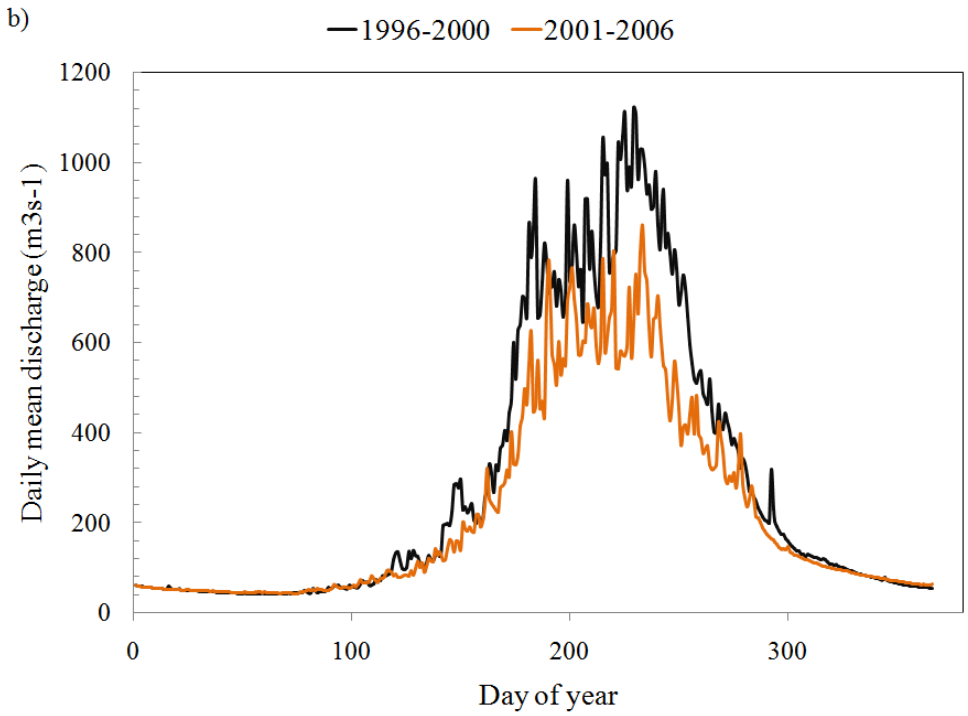
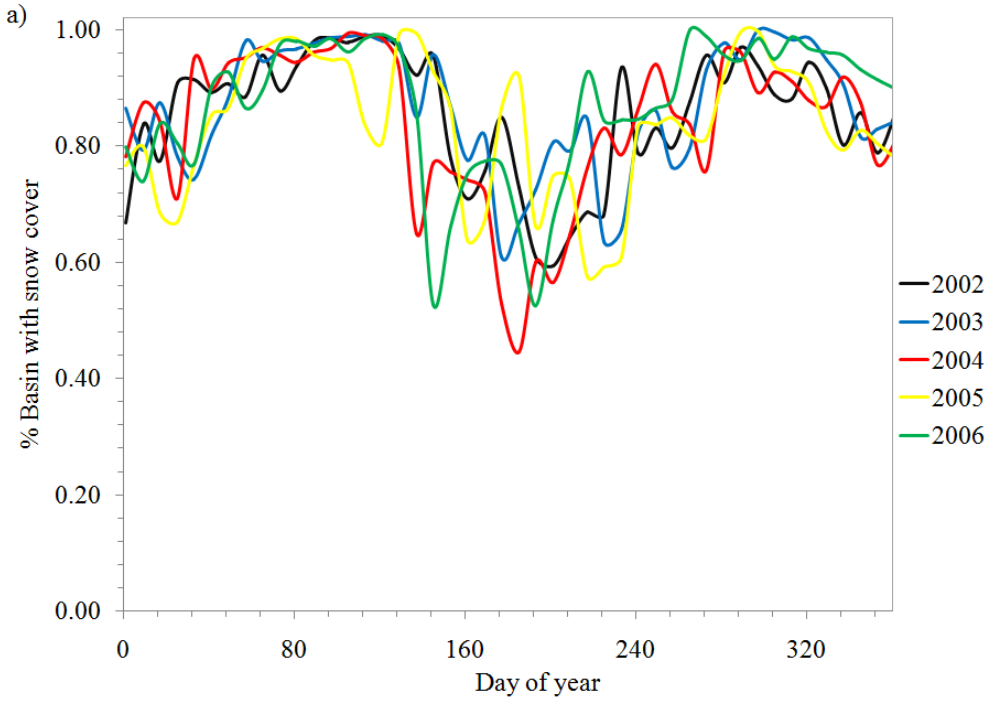



