MODELING WATER AVAILABILITY AND ITS RESPONSE TO CLIMATIC CHANGE FOR THE SPOKANE RIVER WATERSHED

By

GUOBIN FU

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the dissertation of GUOBIN FU find it satisfactory and recommend that it be accepted.

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Abstract

By Guobin Fu, Ph D
Washington State University
December 2005

Chair: Shulin Chen

Water availability at global, national, and regional scales is under threat as never before. Consequently, an important yet challenging issue facing researchers is how to adequately estimate water availability at a basin scale and to predict its response to future climatic change. This doctoral research addressed this need by developing a monthly water availability model to estimate the current water availability at a watershed scale, and by developing a monthly water balance model to simulate and analyze the impacts of future climatic change on water availability.

The applications of these two models upon the Spokane River watershed, which was ranked sixth on the most endangered rivers in American in 2004 due to "too little water, too much pollution, and an uncertain future", produced four important results: (1) The monthly average water availability in the Spokane River watershed was 5,255 cfs, of which 5,094 cfs, or 96.9%, was from surface water, and 753cfs, or 14.3%, was from ground water. However, 592 cfs, or 11.2%, was due to the surface- and ground- water interaction and was double counted; (2) For 16% of the time (123 out of 768 months), mostly in August and September, there was no surface water availability; (3) Water availability within the watershed will be more critical in the future because of potential climatic change, especially for the summer months. Under a climatic scenario when

precipitation remains constant and temperature increases by 2^{o}C, the model predicts a 0.4% decrease in annual streamflow, but a 20–25% decrease in streamflow during July–September; (4) Based on General Circulation Model (GCM) results, the annual streamflow in the Spokane River watershed is likely to increase by 8.6% and 4.8% under the 2020s and 2040s scenarios, respectively, while the streamflow for July–September will decrease by 4.9–7.0% and 14.4–24.6% in the two scenarios, respectively.

The water availability model and the monthly water balance model developed in this study can be applied in other watersheds for estimation of water availability and potential responses to climatic changes. The research results can help managers make more informed decisions in water resource management.

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CHAPTER 1 INTRODUCTION

Water is life, in all forms and shapes.

(World Water Vision: Making Water Everybody's Business, 2000)

1.1 BACKGROUND

Although there is a lot of water in the world, freshwater is a scarce, limited, and most precious natural resource (Loucks and Gladwell, 1999). Indeed, although 71% of the earth surface is covered by water, only about 2.5% of all this water is fresh, and less than 0.4% of the fresh water is renewable. Moreover, most of this renewable fresh water evaporates or becomes lost to deep ground-water aquifers (Loucks and Gladwell, 1999). Consequently freshwater availability is a critical issue facing society today at global, national, regional, and local scales. For example, the World Bank reports that 80 countries now have water shortages that threaten human health and economies while 40 percent of the world — more than 2 billion people — have no access to clean water or sanitation. The United Nations General Assembly in resolution 55/196 proclaimed the year 2003 as the *International Year of Freshwater.* Although the year 2003 is over, the task of protecting this vital resource for our daily lives remains a never-ending task. The UN General Assembly has further proclaimed the period from 2005 to 2015 as the *International Decade for Action, "Water for Life"*, and began on *World Water Day*, the 22nd of March, 2005.

In this 21st century, the United States will be challenged to provide sufficient quantities of high-quality water to its growing population (*National Research Council, 2001*). The Congress in its report on the Fiscal Year 2002 Appropriations for Interior and Related Agencies (House Committee on Appropriations) requested the U.S. Geological

Survey (USGS) to assess future water availability and uses. The Committee concluded that "[they] are concerned about the future of water availability for the Nation [that] water is vital to the needs of growing communities, agriculture, energy production, and critical ecosystems [and] unfortunately, a nationwide assessment of water availability for the United States does not exist, or, at best, is several decades old".

This situation is locally true for Washington State where the last comprehensive water resource study was conducted by the State of Washington Water Research Center (SWWRC) in 1967. Since then, there has been no water resource study at the state scale, which is troubling given the fact that a cursory look at USGS streamflow station data within the state indicates that all of the stations used for the1967 study that are still in operation have a streamflow decreasing trend, with a range of 1% to 49%.

Beyond recognizing the need for various-scaled water availability studies, is the added concern and uncertainty caused by the future climatic change. With higher temperatures and more rapid melting of winter snow-packs, fewer water supplies will be available to farms and cities during summer months when demand is high.

1.2 RESEARCH OBJECTIVES

Although water availability is a commonly used term, it does not have a scientific definition. Nor is there an officially recognized model or methodology for estimating water availability at a watershed scale. Accordingly, the main goals of this doctoral research was to develop a methodology for estimating watershed scale monthly water availability, and to develop a GIS and land use based monthly water balance model for studying the water availability responses to climatic change.

The specific objectives were to:

1. Examine the changes in streamflow since the 1967 study for Washington State and to demonstrate why updating the study is necessary;
2. Develop a methodology to estimate watershed scale monthly water availability, and apply the methodology to estimate the water availability in the Spokane River watershed;
3. Develop a GIS and land use based monthly water balance model and apply the model to study the impacts of climatic change on water availability in the Spokane River watershed;
4. Build a streamflow-precipitation-temperature relationship for the Spokane River watershed with ArcGIS Geostatistical Analyst based on historical data to study the impacts of climatic change on hydrological regimes and to confirm the water balance model results; and
5. Examine the water availability variation in the Spokane River watershed by comparing streamflow and precipitation under El Niño and La Niña events.

1.3 OUTLINE OF RESEARCH

Below is a brief, chapter by chapter, overview of the dissertation.

- Chapter 1 gives a brief introduction as to why this research topic was chosen.
- Chapter 2 is a literature review summarizing the up-to-date research on this topic, including water availability and climatic change impacts.
- Chapter 3 describes the basic setting and hydro-climatic regimes of the Spokane River watershed, which was recently ranked 6th on the most endangered rivers in

America list by *American Rivers and its Partners* due to "too little water, too much pollution, and an uncertain future".

- Chapter 4 examines the streamflow changes since the 1967 SWWRC study.
- Chapter 5 develops a water availability model concerning flood elimination, in-streamflow requirement, and surface- and ground- water interaction. The method was then used for the Spokane River watershed to compute the monthly water availability. The uncertainty and frequency associated with the water availability were also analyzed.
- Chapter 6 develops a GIS and land use based monthly water balance model. The model was then used to study the impacts of future climatic change scenarios on water availability of the Spokane River watershed.
- Chapter 7 builds the streamflow-precipitation-temperature relationship with ArcGIS Geostatistical Analyst based on historical data for studying the impacts of climatic change on hydrological regimes and confirmation of the water balance model results.
- Chapter 8 examines the water availability variation by comparing the streamflow and precipitation under El Niño and La Niña events.
- Chapter 9 summarizes the modeling efforts, implication of the results, and further work recommendations.

CHAPTER 2 LITERATURE REVIEW

In my view, climate change is the most severe problem that we are facing today — more serious even than the threat of terrorism.

David A. King, Chief Scientific Advisor to the British Government

2.1 WATER AVAILABILITY INDICATORS/MODELS

2.1.1 Definition of water availability

Water availability may mean different things to different people. Soil and crop scientists focus on the available water in unsaturated soil which can be used for crops. For example, Groenevelt (2001) developed a new procedure to determine soil water availability. Hydrogeologists, such as Moran (2004), are mostly concerned about the storage and replacement time for ground water, who discussed the ground-water availability. Williams (1981) studied the ground-water availability in a small multiaquifer basin in northern Delaware to determine the hydrologic conditions when pumpage approaches the expected long-term basin-wide rate of ground-water recharge. This doctoral research, in the watershed management point of view, focuses on the water availability at the watershed scale concerning both surface and ground water and their interaction. The intention is that results of this doctoral research could be used for watershed management and water resource planning.

2.1.2 Current Progress

Traditionally, streamflow and ground-water storage are two major indicators for watershed scale water availability. Shafer and Dezman (1982) introduced the surface-water supply index (SWSI) as described below for Colorado to provide a more appropriate indicator of water availability in the western United States than the widely used Palmer drought index (Garen, 1993):

$$\text{SWSI}=\frac{aP_{snow}+bP_{prec}+cP_{strm}+dP_{rese}-50}{12} \qquad (2.1)$$

Where

a, b, c, and *d* are weights for each hydrologic component, and *a*+*b*+*c*+*d*=1;

P_i is the probability of non-exceedance (in percent) for component *i*; and

snow, *prec*, *strm* and *resv* are the snow-pack, precipitation, streamflow, and reservoir storage hydrologic components, respectively.

Subtracting 50 in the numerator of Equation 2.1 centers SWSI values around zero and dividing by 12 compresses the range of values between -4.17 and 4.17. Subsequent studies of SWSIs in Oregon and Montana have followed the same basic procedures as in Colorado, with minor differences in coefficient estimation and data usage (Garen, 1993).

Kresch (1994) defined a monthly water-resources-availability index (WRAI) based on time-weighted and rescaled monthly streamflow departures and standard deviation during the preceding 3-year period as:

$$WRAI=\sum_{n=0}^{35}W(n)\frac{D_x(n)}{S_x} \qquad (2.2)$$

Where

W(n) is the weight factor given by $\left(1-\frac{n}{36}\right)^2$ for month n;

Dx(n) is the rescaled monthly streamflow departure for month n; and

Sx is the standard deviation of the cumulative-annual values.

Slutsky and Yen (1997) calculated water availability on the basis of hydrologic replacement time, volume, and any allowable water source depletion. For a stationary system, the regional water availability at any time is the sum of freshwater volume in the surface source divided by replacement time of surface water and freshwater volume in the ground water divided by replacement of ground water. Krol et al (2001) defined the water availability as "a large scale water balance model [which] describes runoff, storage in water reservoirs and soil moisture based on a hydrotope-approach, accounting for vertical and lateral processes depending on topography, soil, and vegetation cover, with an explicit representation of the main water reservoirs." Ohlsson (2000) also used the concept of "available renewable water".

Some researches have extended this concept and made water availability into a much broader concept. For example, Savenije (2000) partitioned the watershed scale water availability as "white water", "green water", and "blue water". The "blue water" occurs in rivers, lakes, and aquifers, and is the sum of the water that recharges the ground water and surface runs off. The total amount of "green water" resources available over a given period equals the accumulated amount of transpiration over that period, because the process through which "green water" is consumed is transpiration. The storage medium for "green water" is unsaturated soil. "White water" is the portion of the rainfall that feeds back directly to the atmosphere through evaporation from interception and bare soil. The total amount of white water, green water, and blue water is equal to regional precipitation.

The USGS (2002) used the concept of water availability brevity to include both water availability and water use because they are closely linked. The proposed indicators of water availability include three categories and ten items:

- Surface-water indicators (streamflow; reservoir storage, construction, sedimentation, and removal; and storage in large lakes, perennial snowfield, and glaciers);
- Ground-water indicators (ground-water-level indices for a range of hydrogeologic environments and land-use setting; changes in ground-water storage due to withdrawals, saltwater intrusion, mine dewatering, and land drainage; and number and capacity of supply wells and artificial recharge facilities);
- Water-use indicators (total withdrawals by source and sector; reclaimed wastewater; conveyance losses; and consumptive uses).

Jimenez et al (1998) developed a method for water availability assessment that considered quantity, quality and use. The water availability index (AI) is defined as:

$$AI=(a,b) \quad (2.3)$$

Where

a is relative water availability for a certain hydrological region and b is the classification of water in terms of treatment required to upgrade its quality for intended use. Both variables can be assigned values of 1, 2 and 3. The a=1 means there is abundant supply, a=2 means that supply is in equilibrium with demands, and a=3 indicates that supply is scare. The b=1 means water complies with the required quality in its natural condition and no treatment is necessary, b=2 is assigned if the required treatment is simple and economical, and b=3 indicates that a costly treatment process is necessary.

2.1.3 Need for a new model

Assessment of the above models suggests that a new model is needed to estimate the watershed water availability. Regional decision-makers and water resources managers are often more interested in knowing how much water is available for out-stream uses, such as municipalities, irrigation, and industry. None of aforementioned models can supply this information. Both models of Shafer and Dezman (1982) and Kresch (1994) are simple frequency analyses; the USGS method (2002) is a suitable model, but it contains too many indicators and is difficult to use; Savenije's (2000) categorization equates water availability to precipitation; Jimenez et al's relative water availability is a balance analyses between supply and demand. This doctoral research improves the above models by developing a water availability model, which can be used for water resources management and regional economic development planning.

2.2 IMPACTS OF CLIMATIC CHANGE

2.2.1 Facts of climatic change

Climate is a primary input for a hydrological system and its change has significant effects on hydrological regimes. This effect is especially important because the global and regional climates have changed in the past and will change in the future.

The global average surface temperature has dramatically increased since the 1980s (Figure 2.1). The warmest year on record since the late 1800s was 1998, with 2002, 2003, and 2004 coming in second, third, and fourth, respectively. According to

NASA, extra energy, together with a weak El Niño, is expected to make 2005 warmer than 2003 and 2004 and perhaps even warmer than 1998.

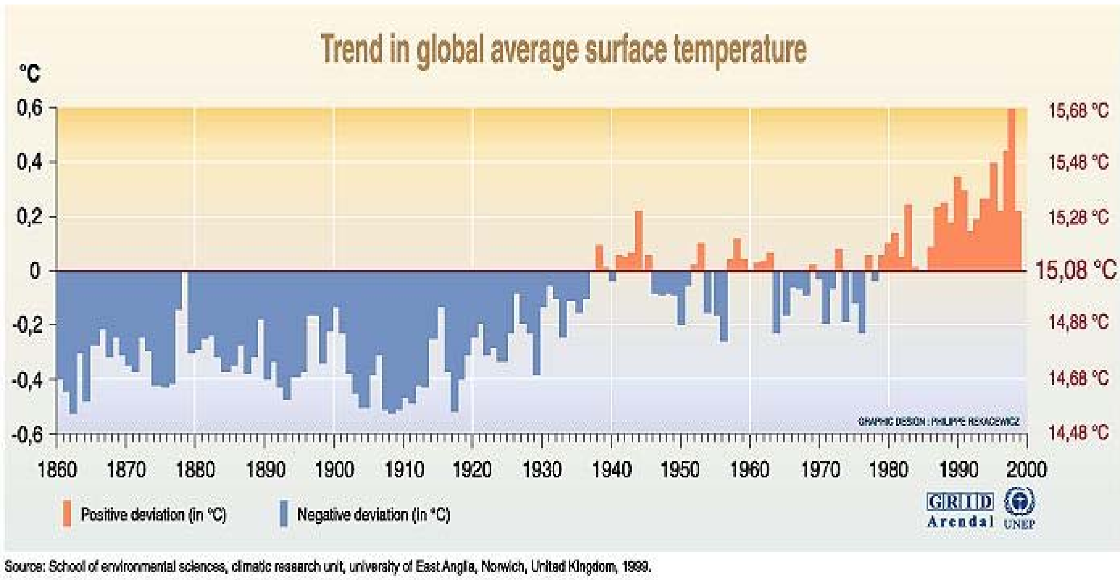


Figure 2.1 Trend in Global Average Surface Temperature (1860–2000)

(http://www.grida.no/climate/vital/17.htm)

2.2.2 Current Methodologies for Assessing the Impacts of Climatic Change on Water Availability

2.2.2.1 Hydrologic Models

Hydrologic modeling is concerned with the accurate prediction of the partitioning of water among the various pathways of the hydrological cycle (Dooge, 1992). Hydrological models can be classified using a number of different schemes (Woolhoser and Brakensiek, 1982; Becker and Serban, 1990; Dooge, 1992; and Leavesley, 1994). Classification criteria include purposes of the models (real-time application, long-term predication, process understanding, and water resources management), model structure (models based on fundamental laws of physics, conceptual models reflecting these laws in a simplified approximate manner, black-box or empirical analysis, and gray-box), spatial discretization (lumped parameters and distributed parameters), temporal scale (hourly, daily, monthly, and annual), and spatial scale (point, field, basin, region, and global).

Singh and Woolhiser (2002) provided a historical perspective of hydrologic modeling, discussed the new developments and challenges in watershed models, and stated "watershed models are employed to understand dynamic interactions between climate and land-surface hydrology."

2.2.2.2 Current Modeling Approaches

(1) Empirical models

Building empirical models to link climate and regional hydrological regimes has a long history. Perrault (1674) proposed the first precipitation-runoff relationship in a study of the River Seine basin. In recent years, many researchers have used this rainfall-runoff empirical model to study the impacts of climatic change on hydrology. For example, the relationship among mean annual precipitation, temperature, and runoff developed by Langbein et al (1949) based on 22 drainage basins in the contiguous United States was used by Stockton and Boggess (1979) to estimate changes in the average annual runoff of 18 designated regions throughout the United States for different climate scenarios. Revelle and Waggoner (1983) used the same model as the basis for investigating the effects of climate change on runoff in the Western United States (Leavesley, 1994).

(2) Water balance models

Water balance models originated with the work of Thornthwaite (1948) and Thornthwaite and Mather (1955). These models are basically bookkeeping procedures which use the balance equation:

$$Q = P - ET \pm \Delta S \qquad (2.4)$$

Where

Q is runoff;

P is precipitation;

ET is actual evapotranspiration; and

ΔS is the change in system storage.

The models vary in their degree of complexity based on the detail with which each component is considered. Most models account for direct runoff from rainfall and lagged runoff from basin storage in the computation of total runoff. In addition, most models compute the actual ET term as some function of potential evapotranspiration (PE) and the water available in storage (Leavesley, 1994). While water balance models can be applied at daily, weekly, monthly, or annual time steps, the monthly time step has been applied most frequently in climate impact studies (Leavesley, 1994).

Recently, many water balance models were developed to study the impacts of climatic change on regional hydrological regimes. A simple three-parameter monthly water balance model was applied by Arnell (1992) to 15 basins in the United Kingdom to estimate changes in the monthly river flow and to investigate the factors controlling the effects of climate change on river flow regime in a humid temperature climate. Gleick (1987a) developed a monthly water balance model for the Sacramento River basin in

California. The model was applied using 18 different climatic change scenarios to evaluate changes in runoff and soil moisture under assumed conditions (Gleick, 1987b).

