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Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin

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Abstract:

The Puget Sound basin in northwestern Washington, USA has experienced substantial land cover and climate change over the last century. Using a spatially distributed hydrology model (the Distributed Hydrology-Soil-Vegetation Model, DHSVM) the concurrent effects of changing climate (primarily temperature) and land cover in the basin are deconvolved, based on land cover maps for 1883 and 2002, and gridded climate data for 1915–2006. It is found that land cover and temperature change effects on streamflow have occurred differently at high and low elevations. In the lowlands, land cover has occurred primarily as conversion of forest to urban or partially urban land use, and here the land cover signal dominates temperature change. In the uplands, both land cover and temperature change have played important roles. Temperature change is especially important at intermediate elevations (so-called transient snow zone), where the winter snow line is most sensitive to temperature change—notwithstanding the effects of forest harvest over the same part of the basin. Model simulations show that current land cover results in higher fall, winter and early spring streamflow but lower summer flow; higher annual maximum flow and higher annual mean streamflow compared with pre-development conditions, which is largely consistent with a trend analysis of model residuals. Land cover change effects in urban and partially urban basins have resulted in changes in annual flow, annual maximum flows, fall and summer flows. For the upland portion of the basin, shifts in the seasonal distribution of streamflows (higher spring flow and lower summer flow) are clearly related to rising temperatures, but annual streamflow has not changed much. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS modeling; land cover change; climate change; streamflow; the Distributed Hydrology-Soil-Vegetation Model (DHSVM)

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INTRODUCTION

Anglo settlement of the Pacific Northwest, which dates to the mid-1800s, was fairly recent by comparison with much of the North American continent. Since that time, the land cover of the region, which once was mostly coniferous forest, has changed dramatically as the population has grown. In the first 100 years or so of the post-settlement era, the major land-use conversion was associated with forest harvest, and some areas have undergone several cycles of forest harvest and regrowth. Especially over the last half century, expansion of the populated areas of the major metropolitan areas, such as the Everett–Seattle–Tacoma corridor of western Washington, has resulted in conversion of substantial portions of the landscape from forest to urban and suburban uses (MacLean and Bolsinger, 1997; Alberti *et al.*, 2004). Concerns have been raised about the effects of ongoing land-use change on various aspects of the hydrologic cycle, including summer low flows, groundwater recharge, and flooding (Leopold, 1968; Jones and Grant, 1996; Thomas and Megahan, 1998; Konrad and Booth, 2002; Burns *et al.*, 2005).

Population density in the Puget Sound drainage basin has increased tremendously over the last 100 years. According to census data from the State of Washington's Office of Financial Management, the population density of the most populated counties in the Puget Sound basin has increased as much as 36 times since 1900 (http://www.ofm.wa.gov/pop/default.asp). Currently, about 70% of Washington's population lives in the Puget Sound basin.

It has been well documented that urbanization increases peak flows (Leopold, 1968; Changnon and Demissie, 1996; Leith and Whitfield, 2000; Jennings and Jarnagin, 2002; Konrad and Booth, 2002; Chang, 2007) by reducing infiltration during storms. Logging, on the other hand, increases total water yield (and in some cases peak flows) primarily by reducing evapotranspiration (Bosch and Hewlett, 1982; Troendle and King, 1985; Hornbeck *et al.*, 1993, 1997; Moscrip and Montgomery, 1997). The specific mechanisms that cause changes in runoff associated with these two types of land cover change that have affected the Puget Sound basin may differ depending on physical characteristics of watersheds and watershed treatments. For example, in the Puget Sound lowlands where snowfall is minimal and the annual hydrologic cycle is dominated by winter rainfall, hydrograph changes resulting from removal of forest

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vegetation are mainly caused either by reduced infiltration associated with wetter soils and hence increased storm peaks, or increased low flows resulting from higher water tables (Moscrip and Montgomery, 1997; Konrad and Booth, 2002; Chang, 2007; Xiao *et al.*, 2007). On the other hand, at higher elevations where winter precipitation is a mixture of rain and snow, hydrograph changes may be related to reduced surface infiltration, reduced evapotranspiration, increased winter snow accumulation, and enhanced runoff from rain-on-snow events (Troendle and King, 1985; Bowling *et al.*, 2000; Jones and Grant, 1996).

In addition to the hydrologic effects of land cover change, it is now apparent that substantial changes in the climate of the region have occurred over the post-settlement era. Mote *et al.* (1999; 2003) found that in the larger Pacific Northwest (PNW) region within which the Puget Sound basin is located, there has been a trend towards warmer (99% confidence level) and wetter (not statistically significant) conditions over the last 80 years. Although Hamlet and Lettenmaier (2007) have shown that these ongoing changes (and projections for further temperature increases) might lead to increased flood risk in rain-fed rivers in winter and increased risk of summer water shortages, analyses of hydrologic records (Bowling *et al.*, 2000) have not yet detected such changes in hydrologic observations. Nonetheless, it is important in any assessment of land cover change to deconvolve the possibly concurrent effects of a changing climate and land cover.

Although we are unaware of previous comprehensive studies of the effects of land cover and temperature change on the hydrology of the Puget Sound basin, the impacts of land cover and climate change have been well studied in the adjacent (and much larger) Columbia River basin of the PNW interior (Mote *et al.*, 1999, 2003; Matheussen *et al.*, 2000; VanShaar *et al.*, 2002; Hamlet and Lettenmaier, 2007). In the Puget Sound basin, on the other hand, there have been studies of the hydrologic effects of land cover change associated with logging, most of which have focused on changes in flooding (Storck *et al.*, 1998; Bowling *et al.*, 2000; La Marche and Lettenmaier, 2001). The intent of this study is to provide a more comprehensive evaluation of the concurrent effects of land cover and temperature change on the hydrology of the Puget Sound basin in the post-settlement era. With respect to climate, we focus on the period 1915 to 2006 during which the quality of climatological data is sufficient to infer hydrologic changes, and with respect to land cover our study period goes back to 1883, the earliest time for which we could obtain credible land cover data.

STUDY AREA

The majority of the Puget Sound basin is located in western Washington, with a small part in south-western British Columbia (Figure 1). The basin is bounded by the Cascade Mountains to the east and the Olympic Mountains to the west. The area of the basin is about

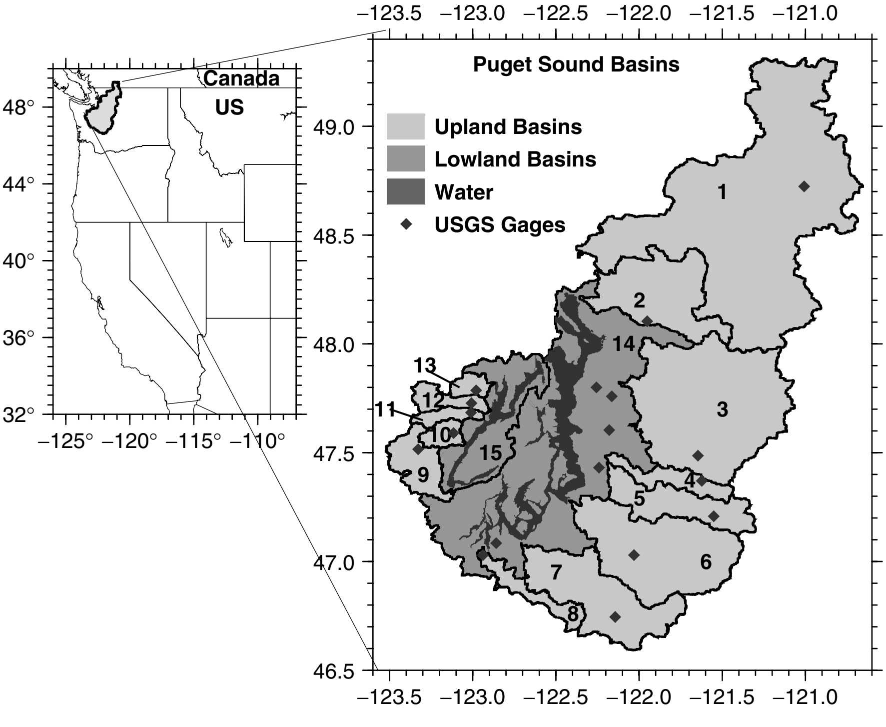

Figure 1. Puget Sound drainage with major upland and lowland basins: 1 Skagit River Basin, 2 Stillaguamish River Basin, 3 Snohomish River Basin, 4 Cedar River Basin, 5 Green River Basin, 6 Puyallup River Basin, 7 Nisqually River Basin, 8 Deschutes River Basin, 9 Skokomish River Basin, 10 Hamma Hamma River Basin, 11 Duckabush River Basin, 12 Dosewallips River Basin, 13 Quilcene River Basin, 14 Eastern lowland basin, 15 Western lowland basin. Dark diamonds show locations of stream gauges used in the study. East is composed of basins 2, 3, 4, 5, 6, 7 and 8; west is composed of basins 9, 10, 11, 12, and 13; upland is composed of east, west and basin 1 (Skagit); lowland is composed of basins 14 and 15; the entire domain is composed of upland and lowland

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30 000 km^2. Its elevation ranges from sea level to 4400 m (top of Mt Rainier). About 80% of the Puget Sound basin is land, and the remainder is water. Soil types are mainly sandy loam and loam. The west slopes of the Cascade Mountains and the east slopes of the Olympic Mountains are primarily covered by coniferous forest. In the Puget Sound lowlands, land cover is mainly urban residential, water, and mixed deciduous and coniferous forest. The Puget Sound basin has a maritime climate with temperate winters and summers. Substantial winter snowfall occurs at high elevations, but rarely in the lowlands. Storms with duration longer than one day mostly occur in the late fall and winter and are controlled by large-scale synoptic weather systems. Annual precipitation ranges from 600 mm to 3000 mm, depending on elevation, most of which falls from October to March. Winter precipitation in upland portions of the basin is a mix of rain and snow at intermediate elevations, and primarily snow at the highest elevations.

Thirteen major basins contribute most of the fresh water to the Puget Sound basin, and in turn most of their runoff is generated from their upland headwaters. In addition to these 13 basins, numerous small creeks drain lowland areas adjacent to Puget Sound proper. Many of these lowland creeks, as well as the lowland portions of the major drainage basins, have been affected by urbanization. For purposes of analysis, the many small creeks draining directly to Puget Sound, along with the lowland portions of the major basins, are grouped into two major basins as shown in Figure 1. We term these two basins the eastern and western lowland basins.

MODEL AND IMPLEMENTATION

The Distributed Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta *et al.*, 1994, 2002) is the basis of our modelling study. DHSVM was originally designed for mountainous forested watersheds and is primarily a saturation excess flow model. Recently, however, Cuo *et al.* (2008) incorporated within DHSVM parameterizations appropriate to urban basins. The Cuo *et al.* (2008) algorithm simulates urban hydrological processes by using parameters such as impervious area fraction, detention storage and detention decay rate, which are specified for model pixels classified as urban. The basic premise of the algorithm is that when there is an impervious surface (which exists only in pixels classified as urban), part of the impervious surface is connected to the stream channel directly and part of the impervious surface is connected with detention storage. When runoff occurs on an urban pixel, a fraction of the runoff goes to the stream channel directly, and the rest goes to detention storage and is discharged slowly. DHSVM represents physical processes such as the land surface energy balance, unsaturated soil moisture movement, saturation overland flow, snow melt and accumulation, and water table recharge and discharge. Using a digital elevation model (DEM) as a base map, DHSVM explicitly accounts for soil and vegetation types, and stream channel network and morphology. Wigmosta *et al.* (1994, 2002) provide a detailed description of the model.

Data

Model input data include both temporally varying and fixed data. The temporally varying data are essentially all surface climatological data used to force the model, and include precipitation and temperature (at daily or shorter time steps), downward solar and longwave radiation, surface humidity, and wind speed. Temporally fixed data include digital topography, soil class and depth, vegetation class, and stream network characteristics. The DEM we used, which was derived from USGS data (US Department of Interior/US Geological Survey, http://seamless.usgs.gov/), has a spatial resolution of 150 m. This DEM was the basis for determination of the boundaries of the 13 upland, and two lowland basins (Figure 1). Table I summarizes the characteristics of the 15 basins. Stream networks were generated using DEM and Arcinfo (ESRI Inc.) macro language (AML) scripts. The Puget Sound soil class map was taken from the US general soil map (STATSGO) generated by the Natural Resources Conservation Service of the US Department of Agriculture. The AML script was used to create a soil depth file based on local slope (determined from the DEM), upstream source area, and elevation. The scripts can be downloaded from the DHSVM website (www.hydro.washington.edu/Lettenmaier/Models/DHSVM). Subsequent changes to model soil depths were made during the calibration process.

Two land cover maps were used: 2002 land cover (Alberti *et al.*, 2004) and reconstructed 1883 land cover. The 1883 land cover map was taken from the Density of Forests—Washington Territory Map (Department of Interior/US Geological Survey, 1883). The 1883 survey map was digitized and georeferenced to maps in the Washington Atlas and Gazetteer (2001) in ArcMap (ESRI Inc.). The 1883 survey map contains nine classes of forest density ranging from 0 to greater than 200 cords per acre. Based on the location and density of the forest, land cover types were reclassified and transformed to be compatible with the land cover types used by Alberti *et al.* (2004). The forest density classes ranging from 0–2 cords per acre for the most part occur near the crests of the Cascade and Olympic Mountains, and so we reclassified these categories as snow/rock to match the Aberti *et al.* (2004) classifications. Forest densities ranging from 2 to 5 cords per acre are mainly located along shorelines and coasts, and these categories were classified as grass/crop/shrub. The other categories, which are mainly located in lowland areas inland from shorelines and on the slope of the mountains, were classified as forest. To distinguish between mixed/deciduous and coniferous forest, an elevation threshold of 300 m was used as in Harlow *et al.* (1991) and Crittenden (1997). Forest above 300 m was assigned to the coniferous category, whereas below 300 m, it was assumed to be mixed

Table I. General characteristics of Puget Sound sub-basins and gauges used in the study

Basins	Area (km^2)	Elevation range (m)	Mean annual T_{min} (°C)	Mean annual T_{max} (°C)	Mean annual Precip. (mm)	Calibrated gauges	Gauge locations	Gauge elevation (m)	Calibration periods	Validation periods
Skagit	8060	0–3300	−0·5	10	2400	12 174 000	Ruby Creek Near Newhalem, WA	474	1935–1945	1945–1949
Stillaguamish	1724	0–2000	2	12·5	2400	12 161 000	SF Stillaguamish River near Granite Falls, WA	94	1960–1970	1970–1980
Snohomish	3985	0–2400	1	11	2400	12 141 300	Middle Fork Snoqualmie River near Tanner, WA	238	1993–2002	1983–1993
Cedar	470	0–1600	2·6	12·6	2100	12 115 000	Cedar River near Cedar Falls, WA	475	1982–1992	1992–2002
Green	1055	8–1700	2·1	12	2000	12 104 500	Green River near Lester, WA	451	1973–1983	1983–1993
Puyallup	2588	0–4400	1·5	11·6	1600	12 094 000	Carbon River near Fairfax, WA	366	1991–2002	1967–1977
Nisqually	1860	0–4400	2·5	13	1600	12 083 000	Mineral Creek near Mineral, WA	408	1982–1992	1992–2002
Deschutes	429	0–1200	4·3	15·4	1200	12 078 720	Black Lake ditch near Olympia, WA	*	1988–1990	*
Skokomish	620	0–1900	2·4	13	3000	12 056 500	NF Skokomish R BL Staircase RPDS NR Hoodsport, WA	232	1982–1992	1992–2002
Hamma hamma	216	3–2000	0·2	10·8	2500	12 054 500	Hamma hamma River near Eldon, WA	155	1951–1961	1961–1970
Duckabush	197	1–2000	0	10·7	2400	12 054 000	Duckabush River near Brinnon, WA	74	1981–1991	1991–2002
Dosewallips	301	0–2300	−1·6	9·4	2100	12 053 000	Dosewallips River near Brinnon, WA	90	1939–1949	1930–1939
Quilcene	178	0–2300	−0·8	10·7	1600	12 052 210	Big Quilcene River below diversion near Quilcene, WA	308	1994–2002	*
Lowland-east	7055	0–1500	3·8	14·2	1500	12 113 349	Mill Creek near mouth at Orillia, WA	*	1997–2002	*
						12 126 900	Scriber Creek near Mountlake Terrace, WA	*	1984–1986	*
						12 120 000	Mercer Creek near Bellevue, WA	5	1997–2002	1992–1997
						12 080 500	Woodward Creek near Olympia, WA	34	1988–1990	*
						12 125 500	Bear Creek at Woodinville, WA	9	1967–1969	*
Lowland-west	1652	0–1900	3·4	13·8	1500	—	—	—	—	—

* Data are not available from USGS website.

conifer/deciduous. On the 1883 survey map, there is no urban category, however, the names of the major cities do exist on the map. Using the names of cities as clues, and based on county historical records and census data, the areas of those cities were outlined and classified as light-medium urban. This is based on an assumption that the cities expanded from the core areas which existed early on, and the core areas developed into the current central metropolitan areas.

