Title

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Publication Date
2009-08-01

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UC Water Resources Center
Technical Completion Report Project No. WR1007

August, 2009

Abstract

The current study was undertaken to improve the understanding of the long-term impacts of urbanization on hydrologic behavior and water supply in semi-arid regions. The study focuses on the Upper Santa Clara River basin in northern Los Angeles County which is undergoing rapid and extensive development. The Hydrologic Simulation Program-Fortran (HSPF) model is parameterized with land use, soil, and channel characteristics of the study watershed. Model parameters related to hydrologic processes are calibrated at the daily timestep using various spatial configurations of precipitation and parameters. Results indicate that the HSPF performs best with distributed precipitation forcing and parameters (distributed scenario), however the model performs fairly well under all scenarios. The model also shows slightly better performance during wetter seasons and years than during drier periods. Potential urbanization scenarios are generated on the basis of a regional development plan. The calibrated (and validated) model is run under the proposed development scenarios for a ten year period. Results reveal that increasing development increases total annual runoff and wet season flows, while decreases are observed in baseflow and groundwater recharge during both dry and wet seasons. As development increases, medium sized storms increase in both peak flow and overall volume, while low and high flow events (extremes) appear less affected. Urbanization is also shown to decrease recharge and, when considered at the regional-scale, could potentially result in a loss of critical water supply to southern California.

1. Introduction

Throughout southern California, large areas of native land cover are disappearing due to rapid and extensive urbanization. The transformation from native to developed lands results in the addition of impervious material (concrete, asphalt, etc.), conveyance (culverts, channels, pipes) as well as detention systems, and transition from native to non-native vegetation species (grass, palms, woody plants, etc.). The culmination of these conversions typically results in hydromodification of stream systems, increasing wet weather runoff and shifting the timing and volume of flood peaks (Leopold 1968; Lazaro 1990; Murdock et al. 2004; Wissmar et al. 2004; White and Greer 2006). Increased flow rates typically lead to extensive channel erosion and instability (Doyle et al. 2000; Bledsoe and Watson 2001). In addition, the compaction of soils and addition of paved surfaces reduces infiltration, channel baseflow, and, more importantly, long-term recharge to regional aquifers (Simmons and Renolds 1982; Spinello and Simmons 1992; Finkenbine et al. 2000). Urbanization-related changes in stream discharge, infiltration, baseflow patterns, and groundwater recharge can significantly impact regional water availability. Along with expanding urbanization, population and water demand are dramatically increasing in many semi-arid regions, including Southern California (SCCWRP 2005). The combination of spreading urbanization and increasing population make historically dependable water supplies suspect in Southern California; which relies heavily on recharged groundwater and imported water (MWD 2005). In this regard, it is of vital importance to predict the potential impact of expanding urbanization on hydrologic processes (baseflow, recharge, infiltration rates) and the specific fluxes critical to regional water supply.

In general, most development impacts are described on an event-specific basis (Bhaduri et al. 2000; Konrad et al. 2005). Relatively few studies (Bhaduri et al. 2000) characterize long-term (e.g., seasonal or annual) alterations in the hydrologic response of urbanized watersheds. McClintock et al. (1995) argues that the long-term impacts of urbanization on water quantity are dominantly controlled by the cumulative effects of minor storm events instead of high-magnitude storm events. Bhaduri et al. (2000) successfully applied the Long-Term Hydrologic Impact Assessment (L-THIA) model to address the long term hydrologic impacts of urbanization. However, limited by the simple structure of the model, Bhaduri et al. (2000) only provided an initial assessment of hydrologic impacts focusing on the response of annual average runoff.

Numerous models have been employed for continuous simulations of basin streamflow, including the Environmental Protection Agency's Hydrologic Simulation Program Fortran (HSPF) model, a hydrologic model that continuously simulates surface and subsurface flow as well as water quality processes (Bicknell et al. 2001). The model has been extensively applied in various practices, including simulation of streamflow (Ng and Marsalek 1989; Bledsoe and Watson 2001; Brun and Band 2000; Im et al. 2003; Hayashi et al. 2004; Angelica and Richard 2005; Chen et al. 2005; Kim et al. 2007; Hayashi et al. 2008; Lamont et al. 2008), baseflow (Brun and Band 2000), stream temperature (Chen et al. 1998a, b), as well as stream loadings of nutrients, pesticide, and sediments from agricultural and urbanizing watersheds (Moore et al. 1988; Chew et al. 1991; Rahman and Salbe 1995; Laroche et al. 1996; Lee et al. 2006; Im et al. 2003; Hayashi et al. 2004; Keller et al. 2004; Jia and Culver 2008). The size of the watersheds studied in these applications ranges from 14.7 km^2 (Des Moines Creek Watershed, Washington, U.S.; Bledsoe and Watson 2001) to 1,000,000 km^2 (Upper Yangtze River Basin, China; Hayashi et al. 2004), indicating the applicability of the HSPF to both small and large watershed systems.

Limited studies (Ng and Marsalek 1989; Brun and Band 2000; Beldsoe and Watson 2001; Im et al. 2003) have demonstrated the capabilities of the HSPF model in simulating urbanization-related changes in discharge. However, none of these studies focused on arid or semi-arid urban regions. Compared to humid regions, arid and semi-arid watersheds provide unique modeling challenges (CWP 2003; Keller et al. 2004; Ackerman et al. 2005). During storm events, flow in arid watersheds is extremely flashy (Tiefenthaler et al. 2001). In the dry season, natural flows can decrease significantly and baseflow may be intermittent. Many arid regions also depend on imported water which is difficult to account for in water budget studies or model simulations (Ackerman et al. 2005). In addition, limited studies have noted that arid environments may be more sensitive to urbanization than humid regions (Caraco 2000; Ourso and Frenzel 2003; SCCWRP 2005). Lack of both hydrological and chemical data has limited rigorous evaluation and implementation of water quality models (e.g. SWAT, HSPF, WARMF) in semi-arid regions. Consequently, this has limited their reliability as predictive tools for establishment of TMDLs or future development scenarios on urbanizing watersheds. Ackerman et al. (2005) evaluated the performance of the HSPF model on two semi-arid watersheds (one urban and one largely undeveloped) in Southern California at three time scales: hourly, daily, and annual. The model performed fairly well at the daily and longer time scales, but problems were noted at shorter model time scales and dry season simulations (especially in the more urbanized system). Poor representation of rainfall spatial variability and dry weather flows from urban runoff (imported water) were key issues in degradation of model performance (Ackerman et al. 2005).

2. Study Objectives

The current study undertakes an assessment of future land cover change in the Santa Clara River Valley in northern Los Angeles County, home to a commuter population for the city of Los Angeles and undergoing rapid and extensive development. To evaluate the impacts of expanding urbanization on overall hydrologic behavior and regional water supply, we address the following objectives:

1. Further assess the applicability of the HSPF model in semi-arid watersheds,
2. Predict changes in the hydrologic response (surface flow, infiltration, baseflow, etc.) to varying levels of potential urbanization, and
3. Quantify the potential loss of subsurface water supply (recharge) given extensive basin development. Urbanization scenarios for future expansion are established based on regional development plans. The hydrologic response from the development scenarios is compared to calibrated, baseline simulations and implications of changes in various flow regimes are discussed.

3. Study area

The current study focuses on the Upper Santa Clara River watershed (USCRW) located approximately 50 km north of the City of Los Angeles (Fig. 1). There is extensive urbanization occurring within the Santa Clarita Valley (SCV) due to northward expansion of the population of Los Angeles County. The 2000 census showed the SCV with a population of 213,178 (U.S. Census Bureau 2000). The valley is one of the fastest growing areas in the United States and is projected to accommodate an additional 140,000 people by 2025 (SCAG 2002). The primary city in the SCV is the city of Santa Clarita, which is currently the fourth largest city in Los Angeles County (California Finance Department 2007).