A monthly water balance model that also accounts for snow processes was developed and applied by Mimikou et al (1991) for evaluating regional hydrologic effects of climatic change in the central mountainous region of Greece. Schaake (1990) developed a nonlinear monthly water balance model for the evaluation of changes in annual runoff associated with assumed changes in climate. The model was applied to 52 basins in the Southeastern United State using a single set of model parameters for all basins.

Panagoulia and Dimou (1997) investigated the variability in monthly and seasonal runoff and soil moisture with respect to global climate change via the Thornthwaite and Mather model (1955) and via the coupling of the snow accumulation–ablation (SAA) model and the soil moisture accounting (SMA) model of the US National Weather Service.

Xiong and Guo (1999) developed a two-parameter monthly water balance model that was used to simulate the runoff of seventy sub-catchments in the Dongjiang, Ganjiang and Hanjiang Basins in south of China. Guo et al (2002) extended the two-parameter water balance model into a macro-scale and semi-distributed monthly water balance model, which was then applied to simulate and predict the hydrological processes under climatic change scenarios.

(3) *Conceptual lumped-parameter models*

Conceptual lumped-parameter models are developed using approximations or simplification of fundamental physical laws and may include some amount of empiricism

(Leavesley, 1994). They attempt to account for the linear and nonlinear relationship among the components of a water balance model. One of the more frequently used models in this group is the Sacramento Soil Moisture Accounting Model (Burnish et al, 1973). The Sacramento model simulates the movement and storage of soil moisture using five conceptual storage zones. The model has 17 parameters that define the capacities and flux rates to and from the storage zones. The Sacramento model was used by Nemec and Schaake (1982) to evaluate the effects of a moderate climate change on the sensitivity of water resources systems in an arid and a humid basin in the United States. The Sacramento model has been coupled with the Hydro-17 snow model (Anderson, 1973) by a number of investigators for applications to basins dominated by snowmelt.

Several other models having a similar structure to the coupled Sacramento and Hydro-17 models, but with different process conceptualizations, have been used to assess the effects of climate change on many regions of the globe. The Institute Royal Meteorology Belgium (IRMB) model (Bultot and Dupriez, 1976) has been applied to basins in Belgium (Bultot et al, 1988) and Switzerland (Bultot et al, 1992). The HYDROLOGY model (Porter and McMahon, 1971) was applied to two basins in southern Australia (Nathan et al, 1988). The HBV model (Bergstrom, 1976) has been applied to basins in Finland (Vehvilainen and Lohvansuu, 1991) and the HSPF model (USEPA, 1984) has been applied to a basin in Newfoundland, Canada (Ng and Marsalek, 1992).

(4) Processed-based distributed-parameter model

These models are established based on the understanding of the physics of the processes that control basin responses. Process equations involve one or more space coordinates and have the capacity of forecasting the spatial pattern of hydrologic conditions in a basin as well as basin storage and outflows (Beven, 1985). Spatial discretization of a basin to facilitate this detail in process simulation may be done using a grid-based approach or a topographically based delineation (Leavesley, 1994).

The ability to simulate the spatial pattern of hydrologic response within a basin makes this approach attractive for the development of models that couple the hydrological process with a variety of physically based models of biological and chemical processes (Leavesley, 1994). The applicability of models of this type to assess the effects of climatic change has been recognized (Beven, 1989; Bathurst and O'Connel, 1992), but few applications have been presented (Leavesley, 1994).

Major limitations to the applications of these models are the availability and quality of basin and climate data at the spatial and temporal resolution needed to estimate model parameters and validate model results at this level of detail. Also these data requirements may pose a limit to the size of basin in which these models are applied (Leavesley, 1994).

(5) Hydrological-General Circulation Model (GCM) coupling models

Since GCM is the only technical source for future climatic scenarios, many hydrologists have tried to couple the hydrological models with GCM to study the impacts of climatic change on regional hydrological regimes. However, there are some gaps between GCMs and hydrology due to spatial and temporal scales (Table 2.1). To circumvent the problems and narrow the gaps between GCM's applicability and hydrology needs, various methodologies have been developed during the last 20 years. Basically these methodologies fall into two groups:

- Down-scaling the GCM results for hydrology. There are basically two methods to downscale the GCM results: statistical-based and regional climate models.
- Up-scaling the hydrological models. Macro-scale or global-scale hydrological modeling approaches for correcting perceived weaknesses in the representation of hydrological processes in GCMs is one of major approaches to deal with the problems.

Table 2.1 Some existing gaps between GCMs and hydrology needs (Xu, 1999)

	Better simulated	Less-well simulated	Not well simulated
Spatial scales mismatch	Global 500 km × 500 km	Regional 50 km × 50 km	Local 0–50 km
Temporal scales mismatch	Mean annual and seasonal	Mean monthly	Mean daily
Vertical scale mismatch	500 hPa	800 hPa	Earth Surface
Working variables mismatch	Wind Temperature Air Pressure	Cloudiness Precipitation Humidity	Evapotranspiration Runoff Soil moisture

GCMs' ability declines →

Hydrological importance increases →

2.2.3 New models proposed in this doctoral research

2.2.3.1 Streamflow-precipitation-temperature relation with ArcGIS Geostatistical Analyst

Because empirical models do not explicitly consider the governing physical laws of the processes involved, but only relate input to output through some transformation functions, the models reflect only the relationship between input and output for the climate and basin condition during the period in which they were developed. Extension of these empirical relationships to climate or basin conditions, different from those used for development of the function is therefore questionable (Leavesley, 1994).

Risbey and Entekhabi (1996) avoided this problem by using the observed data from a single basin and presented their results in the contour format by using the adjustable tension continuous curvature surface grid algorithm of Smith and Wessel (1990).

This doctoral research modified the methodology developed by Risbey and Entekhabi (1996) by using an ArcGIS Geostatistical Analyst to estimate the impacts of climatic change on regional hydrological regimes. There are at least two distinct advantages of the new approach compared to the Risbey and Entekhabi (1996) procedure. First, the ArcGIS Geostatistical Analyst provides a comprehensive set of tools for creating surfaces from measured sample points compared to the adjustable tension continuous curvature surface gridding algorithm used by Risbey and Entekhabi (1996). This allows users to efficiently compare the different interpolation techniques supplied by the ArcGIS Geostatistical Analyst in order to produce the best solution. Second, the methodology can easily be applied and expanded to different watersheds where the results could subsequently be used in a GIS environment for visualization and analyses. As demonstrated by the results from the Spokane River watershed, the research results can be used as a reference for long-term watershed management strategies under global warming scenarios.

2.2.3.2 GIS and land use based monthly water balance model

The major limitations of the water balance model are that it needs to calibrate parameters at observed conditions; it is unable to adequately account for possible changes in individual storm runoff characteristics at the time steps they are applied; and it can not take into account spatial distribution parameters.

With the GIS techniques available, the operation of the water balance model in the GIS environment has been increasingly popular. For example, Yang et al (2002) built a GIS-based monthly water balance model with the MapInfo-GIS package for the Ganjiang River watershed and Knight et al (2001) built a monthly balance model with GIS for the Struma River.

However, these GIS-based water balance models do not have a snow accumulation and snowmelt process and cannot simulate the hydrological responses to climatic and land use/land cover changes simultaneously. Snow accumulation and snowmelt processes are important for mountain and high latitude regions and different land use categories have a lasting important impact on the hydrological processes responsible for converting the precipitation into streamflow and ground-water storage. This doctoral research will develop such a model to overcome these two disadvantages.

2.2.4 Current research results

2.2.4.1 Precipitation in the future

Precipitation is the key input to the hydrological system: variations over space and time in hydrological behavior are largely driven by precipitation (Arnell, 2002). A warmer world means faster speed of hydrological cycle, greater total evaporation, and therefore greater total precipitation. It is in *high confidence* that global average precipitation will increase due to temperature increases and there will be changes in the timing and regional pattern of precipitation. However, researchers have *low confidence* in projections for specific regions because different models produce different detailed regional results (Houghton et al, 2001).

2.2.4.2 Effects on evaporation

If everything else remains constant, an increase in temperature alone would lead to an increase in potential evapotranspiration (PE). However, the magnitude of this increase will depend on a few key parameters (Arnell, 2002): (1) the current vapor pressure deficit; (2) the atmospheric water vapor content; (3) vegetation effects on PE; and (4) wind speed.

The *actual* rate of evaporation (AE) from the land surface depends on not only the PE, but also the amount of soil moisture available. If climatic change results in less soil moisture storage at any time, evaporation may fall even if potential evaporation increases.

2.2.4.3 Effects on streamflow regimes

Impacts of climatic warming on streamflow have been an active research area during the last 20 years. Arnell (1999) used a macro-scale hydrological model to simulate streamflow across the world at a spatial resolution of 0.5° × 0.5°, under the 1961–1990 baseline climate and under several scenarios derived from HadCM2 and HadCM3 experiments (Figure 2.2). The results indicate that the pattern of change in runoff is broadly similar to that of precipitation, although increased evaporation means that runoff decreases in some parts of the world even when precipitation increases.

The streamflow responses to climatic change are different from watershed to watershed. Table 2.2 lists some recent watershed-scale assessments of the implications of climatic change for streamflow based on Arnell (2002) and McCarthy et al (2001) and modified by the author.

2.2.4.4 Effects on ground-water recharge

There has been far less research into the effects of climate change on ground-water recharge (Arnell, 2002). However, a change in the amount of effective rainfall will alter recharge, so will a change in the duration of the recharge season (McCarthy et al, 2001). Increased winter rainfall — as projected under most scenarios for mid-latitudes — is likely to result in increased ground-water recharge (McCarthy et al, 2001). However, higher evaporation may mean that soil deficits persist for longer and commence earlier, offsetting an increase in total effective rainfall (McCarthy et al, 2001). Various types of aquifers will be recharged differently. Some examples of the effects of climatic change on recharge into unconfined aquifers have been described in France (Bouraoui et al, 1999), Kenya (Mailu, 1993), Tanzania (Sandstrom, 1995), Texas (Loaiciga et al, 1998), New York (Salinger et al, 1995), and the Caribbean islands (Amadore et al, 1996).

The general conclusion is that reduction of effective rainfall would result in a reduction in ground-water recharge for unconfined aquifers. For example, Sandstrom (1995) modeled recharge to an aquifer in central Tanzania and showed that a 15% reduction in rainfall — with no change in temperature — resulted in a 40–50% reduction in recharge, suggesting that small changes in rainfall could lead to large changes in recharge and hence ground-water resources.

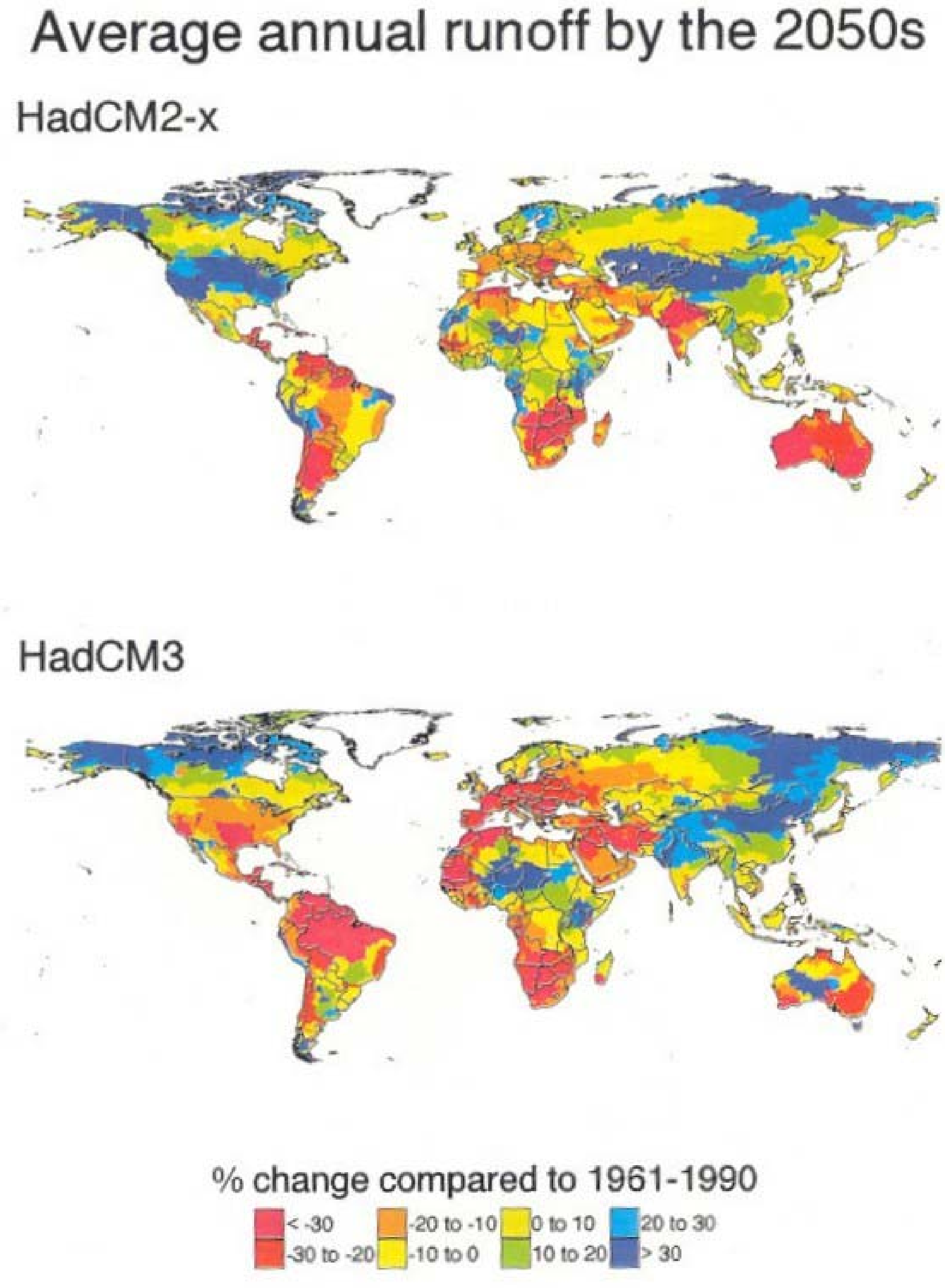


Figure 2.2 Average annual runoff by the 2050s (Arnell, 2002)

Table 2.2 Some watershed-scale studies on the effect of climate change on hydrological regimes

Region/Scope	Reference(s)
Africa	
– Ethiopia	Hailemariam (1999)
– Nile Basin	Conway and Hulme (1996); Strzepek et al (1996)
– South Africa	Schulze (1997)
– Southern Africa	Hulme (1996); Fanta et al (2001)
Asia	
– China	Ying and Zhang (1996); Ying et al. (1997); Liu (1998); Shen and Liang (1998); Kang et al. (1999); Fu and Liu (1991)
– Himalaya	Mirza and Dixit (1996); Singh and Kumar (1997); Singh (1998)
– Japan	Hanaki et al. (1998)
– India	Wilk and Hughes (2002)
– Philippines	Jose et al (1996); Jose and Cruz (1999)
– Yemen	Alderwish and Al-Eryani (1999)
Australasia	
– Australia	Bates et al (1996); Schreider et al (1996); Viney and Sivapalan (1996); Chiew et al (1995)
– New Zealand	Fowler (1999)
Europe	
– Albania	Bruci and Bicaj (1998)
– Austria	Behr (1998)
– Belgium	Gellens and Roulin (1998); Gellens et al (1998)
– Continent	Arnell (1999a)
– Czech Republic	Hladny et al (1996); Dvorak et al (1997); Buchtele et al. (1998)
– Danube basin	Starosolszky and Gauzer (1998)
– Estonia	Jaagus (1998); Jarvet (1998); Roosare (1998)
– Finland	Lepisto and Kivinen (1996); Vehviläinen and Huttunen (1997)
– France	Mandelkern et al (1998)
– Germany	Daamen et al (1998); Muller-Wohlfeil et al (2000)
– Greece	Panagoulia and Dimou (1996)
– Hungary	Mika et al. (1997)
– Latvia	Butina et al. (1998); Jansons and Butina (1998)
– Nordic region	Saelthun et al. (1998)
– Poland	Kaczmarek et al (1996; 1997)
– Rhine basin	Grabs (1997)
– Romania	Stanescu et al. (1998)
– Russia	Georgiyevsky et al, (1995; 1996; 1997); Kuchment (1998); Shiklomanov (1998)
– Slovakia	Hlaveova and Eunderlik (1998); Petrovic (1998)
– Spain	Avila et al (1996); Ayala-Carcedo (1996)
– Sweden	Xu (1998, 2000); Bergstrom et al (2001)
– Switzerland	Seidel et al (1998); Bultot et al (1992)
– UK	Arnell (1996); Holt and Jones (1996); Arnell and Reynard (1996, 2000); Sefton and Boorman (1997); Roberts (1998); Pilling and Jones (1999)
Latin America	
– Continent	Yates (1997); Braga and Molion (1999)
– Panama	Espinosa et al. (1997)
North America	
– USA	Bobba et al (1997); Hanratty and Stefan (1998); Chao and Wood (1999); Hamlet and Lettenmaier (1999); Lettenmaier et al. (1999); Leung and Wigmosta (1999); Miller et al (1999); Najjar (1999); Wolock and McCabe (1999); Miller and Kim (2000); Stonefelt et al. (2000); Gleick (1999)
– Mexico	Mendoza et al (1997)
– Canada	Gan (1998)

A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, and local rainfall does not influence the aquifer. The effects of changes in recharge on discharge from ground water to streams depend on aquifer properties with the faster the rate of water movement through the aquifer, the more rapid the response (Arnell, 2002).

2.3 Summary of the Literature Review

Water availability and its possible responses to climatic changes has been an active research topic over the last several decades. There are many research methodologies and results in the literature.

However, new methodologies and models are still needed for estimating watershed scale water availability and its responses to climatic changes, because the current water availability models and methods are either frequency analyses (Shafer and Dezman, 1982; Kresch, 1994), balance analyses between supply and demand (Jimenez et al, 1998), regional precipitation (Savenije, 2000), or difficult to use (USGS, 2002). The existing GIS based water balance models are lack of snow accumulation and snow melt processes and isolate land use and land cover impacts from climatic change impacts (Yang et al, 2002; Knight et al, 2001).