Figures 2 and 3 show the reconstructed 1883 land cover map, and the 2002 land cover map from Alberti *et al.* (2004). In Figure 3, the major metropolitan areas along the Everett–Seattle–Tacoma corridor of western Washington are evident within the eastern lowland watershed. Table II compares fractions of the various land cover types from the two maps. It should be noted that there are some inevitable inconsistencies. For instance, the high elevation area of snow/rock as delineated in the 1883 map clearly does not match that of the 2002 map, which is based on satellite imagery. Nonetheless, the two maps do form a plausible basis for evaluation of the implications of land cover change on the hydrology of the basin.

Three sets of climate forcing data were generated using methods outlined in Maurer *et al.* (2002). 86 long-term stations from National Climate Data Center (NCDC) records were selected that have observations of daily minimum and maximum temperature (°C), and daily precipitation (m), among which 23 stations for temperature and 27 stations for precipitation have at least 60% non-missing values for the 1915–2006 period. These station data were gridded to one-sixteenth degree spatial resolution using the procedures described by Maurer *et al.* (2002) and Hamlet and Lettenmaier (2005). In addition to precipitation and temperature, DHSVM requires downward solar and longwave radiation, surface humidity, and wind speed. Downward solar and longwave radiation were derived from relationships with the daily temperature range and daily temperature, respectively, whereas surface humidity was derived using an assumption that the daily minimum temperature is equal to the dew point (see Thornton and Running, 1999; and Kimball *et al.*, 1997, respectively). Wind speed (m s^{-1}) was obtained from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis project (Kalnay *et al.*, 1996), also regridded to one-sixteenth degree spatial resolution (prior to the initial year 1949 of the NCEP-NCAR reanalysis, wind speed was set to the monthly climatological average, interpolated to one-sixteenth degree).

Using the procedures developed by Nijssen *et al.* (2001), daily forcings were disaggregated to 3-hour intervals. In brief, daily temperature and relative humidity were interpolated to hourly values using spline interpolation. Daily precipitation was evenly apportioned to hourly. Although hourly data would be ideal if available for the apportionment, there are far fewer hourly than daily stations, and in any event, the largest storms

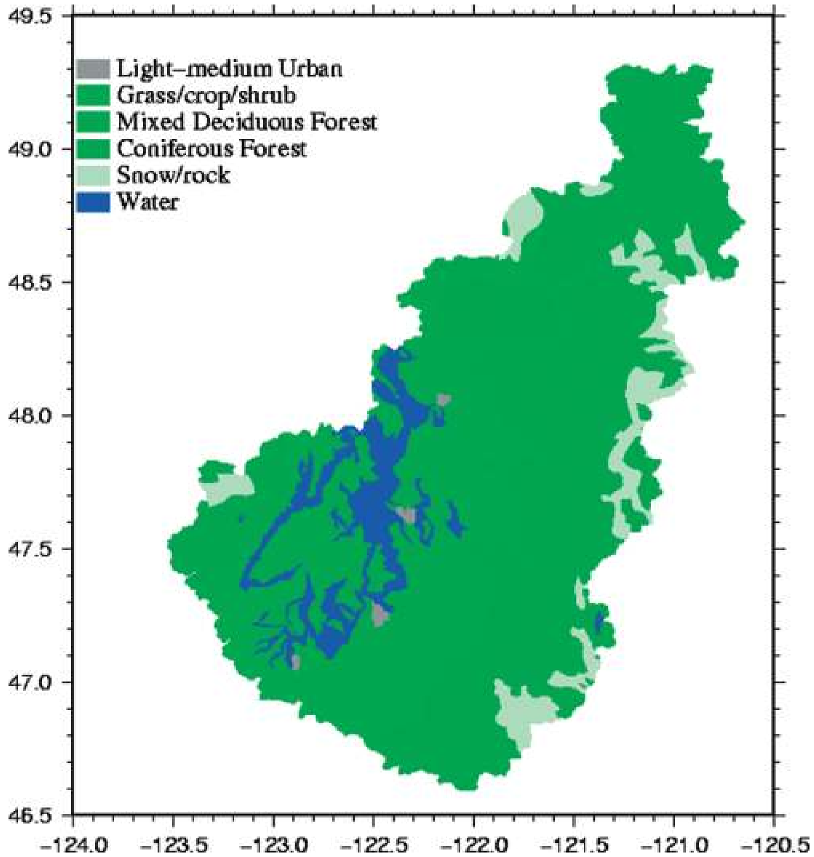

Figure 2. 1883 land cover map (source: US Department of Interior/US Geological Survey, 1883)

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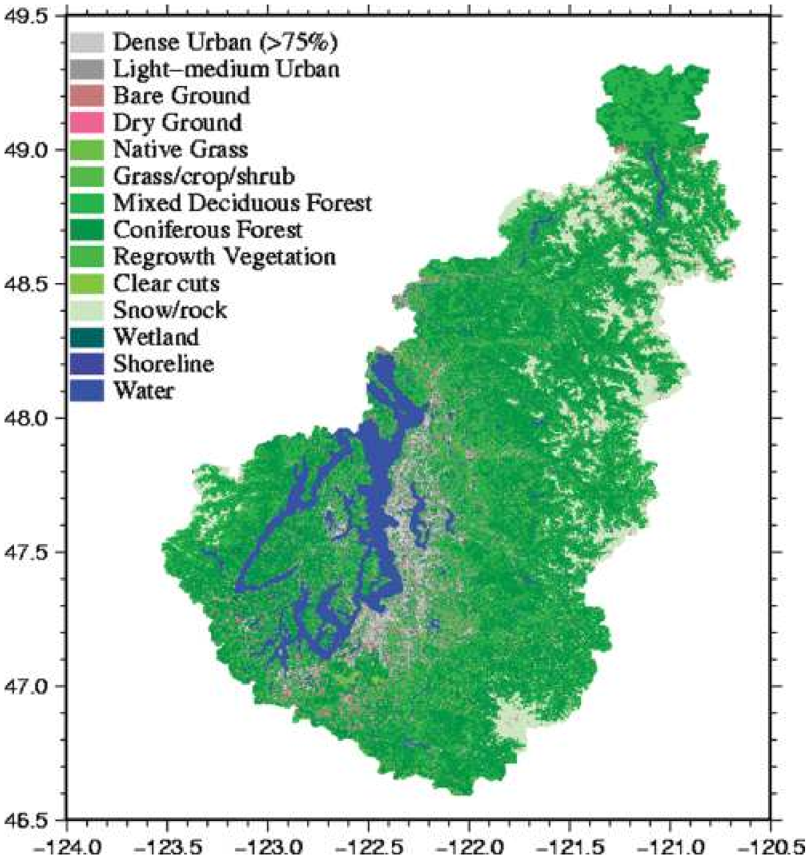


Figure 3. 2002 land cover map (source: Alberti *et al*., 2004)

Table II. Proportions of land cover types in the Puget Sound basin, 1883 and 2002

Land cover types	1883	2002
Dense urban (>75% impervious area)	—	2·41
Light-medium urban (<75% impervious area)	0·4	3·97
Bare ground	—	0·42
Dry ground	—	1·30
Native grass	—	0·05
Grass/crop/shrub	7·43	5·36
Mixed/deciduous forest	29·61	32·19
Coniferous forest	48·23	36·41
Regrowth vegetation	—	0·61
Clear cuts	—	0·50
Snow/rock	6·38	7·85
Wetlands	—	0·34
Shoreline	—	0·13
Water	7·96	8·46

in the Pacific Northwest almost always occur in late fall or winter when weather is controlled by large synoptic weather systems, which typically have durations much longer than one day. Furthermore, our analysis of peak flow changes is based on daily, rather than instantaneous, maximum flows. Daily wind was assigned as hourly wind. Hourly downward shortwave and longwave radiation were calculated by considering station location, date, local time, hourly temperature and humidity, transmissivity, emissivity and cloudiness using methods described in Nijssen *et al.* (2001). Hourly forcing data were then aggregated into 3-hour time steps by averaging or summation. The one-sixteenth degree grid cells were used as pseudo-stations to drive DHSVM at the 3-hour time step, which is essential to account for diurnal variations in snow accumulation and ablation, among other hydrological processes.

Long-term trends in the gridded temperature data were controlled to match those present in the US Historical Climate Network stations (Karl *et al*., 1990), and to avoid spurious trends that otherwise might have been associated with differences in station record lengths following procedures described in Hamlet and Lettenmaier (2007). A second data set was formed in which temperature was adjusted (in the long-term monthly mean) to 1915, the initial year of the historical record. A third data set was formed in the same manner, except that the temperature was adjusted to 2006 conditions. The basic assumption of these adjustments is that temperature trends are linear, an assumption that was verified by visual inspection of the time series. In the adjustment process, trends are computed for each month during the entire period (hence, 12 values for 12 months for the entire period), and the adjustment is made about the specified pivotal years (1915 and 2006). These adjusted data sets were used to segregate effects of long-term changes in temperature from land cover change.

The historical climate data set and current land cover (2002) were used in model calibration and validation. DHSVM was calibrated at 13 upland stream gauges

(Table I and Figure 1) for which no dams exist above the gauges in the Cascade and Olympic regions, and five gauges in Everett–Seattle–Tacoma corridor of lowland Puget Sound to represent varying extents of urbanization). The calibration period varied from station to station depending on the specific period of record, with a maximum of 11 years of record used for this purpose (Table I). Model performance was evaluated using an independent sequence of record of length approximately equal to the calibration period. Calibration was performed primarily by matching monthly simulated and observed mean streamflows, however an attempt was also made to match the mean statistics of daily flow and daily peaks. For the daily peak calibration, the largest 10 daily peaks for independent storms in each year were selected from both simulated and observed time series. In the Deschutes River basin, no upland gauges existed with long-term records that were free from major anthropogenic effects. Therefore, a lowland gauge in the basin was used for calibration. Figure 1 shows the locations of all the gauges used for calibration and validation. Observed and simulated daily, monthly flow means and daily peak flow means, and daily and monthly N-S model efficiency (Nash and Sutcliffe, 1970) were used to evaluate the quality of the model calibrations (Table III).

Model implementation

Figures (4a)–(c) show the calibrated and observed monthly mean streamflows at the 12 upland and six lowland gauges located in the eastern and western upland drainages, and the Everett–Seattle–Tacoma lowland area. As shown in Table III, for the upland gauges, (monthly) simulated means are within 9% to −17% of the observed means; and monthly N-S model efficiencies are in the range 0·59–0·87 for the calibration periods. Daily N-S efficiencies are in the range of 0–0·75. The lowest daily N-S number was for Stillaguamish River, mostly due to the underestimation of large peak flows, quite likely due to precipitation problems. Model performance was slightly degraded in the validation relative to calibration periods. For the lowland basins, simulated validation period means were within 14% to −37% of observed means. Scriber and Mill Creek (12 113 349) had monthly N-S model efficiencies greater than 0·90, whereas the N-S model efficiency for Woodward Creek (12 080 500) was −0·10 in the calibration period. Woodward Creek and Bear Creek streamflow were poorly simulated, which apparently was due primarily to anomalously low precipitation input at these particular sites, rather than model parameters. Table IV shows that during the calibration period, simulated daily peak flow means were within −36% to 47% of the observed means, with the highest (absolute) difference in the Deschutes and Snohomish and lowest difference in Scriber Creek, Woodward Creek, Skokomish River. In general, the model captured the major characteristics of monthly streamflow and daily peak flows in the Puget Sound drainages. Based on the results shown in Figures 4a–c and Tables III and IV, the model performance was deemed acceptable for purposes of evaluating the sensitivity of runoff to land cover and climate change.

Results—land cover change effects

Our assessment of land cover change effects is based on analysis of simulated differences in annual and seasonal flows, as well as annual (daily) maximum

Table III. Statistics of model calibration and validation

Basins (gauge)	Annual mean in calibration period			N-S model efficiency		
	Obs. (m^3 s^{-1})	Sim. (m^3 s^{-1})	Relative error (%)	Calibration (daily)	Calibration (monthly)	Validation (monthly)
		Upland basins				
Skagit (121740000)	15·14	16·56	9	0·75	0·83	0·85
Stillaguamish (12161000)	30·68	31·38	2	0	0·72	0·78
Snohomish (12141300)	35·5	36·08	2	0·50	0·79	0·75
Cedar (12115000)	6·85	6·18	−10	0·61	0·81	0·81
Green (12104500)	9·79	9·76	0	0·54	0·72	0·71
Puyallup (12094000)	12·3	11·6	−6	0·46	0·65	0·62
Nisqually (12083000)	9·18	9·20	−3	0·69	0·87	0·86
Deschutes (12078720)	0·97	1·01	4	0·52	0·74	—
Skokomish (12056500)	14·00	14·05	0	0·60	0·81	0·78
Hamma hamma (12054500)	10·67	10·36	−3	0·44	0·70	0·74
Duckabush (12054000)	11·72	11·01	−6	0·60	0·71	0·73
Dosewallips (12053000)	12·26	10·22	−17	0·55	0·68	0·69
Quilcene (12052210)	4·39	4·76	8	0·52	0·59	—
		Lowland basins				
Mill (12113349)	0·44	0·44	0	0·69	0·90	—
Scriber (12126900)	0·25	0·26	4	0·66	0·92	—
Mercer (12120000)	0·66	0·57	−14	0·51	0·36	0·64
Woodward (12080500)	0·19	0·12	−37	−0·10	0·04	—
Bear (12125500)	0·73	0·83	14	0·44	0·51	—

* Observation data are not available except during calibration periods.