The 1680 km^2 USCRW consists primarily of natural vegetation (chaparral and grassland), with concentrated urban and residential lands in the SCV. The watershed has an average slope of 3.4%, with elevation ranging from 243 to 2014 m. The climate is semi-arid with an average annual precipitation of 461 mm and mean temperature of 25°C in summer and 9°C in winter (United Water Conservation District (UWCD) and Castaic Lake Water Agency (CLWA) 1996). The majority of the annual precipitation occurs between November and April.

Primary land cover in undeveloped areas in the USCRW is chaparral, which collectively accounts for 70% of the total basin area. Grassland accounts for 17% of the basin area. Urbanized land cover, located mostly in the SCV, accounts for about 10% of the basin area. Soils in the watershed are fairly porous and include higher percentages of sandy (sand/loamy sand/sandy loam; 42%) and loamy soils (loam/silty loam; 43%) soils and smaller amounts of clayey soils (loam/silty clay; 15%). There are two water reclamation plants (WRP), Valencia WRP and Saugus WRP within SCV which discharge directly to the main stem of the Santa Clara River. Castaic Lake, a water supply reservoir for the California aqueduct, is located in the northwest corner of the study area.

4. Methods

4.1. Modeling Framework

HSPF is a conceptual, watershed-scale model which simulates channel discharge as well as various water quality constituents. Use of HSPF requires division of the watershed into land segments (based on land cover) and river reaches. Each land segment is referred to as a hydrologic response unit (HRU). Partitioning of surface runoff/infiltration is governed by Philips equation (Philips 1957). Runoff then moves laterally to downslope segments or to a river reach or reservoir. Other simulated processes include interception, percolation, interflow, and groundwater movement. The HSPF applies Manning's Equation for routing overland flow and kinematic wave method for channel routing. In the current study, an hourly timestep was used as the computational interval for model simulations; output was aggregated to the daily timestep for evaluation and comparison since observed streamflow was only available at the daily scale. The model consists of three modules PERLND, IMPLND, and RCHRES which simulate the hydrologic and water quality processes over pervious land segments, impervious land segments, and through free-flowing reaches and well-mixed lakes, respectively. For this study, only the hydrologic processes were simulated using the HSPF (water quantity). The HSPF model requires rainfall, potential evapotranspiration, land use, and channel geometry as inputs.

The USCRW outlet and model simulation point is the U.S. Geological Survey (USGS) stream gauge #11109000. Above this point, the watershed was delineated into four sub-basins (Fig. 1). Basic information for each of the four sub-basins is listed in Table 1. Sub-basin one consists of 401 km^2 of mostly natural land with 3% developed area. The SCV is located across the boundary of sub-basins two and four. Approximately 18% of these two sub-basins are developed. The Newhall Ranch, which is the region undergoing significant urbanization, is located within sub-basin four. The Saugus WRP is located in sub-basin two and was put into operation in 1962. The Valencia WRP is located in sub-basin four and started operation in 1967. Castaic Lake forms most of sub-basin three (outlet USGS streamgage #11108134). The Castaic Lake outflow is formulated as a point source within the HSPF model, releasing flow to sub-basin four. Incorporation of Castaic Lake and the two WRPs into the simulation requires the corresponding flow discharge data from the lake and WRPs. Calibration and validation of the model requires observed streamflow at the outlet.

4.2. Data Collection

Daily rainfall data were obtained from 13 rainfall gages (water years 1966 to 2006) maintained by the Los Angeles Department of Power and Water (LADPW) within the study watershed (Fig. 1). Some gages contained occasional missing data. Rainfall data from nearby gages were used to extrapolate missing data based on the inverse-distance method. Daily data was uniformly disaggregated to an hourly timestep to use as forcing for the HSPF. To facilitate continuous modeling, the Thiessen Polygon method was utilized to create a mean areal rainfall timeseries for the relevant study areas (determined during initial calibration and model discretization). Hourly reference (potential) evapotranspiration (ETo) data was obtained from the California Irrigation Management Information System (CIMIS, 2007) Station #101 (water years 1992 to 2006). CIMIS ETo estimates are derived using a version of the modified Penman-Monteith equation (Pruitt and Doorenbos 1977). Actual evapotranspiration is computed internally in the HSPF based on the input reference evapotranspiration data and model parameters.

Channel networks and cross sections were produced through the U.S. Environmental Protection Agency (USEPA) software Better Assessment Science Integrating Point and Non-point Sources (BASINS) (USEPA 2004) using the BASINS Digital Elevation Model (DEM) data and National Hydrography Dataset (NHD). Outflow data from the Castaic Lake storage facility (sub-basin three outlet) was obtained from the USGS. Discharge data from the Valencia and Saugus WRPs was obtained from the Sanitation Districts of Los Angeles County. A 2000 land cover data set was obtained from the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (NOAA-CSC 2003). This LANDSAT-based data product was used to define the model land segments and calibrate the HSPF model. The 30 m-resolution data contains 39 land use categories which are aggregated into eight land use types based on a similarity analysis (NOAA-CSC 2003). The imperviousness of each aggregated land use was determined using the Los Angeles Department of Power and Water guidelines (DePoto et al. 1991). The aggregated land use categories and corresponding imperviousness for the entire study area are presented in Table 2. Recorded and projected population data from 1960-2030 were obtained from the U.S. Census Bureau (2000) and the Southern California Association of Governments (SCAG 2002). Discharge data from the two WRPs were available from 1975 to 2006 and obtained from the Sanitation Districts of Los Angeles County.

4.3. Model Calibration and Validation

The model simulation period (water years (WY) 1997 to 2006) was selected based on the availability of precipitation, reference evapotranspiration and discharge data. The data period was split to allow a split-sample analysis of model performance (Refsgaard and Knudsen 1996): 1999 to 2002 were used for model calibration and 2003 to 2006 were used for independent model evaluation (validation). The 1997 to 1998 period was used as an initialization (spin-up) period. Calibration was conducted by manually adjusting model parameters to achieve agreement between simulated and observed flows for the outlet location using visual inspection and multiple statistical criteria. Four calibration scenarios with varying lumped and distributed precipitation forcing and model parameters were evaluated in order to determine the most suitable model configuration. A lumped configuration represents a single value (parameter or forcing) is applied to the three modeled sub-basins (one, two and four), while a distributed configuration means different values are applied to each of the three sub-basins (precipitation inputs and parameter values are specific to each sub-basin). Calibration scenario 1 (C1) consists of lumped (same values for all basins) inputs and lumped (same values for all basins) parameters; C2 consists of lumped inputs and distributed parameters (sub-basin specific parameters); C3 consists of distributed precipitation inputs (sub-basin specific precipitation inputs) and lumped parameters; C4 consists of distributed precipitation inputs and distributed parameters.

Results from the various calibration scenarios were evaluated using criteria proposed by Donigian (2002), including bias (BIAS), correlation (R), standard deviation ratio (RSR), and Nash-Sutcliffe efficiency (NSE). Once a calibration scenario is selected and parameters finalized, testing of the calibrated model is undertaken during the validation period. Specific formulations for the evaluation statistics are given as:

$$BIAS = \frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})}{\sum_{i=1}^{n} Q_i^{obs}} \times 100 \quad (1)$$

$$R = \frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_{obs}^{mean})(Q_i^{sim} - Q_{sim}^{mean})}{\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_{obs}^{mean})^2 (Q_i^{sim} - Q_{sim}^{mean})^2}} \quad (2)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_{obs}^{mean})^2}} \quad (3)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^{n}(Q_i^{obs} - Q_{obs}^{mean})^2} \quad (4)$$

where Q^{obs} and Q^{sim} are observed and simulated flows at time *i*, respectively, Q_{obs}^{mean} and Q_{sim}^{mean} are the mean value of observed flows and simulated flows, respectively, $RMSE$ is the root mean squared error, $STDEV_{obs}$ is the standard deviation of observed flows. Statistics were calculated for the calibration and validation periods at the annual, monthly, and daily time scales, as well as for the wet season (Oct 1 to May 31) and dry season (June 1 to September 30) at the daily time scale.