With respect to applications in the Spokane River watershed, there are no reports in the literature that provide a comprehensive analysis of the impacts of climatic changes on its streamflow and water availability.

CHAPTER 3 SPOKANE RIVER WATERSHED

Ranked 6th on the most endangered rivers in America list by due to “too little water, too much pollution, and an uncertain future”.

American Rivers and its Partners, 2004

3.1 BASIC SETTING

The Spokane River watershed covers 6,640 square miles in northern Idaho and northeastern Washington (Figure 3.1). Principal tributaries are the St. Joe and Coeur D'Alene Rivers, which flow into Coeur D'Alene Lake. The Spokane River, the lake's outlet, flows west, across the state line, to the city of Spokane. From Spokane, the river flows in a northwesterly direction to the Franklin D. Roosevelt Lake behind Grand Coulee Dam before its confluence with the Columbia River (Figure 3.1).

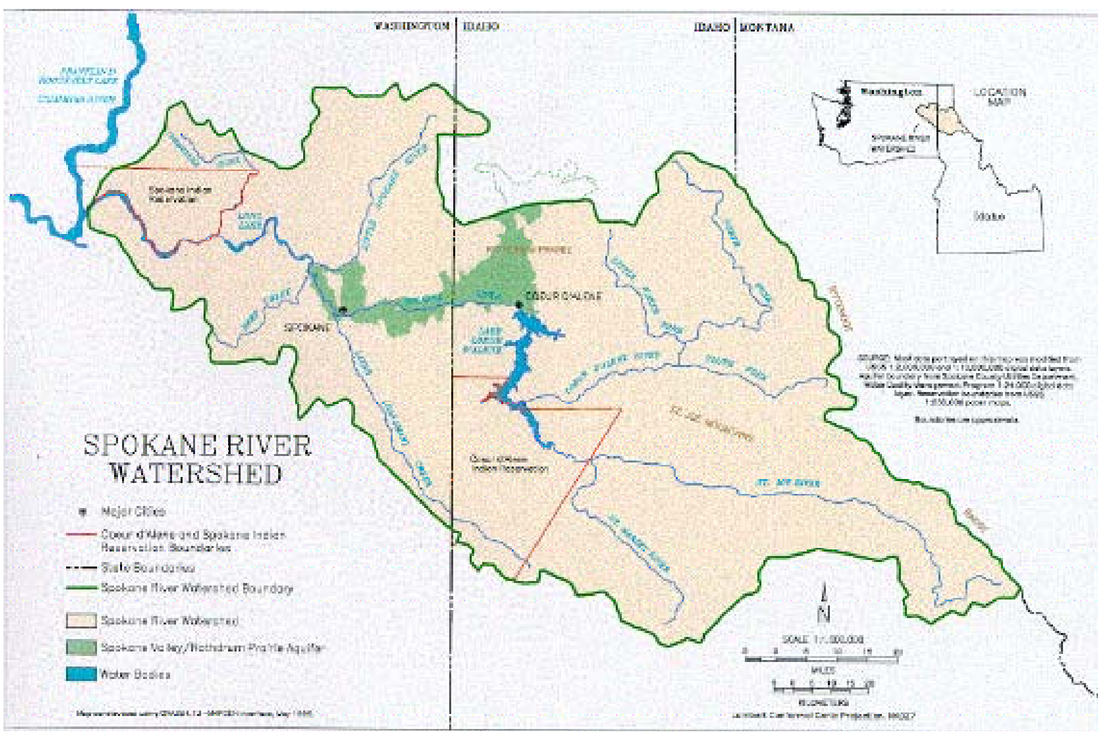


Figure 3.1 Spokane River watershed

3.1.1 Population

Most of the people in the watershed live in the Spokane metropolitan area and the population of the greater Spokane area is about 400,000 in 2000. However, the incorporated area of Liberty Lake on the east side of Spokane and the cities of Coeur D'Alene and Post Falls in Idaho are rapidly growing in population.

The city of Spokane is a fast-growing region whose population has increased from about 50,000 to 400,000 in the last century. The fastest population growth period was from 1900–1910 with the population remaining relatively stable from 1910 to 1940. After 1940 its population growth rate has been almost constant (Figure 3.2).

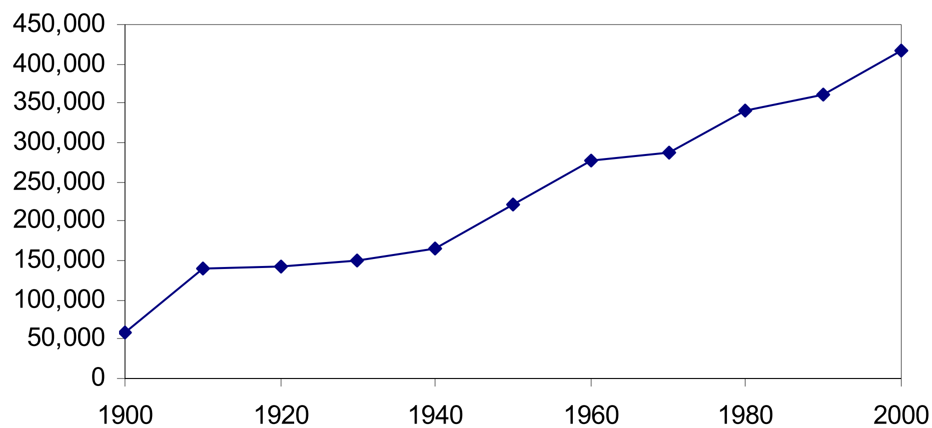


Figure 3.2 Population growths for the City of Spokane

Other urban areas in the watershed include Cheney, Medical Lake, Deer Park, and Airway Heights. The Spokane Indian Tribe's reservation is located in the lower river watershed, covering 155,000 acres of land (Knight, 1998).

3.1.2 Topography

Above Lake Coeur D'Alene, the basin is a mountainous and heavily forested area. Below the lake, the Spokane River flows through a deep valley along the edge of a rolling plateau with little forest cover. The average elevation of the watershed is 3,320 ft with the lowest elevation at 1,289 ft and the highest point at 7,048 ft. The topography of the Washington State portion of the watershed is relatively flat with elevation less than 2,500 ft for almost the entire region. The elevation increases rapidly in Idaho State from 2,500 ft to 7,000 ft (Figure 3.3).

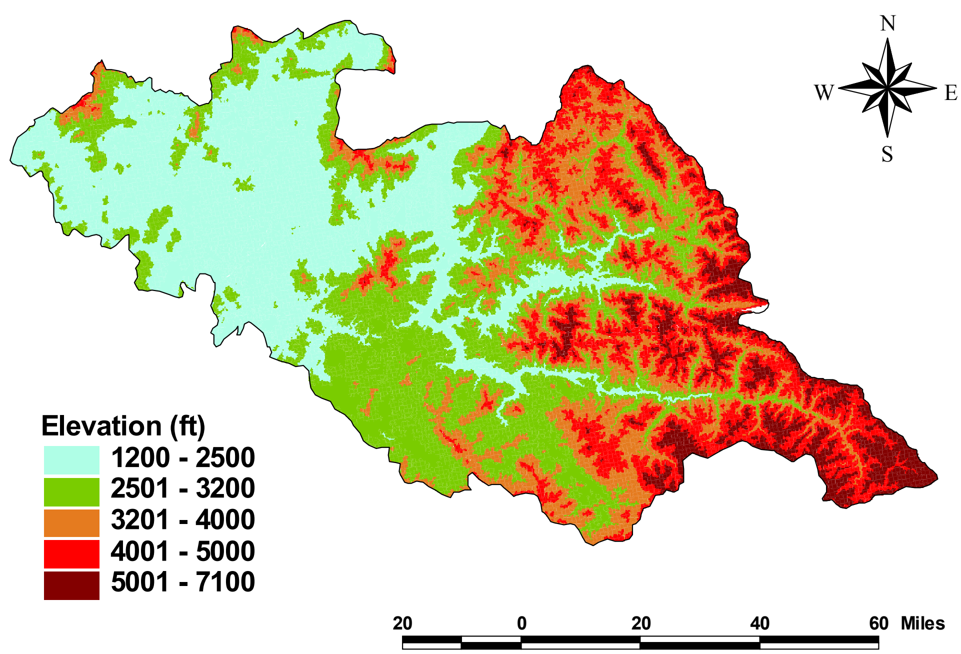


Figure 3.3 Elevation of the Spokane River watershed

3.1.3 Geology

The Spokane River watershed has a complex geological history (Crosby et al, 1971). The basin is composed of highly porous, poorly sorted glacial deposits. The upper and lower river substrate is composed of granitic rock cobble. From river mile 90 to 85 the substrate is composed of rocks and boulders. The river does not exhibit typical riffle-pool morphology (Bailey and Saltes, 1982). Below the river lies the Spokane-Rathdrum Aquifer which is the sole source of drinking water for the region.

3.1.4 Land Use and Land Cover

There are two sets of land use and land cover data available at the USGS website. One is 24K land use data and another is National Land Cover Data (NLCD).

The land use categories of 24K data set are described in Table 3.1. Based on this land use data, the majority of the land use types in the Spokane River watershed are forest and agriculture (Figure 3.4). The evergreen forest (Code 42) occupies about 72.8% of the watershed area and the cropland and pasture (Code 21) occupies 18.3% of the watershed area. The agricultural lands are located in the southwestern portion of the watershed. The following major land use types are residential (code 11, 1.83%), mixed forest land (code 43, 1.62%), shrub and brush rangeland (code 32, 1.52%), and lakes (code 53, 1.17%) (Figure 3.5).

Table 3.1 USGS 24K Land Use Data Categories

- 1 Urban or Built-Up Land
  - 11 Residential
  - 12 Commercial Services
  - 13 Industrial
  - 14 Transportation, Communications
  - 15 Industrial and Commercial
  - 16 Mixed Urban or Built-Up Land
  - 17 Other Urban or Built-Up Land
- 2 Agricultural Land
  - 21 Cropland and Pasture
  - 22 Orchards, Groves, Vineyards, Nurseries
  - 23 Confined Feeding Operations
  - 24 Other Agricultural Land
- 3 Rangeland
  - 31 Herbaceous Rangeland
  - 32 Shrub and Brush Rangeland
  - 33 Mixed Rangeland
- 4 Forest Land
  - 41 Deciduous Forest Land
  - 42 Evergreen Forest Land
  - 43 Mixed Forest Land
- 5 Water
  - 51 Streams and Canals
  - 52 Lakes
  - 53 Reservoirs
  - 54 Bays and Estuaries
- 6 Wetland
  - 61 Forested Wetlands
  - 62 Nonforested Wetlands
- 7 Barren Land
  - 71 Dry Salt Flats
  - 72 Beaches
  - 73 Sandy Areas Other than Beaches
  - 74 Bare Exposed Rock
  - 75 Strip Mines, Quarries, and Gravel Pits
  - 76 Transitional Areas
  - 77 Mixed Barren Land
- 8 Tundra
  - 81 Shrub and Brush Tundra
  - 82 Herbaceous Tundra
  - 83 Bare Ground
  - 84 Wet Tundra
  - 85 Mixed Tundra
- 9 Perennial Snow and Ice
  - 91 Perennial Snowfields
  - 92 Glaciers

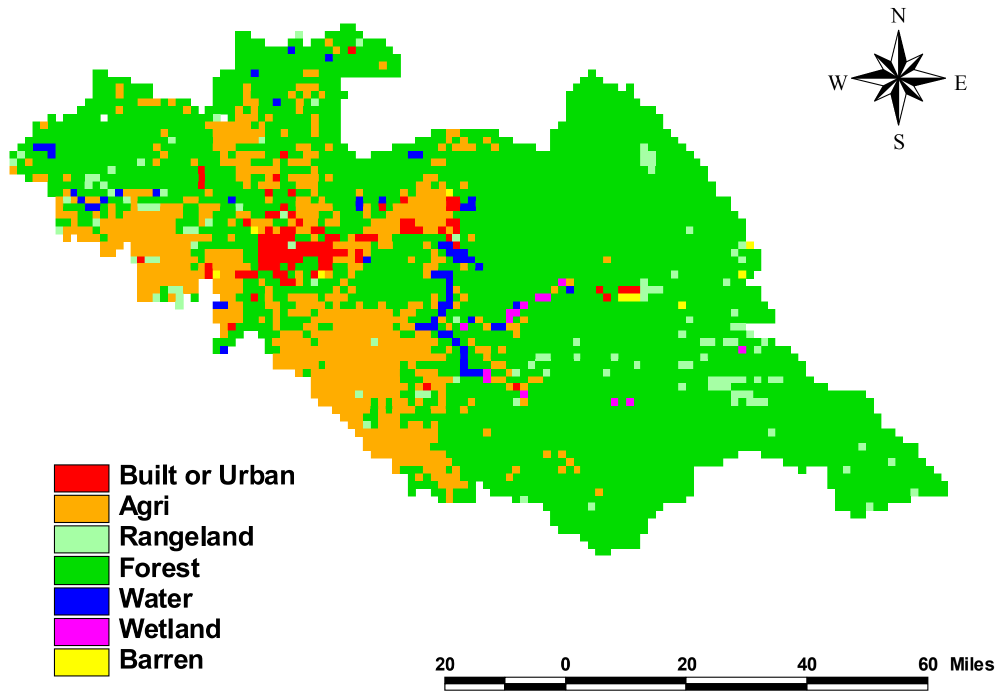


Figure 3.4 Land Use Map of the Spokane River watershed

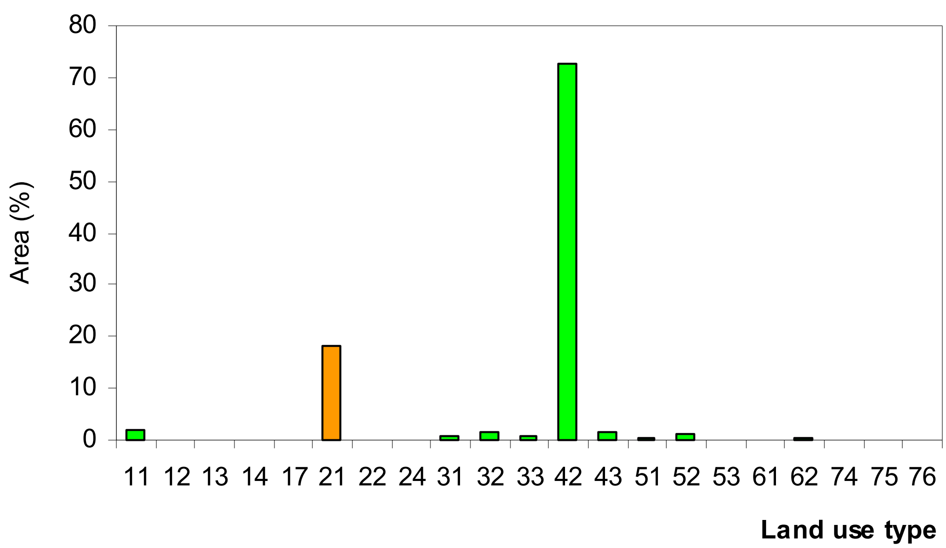


Figure 3.5 Land Use Percentage (%)

USGS National Land Cover Data (NLCD) uses a different classification system, although there are also nine major types. Table 3.2 lists its land classification system.

It is clear that evergreen forest (code 42) is still the dominant land cover with an area percentage of 61.4% (Figure 3.6). This number is smaller than the previous 24K land use data, because the forested land is detailed into different categories. The cropland and pasture are separated in this land cover classification, so there is no obvious second dominant land cover type. Instead, there are several different land cover categories with almost the same areas: small grains (code 83, 7.38%), shrubland (code 51, 6.08%), fallow (code 84, 5.65%), transitional (code 33, 4.61%), grassland/herbaceous (code 71, 3.95%), pasture/hay (code 81, 3.35%), and mixed forest (code 43, 2.51%) (Figure 3.7).

3.2 HYDROLOGIC AND CLIMATIC CHARACTERISTICS OF THE SPOKANE RIVER WATERSHED

3.2.1 Watershed systems

The Spokane River watershed, US EPA Hydrologic Unit Code (HUC), 170103, has eight sub-watersheds (Figure 3.8): Upper Coeur D’Alene (17010301) in Idaho State, South Fork Coeur (17010302) in Idaho State, Coeur D’Alene Lake (17010303) in Idaho and Washington States, St. Joe (17010304) in Idaho State, Upper Spokane (17010305) in Idaho and Washington States, Hangman (17010306) in Idaho and Washington States, Lower Spokane (17010307) in Washington State, and Little Spokane (17010308) in Washington and Idaho States.