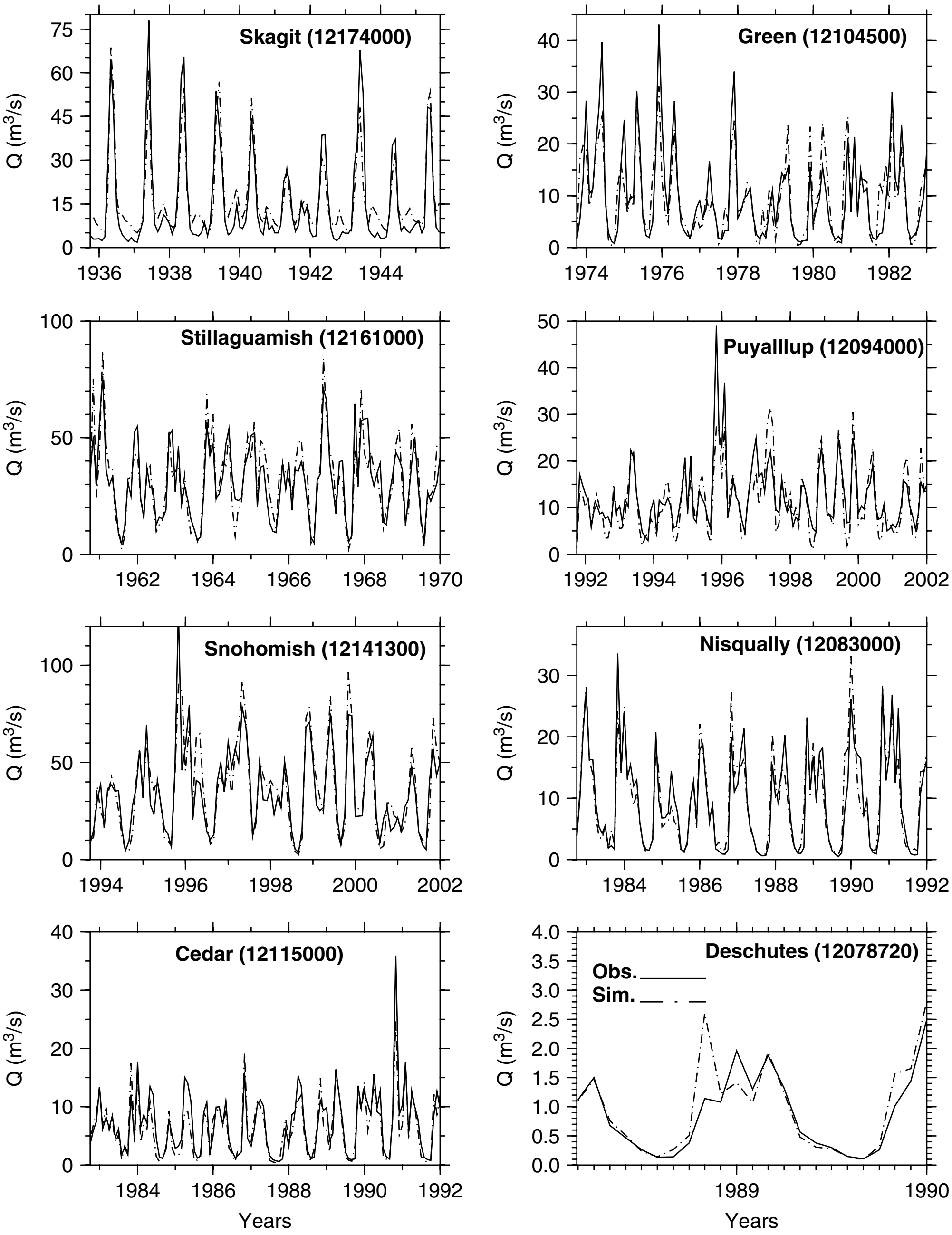


Figure 4. Calibration results for (a) eastern (Cascade) upland gauges; (b) western (Olympic) upland gauges; (c) selected eastern lowland gauges

flows. These metrics provide fundamentally different information, which reflects the potentially complex interactions between vegetation cover, the space–time characteristics of precipitation, and seasonal variations of evaporative demand, which can affect peak, seasonal, and annual accumulated flows somewhat differently. For instance, land cover change is expected to affect flows at all three time scales because of changes in evaporative demand and infiltration dynamics. Temperature change, on the other hand, will mostly likely affect the seasonal flows. Also, we are interested in how temperature change will affect annual and peak flows in the absence of precipitation and land cover change. Examining the same variables for land cover change and temperature change effects provides a common basis for comparing the importance of the effects. Finally, streamflow changes at all three time scales have implications for water resources management.

To isolate land cover change effects on the hydrology of the basin, the long-term temperature trend was removed and temperature was adjusted to 2006 conditions as described earlier. Precipitation trends were not adjusted due to the lack of statistical significance in precipitation trends. The results at 18 calibrated gauges were examined as individual cases. In addition, 13 upland basins and two lowland basins were aggregated to five regions: Puget Sound east and west, upland and lowland, as well as the entire Puget Sound basin. The eastern and western regions were taken to include part of the entire drainage shown in Figure 1, which is an upland region

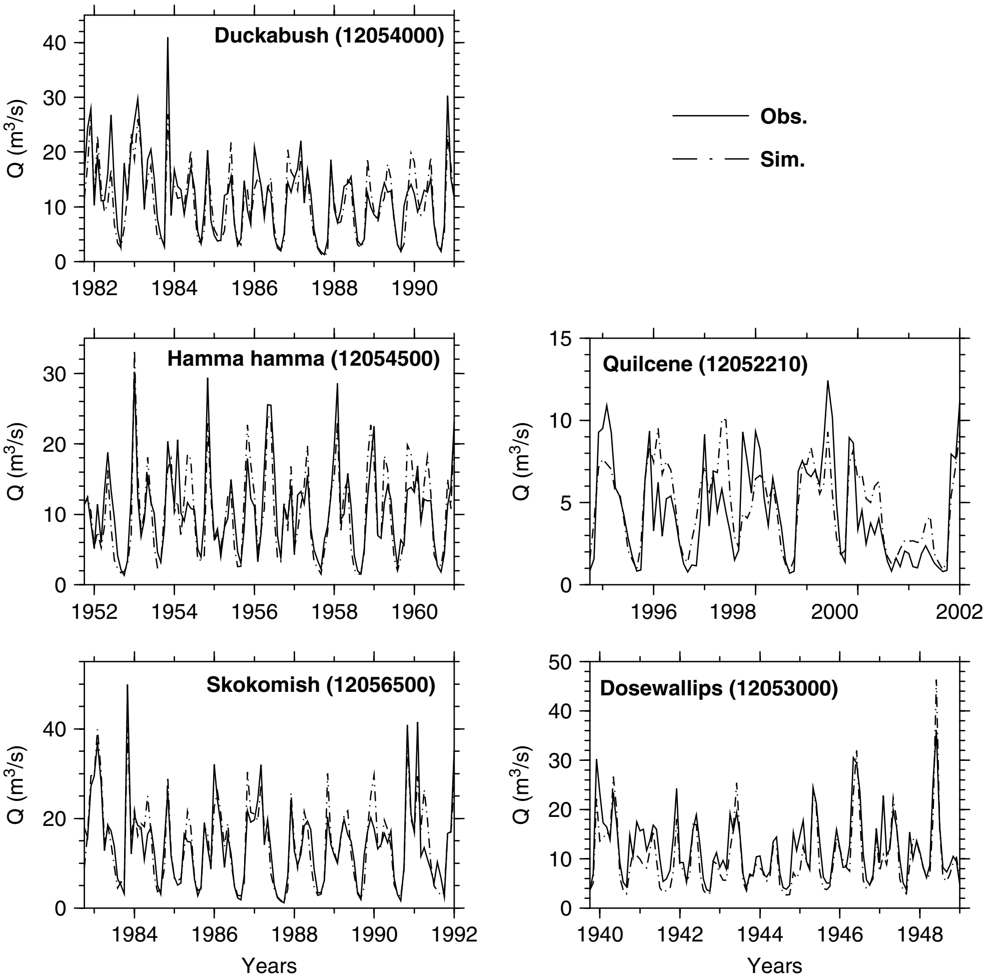


Figure 4. (*Continued*)

south of the Admiralty inlet sill (which is significant to the circulation of the Puget Sound estuary). Of the basins shown in Figure 1, those included in the eastern region are Deschutes, Nisqually, Puyallup, Green, Cedar, Snohomish, and Stillaguamish. Those included in the western region are Skokomish, Hamma Hamma, Duckabush, Dosewallips and Quilcene. The lowland region, which is a mix of residential and forest, includes both eastern and western lowland basins. The upland region, which is mostly non-residential, includes eastern and western regions, as well as the Skagit basin. The entire Puget Sound region includes all 13 upland basins and two lowland basins (Figure 1 shows the delineation of the sub-basins that compose the five regions).

To evaluate land cover change effects, simulations for the period 1915 to 2006 with temperatures adjusted to a 2006 inferred mean and 2002 (current) land cover were compared with simulations using the same forcings, and 1883 land cover. Figure 5a shows that for the upland gauges on the eastern side of Puget Sound, fall, winter and spring streamflow is higher for the 2002 vegetation scenario compared with 1883. At gauges12174000 in the Skagit, 12 161 000 in the Stillaguamish, and12141300 in the Snohomish, summer streamflow is slightly lower for the 2002 scenario. In the western uplands, the 2002 vegetation scenario has higher fall, winter and spring streamflow but lower summer flows. Gauge 12 053 000 in the Dosewallips has slightly lower streamflow in winter and summer but higher spring flow (Figure 5b).

Unlike upland basins, land cover change in lowland basins is primarily associated with urbanization. To evaluate these effects, five lowland gauges having different amounts of urbanization, as well as gauge 12 078 720 in the Deschutes, were evaluated (Figure 5c). Gauges 12 113 349 (Mill Creek near mouth at Orillia, 71% urbanized in 2002), 12 126 900 (Scriber Creek near Mountlake Terrace, 69% urbanized), 12 120 000 (Mercer Creek near Bellevue, 59% urbanized), and 12 080 500 (Woodward Creek near Olympia, 35% urbanized) have similar seasonal patterns: the 2002 land cover scenario has higher flows throughout the year than the 1883 scenario. The figure shows that in these lowland basins, streamflow changes are generally associated with the degree of urbanization. Also, streamflow changes seem to be related to the contributing area to the gauge and do not correspond to the amount of urbanization when urbanization is greater than 60%. For example, the drainage area for Mercer Creek basin is 37·3 km^2, for Scriber Creek basin it is 16·1 km^2, and for Mill Creek basin it is 15·2 km^2. But while Mercer Creek urbanization (59%) is lower than

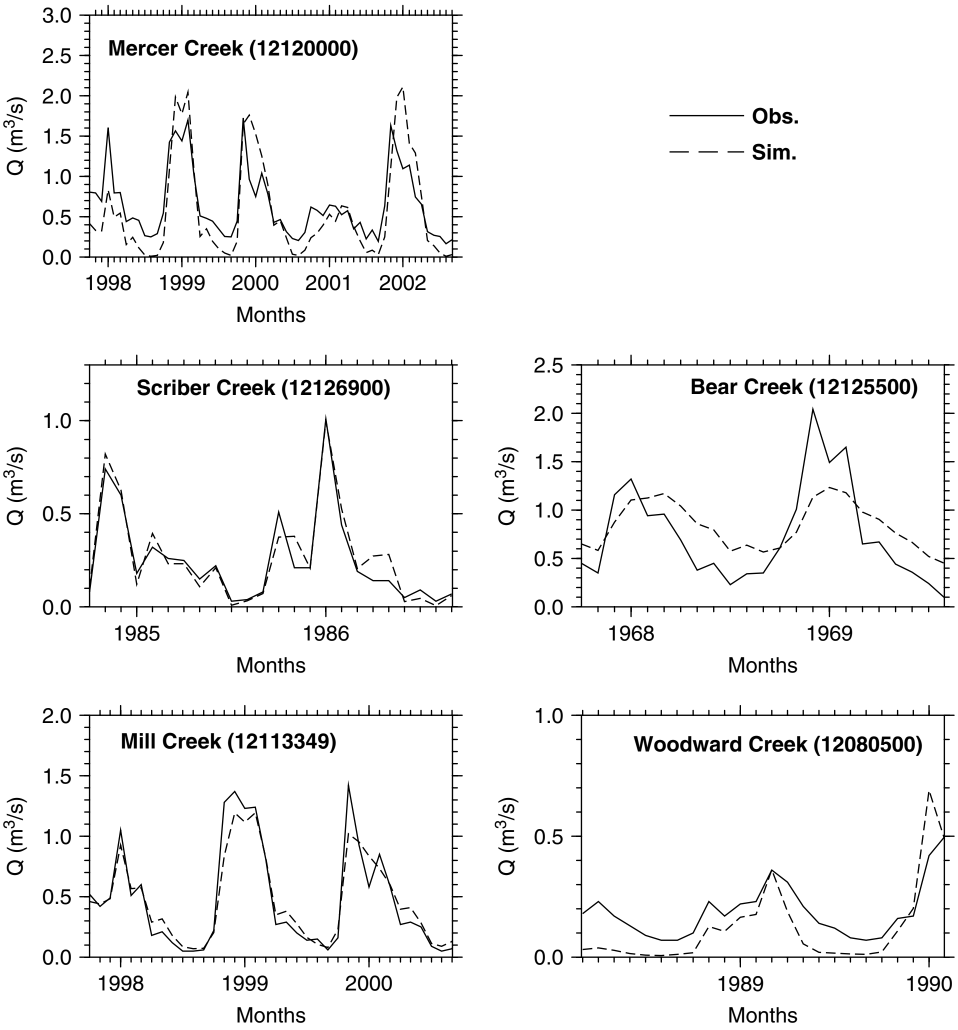


Figure 4. (*Continued*)

Mill Creek (71%), the mean monthly flow change in Mercer Creek (161%) is higher than Mill Creek (53%).

In general, the higher seasonal flows for the 2002 land cover in lowland basins are at the expense of decreased evapotranspiration. 1-day, 3-day and 7-day cumulative flows were examined, which showed that most of the lowland subbasins have higher low flows in the 2002 scenario. This is consistent with a study by Konrad and Booth (2002). In a previous study by Cuo *et al.* (2008) in the Puget Sound urbanizing basin, both low flows and ET were examined using DHSVM for an urbanizing basin in the Puget Sound. The study found that ET decreased for all months in 2002 relative to 1883 land cover conditions. The largest deceases are in winter, and the lowest in the summer. Cuo *et al.* (2008) also found that in the urbanizing basin, decreased ET overwhelmed decreased infiltration.

In contrast to the other lowland basins, the two least urbanized basins—Bear Creek basin at Woodinville (24% urbanized), and Black Lake Ditch near Olympia (31% urbanized) have reduced winter flows in the 2002 land cover scenario relative to 1883. The difference appears to be related to the criterion that was used to divide the mixed/deciduous and coniferous forests from the 1883 land cover map. Patches of coniferous forest existed in lowland basins in the 2002 scenario but there was very little lowland coniferous forest in the 1883 scenario. For example, in the Bear Creek basin, the coniferous forest fraction is 24% in the 2002 scenario, which is the highest among the six lowland creek basins, whereas in 1883 there was no coniferous forest in this basin. Coniferous forest has higher evapotranspiration than deciduous forest (Swank and Douglass, 1974), especially in winter time when deciduous forests have no leaves and soils are wet.