4.4. Scenario Modeling

A second land cover data set was generated from information obtained from the Newhall Ranch Development Plan (Newhall Land 1999). According to the Newhall Plan, approximately 23 km^2 will be developed in 25 years within the Newhall Ranch area located in sub-basin four. The proposed land cover types in the Newhall Plan were aggregated into four categories (commercial/industrial, high residential, low residential and rural residential). The corresponding areas of each of the four categories (and corresponding impervious) were estimated (Table 3). The initial proposed development pattern (current plan) is hereafter referred to as Scenario 1 (S1). Based on S1, three other development scenarios are created to simulate future development which may occur over the long term in the Santa Clara region. Specifically, Scenario 2 (S2) doubles the development areas of S1. Scenario 3 (S3) doubles S2 and Scenario 4 (S4) triples S2 (Table 3). Several of these scenarios (S3 and S4) may currently be somewhat unrealistic given the potential constraints on the system (transportation, water demand, etc.). However, these high density cases were formulated in order to assess the impacts of extreme urbanization on regional water fluxes in the USCRW (and potentially other semi-arid basins undergoing development).

The validated model is run under the proposed development scenarios to simulate flows for the entire watershed for the period WY 1997-2006. Model simulations from sub-basin four are then analyzed to evaluate future urbanization in this region of the watershed. Predictions of total runoff for the various scenarios are compared to the baseline simulation obtained from the current land cover scenario at a range of time scales: daily, seasonal (dry and wet), and annual. The influence of urban development on storm events with varying magnitude is also investigated. The ten largest storm events (based on volume) are selected for each year during the simulation period (100 total storms). Flow duration curves are constructed for baseline and land cover changes scenarios for the selected storms. Changes in peak flow and total storm volume are also analyzed for developed scenarios. In addition, investigation of the influence of urbanization on specific flow components - baseflow, surface (overland and lateral) flow, and recharge to the groundwater system – is evaluated for each of the four proposed scenarios. The HSPF model uses the parameter DEEPFR to estimate the fraction of infiltrating water recharged to deep groundwater; the remaining portion (i.e., 1-DEEPFR) provides baseflow to the stream (Duda et al. 2001). Both baseflow and recharge fluxes are calculated based on DEEPFR. Surface flow is obtained by subtracting the baseflow from the total flow simulated.

5. Results

5.1. Data Analysis

Population in the city of Santa Clarita has been expanding significantly since 1960 (Fig. 2). It is worth noting that the City of Santa Clarita was incorporated in 1987. Population data before 1987 is for the unincorporated areas in that same region.. The most significant increase is observed during the period from 1990-2000; indicating significant development after the city was formed. Population over the next two decades is projected to increase, indicating further development and increasing water demand.

Long-term precipitation for the study period (WY 1966 to 2006) was estimated at 423 mm. A simple assessment of precipitation and streamflow trends was undertaken using the 13 regional precipitation gages and a USGS gage (#11108500) which was originally located slightly upstream (~3.2 km) of the modeling point (#11109000). A 41-year (WY 1966 to 2006) record was established for both data sets. Regression analysis was conducted for the recorded data following the linear regression model of White and Greer (2006).The slope (S) of the regression lines was tested for significance using an analysis of variance (ANOVA), with significance defined as a p-value of less than 0.01. Annual precipitation appears to decrease slightly (slope=-0.48; p-value < 0.001) in the 41-year period, while annual runoff (slope=0.64; p-value <0.001) shows a slight increase (Fig. 3). The estimated runoff coefficient remains relatively stable (slope=-0.0016; p-value <0.001) (integrated response of the decreased precipitation and increased runoff). Further analysis is on-going regarding urbanization and climate trends in the USCRW and other southern California watersheds (not presented here).

The annual maximum, medium, and minimum daily flow discharge were determined from the 41-year period record as well. The effluent discharges of two WRPs are deducted from these statistics during the period from 1975-2006 (when WRP discharge data is available). Regression analysis was conducted for the period 1975-2006 (when the influence of WRP discharge is excluded). Fig. 4 shows these statistics and regression analysis results. Annual minimum and medium flows slightly decrease from 1975 to 2006, while there is a slightly increasing tendency of maximum flow in the same period. Given the observed trends in the USCRW, we hypothesize that the observed increase in streamflow can be attributed primarily to anthropogenic influences (i.e. the addition of impervious surfaces, urban runoff from irrigation, etc.).

Average precipitation for the modeling (baseline) period (WY 1996 to 2006) was estimated at 419 mm, annual discharge at 59.8 mm and runoff partitioning (ratio) at 0.12. The modeling period contains several above normal precipitation years (WYs 1998 and 2005) as well as a few significantly drier years (WYs 1999, 2002 and 2004) (Table 4 and Fig. 5). The runoff ratio during the 10-year period varies from a low of 0.06 (WY 2003) to a high of 0.21 (WY 2005).

5.2. Model Calibration and Validation

Statistics including BIAS, R, RSR, and NSE associated with the four calibration scenarios were computed at the daily scale (calibration timestep) (Table 5). For all four model configurations (C1 to C4), flows are somewhat under-estimated by the model (negative bias ranging from -19.8% for C1 to -9.3% for C4). However, calculated values are in the satisfactory range based on published calibration guidance (Donigian, 2002; Moriasi et al., 2007). In all four scenarios, simulated flows correlate well with the observed discharge ($R^2 > 0.78$). Overall RSR ranges from 0.70 (C1) to 0.37 (C4). The NSE is somewhat low for C1 (0.52), but increases significantly for C3 (0.80) and C4 (0.87). Both the RSE and NSE were considered satisfactory for all scenarios according to the criteria presented by Moriasi et al. (2007). Scenario C1 (lumped) consistently produces the poorest statistics while scenario C4 consistently provides the best statistics (Table 5). For the hybrid configurations (C2 and C3), the distributed precipitation input scenario with lumped parameters (C3) outperforms the distributed parameter scenario with lumped precipitation inputs (C2); highlighting the dependency of the model on spatial precipitation information and that the model is more sensitive to variation in model inputs than model parameters.

Configuration C4 produced the best statistics and visual simulations and is selected as the model configuration for further analysis. Values for the final calibrated parameters, as well as model ranges (Duda et al. 2001) are listed in Table 6. Both calibration (WY 1999 to 2002) and validation (WY 2003 to 2006) results are evaluated for three time scales: annual, monthly, and daily. Statistics for all three time scales, as for dry and wet season flow (daily timestep) are presented in Table 7. Annual (Fig. 6(a)) and monthly (Fig. 6(b)) scatterplots illustrate that simulated flows match the observed discharge fairly well for both the calibration and validation periods. Overall, simulations during the calibration period show a slightly higher bias (-9.3% annual; -9.4% on the monthly) than during the validation period (0.4% annual; 0.5% monthly). However, bias values for both time scales and periods are considered noted in the "very good" range according to Moriasi et al. (2007). However, simulations during the calibration period result in much higher NSE values (0.96 annual and monthly) than during the validation period (0.52 annual; 0.72 monthly) at these time scales (Table 7).

Scatterplots generated at the daily timestep illustrate model performance in both the wet season (Fig. 6(c)) and dry season (Fig. 6(d)) is acceptable but not as good as at the annual and monthly scale. Bias is noted at the low end of model simulations. Performance during the wet seasons during the calibration period (NSE=0.86) is very good, but poorer values are noted during the validation in the wet season (0.29). Dry season daily simulations result in NSE values of 0.72 for the calibration period and 0.48 for the validation period. Biases are increased (worse) during the calibration period for wet season daily flow, however, correlation and RSR values are better for both wet and dry season flows during the calibration period (Table 7).