Table 3.2 USGS National Land Cover Data (NLCD) classifications

1 Water	
	11 Open Water
	12 Perennial Ice/Snow
2 Developed	
	21 Low Intensity Residential
	22 High Intensity Residential
	23 Commercial/Industrial/Transportation
3 Barren	
	31 Bare Rock/Sand/Clay
	32 Quarries/Strip Mines/Gravel Pits
	33 Transitional
4 Forested Upland	
	41 Deciduous Forest
	42 Evergreen Forest
	43 Mixed Forest
5 Shrubland	
	51 Shrubland
6 Non-natural Woody	
	61 Orchards/Vineyards/Other
7 Herbaceous Upland	
	71 Grasslands/Herbaceous
8 Herbaceous Planted/Cultivated	
	81 Pasture/Hay
	82 Row Crops
	83 Small Grains
	84 Fallow
	85 Urban/Recreational Grasses
9 Wetlands	
	91 Woody Wetlands
	92 Emergent Herbaceous Wetlands

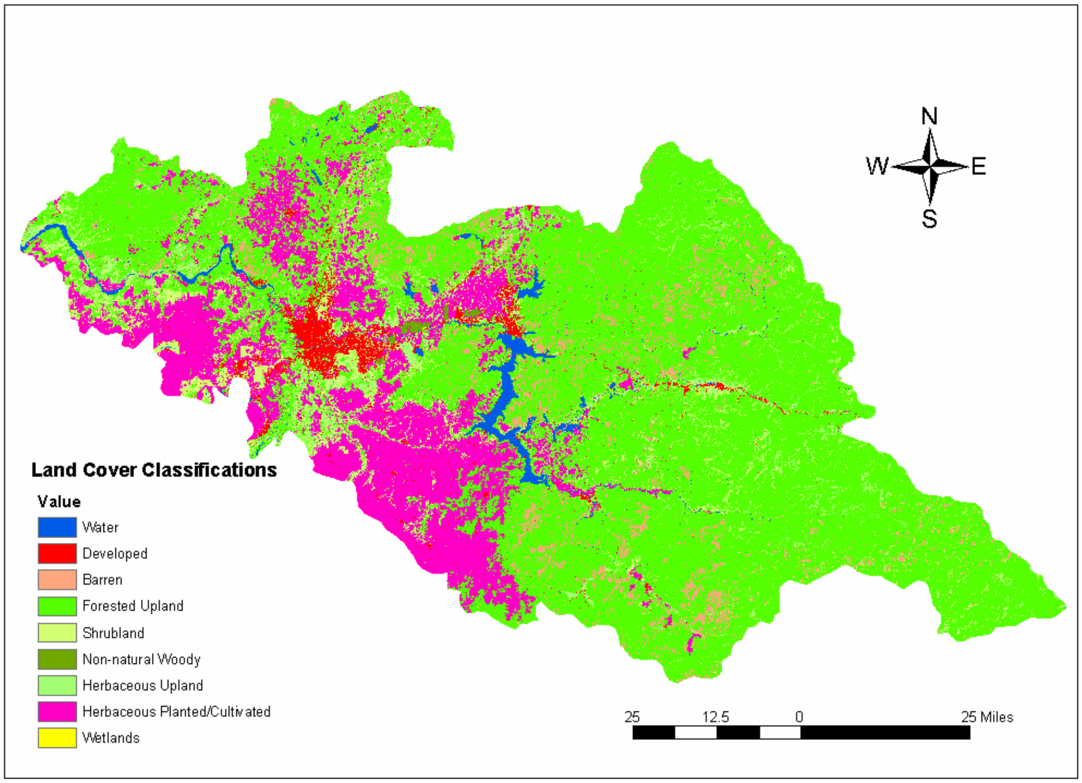


Figure 3.6 Land Cover Map of the Spokane River watershed

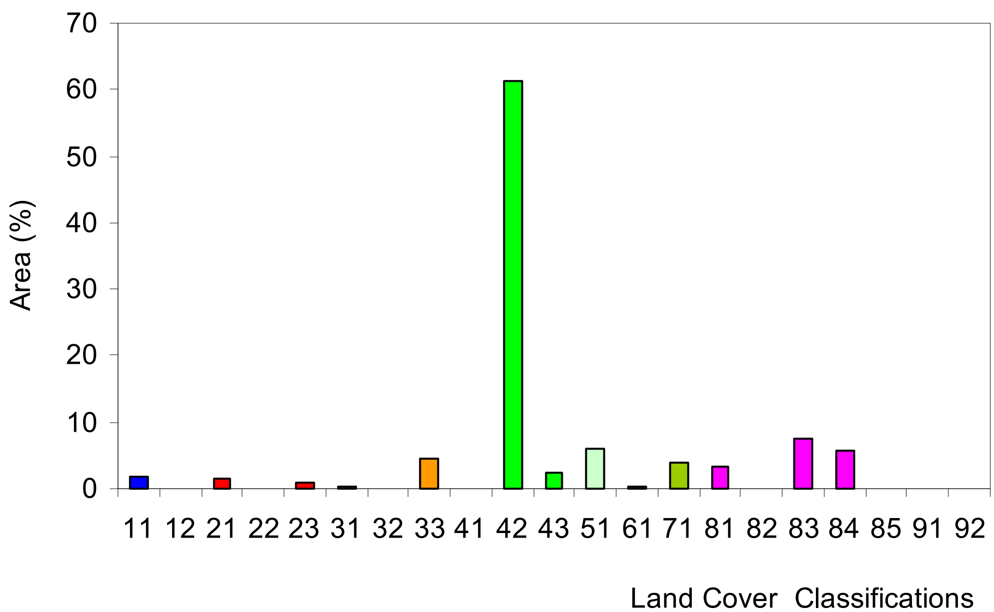


Figure 3.7 Land Cover Percentage (%)

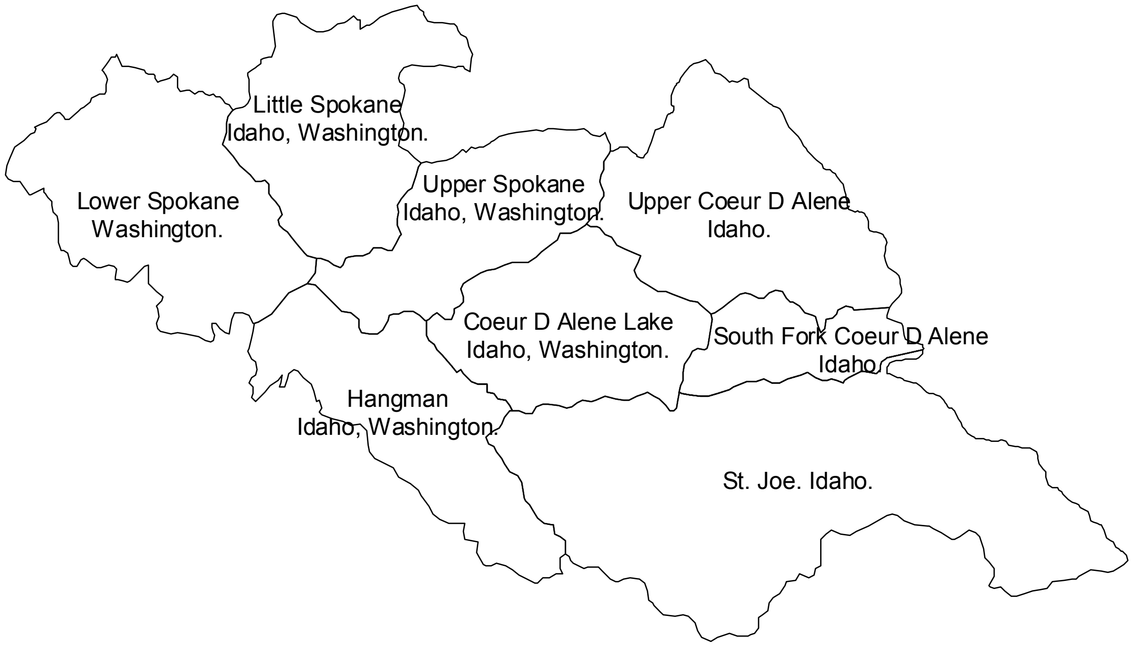


Figure 3.8 Sub-watersheds within Spokane River watershed

3.2.2 Long-term water balance

The long-term (1917–2001) water year (October to next September) annual precipitation in the Spokane River watershed was about 24.6 in. About 70.5% of the precipitation, or 17.4 in., became streamflow, which, when scaled up to the size of the studied drainage area, was equivalent to a flow rate of 7,700 cfs. Making the reasonable assumption that the mean water storage change from 1917 to 2001 is negligible, annual evaporation in the Spokane River watershed is about 7.3 in (Table 3.3).

Table 3.3 Mean, standard deviation and extreme values of precipitation, runoff, and temperature of the Spokane River watershed

	Mean	Standard Deviation	Minimum		Maximum		Periods
			Value	%	Value	%	
Precipitation (in)	24.6	4.5	13.7	55.8	36.2	146.8	1917–2001
Runoff (in)	17.4	5.0	7.2	41.3	30.4	175.1	1917–2001
Temperature (^oF)	46.4	1.2	43.89		49.7		1931–2001

3.2.3 Year-to-year variation

The annual variations of precipitation and runoff varied significantly in the Spokane River watershed (Figure 3.9). The maximum annual precipitation was 2.63 times the minimum value and the maximum annual runoff value was 4.24 times the low-flow year amount during the 85 year period of 1917–2001 (Table 3.4). The temperature statistic was based on the time period of 1931–2001 as most of the weather stations started to record in 1931. The precipitation and temperature data were the spatial average values for 13/15 stations (Appendix B) with individual station having a larger variation. Streamflow data was from USGS Station 12433000 and data from 1917–1938 were regressed (R^2=0.989) from USGS Station 12422500 with annual data for 1939–2001.

3.2.4 Seasonal and monthly variation

The precipitation, runoff and temperature have obvious seasonal and monthly variations in the Spokane River watershed (Figure 3.10). One interesting fact, however, is that runoffs in April, May, and June were larger than the precipitation for their respective months. This suggested that the characteristics of winter hydrology and snowmelt processes were critical for runoff generation.

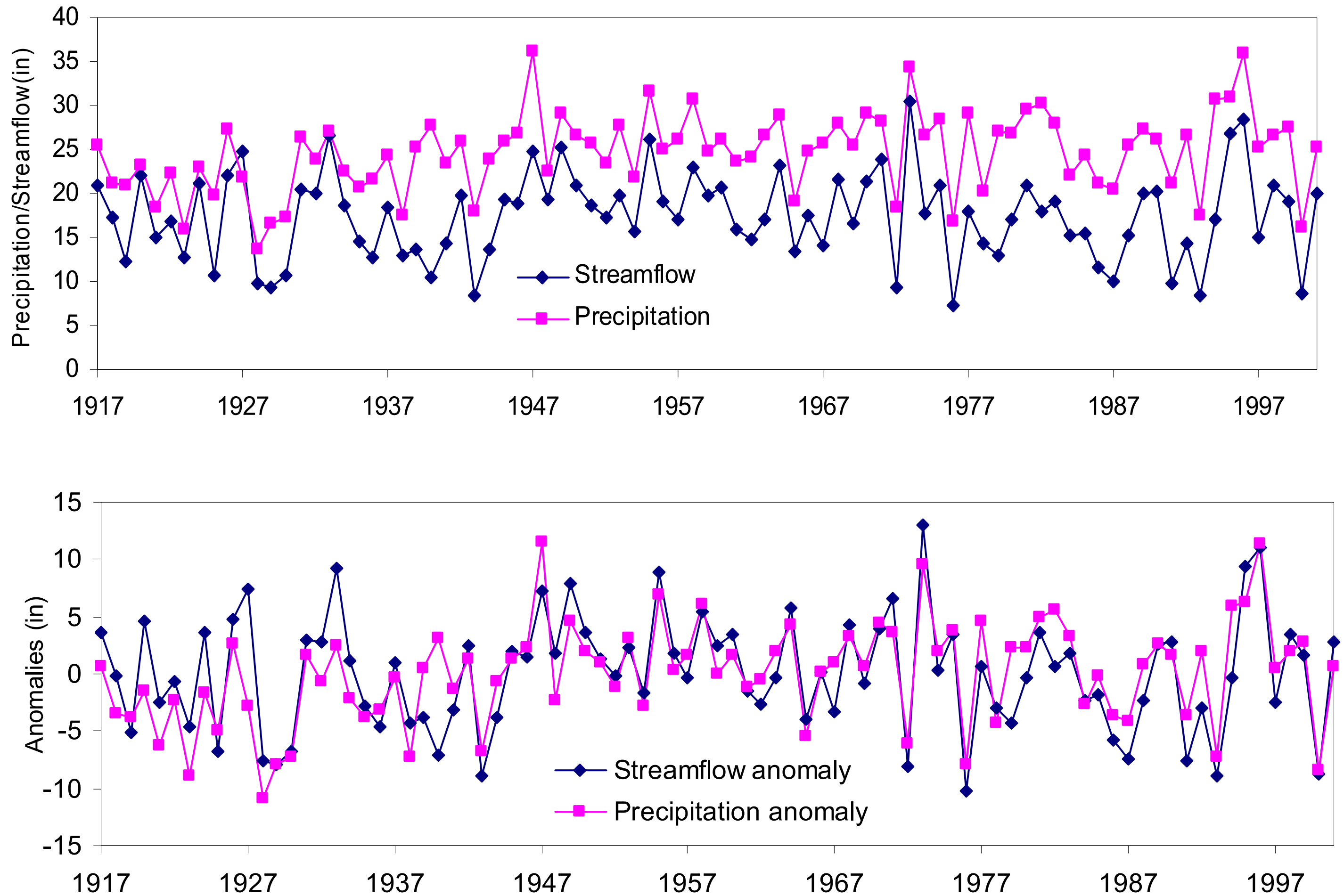


Figure 3.9 Time series and anomalies of precipitation and streamflow in the Spokane River watershed (1917–2001)

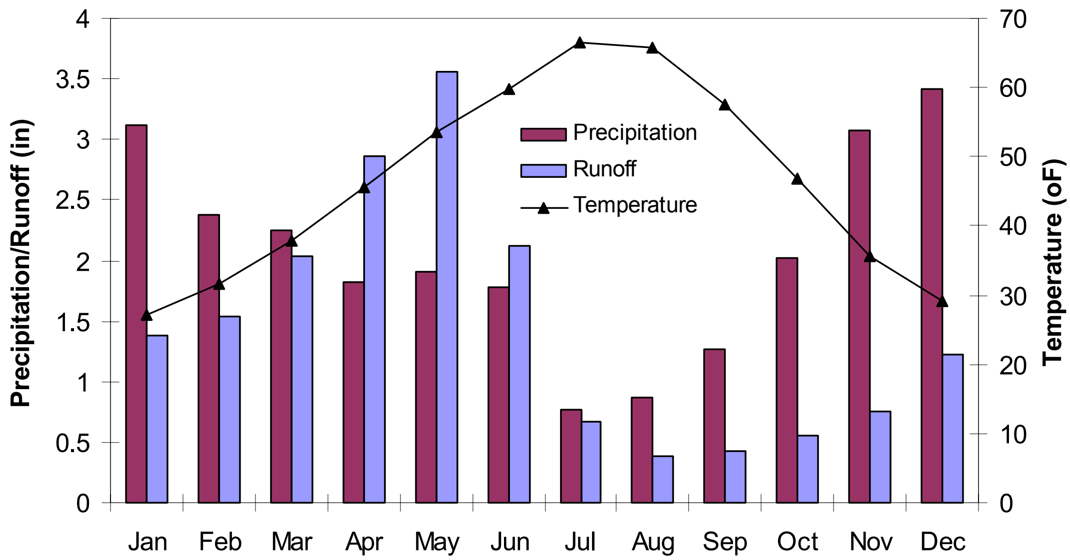


Figure 3.10 Monthly precipitation and runoff in the Spokane River watershed

3.2.5 Spatial pattern

The precipitation and temperature of the Spokane River watershed show a spatial pattern: the precipitation increases from west to east (Figure 3.11) and temperature decreases from southwest to northeast (Figure3.12). This climatic spatial pattern results in the runoff spatial distribution (Figure 3.13). The runoff depth at the Little Spokane sub-basin, located at the northwest portion of the watershed, is only 4.7 in. due to low precipitation and high temperature. This runoff depth is only 27.2% of the average value of the entire Spokane River watershed.

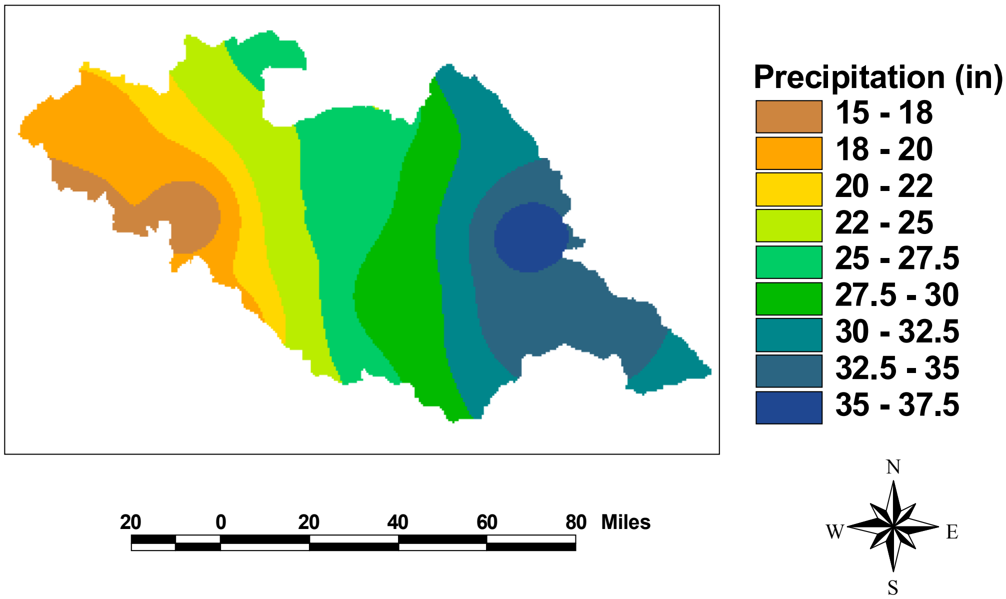


Figure 3.11 Precipitation spatial distributions in the Spokane River watershed

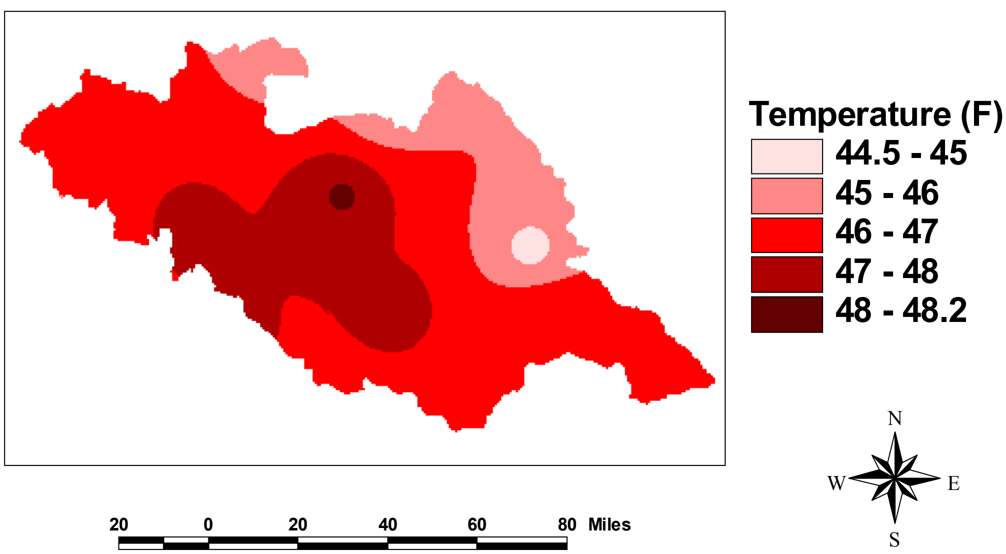


Figure 3.12 Temperature spatial distributions in the Spokane River watershed

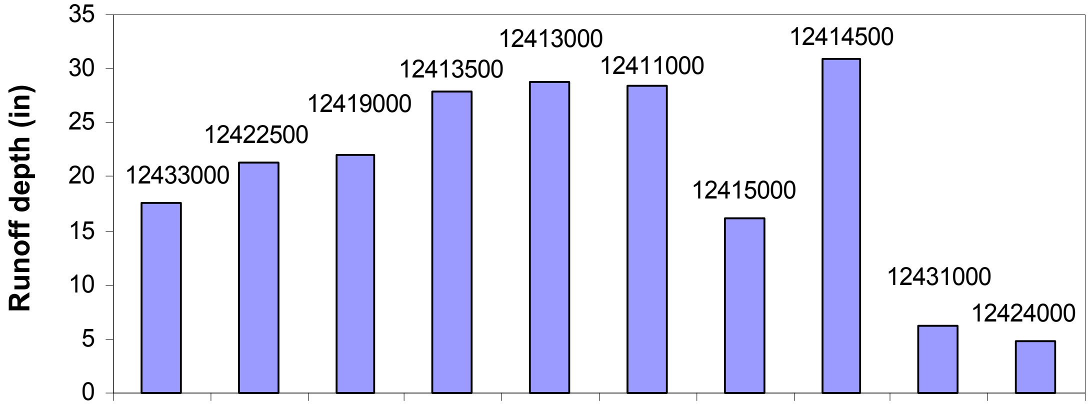


Figure 3.13 Annual Runoff depths at different USGS gauges within the Spokane River watershed

CHAPTER 4 HYDRO-CLIMATIC REGIMES IN WASHINGTON STATE SINCE 1967 STUDY

If you look at the past five years, drought is getting to be a regular occurrence in our state. But what we are seeing in our mountains, and in our streams, and in our reservoirs this year elevates us to a new level of concern.