Simulated seasonal ET in lowland-east was examined for 2002 land cover in which about 22% coniferous forest exists. In winter (December, January and February) mean monthly ET is 55·5 mm, and in summer (June, July and August) mean monthly ET is 52·6 mm. They are comparable in the amount which is largely due to water stress in the summer in the PNW. The high ET exists in the spring (March, April and May). To further demonstrate the difference in ET for coniferous and deciduous forest, an experiment was done in western lowland. Three scenarios were used: (1) all coniferous forest (100% coniferous forest and water); (2) 1883 land cover (9% coniferous forest, about 90% mixed

Table IV. Mean and standard deviation ($m^3 s^{-1}$) of daily peak flows selected from top 10 peaks in each year

Basins (gauge)	Observation mean ± standard deviation	Simulation mean ± standard deviation	Relative error in mean (%)
	Upland		
Skagit (121740000)	52·6 ± 23·7	46·3 ± 21·0	−12
Stillaguamish (12161000)	124·0 ± 81·6	87·2 ± 37·5	−30
Snohomish (12141300)	145·2 ± 119·5	93·6 ± 43·8	−36
Cedar (12115000)	30·1 ± 26·3	32·9 ± 3·0	9
Green (12104500)	44·4 ± 50·2	40·6 ± 30·0	−9
Puyallup (12094000)	43·5 ± 40·3	30·4 ± 16·2	−30
Nisqually (12083000)	41·3 ± 41·8	30·6 ± 23·2	−27
Deschutes (12078720)	1·5 ± 1·2	2·2 ± 2·5	47
Skokomish (12056500)	62·0 ± 49·2	63·8 ± 44·1	3
Hamma Hamma (12054500)	37·2 ± 24·0	47·9 ± 35·1	−29
Duckabush (12054000)	47·3 ± 32·4	42·6 ± 25·1	−10
Dosewallips (12053000)	36·7 ± 18·2	31·0 ± 12·9	−16
Quilcene (12052210)	17·7 ± 13·7	14·7 ± 5·4	−17
	Lowland		
Mill (12113349)	1·87 ± 1·65	1·19 ± 0·87	−36
Scriber (12126900)	1·70 ± 2·41	1·64 ± 2·05	−4
Mercer (12120000)	2·38 ± 2·0	1·89 ± 1·87	−21
Woodward (12080500)	0·35 ± 0·36	0·35 ± 0·79	0
Bear (12125500)	1·15 ± 0·71	1·23 ± 0·43	7

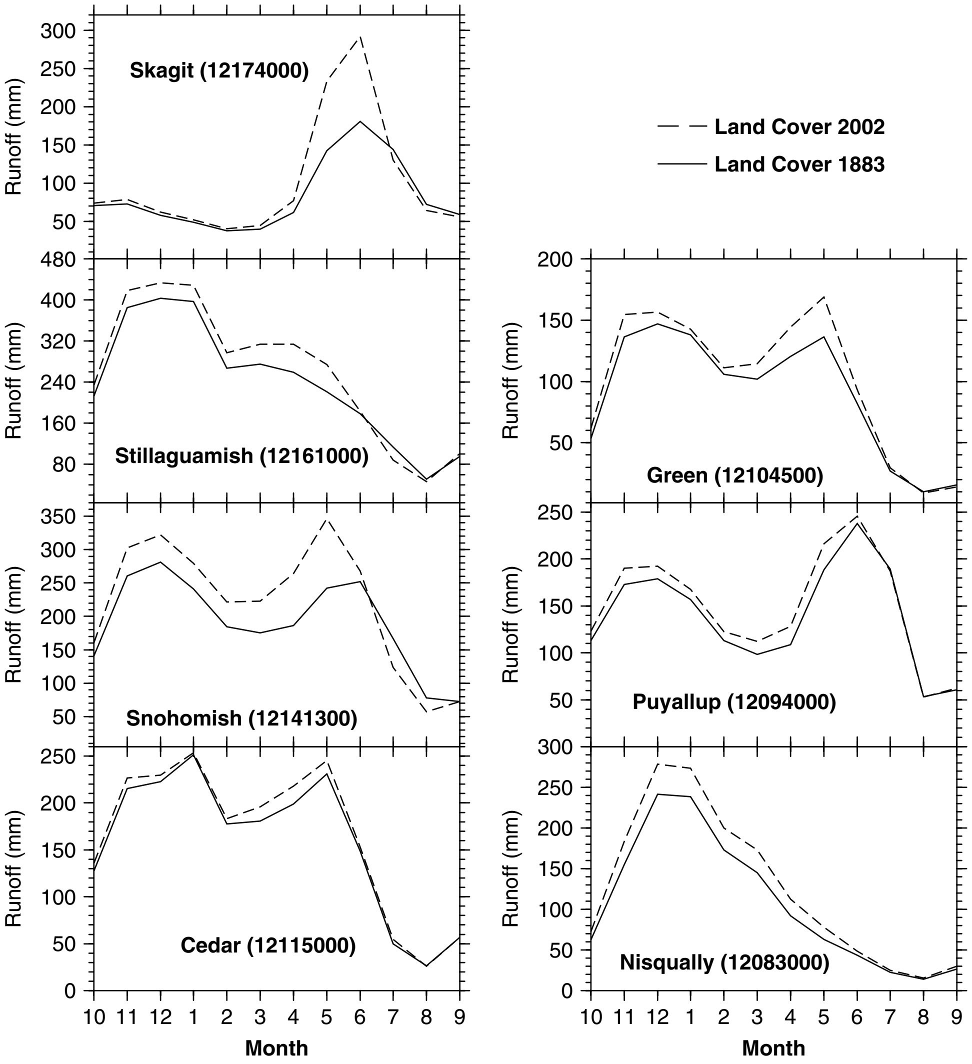


Figure 5. Predicted land cover change effects on seasonal run off for (a) eastern (Cascade) upland gauges; (b) western (Olympic) upland gauges; (c) selected eastern lowland (Greater Seattle area) gauges

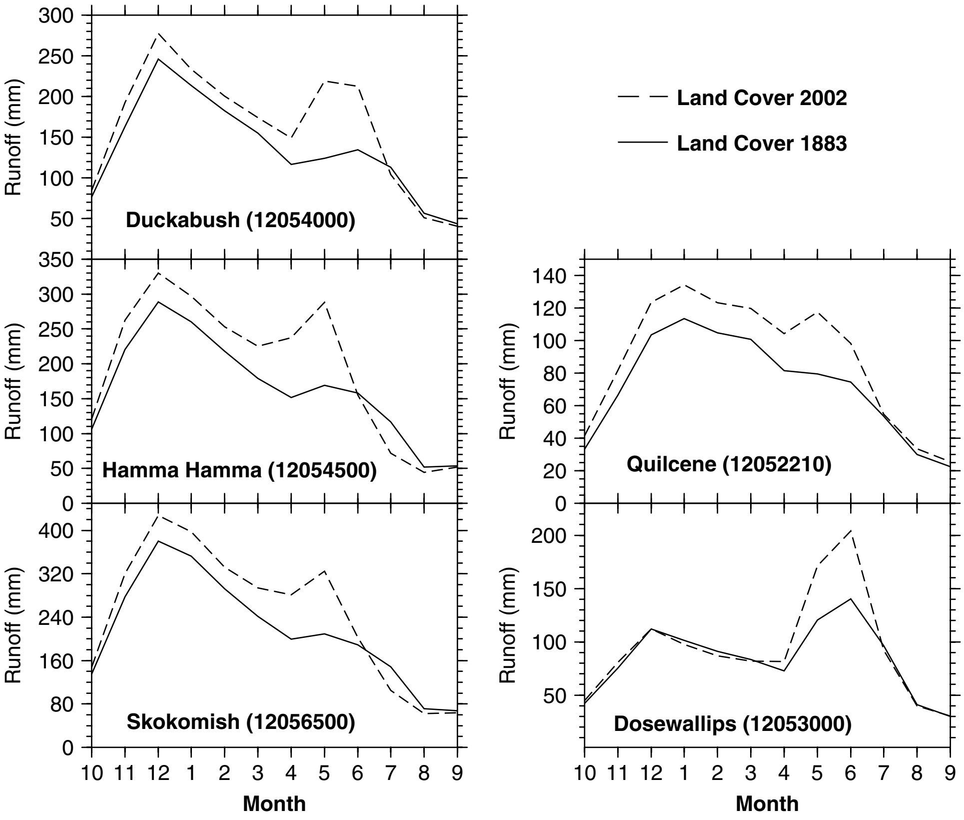


Figure 5. (*Continued*)

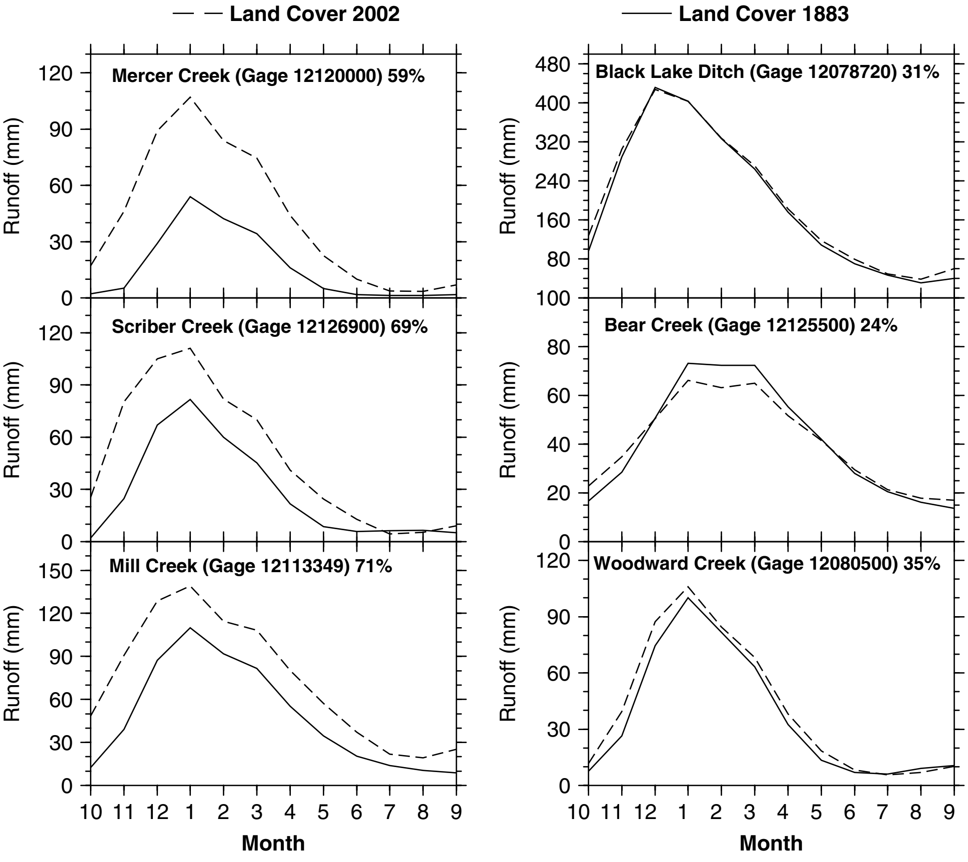


Figure 5. (*Continued*)

deciduous and grass/crop/shrub and water); and (3) 2002 land cover (46% coniferous forest, and about 45% mixed deciduous forest and water). Water area is about the same for all three scenarios. The simulation shows that the higher amount coniferous forest consumes more water, especially in winter time in the western lowland (Figure 6).

At a regional level, eastern and western uplands, and the entire Puget Sound basin appear to have similar patterns as the individual gauges, as shown in Figure 7. However, in the lowland region, the pattern is different from individual urban cases in that the lowland region has lower winter and spring flows. Analysis done in the Spring Brook Creek basin (65% urban, 25% forest) and eastern-lowland region (18% urban, 45% forest) shows different simulated seasonal ET patterns (Figure 8). In the individual urbanizing basin (Spring Brook Creek basin), ET is consistently lower for all months in 2002. But in the eastern lowland region, ET is higher in winter but lower in the late spring and summer for the 2002 scenario. The same ET pattern could be expected in the entire lowland region due to the similarity in the land cover composition between the eastern lowland and the entire lowland region. In the entire lowland region, the total urbanization is slightly reduced to 15%, and forest accounts for about 50%. Apparently, the differences in ET and streamflow between individual urbanizing basins

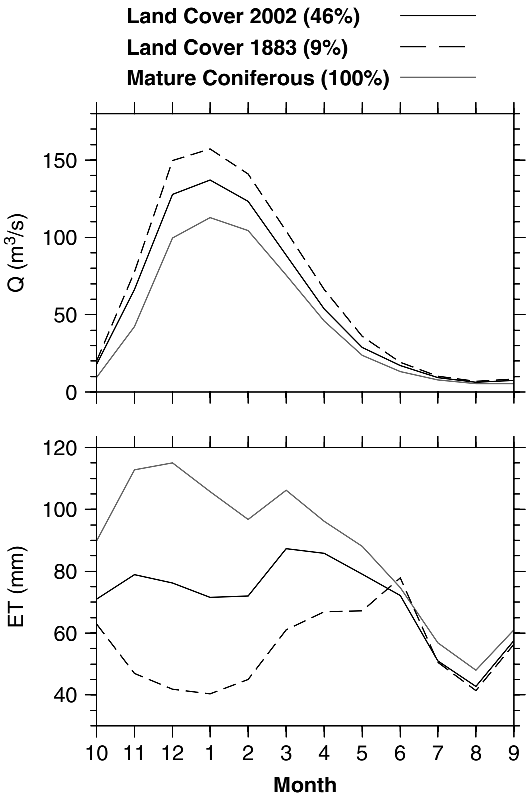


Figure 6. Mean monthly ET consumption and streamflow for coniferous forest, 1883 land cover and 2002 land cover in western lowland

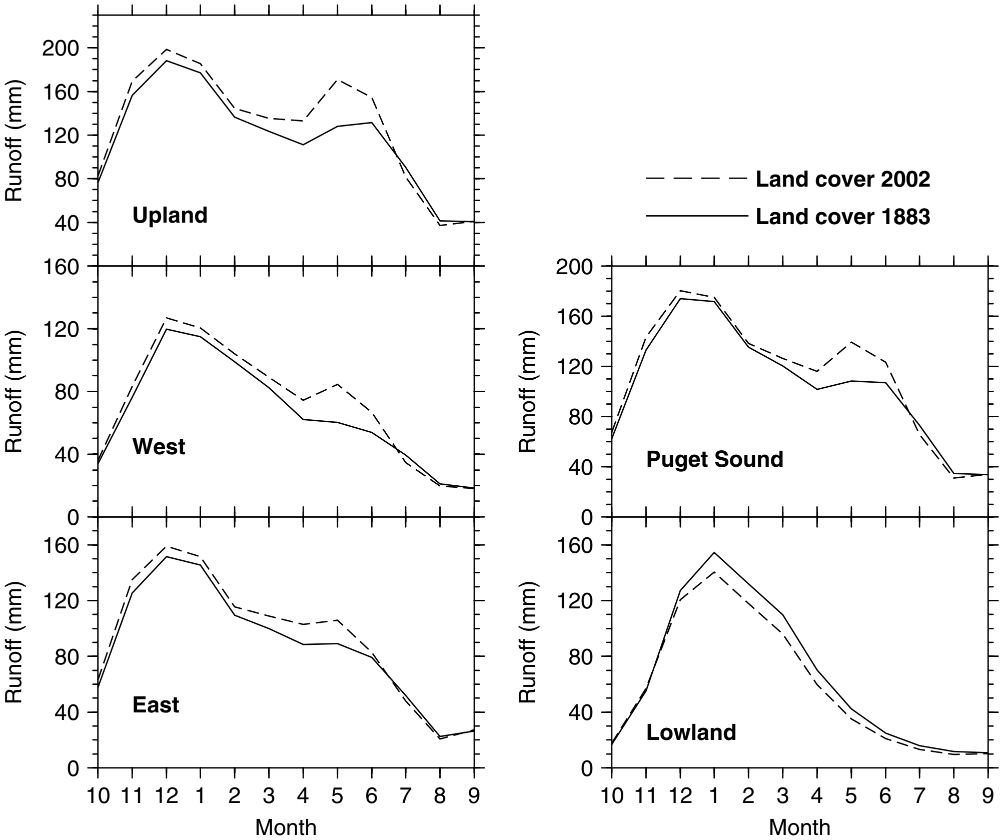


Figure 7. Predicted land cover change effects for five regions in the Puget Sound drainage. Note: East includes Deschutes, Nisqually, Puyallup, Green, Cedar, Snohomish, Stillaguamish; West includes Skokomish, Hamma Hamma, Duckabush, Dosewallips, Quilcene; Upland region includes all upland basins in the east, west and Skagit basin as well. Lowland region includes eastern lowland basin and western lowland basin; Puget Sound includes all basins: 13 upland and two lowland basins