Select hydrographs are also presented to allow visual inspection of model performance for a dry year (WY 2004, Fig. 7(a)) and a wet year (WY 2005, Fig. 7(b)). Transformed flow is used in plotting the hydrograph to allow for improved visualization of lower flows. The transformation is formulated as follows (Hogue et al. 2006):

$$Q_{trans} = \frac{(Q_0 + 1)^{\lambda} - 1}{\lambda}, \quad \lambda = 0.3 \tag{5}$$

where Q_0 represents the raw flow vector, Q_{trans} represents the transformed flow vector, and λ is a constant coefficient (λ=0.3 in this study). Simulated flows closely follow the observed flows (solid circles) for most of both years (Fig. 7). Peak flows are captured for the majority of events (except the first small runoff event in the dry year). Simulation of recessions is somewhat more problematic, especially during WY2004. The model is not able to capture the falling limb of the hydrograph during the first big event in December of 2003, but does somewhat better during the next large runoff event. Recessions are better simulated during the wet year and simulated flows match observations well for most of the entire water year. Timing is also fairly good in both years. In general, R, RSR, and NSE statistics (with the corresponding hydrographs) indicate that the model does consistently better during the calibration period (over the validation period). In addition, model performance is generally better during the wet season rather than the dry season.

5.3. Scenario Modeling

Using the same model design and forcing (WY1997 to 2006 and C4 model configuration), the USCRW model is reformulated by incorporating the proposed land use change for each respective development scenario (S1 to S4). Flow regimes changes corresponding to each scenario are simulated and interpreted on annual, monthly, and daily scales. Percent change is estimated relative to the baseline simulated values for the 1997 to 2006 period. Fig. 8(a) shows the respective change in annual flow for each of the study years (WY 1997 to 2006). Average monthly changes are also shown for the wet months during the 10 year period (Fig. 8(b)) and for the dry months of the same period (Fig. 8(c)). The relative change of predicted total annual flows from the baseline (simulated under the current land cover scenario) varies annually within the 10-year simulation period, mostly due to the non-uniform distribution of precipitation (El Nino event in WY1998; dry years in WY1999 and WY2002). For each year, the simulated annual total flow increases with increasing urbanization in the watershed, with the highest increase near 150% for S4 during El Nino year 1998. A consistent increase in predicted monthly average flows with increasing developed extent during the wet season

(October to May) can also be identified (Fig. 8(b)). The largest change (around 180%) occurs during the wetter months of December and February and the lowest monthly changes occur in May (Fig. 8(b)). Dry season (Fig. 8(c)) changes in simulated monthly flows are significantly less in magnitude than during the wet season. Specifically, in July, the modeled monthly flow decreases with increasing development. Average precipitation in July is near zero during the 10 year period. Observed streamflow during this month is primarily baseflow, with scenario results indicating that increasing urbanization is decreasing system baseflow (based on model simulations).

The selected 100 storms are evaluated with respect to changes in overall volume and peak flow (as compared to the baseline storm simulations). Daily flow exceedance curves for the simulations period (Fig. 9) illustrate that storms with extremely low volume and peak (>95%) and high volume and peak (<5%) for the four development scenarios show relatively little change compared to baseline conditions, while storms in the medium flow range show significant variations with increasing development in both overall volume (Fig. 9(a)) and peak flow (Fig. 9(b)). In general, storm volume and peak increase with increasing development. As expected, the S4 simulations show the most significant increase. The average volume and peak of storms with various magnitudes (high, medium, and low) under the current condition and proposed scenarios are calculated (Table 8), as well as the percent change of average volume and peak simulated under projected development scenarios over the baseline condition (simulated under the current land cover). It is clear the quantified results confirm the noted observations in the flow duration curves (Fig. 9). Specifically, in the extreme development scenario (S4), the average peak of medium storms is doubled (111.11% increase) and the average volume is increased 54.77%. In comparison, urbanization appears to have more influence on storm peaks rather than overall storm volume.

In addition to total runoff, changes in specific flow regimes - baseflow, surface (overland and lateral) flow, and recharge (deep groundwater contribution) - are investigated for both wet and dry seasons (Table 9). The current flow (depth in mm) for each component – total runoff, surface flow, baseflow, and recharge – is noted for the current (baseline) conditions as well as each scenario. Percent change from the total simulated depth for each component is then calculated. In general, urbanization increases surface flow and generally decreases baseflow and recharge for both the wet and dry seasons. Baseflow and groundwater recharge estimates are both linearly related via the model parameter DEEPFR (discussed previously), thus the percent change of baseflow and groundwater recharge for specific development scenario show similar values for each scenario. For surface flows, an increase in average wet season flow varies from ~25% (S1) to 150% (S4). In contrast, increase in average dry season flow only ranges from 0.16% to 0.93%. For baseflow, the magnitude of percent decrease in both seasons is comparable, with changes ranging from -1.74% (S1) to -9.94% (S4) percent for the dry season and from -1.72% (S1) to -10.19% (S4) for the wet season. The decrease in groundwater recharge is also comparable for both seasons, with losses up to ~10% for the most extreme development (S4). The current proposed development plan, results in nearly a 25% increase in daily wet season surface flows and an approximately 2% loss in baseflow and deeper subsurface flows (recharge). More extreme urbanization (S3 and S4) significantly impacts surfaces flows – increasing surface flow over 100% for extreme development cases.

6. Conclusions

The current study was undertaken to evaluate the long-term hydrologic impacts of adding additional impervious surfaces in a developing semi-arid watershed. The HSPF model was selected to simulate baseline or current conditions, future development scenarios (based on proposed development plans) were derived, and hydrologic response of various flow components was assess for the planned development, as well as more extensive development. To focus discussion of the results, we review the objectives posed at the beginning of our analysis:

1) Further assess the applicability of the HSPF model in semi-arid watersheds. The results presented in the current study demonstrate the applicability of the HSPF model for semi-arid watersheds. The model was calibrated with various spatial configurations of forcing and parameters values. Results show that HSPF performs fairly well in all calibration configurations, however, simulations with distributed precipitation forcing and parameter sets provide the best simulations. In addition, the calibration results at the daily time scale show a slight improvement over those previously reported in the literature (Brun and Band 2000; Hayashi et al. 2004; Ackerman et al. 2005), with an overall bias of -9.3% and a NSE of 0.87 (calibration period). Percent bias and NSE values for simulated dry and wet season daily flows are -10% and -1.9%, and 0.86 and 0.72, respectively. On the annual and monthly scales, the HSPF has similar, or better, performance when compared to the daily time scale results. Visual inspection of simulated hydrographs further reveals that the model simulates the event peaks well in both dry and wet years and in general, captures overall flow variability. Simulations during the validation period are acceptable, but generally not as good, as simulations during the calibration period. Correlation (R), RSR, and NSE values are degraded slightly for daily simulations during the validation period. However, biases are generally lower (better) in the validation period, except for dry season flows, where an increased bias of 8.5% is noted, compared to a bias of -1.9% for the dry season calibration period flows. In summary, the current analysis reveals that the HSPF model performs well for this semi-arid watershed at a range of time scales (daily to annual). Secondly, the model performs slightly better during wetter seasons and years than during drier periods.