Governor Christine Gregoire, 2005

4.1 REVIEW OF THE 1967 STUDY

In 1967, the State of Washington Water Research Center (SWWRC) conducted a comprehensive water resource study for the entire Washington State. The results of this research were published in four volumes as "An Initial Study of the Water Resources of the State of Washington".

- Vol. I *A First Estimate of Future Demands*
- Vol. II *Water Resources Atlas of the State of Washington: Part A and B*
- Vol. III *Irrigation Atlas of the State of Washington*
- Vol. IV *Water Quality of the State Washington*

This research divided the entire state into 50 sub-watersheds (Table 4.1). The mean annual runoff for the entire State of Washington, at that time, was 96,221,000 acre-feet based on the 2.33-year return period. This value was, however, the virgin-flow and did not represent the depleted value. The eastern portion of the state which is an entire tributary to the Columbia River and includes Watersheds 24–50, had a gross land area of 47,929 mi^2, and contributed approximately 33,301,000 acre-feet annually. The western portion of the state which drains to the Pacific Ocean and Puget Sound, comprised a gross land area of only 19,558 mi^2 and had a mean annual runoff of approximately 62,920,000 acre-feet. Thus the western portion, which encompassed less than 29% of the total state area, produced approximately two-thirds of the mean annual runoff. This reflects the basic characteristics of water resources for Washington State: uneven spatial distribution.

The main concern of this doctoral research is whether or not there are any significant changes in the water resource regimes for Washington State since the 1967 study was completed and can those 1967 results still be used for water resource management and planning?

4.2 HYDRO-CLIMATIC CHANGES

4.2.1 Data Sets

There were 42 USGS gages used in 1967 by SWWRC for water resource assessment. Streamflow data were used only from 1954 to 1960 (Table 4.1). However, there are only 27 of these 42 USGS stations having continuous streamflow records up to 2002. These 27 stations were then chosen for comparing the streamflow from 1961 to 2002 with the data from 1954 to 1960. Because 27 stations are a little sparse in spatial distribution, 12 more USGS gages based on Kresch (1994) were also used in the study. The major criteria used by Kresch (1994) to select USGS stations were that they: (1) have continuous records throughout the base period 1937–1976; (2) be widely distributed to adequately define variations in streamflow patterns throughout the state; and (3) represent natural conditions not significantly affected by man's activities, such as water diversion or import (Kresch, 1994). There were 32 streamflow stations in Washington State that meet Kresch's standards. Twenty of these 32 stations were either used by SWWRC or did not have a continuous records up to 2002, which left only 12 stations available for use

Table 4.1 Hydrological gages used for water resources study by SWWRC

No	Watershed	Area	Gage	Drainage	Station ID	Remark
1	Nooksack;	948	near Lynden	648	12211500	
2	Samish;	316	near Burlington	87.8	12201500	
3	San Juan;	228				60% precipitation=runoff
4	Skagit;	2924	near Concrete	2737	12194000	
5	Stillaguanish;	707	near Arlington	262	12167000	
6	Islands;	206				68% precipitation=runoff
7	Snohomish;	1852	Snoqualmie River near Carnation	603	12149000	
8	Sammamish-Cedar;	647	Sammamish River at Bothell	212	12126500	
9	Green River;	517	near Auburn	399	12113000	
10	Puyallup;	1030	Puyallup	948	12101500	
11	Nisqually;	716	near McKenna	445	12088500	
12	Deschutes;	270	near Olympia	160	12080000	
13	Tacoma;	193	Chambers Creek below Leach	104	12091500	
14	Shelton;	358	Goldsborough Creek near Shelton	39.3	12076500	
15	Kitsap;	666	Dewatto Creek near Dewatto	18.4	12068500	
16	Hood Canal;	596	N.F.Skokomish River near Hoodsport	93.7	12057500	
17	Port Twonsend;	400	Snow Creek near Maynard	11.2	12050500	
18	Elwha-Dungeness;	717	Elwha R at McDonald Bridge near Port Angeles	269	12045500	
19	Norht-Peninsula;	375				no gages
20	Olympic Coast;	2332	Quinault R at Quinault Lake	264	12039500	
21	Chehalis Norht;	1660	Humptulips R near Humptulips	130	12309000	
22	Chehalis South;	968	near Grand Mound	895	12027500	
23	Willapa;	932	Naselle R near Naselle	54.8	12010000	
24	Cathlamet;	503	Elochoman R near Cathlamet	65.8	14247500	
25	Cowlitz;	2503	Castle Rock	2238	14243000	
26	Kalama-Lewis;	1313	Lewis R at Ariel	731	14220500	

27	Vancouver;	410	Washougal R near Washougal	108	14143500	
28	Wind River-White Salmon;	952	White Salmon R near Underwood	386	14123500	
29	Klickitat;	1446	near Pitt	1297	14113000	
30	Rock Creek – Horse Heaven;	1659				no gages
31	Yakima South;	3330	Kiona	5615	12510500	
32	Yakima West;	1608	Naches R below Tieton R near Naches	941	12494000	
33	Yakima North;	1966	Untanum	1594	12484500	
34	Wenatchee;	2560	Peshastin	1000	12459000	
35	Douglas-Moses Coulee;	1996	Columbia			no gages
36	Chelan;	1466	Chelan	924	12452500	
37	Methow;	2274	Twisp	1301	12449500	
38	Okanogan;	2260	Similkameen R near Nighthawk	3550	12442500	
39	Sanpoil;	1307				no gages
40	Kettle;	1014	Laurier	3800	12404500	
41	East Ferry;	1146				no gages
42	Colville;	1569	Kettle Falls	1007	12409000	
43	Pend Oreille;	1276	below Z Canyon	25200	12398500	
44	Spokane North;	735	Little Spokane R at Dartford	665	12431000	
45	Spokane South;	1555	Spokanr R at Long Lake	6020	12433000	
46	Palouse Watershed;	2733	near Hooper	2500	13351000	
47	Upper Snake;	2226	Asotin Creek near Asotin	170	13334700	
48	Walla Walla;	1358	near Touchet	1657	14018500	
49	Lower snake;	927				no gages
50	Crab Creek.	6837	Irby	1042	12465000	

in this doctoral research. Therefore, the total number of streamflow stations studied was 39.

4.2.2 Method

A simple monthly mean streamflow comparison between 1961–2002 and 1954–1960 was made and the results have been expressed as percentage change, i.e.

$$Change(\%) = \frac{Mean_{1961-2002} - Mean_{1954-1960}}{Mean_{1954-1960}} \times 100\% \qquad (4.1)$$

4.2.3 Results

The results indicated that all 39 USGS streamflow stations showed a decreasing trend in annual streamflow that ranged from -0.9% to -49.4%, with an arithmetic mean of -11.2% (Table 4.2 and Figure 4.1).

However, the trend was significantly different from month to month. In October, November, and December, almost all stations indicated a decreasing trend (Figure 4.2).

Table 4.2 Stream flow difference between 1961–2002 and 1954–1960 (%)

Annual Stream flow Change (%)	Number of Stations
Less than -5%	2
-5% to -10%	20
-10% to -20%	16
More than -20%	1
39 stations average change (%)	-11.2%
Minimum Change	-0.9%
Maximum Change	-49.4%

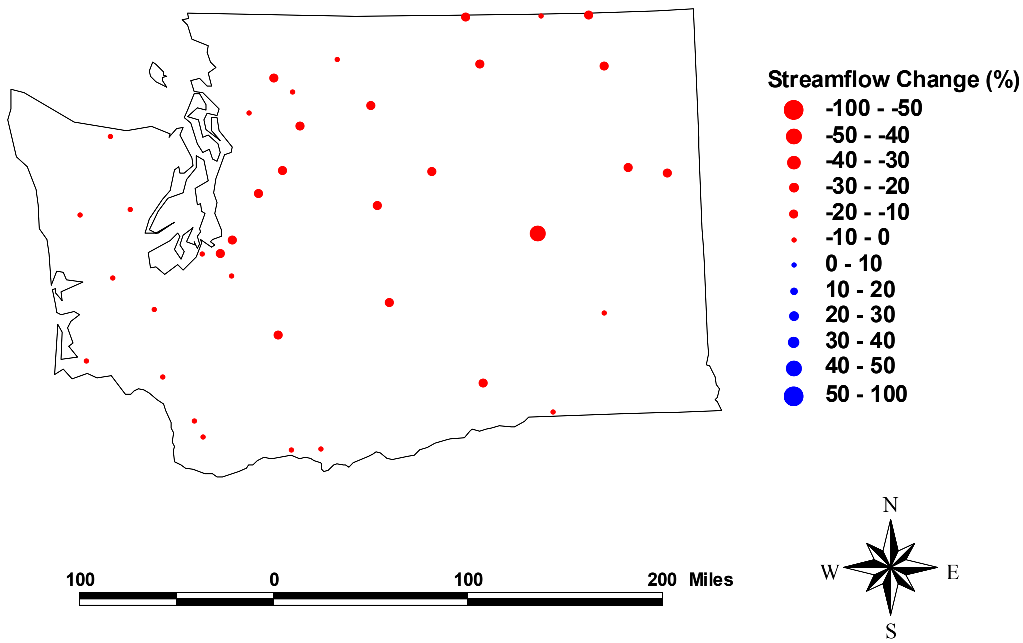
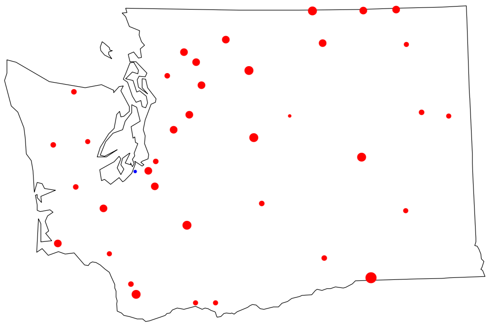


Figure 4.1 Annual streamflow changes after 1967 study

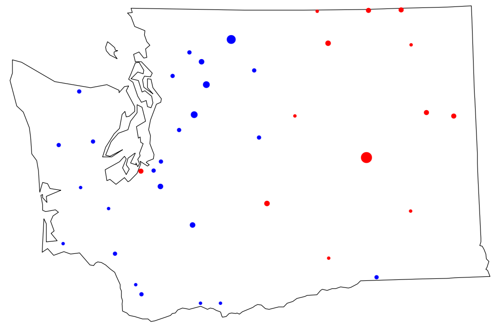
In January, the trend had a significantly different pattern than December with the Western part of the state showing an increasing trend and the Eastern part of the state showing a decreasing trend. In February and March, the increasing trend dominated the entire state with few stations showing a decreasing trend. The increasing trend almost disappeared in April with the exception of a few stations in the northern center part of the state. May and June had a decreasing period for almost all stations. There were only a few stations showed an increasing trend in July, concentrated in the southeastern corner of the state. There were more stations showing an increasing trend in August than that in July at the southern portion of the state, although the decreasing trend still dominated the state. September was also a decreasing month with only a few exceptions. This temporal distribution was clearer in Figure 4.3 by looking at the minimum, maximum, and mean streamflow changes for the entire 39 stations in Washington State through comparing the 1961–2002 means with the 1954–1960 mean values.

4.3 DISCUSSIONS AND CONCLUSIONS

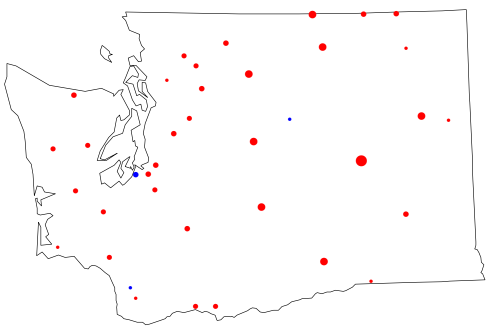
The preliminary result concluded that the 1967 state wide water resource assessment needs to be updated for water resource management and planning usage. Specifically, the report would overestimate the current streamflow for most stations for most months and underestimate in general for January, February, and March. However, one critical question remains unclear, which is whether or not the streamflow's decreasing trend was a result of increased water withdrawal, climatic change, or the baseline during 1954–1960 being a "wet" period. Karl and Knight (1998) has shown that the precipitation has increased by 5–20% and temperature has increased by 1–2^{o}C/100years from 1900 to1994 for Washington State's meteorological stations. The average annual streamflow of 1954–1960 at USGS Station 12433000 (Spokane River at Long Lake) was about 9.5% higher than the 1940–1960 average, and 14.2% higher than the 1940–2002 average value. A further investigation may clarify this, but it is beyond the scope of this doctoral research.



October



January



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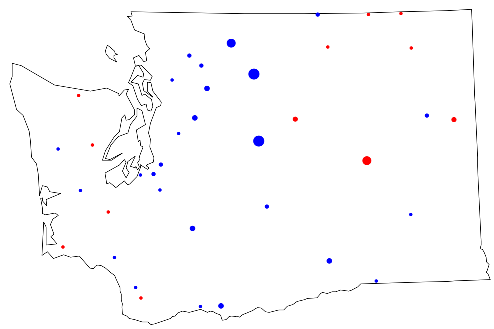

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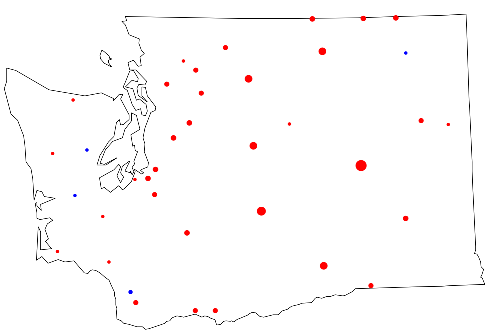

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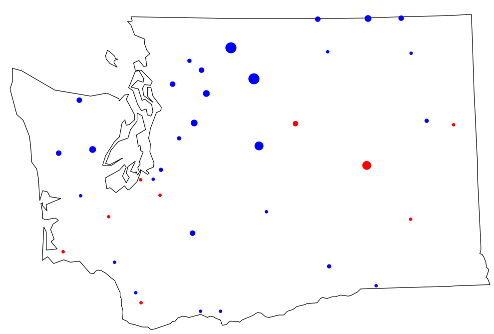

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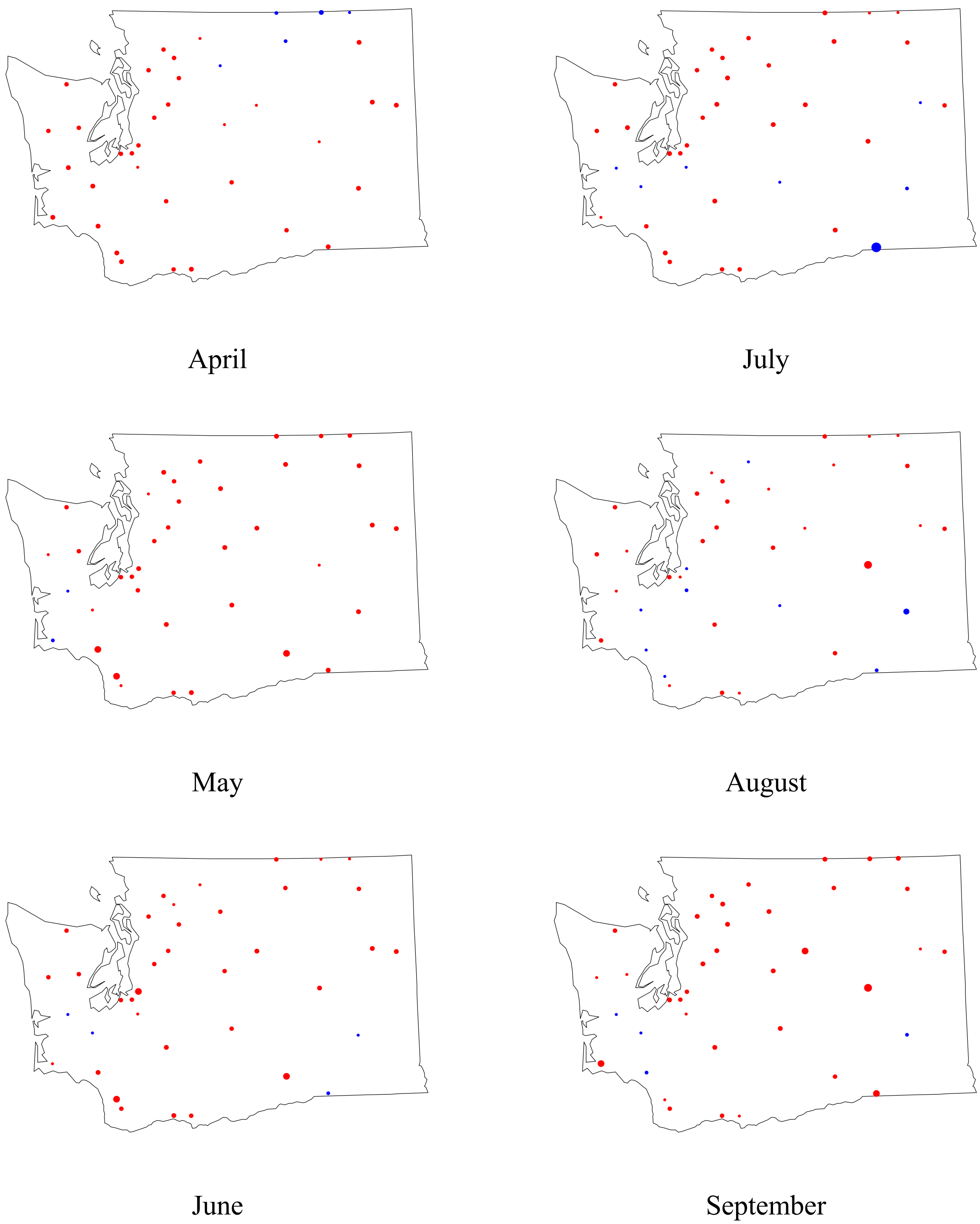