Figure 5. a) Observed, 5-year moving average and trend line of annual mean air temperature at the Taplejung station for the period 1970-2006 and b) Annual hydrographs composed of average mean daily flows for 1996-2000 and 2001-2006 period for the Tamor River Basin at Majhitar station;



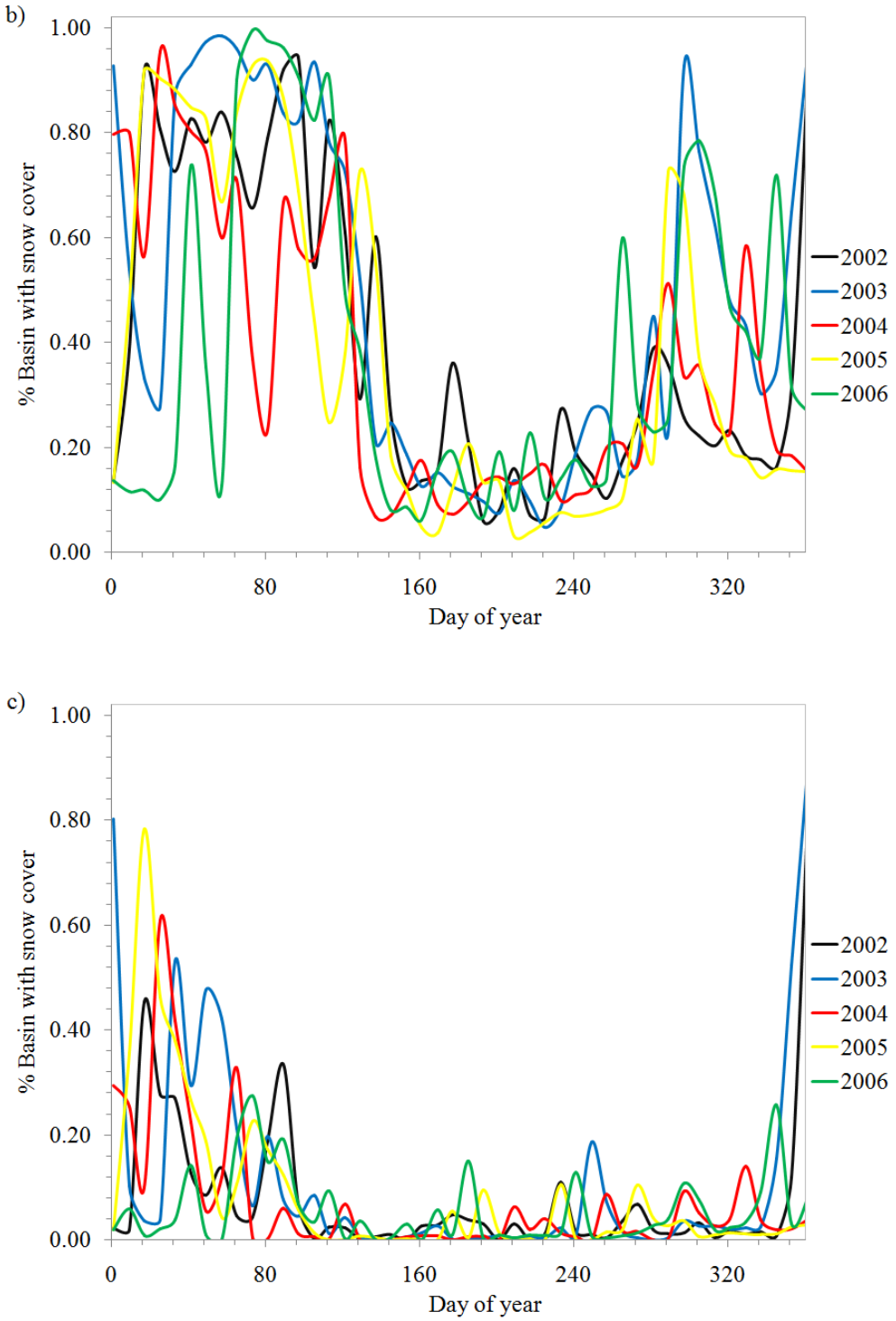



Figure 6. Snow cover depletion curves from the MODIS 8-day maximum snow cover 500-m resolution product in the Tamor River basin from 2002 to 2006 in a) zone 4 – elevation range greater than 5500 m b) zone 3 – elevation range from 4000 – 5500 m and c) zone 2 – elevation range from 2500 – 4000 m.