2) Predict changes in the hydrologic behavior (surface flow, infiltration, baseflow, storm response, etc.) to varying levels of potential urbanization. The distributed, validated HSPF model was used to evaluate the impacts of future urbanization on flow regimes in the USCRW. Results show that increasing development generally increases total annual runoff and wet season flows (total channel discharge). In comparison, the influence of development on total dry season flow is less certain due to the lack of rainfall during the dry months. In months with little to no precipitation, discharge was noted to decrease with increasing urbanization. Exceedance curves reveal that storms with medium discharge volumes (5-95% flow ranges) gradually increase as developed areas increase while storms with extremely low volumes or high volumes appear less affected. As with previously published studies, urbanization increases surface (overland and lateral) flow (Leopold 1968; Lazaro 1990; Wissmar et al. 2004; Murdock et al. 2004). Model simulations also indicate a decrease in baseflow response and a decrease in deep groundwater recharge in both the dry season and wet season. Under the proposed development plans (S1) both baseflow and recharge decrease by about 2% in sub-basin four. Given extreme development (S4), the decrease in baseflow and groundwater is estimated to be around 10%. Of note in the current study is the inability to account for potential increases in urban runoff during the dry season in HSPF model simulations. As previously discussed by Ackerman et al. (2005), heavily urbanized surfaces in semi-arid regions may see an increase in dry weather flows due to various anthropogenic activities that may use imported water which eventually ends up as channel flow during the dry season. An increase in dry weather flow will most likely be evidenced in the USCRW given increasing urbanization. Given the current HSPF model structure and lack of information on future imported water use, the estimates of baseflow response produced during the predictions of future urbanization (S1 to S4) may have significant uncertainty. However, previous studies have noted general decreases in infiltration in urbanized regions (Simmons and Renolds 1982; Spinello and Simmons 1992; Finkenbine et al. 2000), which will most likely be evidenced in the USCRW and is supported by the presented model predictions of declining recharge with increasing development. Although recharge validation is difficult, we feel fairly confident in the range of estimates produced from the model simulations. The HSPF model was well calibrated and showed improved results over previous studies. The model was calibrated primarily to total discharge, which includes both surface and baseflow components. Given the relative success of the model during low flows during inter-storm periods and relatively dry periods, we assert that both surface flow and baseflow processes are fairly well-estimated under the current conditions. Hence, the residual component, recharge, is well-estimated under current conditions given the success of the calibration and that predictions of changes in recharge for the proposed developments are therefore reasonable.

3) Quantify the potential loss of subsurface water supply (recharge) given extensive basin development. Water supplies in Southern California are somewhat variable by water district and region, but in general, include about half from imported water supplies (northern California, Colorado River, and Owens Valley) and the other half from local supplies (MWD 2005). Regional aquifers provide, on average, about 1.41maf (1.74 Gm^3) water groundwater per year (MWD 2005). Southern California's imported water supply may be extremely vulnerable to climate change effects. Observed declines in snowpack, along with projected declines in winter precipitation, could fundamentally disrupt the California water cycle (Hayhoe et al. 2004; CCCC 2006). There is evidence that some changes have already occurred, such as an earlier beginning date of spring snowmelt, an increase in winter runoff as a fraction of total runoff, and an increase in winter flooding frequency (Dettinger and Cayan 1995; Mote et al. 2005). The likelihood of dramatic declines in Colorado River flow is also significant (Christensen et al. 2004) and reservoir levels in the river have been significantly below capacity for several years (USBR 2008). California, which has been receiving more than its share of the Colorado River (~5.2 maf/year (6.41 Gm^3/year)), is under order by the Secretary of the Interior to return to regulated allocation levels of 4.4 maf/year (5.43 Gm^3/year) (Gelt 1997). Minor fluctuations in local groundwater supplies (i.e. potential loss of recharge to existing aquifer systems) will exacerbate already sensitive water supplies for the increasing population in southern California.

The estimated changes in recharge for potential development in the USCRW, although relatively small in absolute numbers, equate to significant loss in recharge volume for the developing area. Sub-basin four in the USCRW, where the proposed development is focused, is approximately 217 km^2. A decline in recharge of 0.67 mm over the proposed basin (from aggregated model output) results in a volume loss of 0.145 Mm^3/year (primarily during the wet season). Given the current per capita water use in southern California (~185 gal/day (0.7 m^3/day); MWD 2005), the recharge volume loss equates to a supply for around 600 people each year on average. For the extreme case (S4), the decrease in recharge of 3.96 mm across the sub-basin results in an estimated loss of 0.859 Mm^3/year, or enough water to supply approximately 3400 people each year. Although the estimate of recharge loss from the S4 case is more extreme and includes significantly more uncertainty than estimates for the proposed level of development under S1, the case is presented to illustrate the potential impacts of cumulative, long-term development on watershed function and recharge loss.

In summary, this study is one of the first to address the impacts of cumulative development in a semi-arid watershed undergoing rapid and extensive development. Long-term, continuous simulations of potential urbanization are critical to further our understanding of basin-scale changes in flow regimes, especially in less-studied semi-arid watersheds. Seemingly minor decreases in recharge to local aquifers may result in significant volume losses when aggregated to the regional scale and considered over long time periods. Expanding populations in southern California will be moving into regions where natural and extensive recharge has been occurring. Given the current uncertainty in precipitation and temperature trends, potential changes in existing and future water supplies need to be rigorously evaluated. Novel engineering and development strategies will be needed to prevent and/or mitigate alterations in watershed and recharge processes due to continuing urbanization

7. Tables and Figures

Table 1. Model sub-basins with relevant areas and percent of area that is developed based on land cover from the NOAA Coastal Services Center (NOAA-CSC, 2003)

Sub-basin #	Area (km^2)	Developed Area (%)
1	401	3
2	685	18
3	377	-
4	217	18

Table 2. Upper Santa Clara River Watershed (USCRW) land use (as % of Area) and estimated imperviousness for each aggregated land use. Impervious estimates derived from Los Angeles Department of Water and Power (LADWP) (DePoto et al., 1991)

Aggregated Land Use	% Area	% Imperviousness
Commercial/Industrial	0.78	90
High residential	1.34	60
Low residential	1.45	40
Rural residential	6.81	20
Chaparral	88.70	6
Open ground	0.12	3
Water and wetlands	0.80	0

Table 3. Current and proposed land use scenarios for sub-basin four: Scenario one (S1) is derived using regional development plans, scenario two (S2) is double the development area of S1, scenario three (S3) is double the development area of S2 and scenario four (S4) is triple the development Area of S2

	Current Area	S1 (km^2)		S2 (km^2)	
Land Use Type	(km^2)	Proposed	Aggregated	Proposed	Aggregated
Commercial/Industrial	2.13	2.30	4.43	4.60	6.73
High residential	1.85	11.52	13.37	23.04	24.89
Low residential	2.17	6.91	9.08	13.82	15.99
Rural residential	33.41	2.30	35.71	4.60	38.01
Total	39.56	23.03	62.59	46.06	85.62
Fraction of Sub-basin Four (%)	18.23		28.84		39.46

	Current Area	S3 (km^2)		S4 (km^2)	
Land Use Type	(km^2)	Proposed	Aggregated	Proposed	Aggregated
Commercial/Industrial	2.13	9.20	11.33	13.80	15.93
High residential	1.85	46.08	47.93	69.12	70.97
Low residential	2.17	27.65	29.82	41.46	43.63
Rural residential	33.41	9.20	42.61	13.80	47.21
Total	39.56	92.13	131.69	138.18	177.74
Fraction of Sub-basin Four (%)	18.23		60.69		81.91

Table 4. Annual observed precipitation and streamflow data for the study period. Precipitation average is derived using 13 regional rain gages, streamflow is from USGS gage #11109000, and runoff coefficient is the ratio of runoff to precipitation

Water Year	Precipitation (mm)	Streamflow (mm)	Runoff Coefficient
1997	304.80	28.27	0.09
1998	815.34	155.58	0.19
1999	213.36	31.00	0.15
2000	330.20	32.75	0.10
2001	363.22	24.86	0.07
2002	139.70	17.50	0.13
2003	424.18	26.15	0.06
2004	246.38	25.44	0.10
2005	975.36	205.05	0.21
2006	375.92	51.84	0.14
Average	418.85	59.84	0.12
Long-term Average (1966-2006)	422.56	-	-

Table 5. Calibration scenarios used to establish model design and corresponding statistics for model performance when compared to observed streamflow (USGS Gage #11109000). Calibration statistics include percent bias (%Bias), correlation coefficient (R), ratio of root mean squared error (RMSE) to standard deviation (RSR) and Nash Sutcliffe Efficiency (NSE)

Scenarios			Calibration Statistics			
Number	Precipitation Input	Model Parameters	% Bias	R	RSR	NSE
C1	Lumped	Lumped	-19.8	0.78	0.7	0.52
C2	Lumped	Distributed	-10.5	0.85	0.55	0.69
C3	Distributed	Lumped	-10.1	0.93	0.44	0.8
C4	Distributed	Distributed	-9.3	0.93	0.37	0.87