Figure 4.2 Monthly streamflow changes after 1967 study

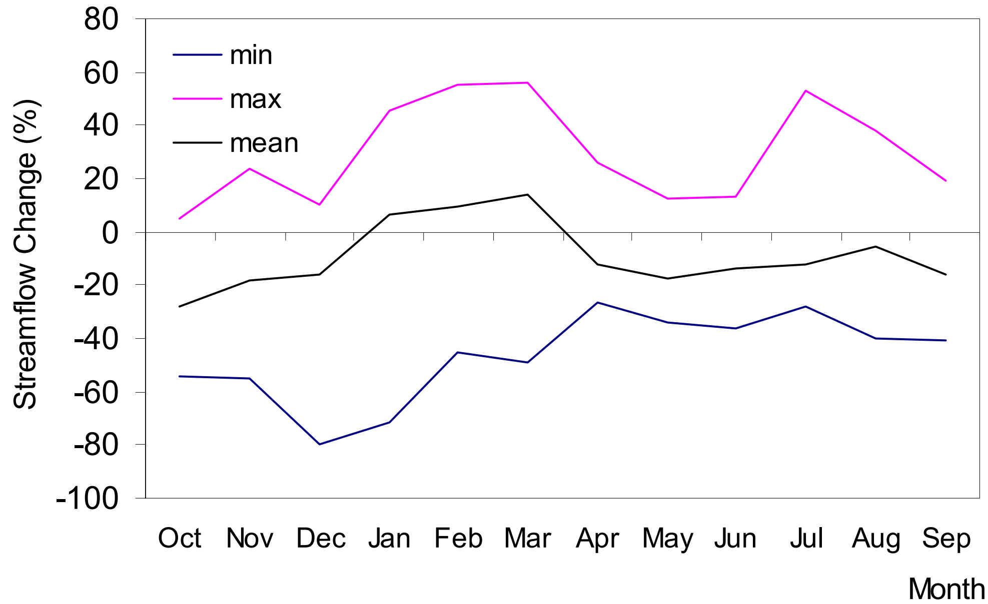


Figure 4.3 Streamflow changes by month for 39 stations at Washington State

CHAPTER 5 MODELING WATER AVAILABILITY FOR THE SPOKANE RIVER WATERSHED

Everything of importance has been thought of before by someone who did not invent it.

Alfred North Whitehead, 1920

5.1 MODELING WATER AVAILABILITY

5.1.1 Concept model of water availability

Watershed water availability occurs as surface water in water bodies and as renewable ground water in aquifers (Figure 5.1). However, these two resources can not simply be added, since surface- and ground- water interaction and the recharge of the renewable ground water eventually ends up in the surface water system. The basic equation is:

$$W_a = W_s + W_g - W_i \quad (5.1)$$

Where

W_a is the watershed scale water availability;

W_s is the watershed surface water availability;

W_g is the watershed ground-water availability; and

W_i is the repeated water availability due to surface- and ground- water interaction.

Depending on climate, topography, geology, soil, vegetation, and time, the surface- and ground- water interaction can be very active or completely inactive. For a watershed with active surface- and ground- water interaction, the ground-water availability has a high percentage of watershed water availability. The contribution of ground water to total streamflow varies widely among streams. The 54 streams in 24 regions in the continent United States over the 30-year period (1961–1990) indicated that 52 percent of the streamflow was contributed by ground water. Ground-water contributions ranged from 14 percent to 90 percent, and the median was 55 percent (Winter et al, 1998).

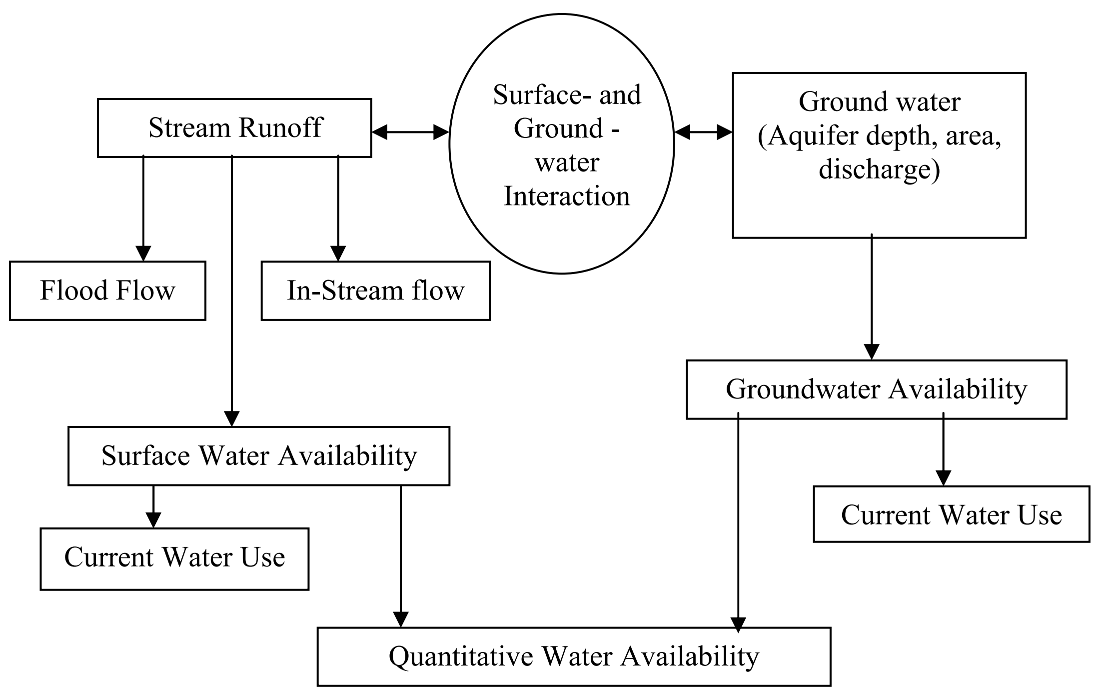


Figure 5.1 Framework of watershed scale water availability

5.1.2 Surface water availability

Surface water availability (W_s) is basically a function of stream runoff (R) with a deduction of instream flow requirement and flood flow. However, as ecologists recognize the importance of high flows for maintaining river ecosystems, the instream flow requirements would be automatically satisfied during a flood event. Therefore, surface water availability could be estimated as:

$$W_s = \begin{cases} R_f & If \quad R > R_f \\ R - R_{in} & If \quad R_{in} < R < R_f \\ 0 & If \quad R < R_{in} \end{cases} \tag{5.2}$$

Where

R_{in} is the instream flow;

R_f is the flood flow event criterion; and

R is the monthly streamflow.

5.1.2.1 Instream flow estimation

To accurately estimate instream flow is complex and complicated work, since the amount of instream flow affects many issues of water quality and water quantity. Instream flow will affect not only instream water uses, but also out-of-stream water uses. In general, the following aspects should be taken into account when estimating instream flow requirement.

Aquatic habitat is the most obvious water use affected by instream flow. A low instream flow could result in the decline of many species while a deeper, more varied, and more abundant instream flow could allow for an abundant and diverse life.

Recreational water use is closely related to the amount of instream flow. Instream flow significantly affects many sports, such as rafting, canoeing, and fishing.

Scenic beauty and natural environment also need a certain amount of water in the river channel. The quality of scenic beauty and the natural environment are closely related to the amount of instream flow.

Transportation requires a certain amount of water in the stream if the stream has a water transportation function.

Hydroelectric power generation need a certain amount of water and a certain amount of hydraulic head if the power generation facilities were installed.

Maintenance of the riparian zone water uses is also related to the amount of instream flow.

Pollutant concentration is controlled by the amount of instream flow. Higher flow is important for dilution of pollutants; in fact, many rivers and streams violate water quality standards for common pollutants when flows are abnormally low. A higher pollutant concentration affects all of the instream flow water uses and out-stream water uses, such as municipal, industry, and agricultural water uses.

Water temperature becomes too warm if instream flow is too little, thus can affect both the instream flow and out-stream water uses. Temperature is one of the major parameters for the Total Maximum Daily Loads (TMDL) study. Within the Unites States, 44,962 miles of stream fail to meet state water temperature criteria (EPA, 2002). Washington alone has about 15,843 miles of such failed streams, which is about 35.2 % of that of the entire nation.

Because instream flow affects not only the many instream water uses, but also out-stream water uses, attention should be paid to both the amount of water that is made available for out-of-stream uses (e.g. irrigation, municipalities, commercial and industrial uses) as well as for the protection of instream uses. The Washington State Department of Ecology is required by law to protect instream flows by adopting regulations and to manage water uses that affect stream flows. Once adopted, an instream flow rule acquires a priority date similar to that associated with a water right.

The basis for setting the instream flow is accomplished through consideration of several factors, including: existing data, the hydrology of a stream and its natural variations in stream flow and base flow over the course of the year, a study of the needs for fish and other aquatic habitats, recreation activities, scenic beauty, dilution of pollutants, and water temperature.

The most popular method, the Instream Flow Incremental Methodology (IFIM), is based on the understanding that fish prefer water with a certain depth and velocity: i.e., that different species of fish have different preferences. IFIM is developed by the Aquatic Systems Branch of the US Fish and Wildlife Service to consider ecological demands when recommendations for instream flow regimes are determined. The *Physical HABitat SIMulation* (PHABSIM) model, enhanced by the Institute of Hydrology (now CEH, Wallingford) of the UK, is a suite of computer programs that is used to generate habitat verse discharge relationships for use in IFIM studies and is also based on fish species. A study by Merrill and O'Laughlin (1993) serves as one resource for determining minimum instream flows for recreation.

5.1.2.2 Flood flow deductions

Hydrologically, a flood occurs when the drainage basin experiences an unusually intense or prolonged water-input event and as a result, streamflow rates exceed the channel capacity (Dingman, 2002). Because of this characteristic, the flood streamflow is not the available water resources that can be used by out-stream purposes, such as irrigation, domestic, and industry water use. The flood flow deduction for estimating water availability on a watershed scale depends on the intensities of precipitation, runoff, snowmelt, and hydraulic engineering facilities.

There are two issues related to flood flow that should receive attention: First, it is important to understand that floods are natural events that occur fairly frequently on virtually all streams — a stream that is unaffected by dams or other hydrologic modifications will typically overflow its bank every one to three years (Dingman, 2002). This means that part of the streamflow (flood flow) is not available water at a watershed scale. However, hydraulic facilities, such as dams, reservoirs, lakes, etc., could increase water availability on a watershed scale. Second, although flood damage fluctuates greatly from year to year, estimates indicate that there has been an increasing trend over the past century (Pielke and Downton, 2000). This implies that water availability as a percentage of streamflow may have decreased over the past century. Some have speculated that the trend is indicative of a change in climate (Hamburger, 1997) while some blame population growth and development (Kerwin and Verrengia, 1997) or federal policies (Coyle, 1993). Others suggest that the trend distracts from the larger success of the nation's flood policies (Labaton, 1993).

5.1.3 Ground-water availability

Ground water is a crucial source of freshwater throughout the world. More than 1.5 billion people worldwide (Clarke et al, 1996) and more than 50% of the population of the United States (Solley et al, 1998) rely on ground water for their primary source of drinking water. Ground water is an essential part of the hydrologic cycle and its availability is important for water resources management and regional development. Ground-water systems have values not only as perennial sources of water availability, but also as reservoirs for cyclical injection and withdrawal to modulate the variability inherent in surface water supplies (Alley et al, 2002).

There are two terms associated with ground-water availability: storage and residence time. Storage refers to how much water is available in the aquifer while residence time characterizes the time the water spends in the ground-water portion of the hydrologic cycle. The ratio of these two parameters is the average ground-water recharge or discharge rate.

It is widely believed, even by many hydrologists and water resource managers, that the sustainable rate of extraction, or "safe yield", of ground water from a watershed equals the rate of natural recharge. However, this is not true (Alley et al, 2002; Dingman, 2002) because the rate of extraction is supplied by a decrease in storage, and in general by changes in recharge and discharge. The watershed ground-water availability is best defined as ground-water availability minus the ground- and surface- water interaction portion.

The interactions between ground water and surface water are very complicated processes and are governed by the positions of the water bodies relative to the ground-water flow systems, the characteristics, and their climatic setting (Alley et al, 2002; Jones and Mulholland, 2000). The exchange of water across the interface between surface water and ground water can result from downstream movement of water in and out of stream beds and banks, tides, wave actions; filling or draining of reservoirs; or transpiration of water by vegetation at the edge of the wetland and other surface waters (Alley et al, 2002; Jones and Mulholland, 2000).

From the watershed scale water availability point of view, the main concern centers about the fact that the water withdrawn from a ground-water system initially comes from storage. Over time, the effects of the withdrawal are propagated through the system as heads decrease at greater distances from the point of withdrawal. Ultimately, the effect of the withdrawal reaches a boundary where either increased recharge to the ground-water system or decreased discharge from the system occurs (Alley et al, 2002). In either case, the surface water availability decreases because of these interactions.

5.2 APPLICATION OF THE WATER AVAILABILITY MODEL TO THE SPOKANE RIVER WATERSHED

5.2.1 Surface water availability

5.2.1.1 Streamflow

Within the Spokane River watershed, there are 60 USGS streamflow stations available on the USGS website. The most downstream station is USGS Station 12433000, Spokane River at Long Lake, with a drainage area of 6,020 square miles. This record begins in 1939. Thus, for this doctoral research, the data from Station 12433000 was used to estimate the monthly water availability for water year 1940–2003, i.e. from October 1939 to September 2003.

The monthly streamflow is the upper limit of surface water availability. The average monthly streamflow is 7,755 cfs with a minimum monthly streamflow of 1,104 cfs in August 1994 and a maximum monthly streamflow of 36,910 cfs in May 1997 (Figure 5.2).

The monthly average streamflow has significant differences from month to month with the minimum in August of about 2,013 cfs from 1940 to 2003 (Figure 5.3).

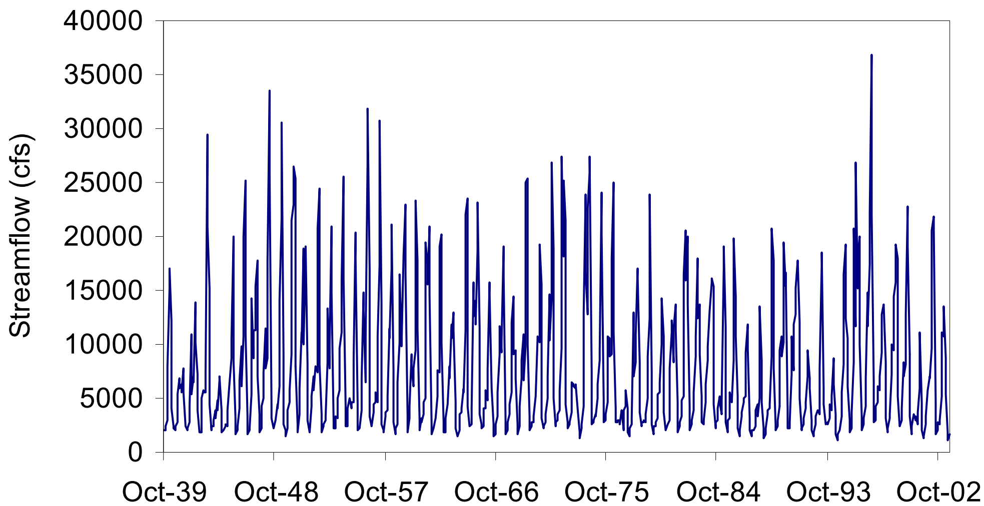


Figure 5.2 Monthly time series streamflow of the Spokane River at Long Lake (USGS 12433000)

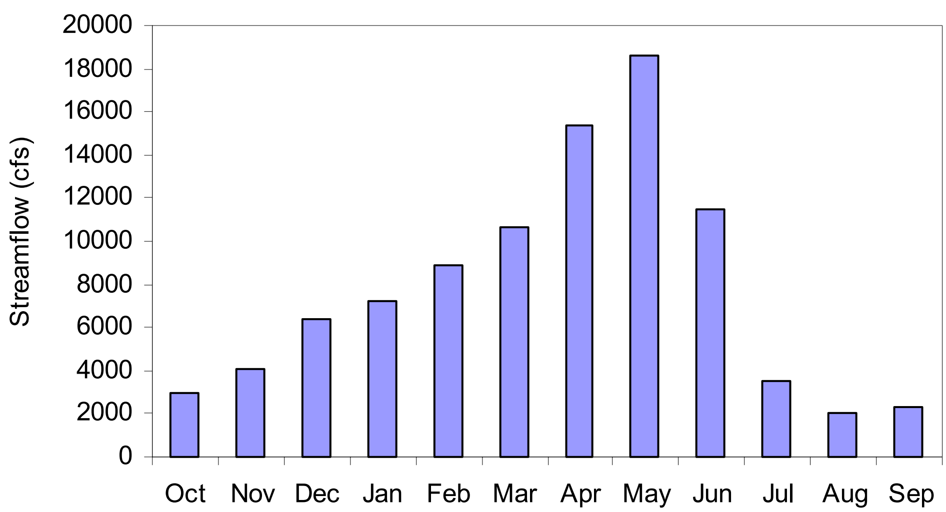


Figure 5.3 Monthly average streamflow of the Spokane River at Long Lake (12433000)

5.2.1.2 Instream flow requirements

At present, the Little Spokane is the only river in the Spokane River watershed that has an established instream flow mandated back in 1976 under Chapter 173-555 WAC. The Spokane River is presently on the high priority list for adoption of instream flows by Washington State Department of Ecology (WSDOE, 2005) in the State Agencies' Action Plan for Fiscal Year 2000 and Instream Flow Recommendations for Hangman (Latah) Creek were recently proposed in 2002. This doctoral research, however, estimates the instream flow for the entire Spokane River by adding the recommended minimum flow target set by the WSDOE in 1999, which is 2,000 cfs at USGS gage 12422500 (Spokane River at Spokane) with a drainage of 4,290 square miles, and the instream requirement of the Little Spokane River at its confluence under Chapter 173-555 WAC. Because the target for Spokane River at Spokane is the minimum requirement, the instream requirements for other periods are estimated proportionally to its streamflow magnitude. The results of instream flows are listed in the below Table 5.1.