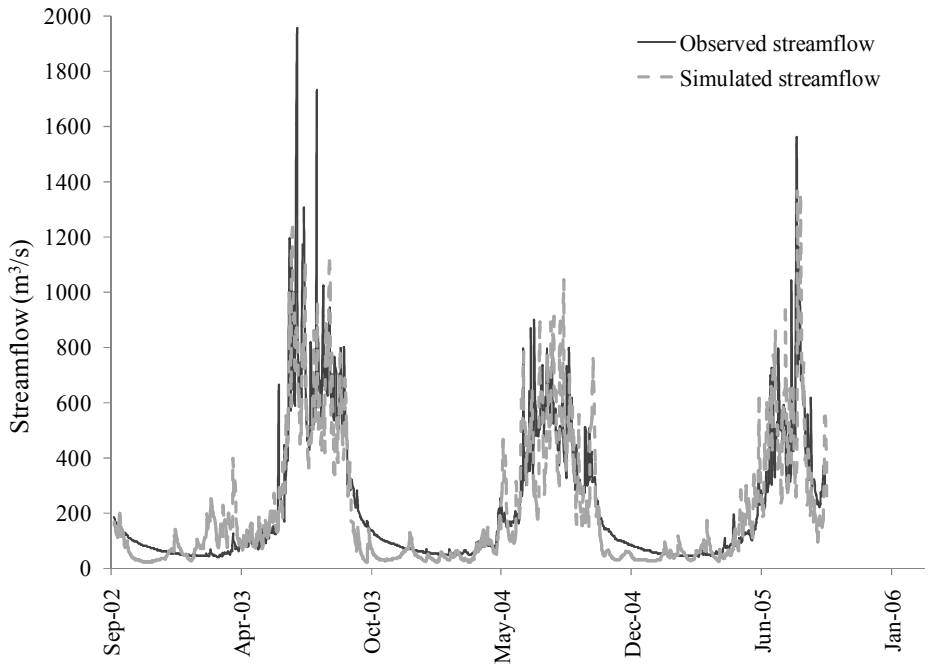



Figure 7. Observed and simulated streamflow for the Tamor River basin at Majhitar station for hydrologic years 2002/03 to 2004/05.

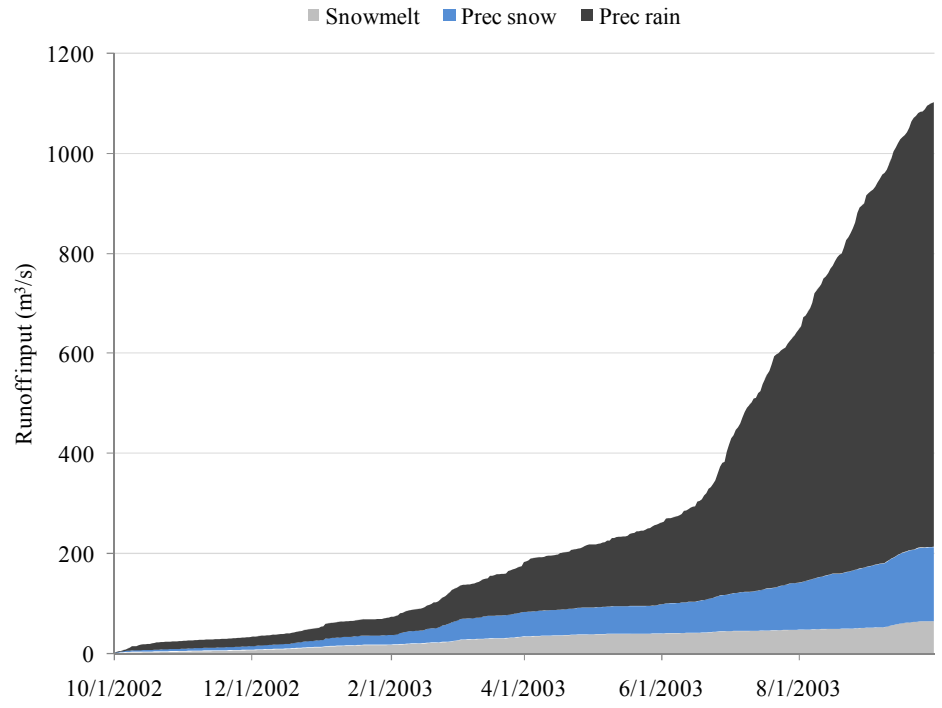



Figure 8. Cumulative curves of computed daily snowmelt depth, rainfall depths, and melted precipitation in the form of snow in the Tamor Basin.