Table 6. Calibrated model parameters, description, model range and units for both pervious and impervious land cover in the HSPF model

Parameters		Values: Calibrated Values	Values: Model Range*	Unit
		Previous Cover		
FOREST	Fraction Forest Cover	0	0-1	None
LZSN	Lower Zone Nominal Soil Moisture Storage	127-203	0.25-2540	mm
INFILT	Index to Infiltration Capacity	1	0-2540	mm/hr
LSUR	Length of Overland Flow	152	>0.3	m
SLSUR	Slope of Overland Flow Plane	0.009-0.025	0-10	None
KVARY	Variable Groundwater Recession	0.59	>0	1/mm
AGWRC	Base Groundwater Recession	0.99	0-0.99	1/day
PETMAX	Temperature below which ET is Reduced by Half	4.4	0-8.8	°C
PETMIN	Temperature below which ET is Set to Zero	1.7	-1.1-4.4	°C
INFEXP	Exponent in Infiltration Equation	2	0-10	None
INFILD	Ratio of Max/Mean Infiltration Capacities	2	1-2	None
DEEPFR	Fraction of Groundwater Inflow to Deep Recharge	0.5-0.9	0-1	None
BASETP	Fraction of Remaining ET from Baseflow	0.02	0-1	None
AGWETP	Fraction of Remaining ET from Active Groundwater	0	0-1	None
CEPSC	Interception Storage Capacity	2.54	0-254	mm
UZSN	Upper Zone Nominal Soil Moisture Storage	51-89	0.25-2540	mm
NSUR	Manning's n for Overland Flow	0.2	0-1	None
INTFW	Interflow Inflow Parameter	0.1	>0	None
IRC	Interflow Recession Parameter	0.5	0-0.99	1/day
LZETP	Lower Zone ET Parameter	0.7	0-1.5	None
		Impervious Cover		
LSUR	Length of Overland Flow	152	>0.3	m
SLSUR	Slope of Overland Flow Plane	0.009-0.025	0-10	None
NSUR	Manning's n for Overland Flow	0.05	0-1	None
RETSC	Retention Storage Capacity	2.54	0-254	mm
PETMAX	Temperature below which ET is Reduced by Half	4.4	0-8.8	°C
PETMIN	Temperature below which ET is Set to Zero	1.7	-1.1-4.4	°C

* Ranges of model parameters obtained from Duda et al., 2001.

Table 7. Statistics for model performance for both the calibration period (1999-2002) and validation period (2003-2006). Results are presented for annual total flow, monthly average flow, daily flow, and wet and dry season daily simulations

Scenarios	Categories	% Bias	R	RSR	NSE
Calibration (1999-2002)	Annual Total Flow	-9.3	0.99	0.21	0.96
	Monthly Average Flow	-9.4	0.99	0.20	0.96
	Daily Flow	-9.3	0.93	0.36	0.87
	Daily Wet Season Flow	-10.0	0.93	0.37	0.86
	Daily Dry Season Flow	-1.9	0.85	0.53	0.72
Validation (2003-2006)	Annual Total Flow	0.4	0.76	0.70	0.52
	Monthly Average Flow	0.5	0.87	0.52	0.72
	Daily Flow	0.3	0.69	0.82	0.32
	Daily Wet Season Flow	-1.8	0.68	0.84	0.29
	Daily Dry Season Flow	8.5	0.76	0.72	0.48

Table 8. Predicted volumes and peaks of storms for high (<5%), medium (5-95%), and low (>95%) magnitude flows, as well as relative change from current conditions for the proposed development scenarios (S1 to S4)

Scenarios	High		Medium		Low	
	Value	% Change	Value	% Change	Value	% Change
			Average Volume($10^6 m^3$)			
Current	61.04	-	3.96	-	0.47	-
S1	62.62	2.58	4.32	9.11	0.49	3.00
S2	64.22	5.20	4.68	18.23	0.50	6.06
S3	67.44	10.48	5.41	36.48	0.53	12.03
S4	70.65	15.73	6.13	54.77	0.56	18.05
			Average Peak (m^3/s)			
Current	207.70	-	12.06	-	1.15	-
S1	215.12	3.57	14.24	18.12	1.21	5.37
S2	222.65	7.20	16.46	36.46	1.27	10.74
S3	238.28	14.72	20.93	73.56	1.40	21.43
S4	254.08	22.33	25.46	111.12	1.52	32.27

Table 9. Predicted flow regimes for surface flow, baseflow, and recharge, as well as relative change from current conditions for the proposed development scenarios (S1 to S4)

Scenarios	Runoff (mm)	Runoff % change	Surface Flow (mm)	Surface Flow % Change	Baseflow (mm)	Baseflow % Change	Recharge (mm)	Recharge % Change
				Dry Season Average				
Current	28.31	-	27.94	-	0.38	-	3.40	-
S1	28.35	0.13	27.98	0.16	0.37	-1.74	3.34	-1.74
S2	28.39	0.26	28.02	0.31	0.36	-3.31	3.28	-3.31
S3	28.46	0.53	28.11	0.62	0.35	-6.60	3.17	-6.60
S4	28.54	0.78	28.20	0.93	0.34	-9.94	3.06	-9.94
				Wet Season Average				
Current	85.68	-	81.37	-	4.31	-	38.80	-
S1	106.06	23.78	101.82	25.13	4.24	-1.72	38.13	-1.72
S2	126.47	47.60	122.30	50.31	4.16	-3.40	37.48	-3.40
S3	167.03	94.95	163.02	100.34	4.02	-6.80	36.16	-6.80
S4	207.60	142.30	203.73	150.38	3.87	-10.19	34.84	-10.19

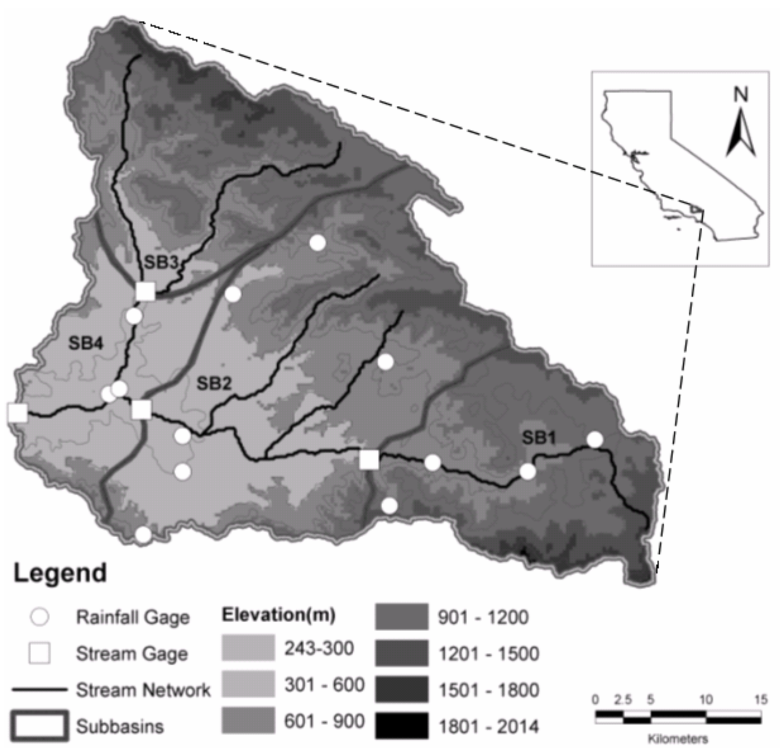

Fig.1. Upper Santa Clara River Watershed (USCRW) located in northern Los Angeles County, including shaded elevation bands. Precipitation gages (circles) and stream gages (squares) are shown, as well as channel network (dark lines) and sub-basin designations (SB1 to SB4)