Table 5.1 Instream flow for Spokane River by months

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Little Spokane	387.5	400	400	400	410	447.5	475	430	390	375	375	377.5
Spokane R at Spokane	2067	2133	2133	2133	2187	2387	2533	2293	2080	2000	2000	2013
Entire Watershed	2454	2533	2533	2533	2597	2834	3008	2723	2470	2375	2375	2391

5.2.1.3 Flood flow deductions

The 1.5-year recurrence interval discharge was used by Cuhaciyan (2002) to estimate the bankfull discharge at Eastern Washington, because the discharge associated with the 1.5-year recurrence interval in the annual peak series has been shown to approximate bankfull and effective discharge by many studies (Dury et al, 1963; Dunne and Leopold, 1978; Leopold, 1994; Leopold et al, 1964; Wolman and Miller, 1960). Castro and Jackson (2001) concluded that the discharge associated with the 1.5-year recurrence interval is indeed appropriate for estimating bankfull discharge for eastern Washington.

The sixty-four-year (1939–1943, 1946–2004) annual peak discharge at Spokane River Long Lake Station showed that the annual peak discharge has a normal distribution (Figure 5.4) with a mean value of 30,544 cfs and a standard deviation of 9,624 cfs. The $Q_{1.5year}$ was then estimated to be about 26,399 cfs. Based on this value, there were 40 out of 64 years having a flood. However, this is the annual peak flow and this criterion could not be used for monthly flood, because a month might have a peak discharge larger than 26,399 cfs and monthly mean discharge is much less than this value. If this criterion were used, there would be only 12 flood event months in 11 years. Instead, we used $Q_{18months}$ for the monthly streamflow series. Since monthly streamflow is not normally distributed, $Q_{18moths}$ (18,131cfs) underestimated the monthly flood discharge. The log-normal and Log-Pearson Type III distributions gave $Q_{18moths}$ 19,989 cfs and 20,870 cfs, respectively. Both of them were overestimations of the monthly flood discharge as the numbers of years with a flood event were only 32 and 26 for the log-normal and Log-Pearson Type III distributions. $Q_{0.05}$ has a discharge of 18,486 cfs, which was between these values and has the number of years with a flood equal to 41. So $Q_{0.05}$=18, 486 cfs was finally adopted by this doctoral research. Based on this criterion, there were 71 flood event months (in 41 years) out of the 768 months in the Spokane River watershed. Half of these

71 flood months (36) happened in May, which has a corresponding probability of 56.5% (36/64) to be a flood month. Next in monthly significance were April and June with 16 and 9 floods, respectively.

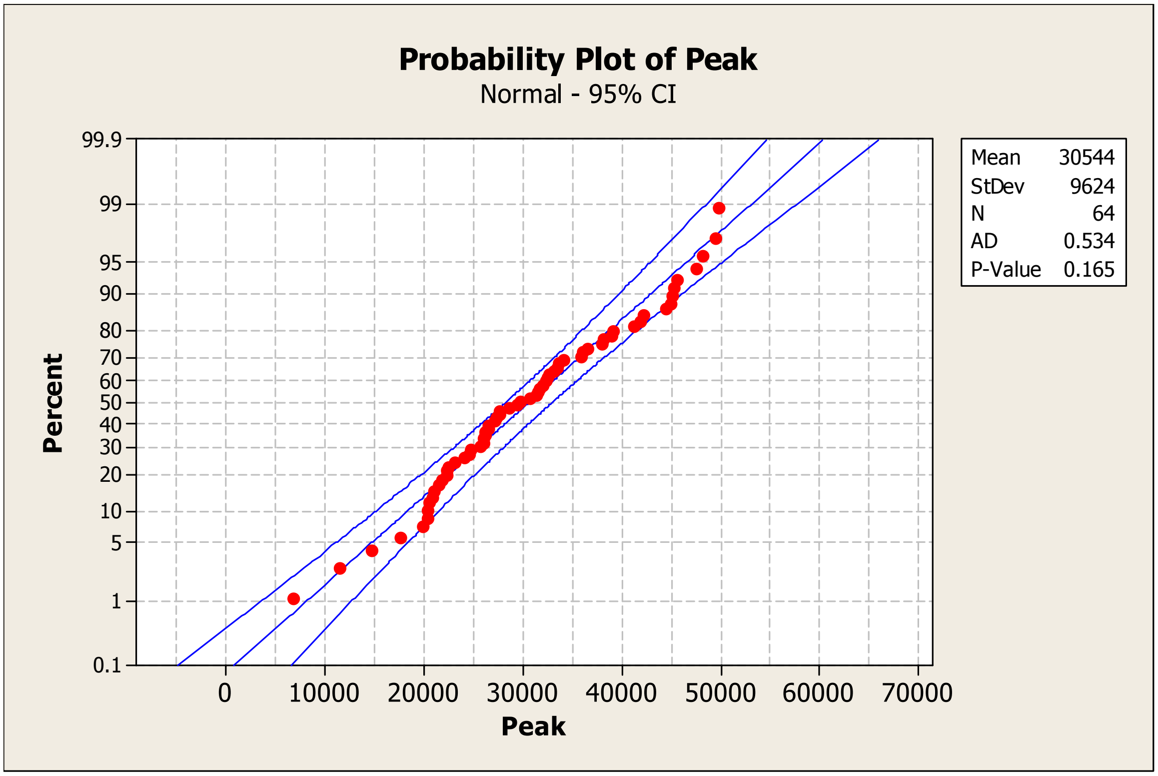


Figure 5.4 Normal probability plot of the sixty-four year annual peak discharge

Table 5.2 Selection of monthly flood

Parameter	Monthly Discharge (cfs)	# of flood months	# of flood year
Q18month (Normal)	18,131	73	41
Q0.05	**18,486**	**71**	**41**
Q18month (Log Normal)	19,989	53	32
Q18month (Log Pearson III)	20,870	42	26

5.2.1.4 Surface water availability

After instream flow requirements and flood flow deductions, the monthly surface water availability in the Spokane River watershed was obtained. The 64-year-average monthly surface water availability is about 5,094 cfs, which is about 65.7% of the average monthly streamflow (Figure 5.5).

There are two significant differences for the monthly water availability when compared to the monthly streamflow (Figure 5.5): (1) the monthly surface water availability has an upper limit that is set by the flood discharge, and (2) there were 123 months (in 55 years) with zero surface water availability (Figure 5.5). That is to say that 16% of the months had streamflow less than the proposed instream flow and 86% (55 years) of the 64 years have at least one month when the streamflow was less than the recommended instream flow. Typically, the low-flow situation occurred during August (49 out of 64 months) and September (43 out of 64 months). There were 38 years when both August and September had no surface water availability.

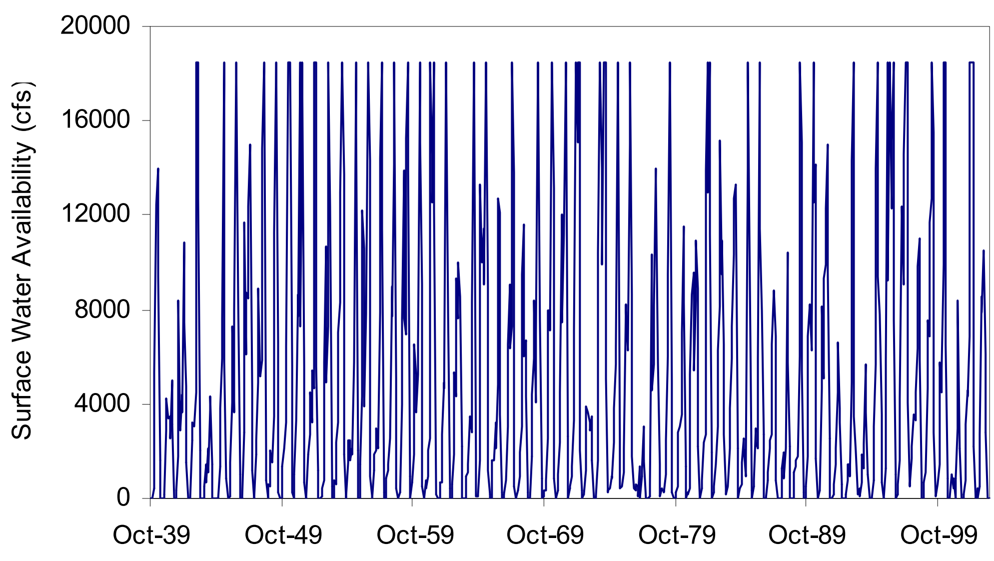


Figure 5.5 Monthly surface water availability in the Spokane River watershed

5.2.2 Ground-water availability

5.2.2.1 Spokane Valley-Rathdrum Prairie (SVRP) Aquifer

Because of the critical situation of surface water availability, ground-water availability in the Spokane River watershed becomes very important. The Spokane Valley-Rathdrum Prairie Aquifer, discovered in 1895, has become one of the most important resources in this region, supplying drinking water for 400,000 people. In 1978, the Environmental Protection Agency (EPA) designated this aquifer as a "Sole Source Aquifer" in an effort to protect its water quality (IDEQ, 2000). The Aquifer was the second aquifer in the nation to receive this special designation.

The Spokane Valley-Rathdrum Prairie Aquifer has ancient geologic features that have, for millions of years, been slowly formed by water flowing towards the Pacific Ocean. The Aquifer deposits range from about 150 feet to more than 600 ft and cover 321 square miles (IDEQ, 2000).

The Aquifer begins in Idaho between Lake Spirit and the south end of Lake Pend Oreille at which point its water flows south until it reaches the middle of the Rathdrum Prairie, then turns west and flows into Washington under the Spokane Valley. When the aquifer reaches downtown Spokane, most of it turns north, flows under the city, and discharges into the Little Spokane River.

The volume of the entire aquifer is about 10 trillion gallons, making it one of the most productive aquifers in the United States (IDEQ, 2000). However, this is its total estimated volume. Without understanding the recharge rate of the aquifer, it is difficult to know the ground-water availability. This is exactly why the Idaho Department of Water

Resources (IDWR) has denied the permits from Cogentrix and Newport Generation to withdraw 17 million gallons of water per day from the aquifer at Post Falls, because IDWR conceded that withdrawals as large as proposed could make withdrawals exceed the recharge rate of the aquifer (Kootenai Environmental Alliance, 2005).

5.2.2.2 Ground-water availability

The ground-water availability in the Spokane River watershed comes from five sources: (1) ground-water discharge from Idaho portion; (2) recharge from the local watersheds in Washington; (3) Spokane River recharge; (4) irrigation return; and (5) septic systems. The Idaho Department of Environmental Quality (IDEQ, 2000) estimated that the irrigation return and septic systems contributed only about 1% and 2%, respectively, to the aquifer recharge. Their amounts are limited so for the purposes of this doctoral research they have been neglected.

(1) Ground-water discharge at state line

Estimating the flow of the SVRP aquifer has a long history and the results are not consistent. Piper and Huff (1943) estimated that the discharge from the aquifer to springs and rivers was 900 cfs. Huff (1944) estimated the total discharge from the aquifer to be about 1,100 cfs, which included an estimated total pumpage of 100 cfs in 1942. Anderson (1951) calculated the discharge from the aquifer to the Spokane River and Little Spokane River to be about 470 cfs and 250 cfs, respectively. Thomas (1963) estimated total discharge to be about 1450 cfs. Frink (1964) evaluated at least 600 cfs of recharge occurred east of Post Falls, Idaho, and another 150 cfs occurred between Post Falls and the state line. Rorabaugh and Simons (1966) predicted a decline of about 12 ft/year in the aquifer if all recharge ceased. Pluhowski and Thomas (1968) estimated that the ground-water flow at the state line at about 1,000 cfs. Seven science-based flow estimates have been made from 1970 through 1999, and the estimates vary from 320 cfs to 1,000 cfs (IDEQ, 2000).

Recent technical studies by consultants to the City of Spokane, by Eastern Washington University and the Idaho Department of Environmental Quality, have shown that the flow of ground water across the state line was less than the original estimates made in the 1960s. The most recent effort, using the latest computer modeling and with the most current information, estimated the ground-water flow at the state line was 390 cfs. The actual flow of water probably has not changed in this time; just that our estimates are getting better (http://www.geology.ewu.edu/spokaq.htm). The minimum daily flow at Spokane (USGS 12422500) for the last 65 years supports this statement that the actual flow of ground water probably has not changed in the last 60 years, as there was no significant trend for the minimum daily flow over last 65 years (1940–2004) (Figure 5.6).

(2) Recharge from the local watershed in Washington

During the journey from the state line to the discharge along the Little Spokane River, the aquifer gains about 350 cfs of water from the local watersheds (IDEQ, 2000).

(3) Spokane River recharge

The third component of aquifer recharge comes from the Spokane River itself. However, the strong surface- and ground- water interaction makes the exact amount difficult to estimate (Table 5.3). For example, Broom (1951) estimated the aquifer lost about 1,123 cfs (including Little Spokane) from Post Fall to Long Lake. Drost and Seitz

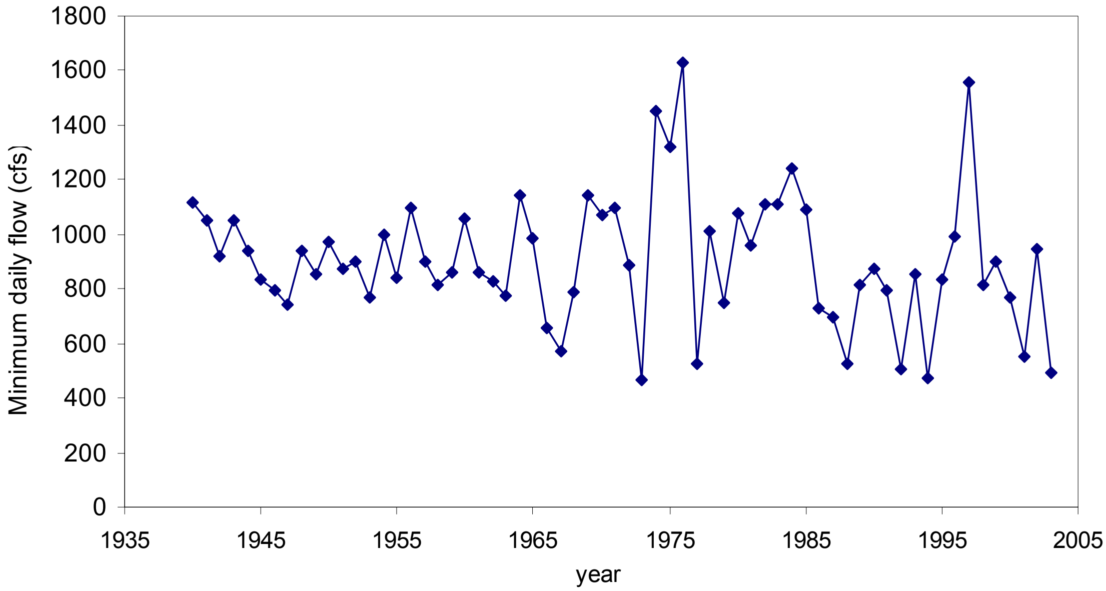


Figure 5.6 Minimum daily discharge of Spokane River at Spokane (1940–2004)

(1978) estimated the river loss at an amount of 700 cfs from Post Fall to Nine Mile Falls. Bolke and Vaccaro (1981) used a digital-model to simulate the ground-water flow system showing the aquifer losing 525 cfs (including 250 cfs discharged into Little Spokane River). CH2M Hill (1997) in preparing the City of Spokane Wellhead Protection Program, Phase-I Technical Report, built a finite-element ground-water flow model. This model estimated that, over the entire study area, the aquifer gained 83 cfs during the fall of 1994 and lost 70 cfs in the spring of 1995, resulting in a net gain of 13 cfs. For purposes of this doctoral research values obtained from the most recent study, with the most advanced computer modeling was used, that is 13 cfs in net gains for the aquifer from the Spokane River.

(4) Total ground water availability

Based on these studies, the total ground-water availability in the Spokane River watershed was estimated at about 753 cfs.