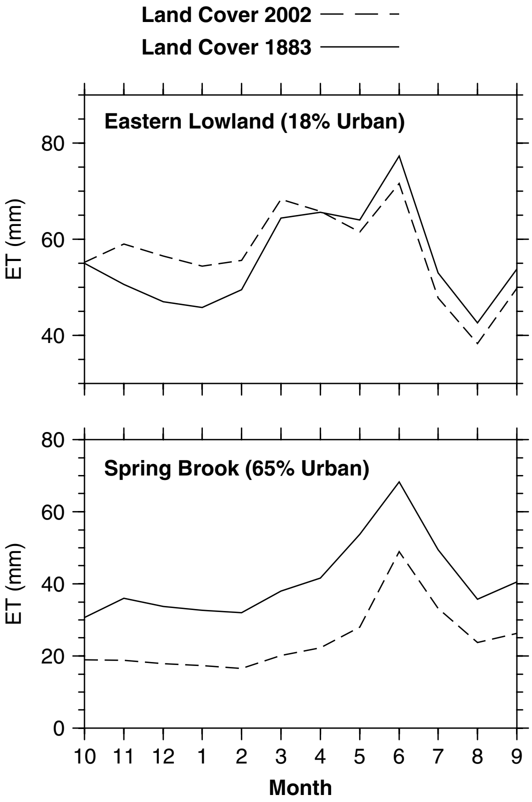


Figure 8. Comparison of mean monthly ET pattern in individual urbanizing basin (Spring Brook Creek basin) and eastern lowland region

and the entire lowland region are due to the composition of land cover classes.

Table V and Figures 9a–c show the land cover change effects on mean annual streamflow and annual maximum flow at all 18 gauges and five regions. The table and figures show that in general the 2002 land cover scenario has higher mean annual streamflow and annual maximum flow than the 1883 scenario. At individual gauges, the increase in annual discharge at the upland gauges ranges from 5% to 23%. The range of change at the lowland gauges is much larger: −2% to 162%. The increases in annual streamflow at individual gauges are mainly caused by decreased evapotranspiration due to much less vegetation coverage in the 2002 scenario. However, over the entire lowland region, the estimated change in annual streamflow was −6% and annual maximum flow was −3%. Again, the decrease in the two series in the lowland region appears to be associated with the criterion used in the partitioning of mixed/deciduous and coniferous forests (see, for example, Figure 6).

For the annual maximum peak flow in Figure 9a–c, gauge 12 174 000 in the Skagit basin and gauge 12 053 000 in the Dosewallips basin show a dramatic difference in peak flows between the two land cover conditions but it is probably due in part to inaccuracies in the 1883 land cover. Specifically, snow and rock, which were from the lowest density forest located near the mountain crest on the original USGS 1883 map, are more dispersed in the 2002 land cover than in the 1883 land cover map. On the other hand, the large inferred changes at lowland gauges appear to correspond to observed land cover change (Figure 9c), and in particular, to increases in impervious area.

Table V. Model predicted percent change in mean annual runoff and annual maximum flow due to land cover change, 1883–2002

Basins (gauge)	2002 vs 1883 change in annual flows (%)	2002 vs 1883 change in annual maximum flows (%)
Upland		
Skagit (12174000)	22·0	89·8
Stillaguamish (12161000)	9·6	6·4
Snohomish (12141300)	15·8	13·8
Cedar (12115000)	4·8	−0·4
Green (12104500)	11·8	2·6
Puyallup (12094000)	7·7	5·8
Nisqually (12083000)	16·7	11·4
Skokomish (12056500)	15·3	13·4
Hamma Hamma (12054500)	18·4	13·4
Duckabush (12054000)	19·3	15·7
Dosewallips (12053000)	11·6	24·1
Quilcene (12052210)	22·4	13·2
Lowland		
Deschutes (12078720)	4·7	12·6
Mill (12113349)	53·8	49·8
Scriber (12126900)	70·6	66·4
Mercer (12120000)	161·9	64·2
Woodward (12080500)	12·1	−4·0
Bear (12125500)	−1·6	17·1
Regional		
East	7·1	3·7
West	9·7	7·0
Upland	9·5	5·0
Lowland	−6·4	−2·8
Whole region	6·8	4·3

Cuo *et al.* (2008) performed a similar land cover change analysis in an urbanizing basin in the Puget Sound basin. That study shows that strong peak flow increases occur in response to increased imperviousness in the model, which is to be expected. For example, during 1 November 1995 to 30 June 1996, the average maximum peak of individual storms increased by 112% for the impervious surface existed model compared with the non-impervious surface model. Regionally, the difference between annual maximum flow for 2002 and 1883 land cover is modest (Figure 10), and is due mostly to the large amount of coniferous forest and mixed/deciduous forests in the western lowland area.

An obvious question, given the prevalence of inferred changes in streamflow associated with land cover change, is are these trends detectable in observations? Bowling *et al.* (2000) used a procedure that they termed residuals analysis to avoid the confounding effects of changes other than land cover (principally climate) on streamflow changes. The method tests for trend in the residuals of model simulations with fixed land cover (e.g. 1883) from observations. The idea is that the model simulation and observations are both affected by the same climate variations, so any trends in the residuals series can be

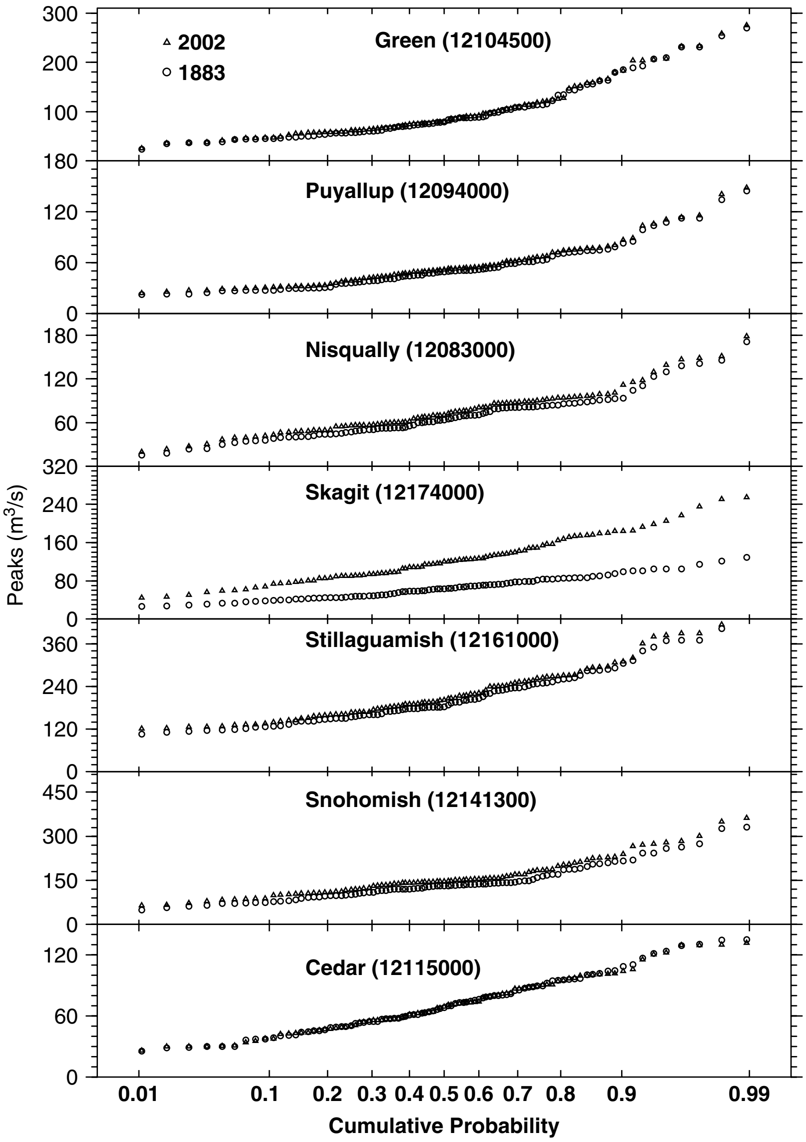


Figure 9. Predicted land cover change effects on annual maximum flow at (a) eastern (Cascade) upland gauges; (b) western (Olympic) upland gauges; (c) selected eastern lowland gauges (greater Seattle area)

attributed to land cover change. We identified the following gauges as having long enough streamflow records to be suitable for a statistical (Mann–Kendall) trend analysis of residuals: upland gauges 12 115 000 (Cedar River near Cedar Falls), 12 054 000 (Duckabush River near Brinnon), 12 056 500 (North Fork Skokomish River at Hoodsport), 12 133 000 (South Fork Skykomish at Index), 12 161 000 (South Fork Stillaguamish at Granite Falls), and lowland gauge 12 120 000 (Mercer Creek near Bellevue). The upland gauges all have at least 52 years of observations and are free from the effects of dams and streamflow diversions. Gauge 12 120 000 is affected by urbanization and has a record that starts in 1955. At each of these sites, we tested for trends in the annual flow, annual maximum flow, and seasonal flows using the Mann–Kendall test (Hirsch and Slack, 1984; Helsel and Hirsch, 2002).

Tables VIa and b summarize results of the Mann–Kendall trend analysis for the residuals (model minus observed) of annual maximum daily peaks (i.e. annual maximum flow), and annual and seasonal streamflow. The residual analysis shows that most of the gauges have increasing trends in annual maximum with three gauges having statistical significance, and half of the gauges show increasing trend in annual flow (Table VIa). Also, the Duckabush, Skokomish and Mercer Creek gauges have statistically significant increasing trends in either annual maximum or annual mean flows. At the other gauges, the minimum detectable differences are larger than the trends shown in Table VIa (see Table VIc for the minimum detectable differences). Duckabush and Skokomish gauges have statistically significant increasing winter trends. Most gauges have decreasing summer trends, and among them the Cedar basin has a statistically significant decreasing trend in the summer. The trends in the winter and summer are largely consistent with the model predictions. In Mercer Creek (lowland), almost all seasons have increasing trends

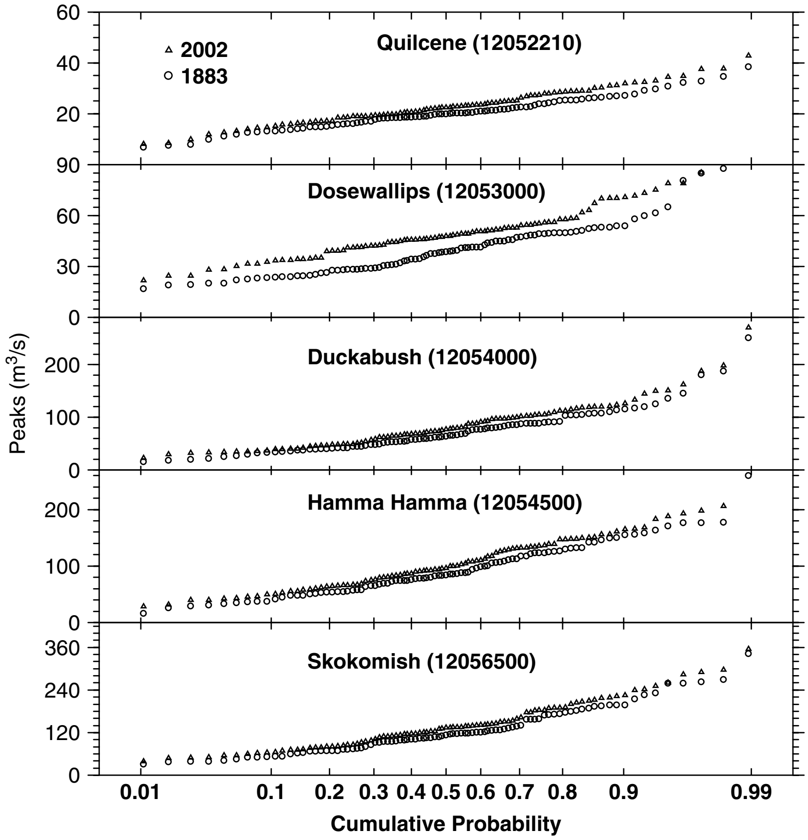


Figure 9. (*Continued*)

(Table VIb) which is also consistent with the model prediction

Results—temperature change effects

To study temperature change effects, two temperature scenarios were used in conjunction with 2002 land cover: temperature adjusted to the 1915 mean ('1915 climate'), and temperature adjusted to the 2006 mean ('2006 climate'). Like the land cover change analysis, we evaluated simulations for the 18 upland and lowland gauges and five regions.

Figures 11a–c and 12 show the simulated effects of temperature change on seasonal flow. For all of the upland gauges with the exception of gauge 12 174 000 (Skagit) and gauge 12 053 000 (Dosewallips), and all the regions except the lowland region, the flows for 2006 conditions are higher in late winter and early spring, lower in late spring and summer, which reflects generally warmer winter temperatures for 2006 relative to 1915. For the Skagit River gauge and Dosewallips River gauge, the 2006 scenario has higher spring and early summer flows, and lower late summer flow. The Skagit basin has much of its contributing area at high elevation, where the slight increase in winter temperature for 2006 relative to 1915 did not affect winter snow accumulation and melt patterns as much as in the other basins. The April snow water equivalent (SWE) analysis for the upland basins shows that the Skagit, Dosewallips, Nisqually and Puyallup basins, which have much of their area located at relatively high elevation, had reductions in SWE less than 23%. For the other upland basins in the intermediate elevation zone, the reductions in SWE were all more than 30%. In general, the warmer temperature regime tends to generate higher winter and late autumn flows but lower summer and spring flows.

Temperature change effects are manifested mainly through changes in snow accumulation and ablation and ET, which are evidenced primarily in the upland basins. Examination of April SWE shows that reductions due to temperature increases range from 16–74% in the upland basins. Temperature changes also affected ET in the upland basins, mostly in the winter months when increases ranged from 10–56%.

At the lowland gauges, seasonal streamflow trends due to temperature change are not as dramatic as at the upland gauges (Figure 11c). Also, the lowland urbanized gauges do not respond to temperature change as much as to land cover change (Figures 5c and 11c). Figure 11c shows that temperature change doesn't affect seasonal flow much at the lowland urbanized gauges because they are relatively unaffected by snow, which is the primary agent that responds to temperature change. For example, in the eastern lowlands, SWE is essentially zero in April for both 1915 and 2006 climate conditions. Also, ET changes are relatively small at lowland urbanized gauges. For example, the analysis of ET simulations by Cuo *et al.* (2008) shows that the largest difference is in January with a 13% increase for the warmer climate. In the other months, the changes are between −1% and 7%.