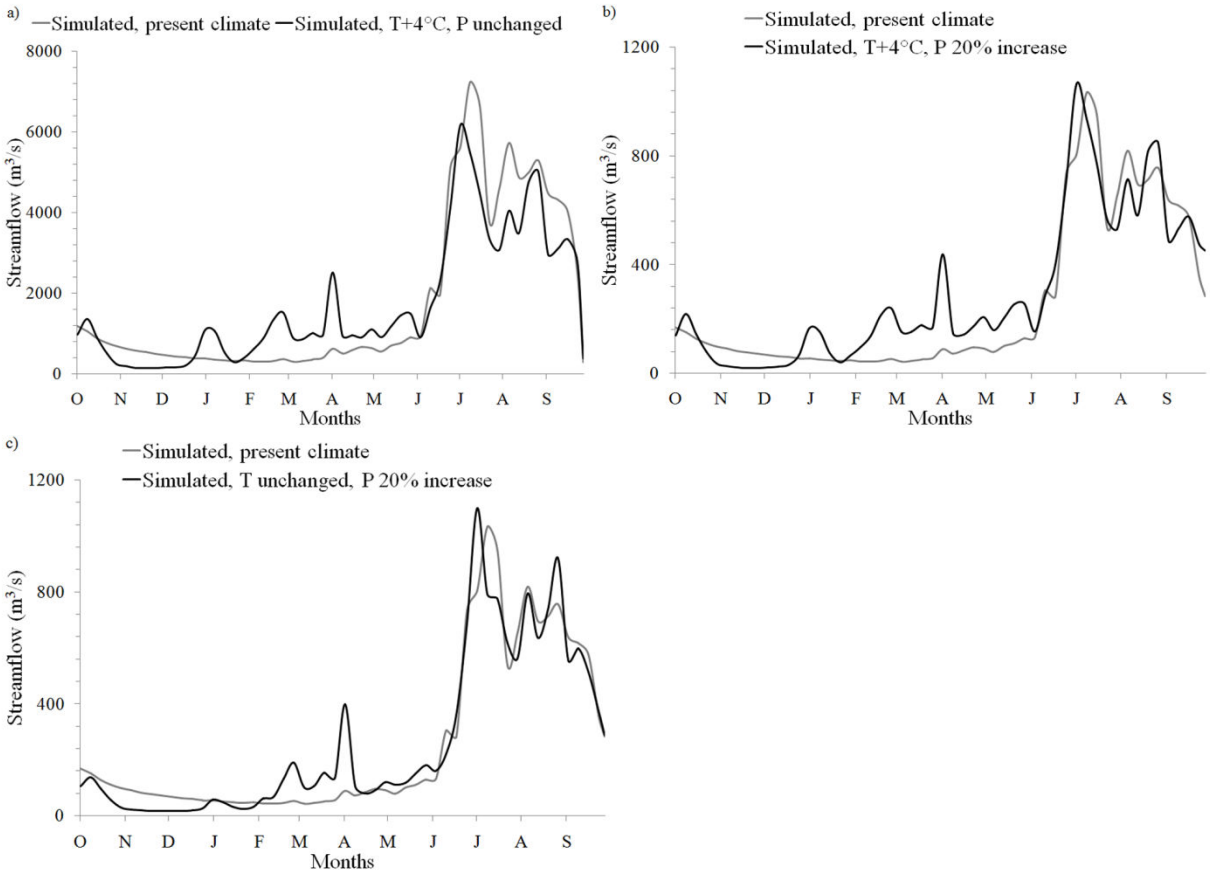



Figure 9. Computed streamflow in the Tamor basin compared with the original runoff simulation for the hydrological year 2002/03 for hypothetical climate scenarios a) Scenario A with temperature increased by 4°C and precipitation unchanged, b) Scenario B with temperature increased by 4°C and precipitation increased by 20%, and c) Scenario A with temperature unchanged and precipitation increased by 20%.