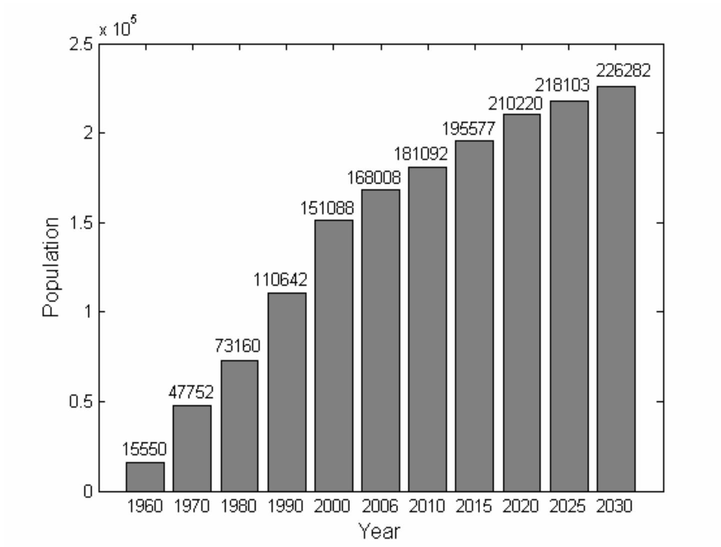

Fig.2. City of Santa Clarita population; 1960-2006 data is from the U.S. Census Bureau (2008) and 2010-2030 population forecasts are from SCAG (2008)

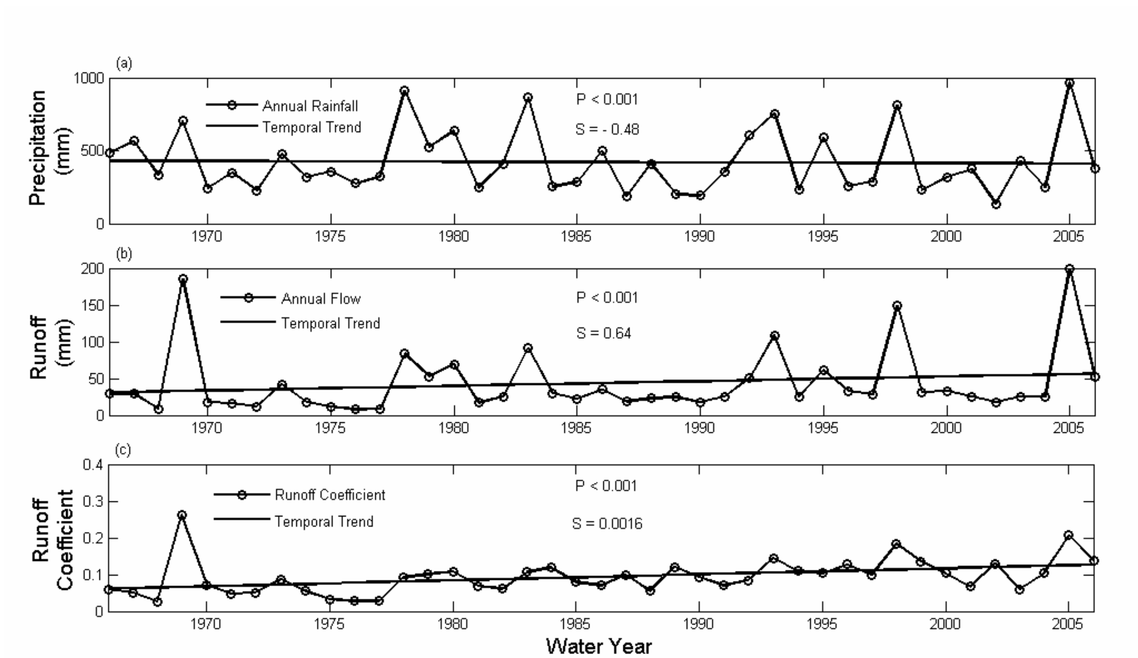

Fig. 3. Observed (a) precipitation, (b) runoff, and (c) runoff coefficient in the period from water year 1966-2006 of the study watershed. Linear regression lines are predicted from the 41-year data. P: significance of regression coefficient; S: slope of the linear regression line

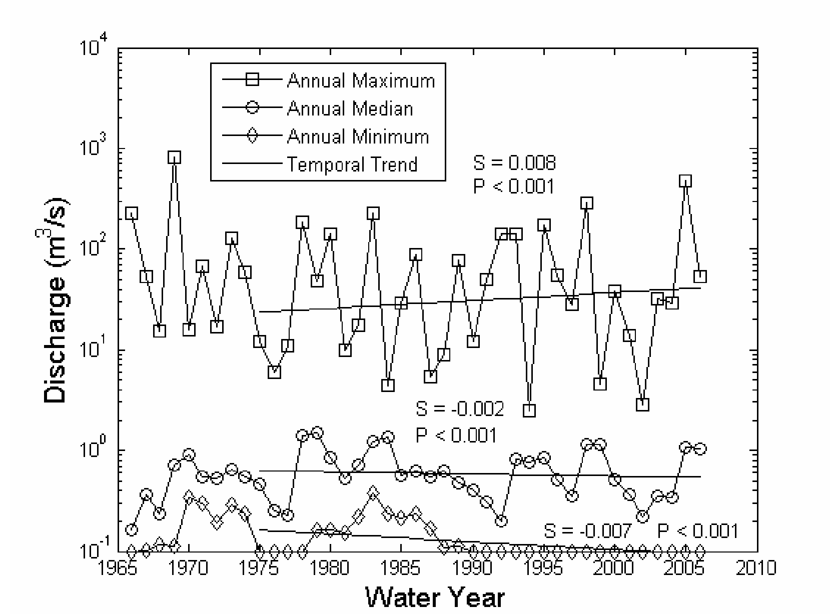

Fig. 4. Recorded annual maximum, median, and minimum discharge of the study watershed during the period 1966-2006. Linear regression lines are predicted from1975-2006. P: significance of regression coefficient; S: slope of the linear regression line

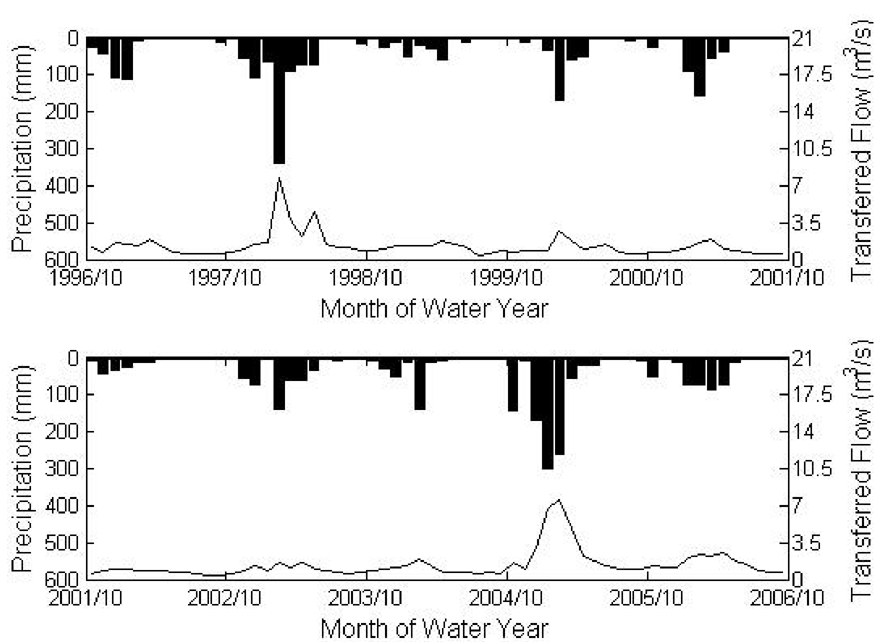

Fig.5. Monthly time series of observed data for the model study period. Precipitation is shown as a hyetograph (inverted bars) and monthly discharge (transformed flow) is shown as a solid line