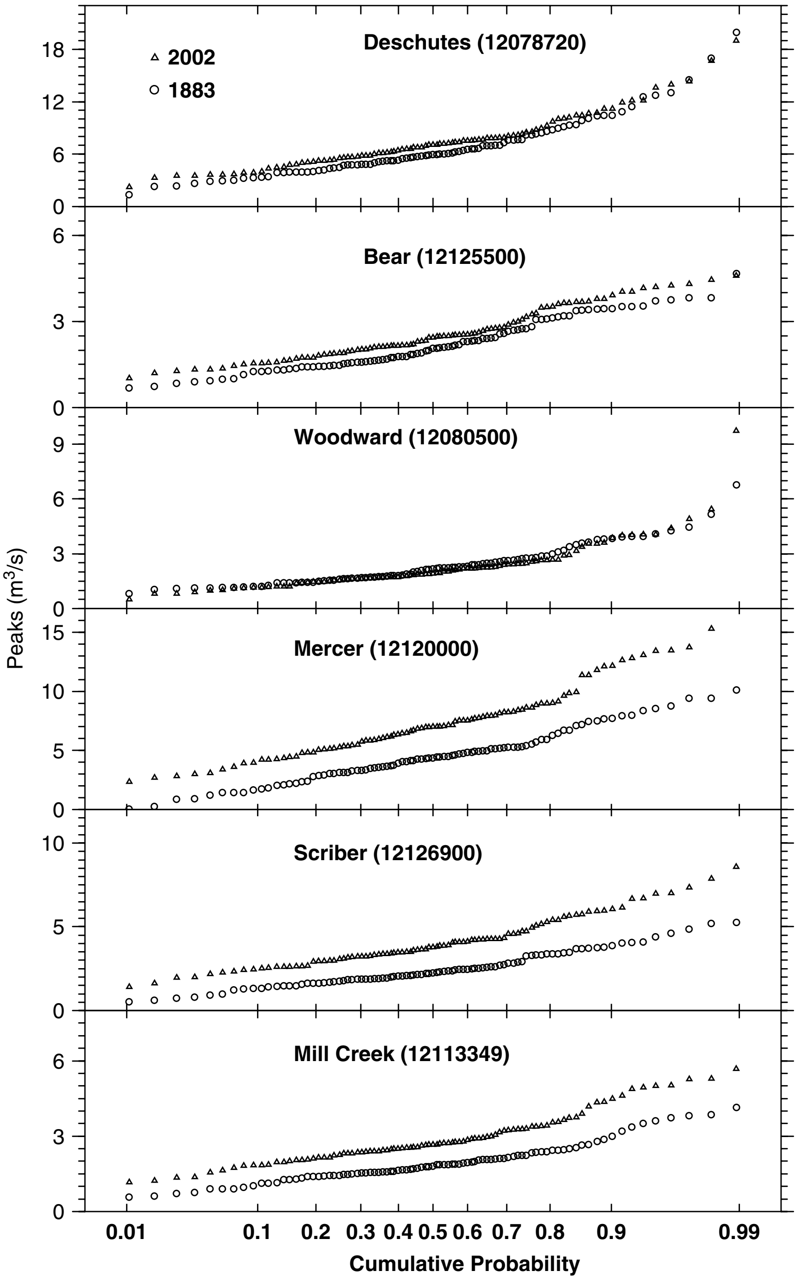


Figure 9. (*Continued*)

Table VII shows the relative change in winter and summer streamflow and annual streamflow due to temperature change. Besides showing that the warmer temperature regime tends to generate higher winter flow and lower summer flow in the upland, the table also shows that the gauges draining intermediate elevation basins which have mixed rain and snow precipitation in winter (hence resulting in double-peaked seasonal hydrographs, e.g. at gauge 12 115 000 in the Cedar basin) are more affected by the temperature change than either lowland basins or basins dominated by high elevation areas (see the single peak seasonal hydrographs for the Skagit). Regionally, the seasonal streamflow changes are similar to those for individual gauges. Table VII also shows that temperature change primarily affects the seasonal streamflow distribution rather than the mean annual streamflow.

Figure 13a–c shows temperature change effects on annual maximum flows at all 18 gauges. In general, the figure shows that gauges located in the uplands have higher annual maximum flows for the warmer temperature scenario. Gauges located at low elevations, on the other hand, show little sensitivity of the annual maximum flows to temperature. At the regional level, except lowland region, all regions show that 2006 condition has higher annual maximum flows than 1915 condition (Figure 14). Annual maximum flows in the lowland region are only slightly affected by the temperature, which is consistent with the individual urban gauges.

Land cover and temperature change effects comparison

Based on our analysis of the respective effects of land cover and climate change, it would be useful to

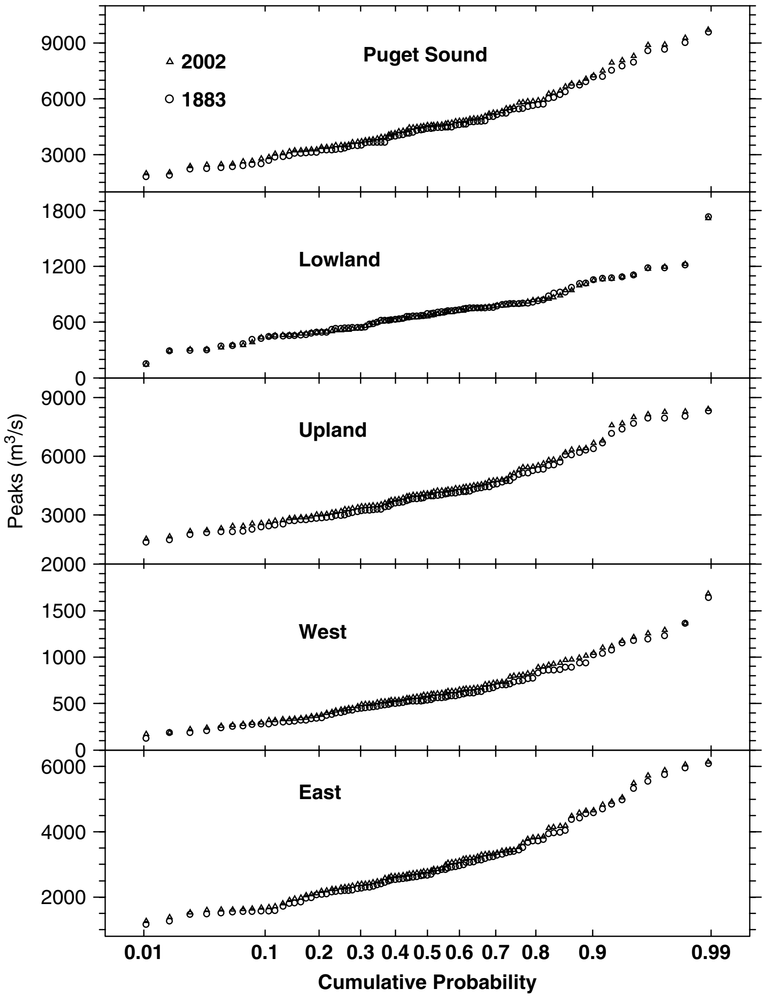


Figure 10. Predicted land cover change effects on annual maximum daily peaks for five regions in the Puget Sound drainage (see Figure 1 caption for the definition of the five regions)

Table VIA. Model residual trend analysis results for annual maximum flows, and annual flows. Trends are in per cent over period of record, trend test is two-sided

Gauge Locations	USGS gauge IDs	Start date	End date	Annual maximum flows		Annual flow	
				P	Trend	*P*	Trend
Cedar river near Cedar Falls, WA	12 115 000	1945-10-1	2006-9-30	—	−402·3	—	−45·5
Duckabush River near Brinnon, WA	12 054 000	1938-7-1	2006-9-30	<0·1	49·7	—	17·9
NF Skokomish at Hoodsport, WA	12 056 500	1924-10-1	2006-9-30	<0·05	36·7	<0·05	16·5
SF Skykomish at Index, WA	12 133 000	1922-10-1	1982-9-30	—	3·2	—	−28·0
SF Stillaguamish at Granite Falls, WA	12 161 000	1928-10-1	1980-9-30	—	32·0	—	−65·5
Mercer Creek near Bellevue, WA	12 120 000	1955-10-1	2006-9-30	<0·01	163·1	—	17·9

Table VIB. Model residual trend analysis results for seasonal flows. Trend test is two-sided; trends are in per cent over period of record. Fall: SON, winter: DJF, spring: MAM, summer: JJA

Gauges	Fall		Winter		Spring		Summer	
	P	Trend	*P*	Trend	*P*	Trend	*P*	Trend
12 115 000	—	−53·6	—	−21·1	—	−45·9	<0·05	−65·7
12 054 000	—	54·0	<0·05	100·5	—	6·4	—	−43·5
12 056 500	—	20·3	<0·05	30·7	—	10·7	—	−9·6
12 133 000	—	23·4	—	−45·7	<0·05	−87·9	—	77·6
12 161 000	—	−96·6	—	−12·4	—	−76·7	—	−25·5
12 120 000	<0·01	51·6	—	24·8	<0·1	23·7	<0·01	42·1

Table VIC. Minimal detectable trend in model residuals when power = 0·5 and $\alpha = 0{\cdot}05$, units: in per cent over period of record

Basins	Gauges	Peak	Annual	Fall	Winter	Spring	Summer
Cedar	12 115 000	*	58·6	233·2	100·2	76·4	67·6
Duckabush	12 054 000	55·3	41·1	80·7	100·9	39·2	76·2
Skokomish	12 056 500	33·5	15·9	33·2	26·6	16·7	35·2
Snohomish	12 133 000	55·5	105·0	242·0	*	91·0	123·5
Stillaguamish	12 161 000	77·2	85·6	318·6	175·1	108·7	152·4
Mercer Creek	12 120 000	92·9	*	29·4	46·2	24·5	29·1

Due to large variance (standard deviation), the minimum detectable difference is larger than 500%.

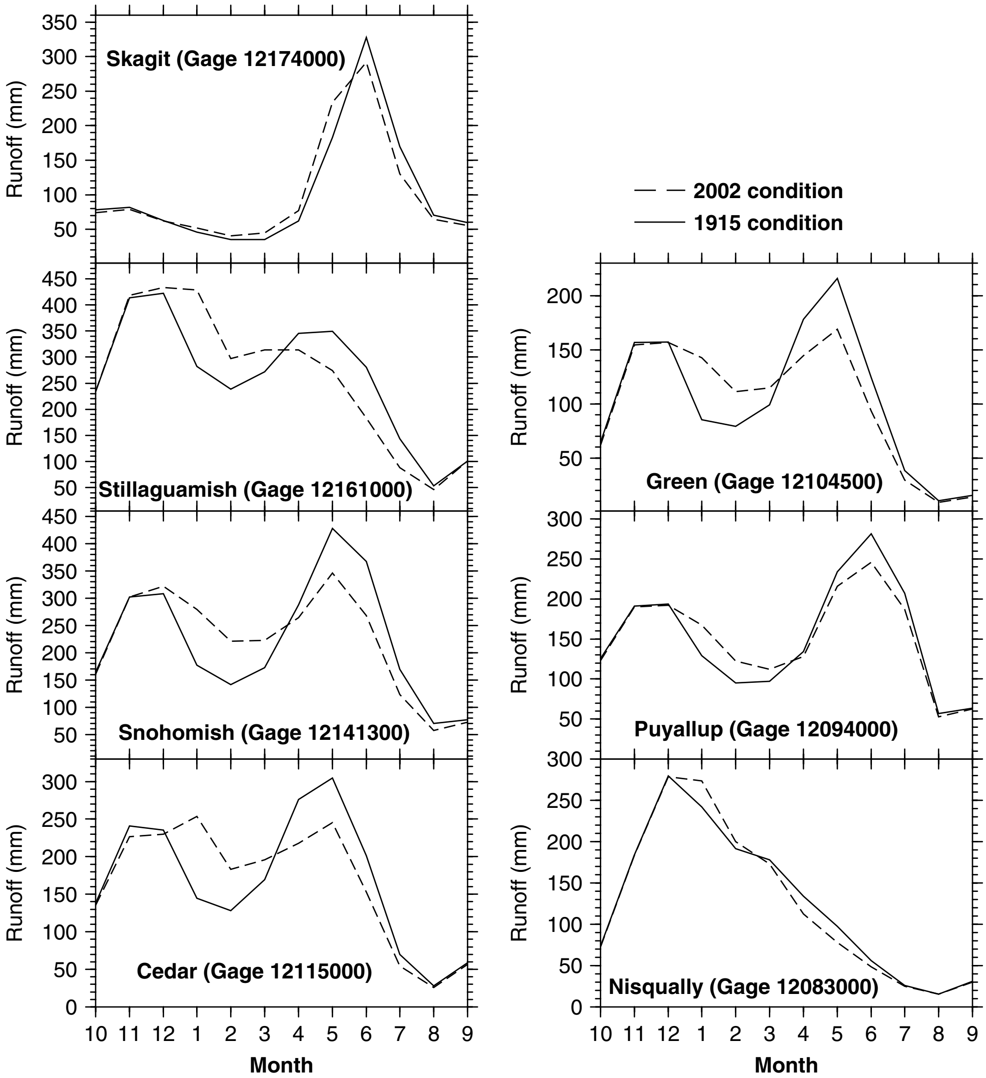


Figure 11. Predicted temperature change effects on seasonal run off at (a) eastern (Cascade) upland gauges; (b) western (Olympic) upland gauges; (c) selected eastern lowland gauges (greater Seattle area)

know which effect is dominant where? To address this question, gauges 12 094 000 in Puyallup and 12 053 000 in Dosewallips, which have much of their contributing area at high elevation, gauges 12 161 000 in the Stillaguamish and 12 056 500 in the Skokomish, which are located in intermediate elevation zone, and Mill Creek basin (12 113 349) and Scriber Creek basin (12 126 900) in the lowland area, were selected to examine mean monthly and annual maximum flows. Our comparison is for the mean monthly runoff difference between land cover 1883 and 2002, and the mean monthly runoff difference between climate 1915 and 2006. For example, if the runoff difference between land cover 1883 and 2002 is larger than the runoff difference between climate 1915 and 2006 at an examined site, we could argue that land cover change effect is greater than the temperature change effect. Similarly, comparison of relative changes in peak flow can be assessed in the same way. The most obvious feature of Figures 15 and 16 is that at the lowland urbanizing gauges, land cover change effect is much larger than

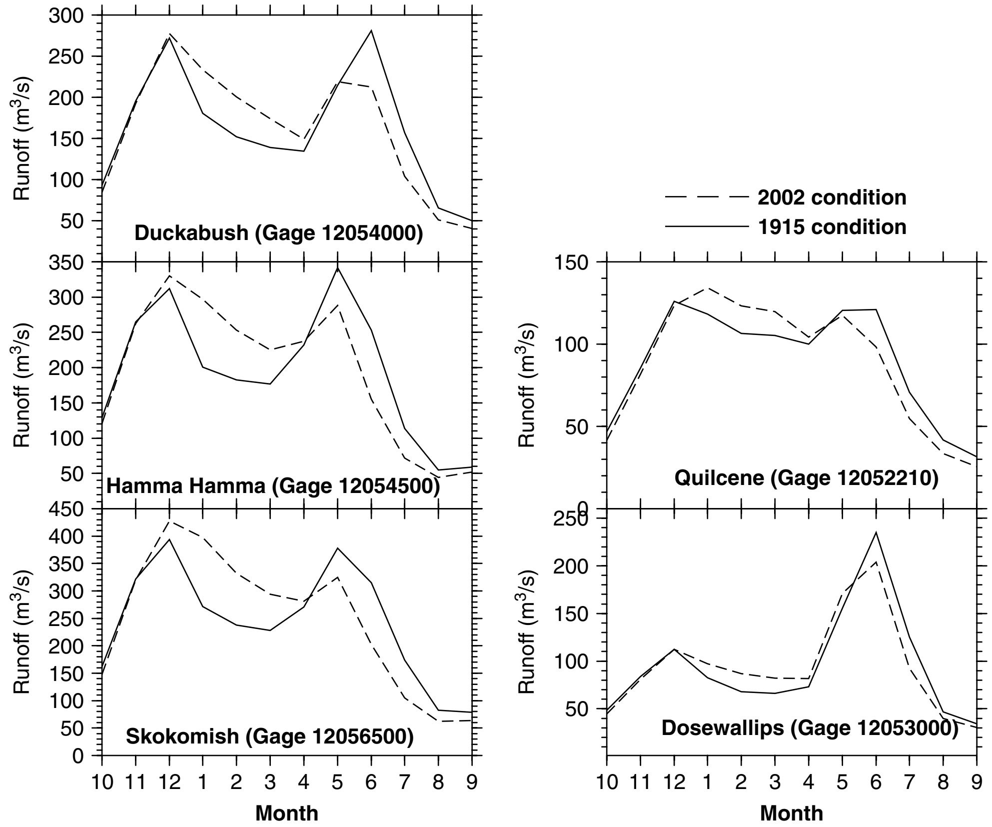
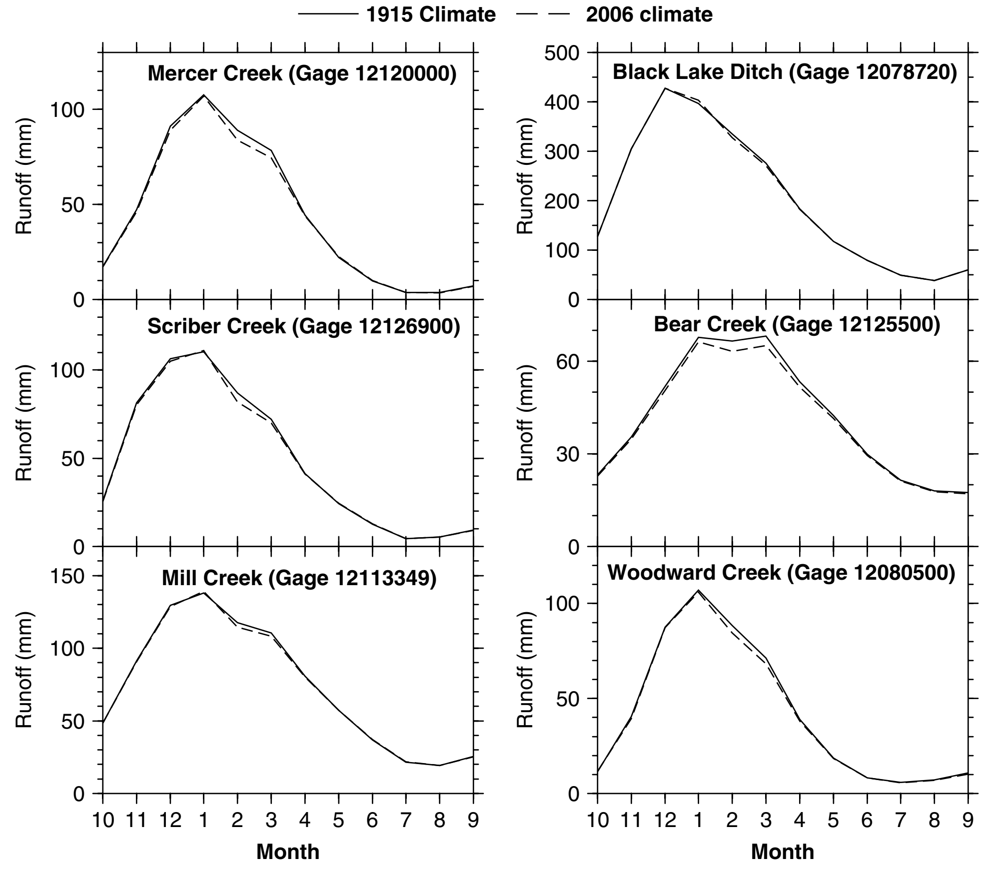


Figure 11. (*Continued*)



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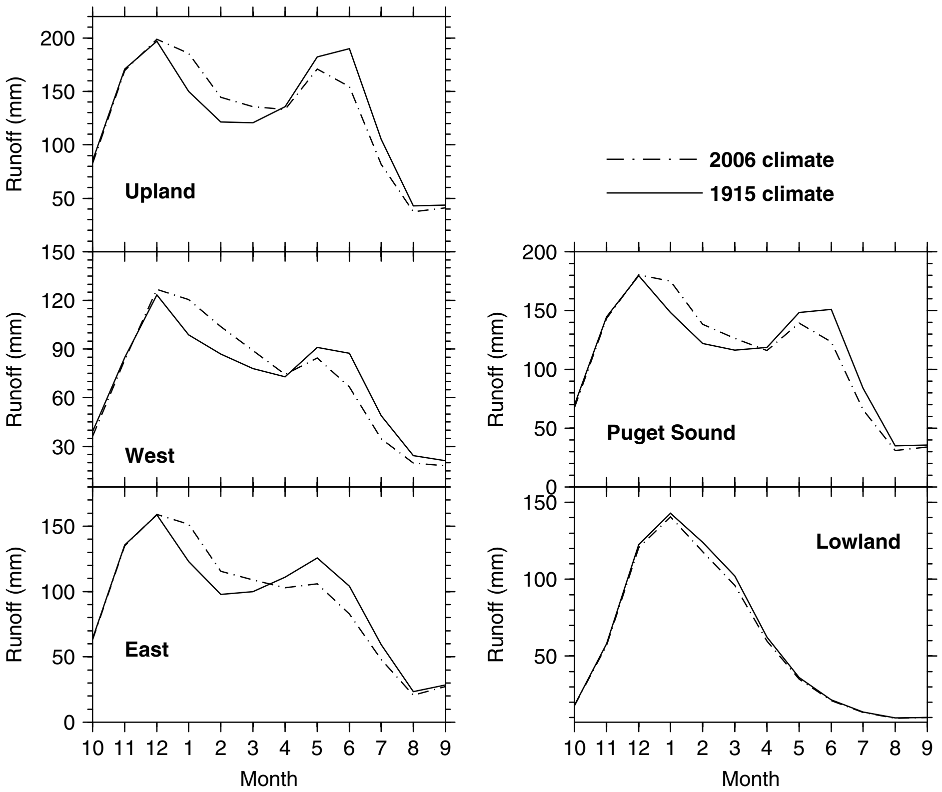

Figure 12. Predicted temperature change effects on seasonal run off for five regions in the Puget Sound drainage (see Figure 1 caption for the definition of the five regions)

the climate change effect. At the upland gauges, temperature change effects mainly show up in the mid-winter and early summer, while land cover change effects are mostly evidenced in the late spring and early summer (Figure 15). Also, their effects on mean annual maximum peak flow are about the same (Figure 16). In general, land cover change effects do not overwhelm temperature change effects in the high and intermediate elevation zones in the same way as they do at the lowland gauges, instead, their effects are more balanced.

DISCUSSION

In the Puget Sound region, the first round of forest harvest occurred in the late 1880s, when timber close to Puget Sound almost disappeared. In the 1940s, logging of old growth and regrowth expanded to the upland regions. Although sporadic cutting continues in the Puget Sound uplands, much of the non-urban area is covered by forest of varying maturity. For example, in the Mill Creek basin, mixed/deciduous forest accounted for 100% of land cover in 1883, but in 2002, 71% of the basin was urbanized. However, compared with 1883 land cover, forest cover in 2002 in the upland basins has not changed much from a hydrologic standpoint. In the Cedar River basin, mixed/deciduous and coniferous forest accounts for 85% of the area in the 2002 scenario, and was about 96% in the 1883 scenario. The change in forest coverage of about 10% is similar for the Skokomish River basin in the western uplands. While there are differences in

Table VII. Temperature change effects on winter, summer, and annual streamflow trends. DJF—December, January, and February; JJA—June, July, and August

Basins (gauge)	2006 condition vs 1915 condition (%)		2006 condition vs 1915 condition (%)
	DJF	JJA	Annual
	Upland		
Skagit (12174000)	8·1	−14·4	0·6
Stillaguamish (12161000)	22·9	−33·5	−0·1
Snohomish (12141300)	31·2	−26·0	−0·9
Cedar (12115000)	31·3	−22·1	−0·9
Green (12104500)	27·6	−24·0	−2·0
Puyallup (12094000)	15·4	−10·9	−0·5
Nisqually (12083000)	5·6	−8·9	−1·2
Skokomish (12056500)	28·1	−35·4	1·5
Hamma Hamma (12054500)	26·6	−35·8	0·7
Duckabush (12054000)	17·7	−27·0	0·2
Dosewallips (12053000)	12·7	−17·4	−0·7
Quilcene (12052210)	8·7	−20·0	−1·5
	Lowland		
Deschutes (12078720)	−0·04	0·7	−0·2
Mill (12113349)	−0·7	0·4	−0·7
Scriber (12126900)	−1·9	1·0	−1·6
Mercer (12120000)	−2·8	1·3	−2·5
Woodward (12080500)	−1·8	−1·6	−2·2
Bear (12125500)	−3·3	−1·2	−2·9
	Regional		
East	23·2	−19·1	−0·9
West	21·9	−29·3	0·0
Upland	23·7	−22·5	−0·6
Lowland	−1·8	−2·1	−3·0
Entire Puget Sound basin	18·1	−21·8	−0·9

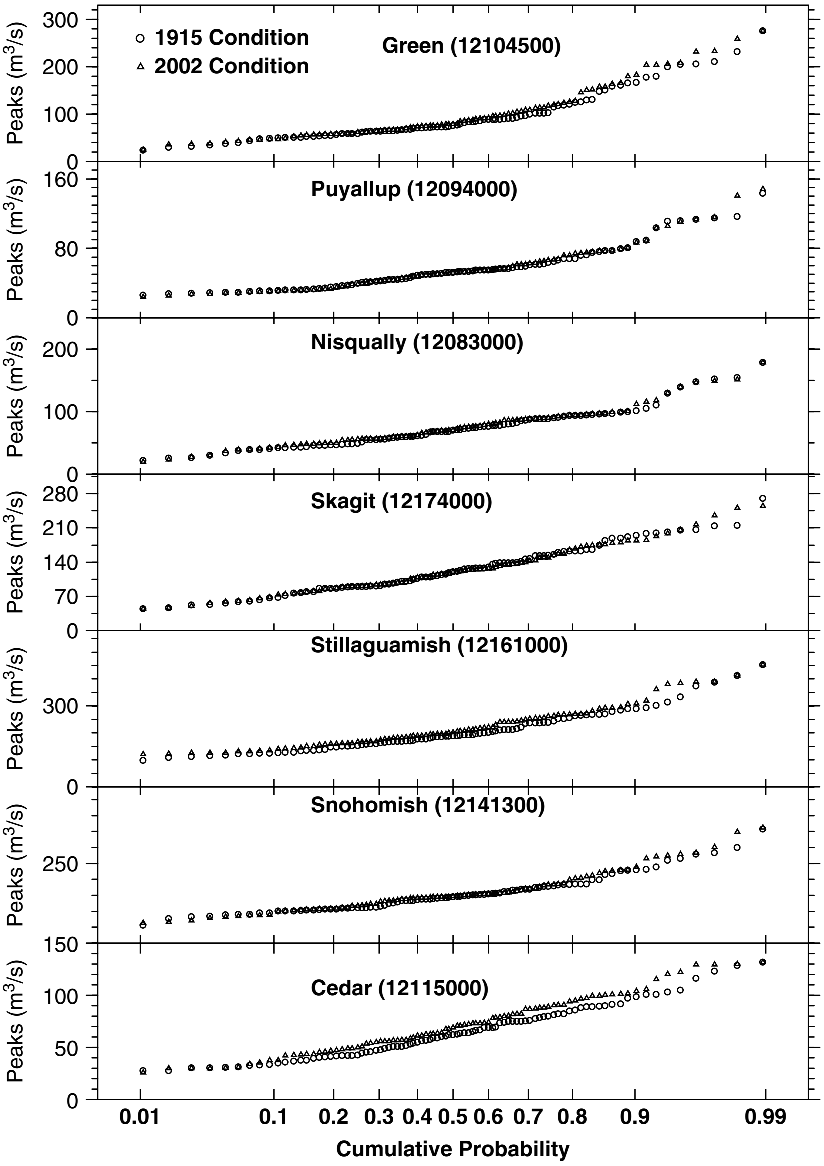

Figure 13. Predicted temperature change effects on annual maximum flow at (a) eastern (Cascade) upland gauges; (b) western (Olympic) upland gauges; (c) selected lowland gauges in the greater Seattle area

forest maturity, and associated differences in ET (usually, after harvest, streamflow increases due to the decrease in ET), the increase persists only for a certain period after cutting. Hornbeck *et al.* (1993, 1997) found that after 10 years of cutting, streamflow increases decline in watersheds in the north-eastern USA. According to Washington State Department of Natural Resources (2005), after 60–80 years of regrowth following logging, western Washington forests had essentially recovered to have hydrological characteristics close to those of mature forest. It is therefore understandable that after more than 60 years of regrowth, even if there are differences in water consumption between old growth and the second or third growth, the differences are not as dramatic as those for urbanization hydrologically. In DHSVM, the hydrologic effects of vegetation maturity are traceable primarily to the prescribed leaf area index (LAI), which strongly affects ET, and to a lesser extent to vegetation height, clumping factor, trunk space, and albedo.

Reduced forest cover due to logging generally results in decreased ET, increased snow accumulation, and increased severity of rain-on-snow events, and increased streamflow during fall, winter and spring and increases in annual maximum flows. Due to earlier snow melt, summer streamflow is lower for 2002 land cover than for 1883 land cover in the summer. In the lowland basins, snow is not a major factor, instead logging and urbanization are the primary contributors to hydrograph changes. Compared with the 1883 land cover scenario, the inferred increase of annual streamflow at the urban gauges for 2002 relative to 1883 land cover is very large and is mainly the result of reduced ET. The large inferred increase in annual maximum flows for the lowland urban basins is the result in part of reduced ET (and hence higher water tables), but more from reduced infiltration capacity, which reduces storm response times, and increases the connectivity of the channel system to runoff generating areas, which is simulated in the DHSVM.