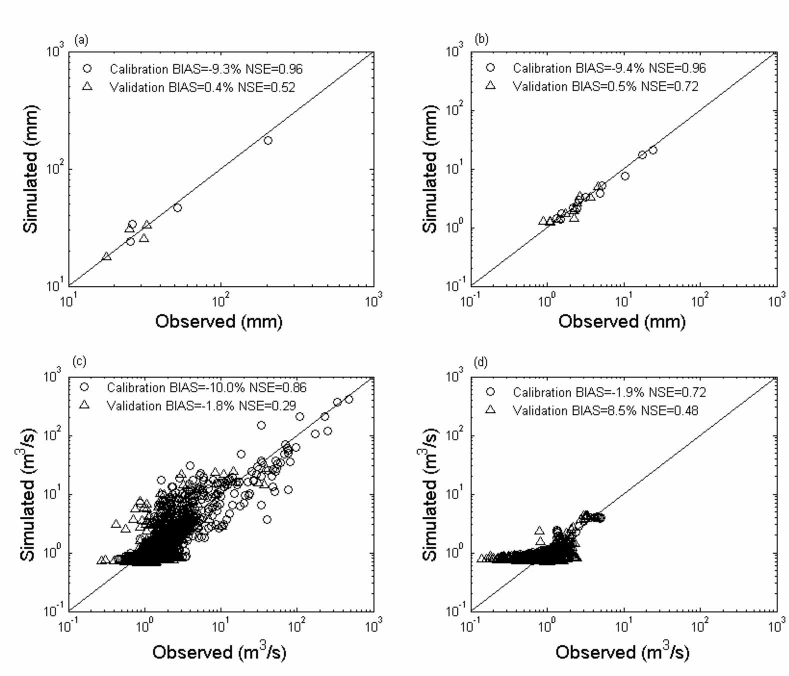

Fig. 6. Model calibration and validation results (a) observed *vs.* simulated annual flow, (b) observed *vs.* simulated monthly flow, (c) observed *vs.* simulated daily flow during the wet season (October to May) and (d) observed *vs.* simulated daily flow during the dry season (June to September)

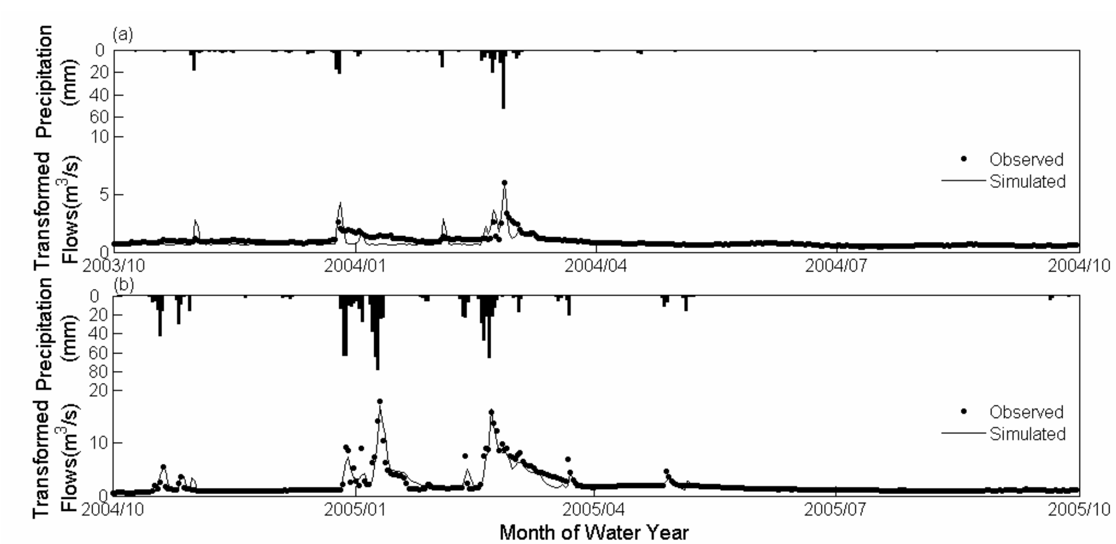

Fig. 7. Daily model simulation results for (a) a dry year (WY 2004), and (b) a wet year (WY 2005). Observed flow is shown as the closed circles (•) while model simulation is shown as the solid line. Precipitation for each year is also shown as an inverted bar above each hydrograph

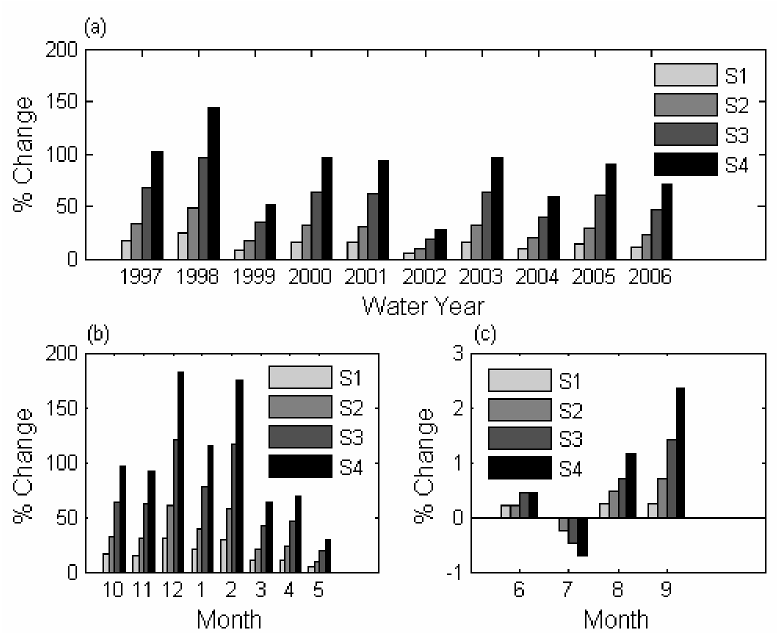

Fig. 8. Deviation (% change) from current streamflow conditions for (a) predicted annual total flow, (b) predicted monthly average flow during the wet season, and (c) predicted monthly average flow during the dry season for the four proposed development scenario

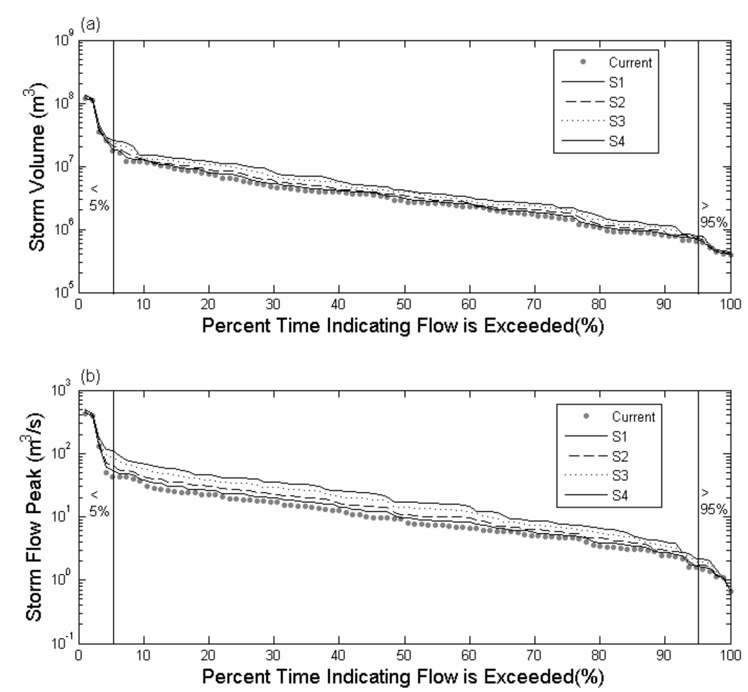

Fig. 9. Exceedance curve for (a) storm volume, and (b) storm flow peak simulated under current conditions and the four proposed development scenarios. Vertical solid lines represent 5% or 95% thresholds as designated

8. Publications

n/a

9. References

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