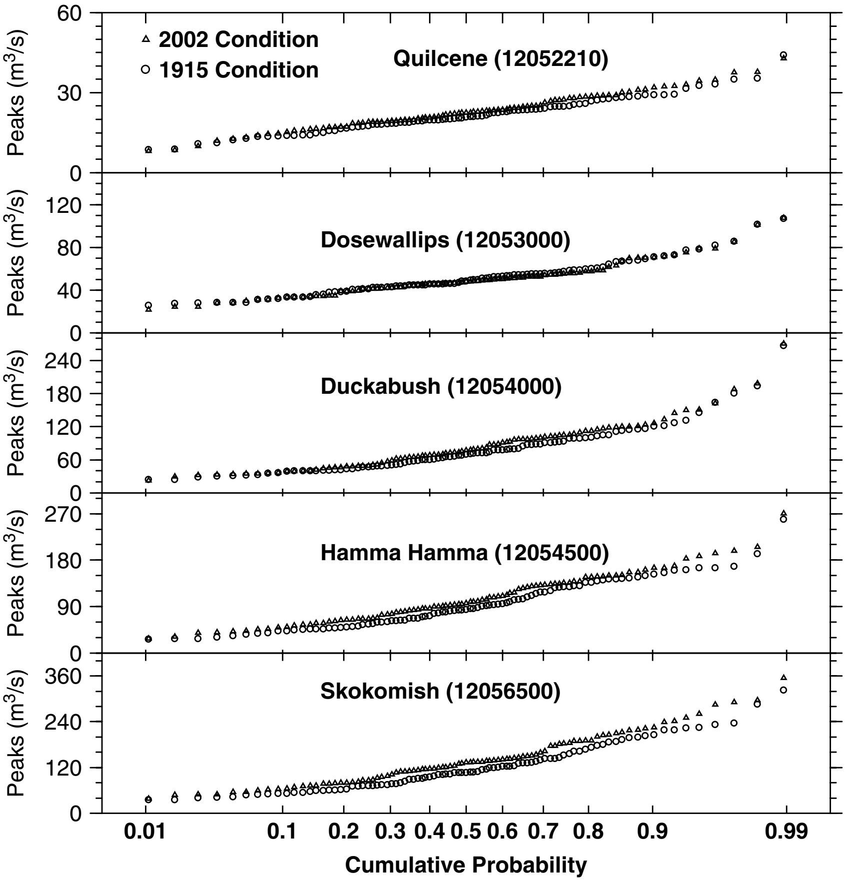

Figure 13. (*Continued*)

The response of the entire lowland region to land cover change is generally more modest than for individual urbanized catchments due to differences in deciduous forest extent in the 2002 relative to 1883 land cover maps. In the 1883 map, there was relatively little coniferous forest in the lowland region based on the 300 m separation criterion from Harlow *et al.* (1991) and Crittenden (1997) (Figure 2), which we believe may not be realistic for our study. In contrast, in the 2002 map, there is considerable coniferous forest in the lowland region (Figure 3), and the difference in cool season evapotranspiration between coniferous and deciduous forest is sufficient to drive major changes in the model-inferred hydrologic response. Our study shows that increasing areas of coniferous forest consume more water, especially in winter (Figure 6). This result is consistent with the study done by Swank and Douglass (1974) in Coweeta experimental watershed in eastern USA.

In Japan, Komatsu *et al.* (2007) also studied ET differences between coniferous and broad leaf deciduous forests. They found that there was no difference between coniferous and broad leaf forests with respect to ET. They attributed this to the precipitation pattern. In Japan, precipitation mostly falls in summer, while in Coweeta precipitation is evenly distributed throughout the year. In the Pacific Northwest, precipitation mostly occurs in the winter time. Large amounts of precipitation in winter result in a substantial difference in wet canopy evaporation between coniferous and deciduous forests, even though the potential evaporation in winter is relatively low (Komatsu *et al.*, 2007). In general, the coniferous forest canopy structure including LAI does not change much from summer, while LAI for the deciduous forest canopy changes dramatically in the winter. Also, even though the evaporative demand in winter is low, the (coniferous) vegetation generally is not water stressed, and this further amplifies differences in ET between coniferous and deciduous forests. In contrast, in the summer, both coniferous and deciduous forests are water stressed, hence reducing differences in ET between these two vegetation types.

In general, simulations suggest that temperature changes affect runoff from upland basins more than from lowland basins. Warmer temperatures reduce the occurrence of snowfall (especially at intermediate elevations where mixed rain and snow conditions dominate) and increase rainfall occurrences, resulting in substantial shifts in runoff from spring and summer to winter. A secondary effect is that winter ET is increased. With warmer temperatures, even if snow falls, it melts quickly. In contrast, at the highest elevations, winter temperatures are already low and slight changes do not result in much change in the partitioning of snow and rain. But spring temperature increases result in faster snow melt. In the

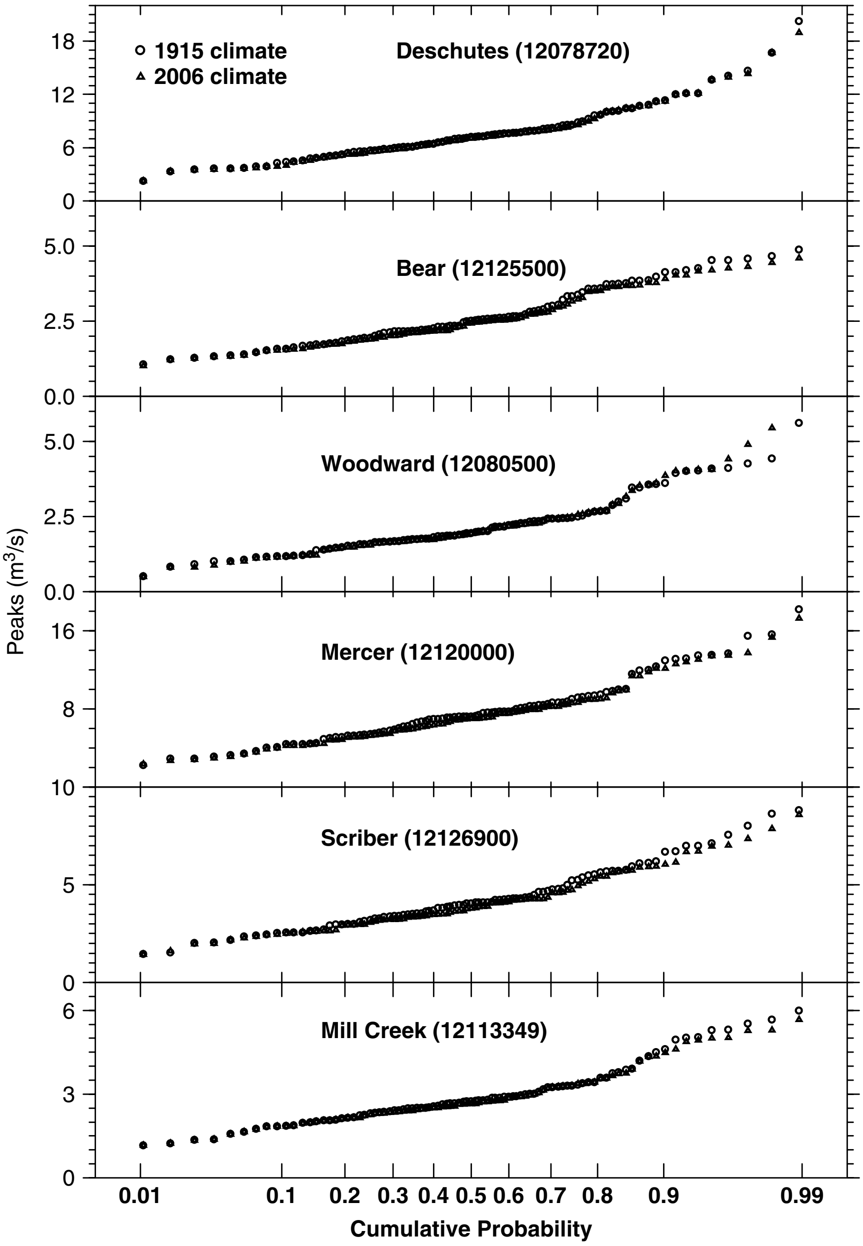

Figure 13. (*Continued*)

upland basins, temperature change mostly affects the seasonal distribution of streamflow but has relatively modest effects on annual streamflow.

CONCLUSIONS

Our results suggest that in the Puget Sound lowlands, land cover change has been the dominant factor controlling hydrologic change. In contrast, in the uplands, both land cover and climate change appear to have been important factors. Key reasons for these different hydrologic sensitivities are the importance of snow in the seasonal hydrologic cycle of the uplands, and its general absence in the lowlands, and forest regrowth in the upland basins. In the lowland urbanizing basins, land cover change dominates primarily due to increased permanent imperviousness and hence increased runoff. In the uplands, the intermediate elevation zone (generally taken as roughly 300–900 m) which experiences many transitions each winter between snow and rain is more sensitive to temperature change than is the high elevation zone.

Land cover change is manifested through the snow accumulation/ablation, rain-on-snow events, evapotranspiration and changes in infiltration capacity. Our model simulations show that for current land cover, fall, winter and early spring streamflow is higher than for predevelopment conditions, but summer flows are lower; while the annual maximum flows are higher, as is annual average streamflow in general. These predictions are roughly consistent with analysis of historical trends in observed streamflow, to the extent that record lengths are long enough, and/or the signals large enough, to be detected. Temperature change mainly affects seasonal

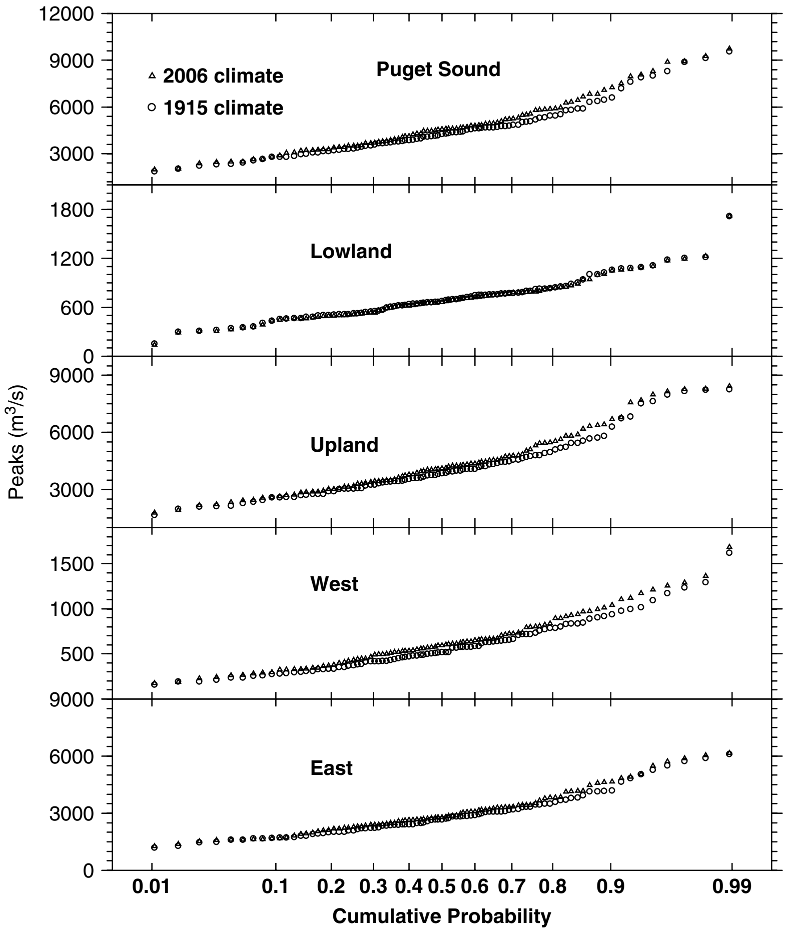

Figure 14. Predicted temperature change effects on annual maximum flow for five regions in the Puget Sound (see Figure 1 caption for the definition of the five regions)

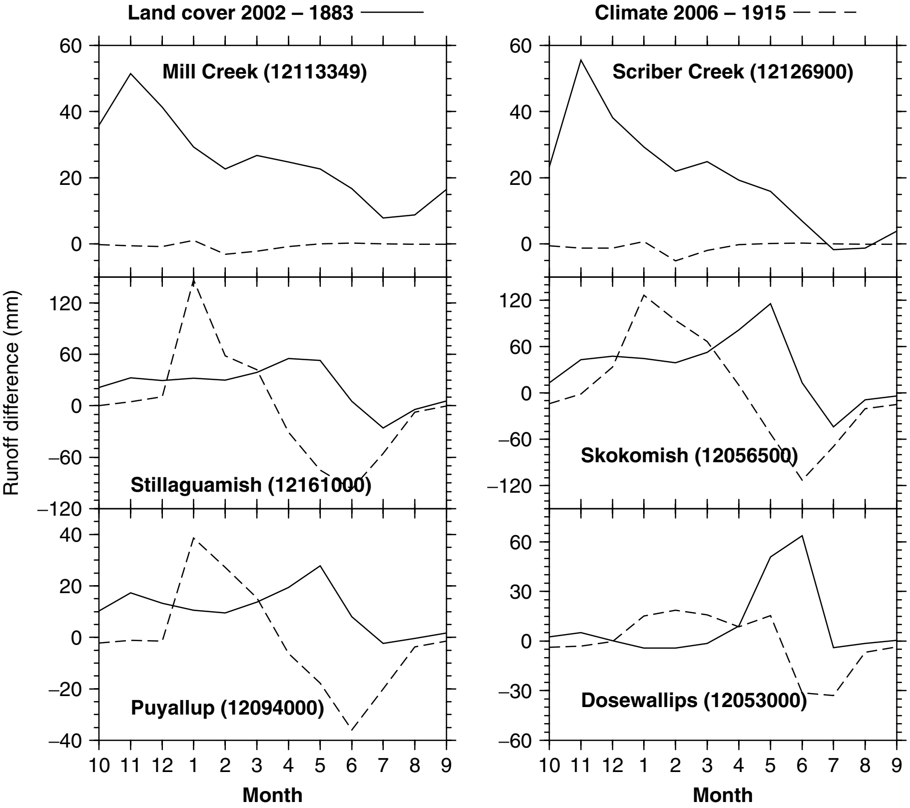

Figure 15. Comparison of climate change and land cover change effects on seasonal runoff. Runoff difference for land cover scenario is the difference between land cover 2002 and 1883. Runoff difference for climate scenario is the difference between climate 2006 and 1915

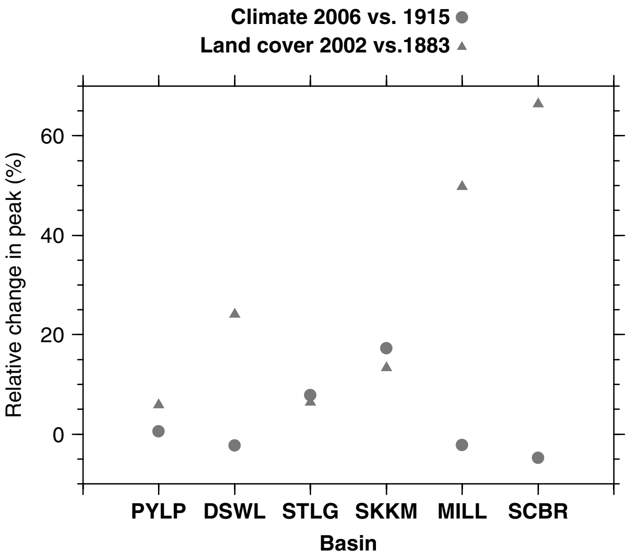

Figure 16. Comparison of climate change and land cover change effects on annual maximum peak flow. Relative change in peak of land cover scenarios was calculated by the difference in means of the annual maximum peak flow for 2002 and 1883, and divided by the mean in 1883. Relative change in peak of climate scenarios was calculated by the difference in means of the annual maximum peak flow for 2006 and 1915, and divided by the mean in 1915. PYLP-Puyallup, DSWL-Dose wallips, STLG-Stillaguamish, SKKM-Skokomish, MILL- Mill Creek, SCBR-Scriber Creek

streamflow distribution, not annual streamflow amount in the upland basin.

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