Table 5.3 Interactions between Spokane River and SVRP aquifer

<table>
<tr><th>Reach</th><th>Upstream</th><th>Downstream</th><th>Broom (1951)</th><th>Drost & Seitz (1978)</th><th>Bolke & Vaccaro (1981)</th><th>Miller(1996)</th><th>CH2M Hill (1997)</th><th>Gearhart (2001)</th><th>Streamflow measurement</th></tr>
<tr><td>1</td><td>State Line</td><td>Barker Rd</td><td>-78</td><td rowspan="2">-50</td><td rowspan="2">-50</td><td rowspan="2">-319 to -207</td><td>-71 to -45</td><td>-444 to -76</td><td>-660 to -142</td></tr>
<tr><td>2</td><td>Barker Rd</td><td>Sullivan Rd</td><td rowspan="3">370</td><td>-100 to -91</td><td>-423 to 240</td><td rowspan="4">110 to 493</td></tr>
<tr><td>3</td><td>Sullivan Rd</td><td>Kaiser Aluminum</td><td rowspan="3">240</td><td rowspan="2">240</td><td rowspan="3">206-160</td><td>-7 to -5</td><td rowspan="2">-288 to 164</td></tr>
<tr><td>4</td><td>Kaiser Aluminum</td><td>Trent Ave.</td><td>64 to 22</td></tr>
<tr><td>5</td><td>Trent Ave.</td><td>Plantes Ferry</td><td rowspan="4">556</td><td rowspan="3">-40</td><td>12 to 1</td><td>-121 to 69</td></tr>
<tr><td>6</td><td>Plantes Ferry</td><td>Argonne</td><td rowspan="2">-40</td><td rowspan="2">Unquantified Loss</td><td>-12 to -4</td><td rowspan="3">Not calculated</td><td rowspan="3">Not measured</td></tr>
<tr><td>7</td><td>Argonne</td><td>Upriver Dam</td><td>-6 to -4</td></tr>
<tr><td>8</td><td>Upriver Dam</td><td>Greens St.</td><td>270</td><td>270</td><td>377 to 209</td><td>194 to 149</td></tr>
</table>

5.2.2.3 Surface- and ground- water interaction

The surface- and ground- water interaction between the Spokane River and the SVRP aquifer is very complex. The Spokane River recharges the SVRP aquifer in places while Aquifer discharges to the river in other places (Drost and Seitz, 1978; Bolke and Vaccaro, 1981; Gearhart and Buchanan, 2000; Caldwell and Bowers, 2003). Although the aforementioned researches have calculated/estimated the gains and losses, there are still uncertainties and inconsistent, including the quantification of the gains to or losses from the river, the temporal variation of the gains and losses due to changes in streamflow and ground-water levels, and the conditions (saturated or unsaturated) beneath the losing reaches of the river (Caldwell and Bowers, 2003).

The major discharges of SVRP aquifer ground water flow into: (1) Spokane River, which has already been counted in the aquifer recharge from the Spokane Rivers; (2) Little Spokane River, which will be estimated below; (3) pumping wells, which are estimated to be at 350 cfs; (4) flow out the watershed; (5) exchange with the vados zone as soil moisture, and (6) lost to the deep ground-water aquifer. As (1) and (2) have been counted as part of streamflow and (3) has been consumed, they collectively represent the surface-and ground- water interaction term.

(1) Ground-water discharge to the Little Spokane River

The ground-water discharge to the Little Spokane River was estimated by the streamflow difference between the two USGS stations located on the lower Little Spokane River in the vicinity of Dartford, WA. The upstream gage (12431000) is located at River Mile (RM) 11.4 while the downstream gage (12431500) is located at RM 3.8

(this station was discontinued in 2003). The pattern of runoff in the Little Spokane River is consistent with typical snowmelt watersheds having peak discharges occurring in April followed by dramatic decreases in streamflow during the late summer months of August and September. It was observed that there was substantially more flow at the downstream gage. The downstream gage (12431500) has data available from April 1948 to March 1952 and from Oct 1997 to Sep 2003. Data from these time periods were then used to estimate monthly surface- and ground- water interaction. The results indicated that ground-water discharge into Little Spokane River was very stable from year to year, during both periods 1948–1952 and 1997–2003, with little monthly variations (Figure 5.7).

(2) Surface- and ground- water interaction

Based on this information, the monthly surface- and ground- water interaction (W_i) was estimated as shown in Table 5.4.

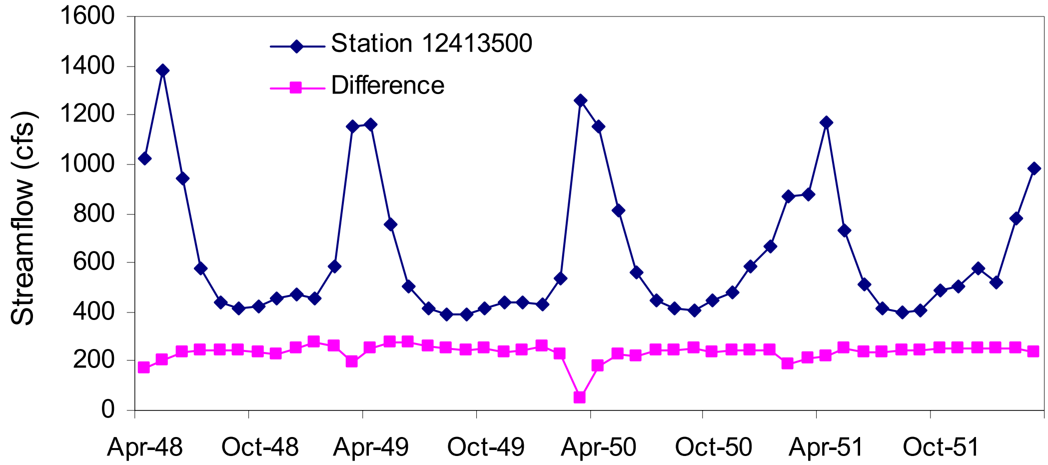
Table 5.4 Surface- and ground- water interaction (W_i)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Mean
LSR	249	248	249	251	241	207	239	247	242	244	245	246	242
Spokane R	Already included in the Spokane River recharge to Aquifer												
Pumping	350	350	350	350	350	350	350	350	350	350	350	350	350
W_i	599	598	599	601	591	557	589	597	592	594	595	596	592
W_g	753	753	753	753	753	753	753	753	753	753	753	753	
W_g-W_i	154	156	154	152	162	196	164	156	162	159	158	157	161

5.2.2.4 Ground-water availability minus surface- and ground- water interaction

The actual ground-water availability, i.e. the difference between ground-water availability and the surface- and ground- water interaction, for the Spokane River was

161 cfs (Table 5.4). The monthly variation was relatively small when compared to the streamflow variation.



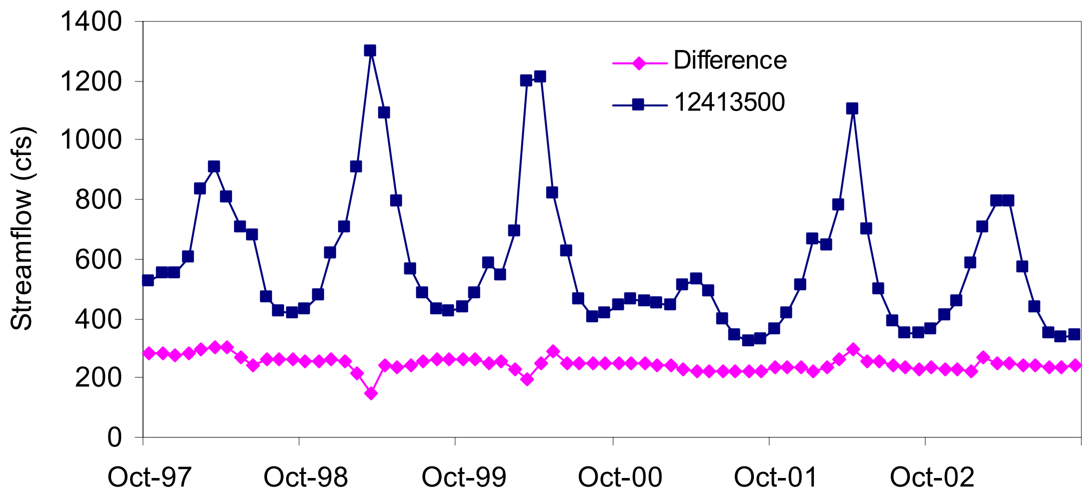


Figure 5.7 Ground-water discharge into Little Spokane River
Above: Apr 1948–Mar 1952
Below: Oct 1997–Sep 2003

5.2.3 Water availability for Spokane River watershed

Based on Equation (5.1), the monthly water availability in the Spokane River watershed was 5,255 cfs. The surface water availability is 5,094 cfs that accounts for about 96.9% of the watershed water availability. The ground-water availability was about 753 cfs, or 14.3% of the watershed water availability. However, 592 cfs (including 350 cfs has already been pumped), or 11.2%, was the surface- and ground- water interaction portion that cannot be double counted for watershed water availability. The additional ground-water availability, besides the surface water availability, was only 161 cfs (Table 5.4).

There were 123 months out of 768 months without any surface water availability and for these months ground-water supply becomes the sole source of water availability. These 123 months mostly occur in August and September, which indicates that the Spokane River watershed has a critical water availability issue in August and September (Figure 5.8). Moreover, these 123 months are distributed in 55 years out of the 64-year-study-period.

The Spokane River watershed water availability was also different from year to year. There was no significant trend during the last 64 years other than a 3–5 year oscillation (Figure 5.9), which was directly related to the climate/precipitation pattern. There was an average annual water availability of 5,255 cfs, with a minimum annual water availability of just 943 cfs in drought 1977. There were also several years when water availability was less than 2,000 cfs (1944, 1973, 1994, and 2001). Conversely, the maximum annual water availability was about 9,793 cfs in 1974.

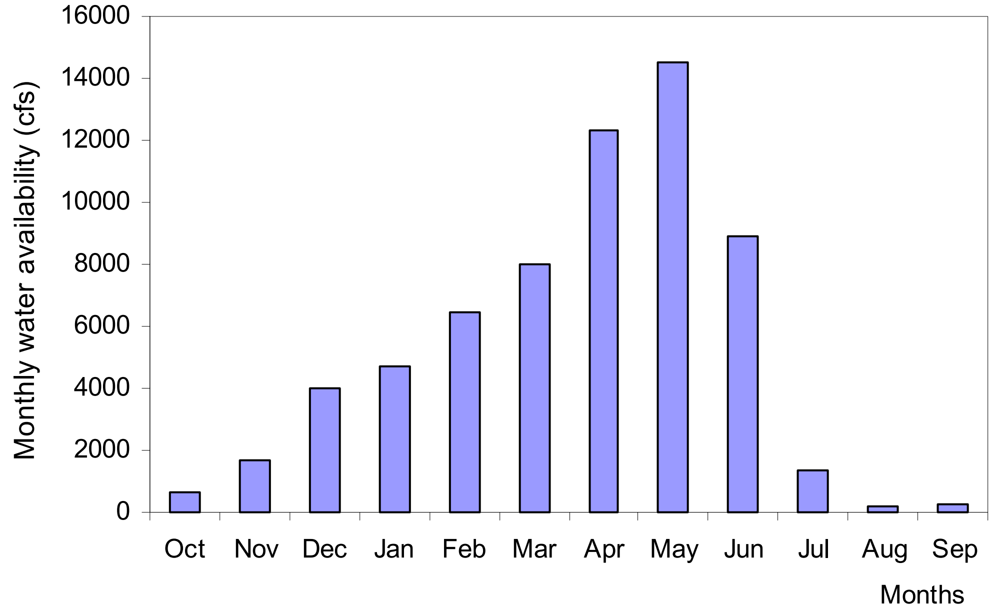


Figure 5.8 Monthly water availability of the Spokane River watershed (1940–2003)

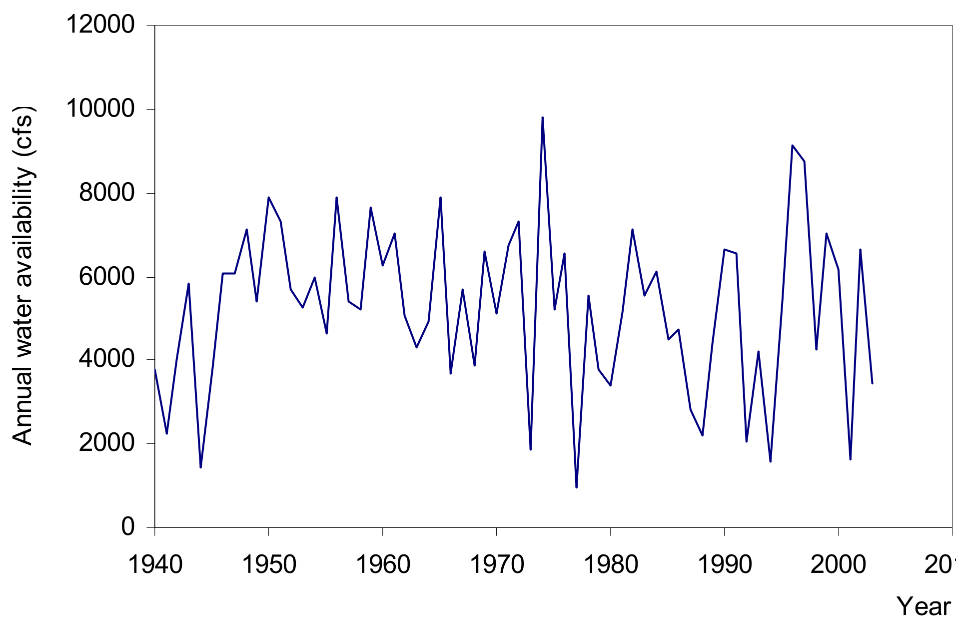


Figure 5.9 Annual water availability of the Spokane River watershed (1940–2003)

5.2.4 Sensitivity Analyses of Instream Flow Setting

Water availability depends on the instream flow setting. A sensitivity analysis of surface water availability to instream flow setting will explore the relationship between them and provide information for setting the instream requirement. Eight scenarios, in which the instream flow requirement was increased and decreased by 5%, 10%, 15%, and 20%, were run to study the surface water availability responses to instream changes. The results indicated that a 20% reduction in the recommended instream flow still resulted in 55 months with zero surface water availability and 38 out of 64 years would have at least one month when the streamflow is less than the required instream flow. If an increase of 20% of the recommended instream flow were required for the Spokane River, then 62 out of 64 years would have at least one month when the streamflow was less than the required instream flow (Table 5.5). Because the months when the streamflow was less than instream flow were typically in August and September, water availability was limited during the later summer for Spokane River watershed.

Table 5.5 Sensitivity of instream flow

Instream Change	# of months*	# of year**
-20%	55	38
-15%	68	42
-10%	90	47
-5%	104	48
0%	123	55
5%	138	59
10%	158	61
15%	173	61
20%	192	62

* Number of months when the streamflow is less than the required instream flow;

** Number of year when there is at least one month the streamflow is less than the required instream flow

5.2.5 Uncertainty Analyses

Since there are uncertainties in estimating every component, a larger uncertainty exists for watershed scale water availability. If it is assumed that an error term distribution for each component can be ascertained, then an overall uncertainty for water availability could be proposed, which would be important for water resource management and regional planning.

The general assumption is that all components have normal distributions. The water availability is then also normal distributed because the linear combination of normal variables still has a normal distribution.

If X_i has a normal distribution, N(μi, σ_i^2) and i=1,2,3..n denote independent normal variables such as streamflow, instream flow, ground-water availability, and surface- and ground- water interaction, then the watershed scale water availability *Y* is defined by the following equation:

$$Y = \sum_{i=1}^{n} a_i X_i \sim N\left(\sum_{i=1}^{n} a_i \mu_i , \sum_{i=1}^{n} a_i^2 \sigma_i^2\right) \qquad (5.3)$$

Note that if a_i=1, then the two terms are added together, and if a_i=-1, then the term is subtracted from the water availability.

The uncertainty of monthly water availability was estimated based on Equation (5.3). The error term for each component was estimated by existing studies as below.

Caldwell and Bowers (2003) estimated that the measurement errors in streamflow for the Post Fall, Idaho (12419000) and Otis Orchards, Washington (12419500) were within ±5 percent. For the purposes of this doctoral research, it has been assumed that this level of accuracy was also applied to the Long Lake gage of Spokane River (12433000). If the confidence level is 95%, then variance could be estimated as,

$$\sigma_k^2 = \frac{0.05*0.05}{1.96*1.96} X_k^2 \qquad (5.4)$$

Where

k=1,2,…768 for every month of 64 years;

σ_k^2 is the streamflow variance for the kth month;

0.05 is the significant level α; and

Z is the standard normal distribution value corresponding to 1-α/2, or $Z_{0.975}$.

Once adopted, an instream flow rule has a fixed number and there is no uncertainty associated with it.

Flood flow deduction has uncertainties that may change with hydraulic engineering, such as dams, reservoirs, etc. The ranges of normal $Q_{18months}$, log-normal $Q_{18months}$, and Log-Pearon Type III Q_{months} were used to estimate the error, that is, 15% error of flood flow would be suitable to cover all these values.

Based on these estimations and assumptions, the 95% confidence interval of surface monthly water availability ranges from 4,817 cfs to 5,640 cfs, which was about 5.4% less than or 10.1% larger than the mean value (5,094 cfs). This is not symmetrical on a yearly basis, because for the months with zero water availability, the lower limits are still zero water availability. For the months when the instream flows do not meet the requirements, the upper limits will satisfy the instream flow first and the extra amount will be monthly surface water availability.

The number of months with zero surface water availability increased from 123 to 144 for the 95% lower limits and decreased from 123 to 103 for the 95% upper limits.

Ground-water availability as well as the surface- and ground- water interaction estimates has larger uncertainties, because various research efforts derived quite different results. This doctoral research compared recent studies for common river sections, from State line to Trent Avenue. The values are, -110 cfs (Ch2M Hill, 1997), -80 cfs (Miller, 1996), -439.5 cfs for the model (Gearhart, 2001), and -99.5 cfs for observed values (gearhart, 2001). Based on these research results, 200% error for surface- and ground-water interaction was used in this doctoral research.

Applying these estimated errors into Equation (5.3) resulted in the upper and lower limits at confidence level 95% of the monthly water availability for Spokane River for the last 64 years. The lower limit of the monthly water availability in the Spokane River watershed was about 4,902 cfs and the upper limit of the monthly water availability was about 5,896 cfs. The lower limit was about 6.7% less than the mean value and the upper limit was about 12.2% larger than the mean value.

The lower and upper monthly water availability limits showed variations from year to year and from month to month. However both the lower and upper limits had the same pattern as the mean value. The confidence interval was narrower in the drought years and wider in the wet years (Figure 5.10).

From the monthly point of view, August and September still were critical months in the Spokane River watershed. The water availability was limited in these two months even in the upper limit case (Figure 5.11).

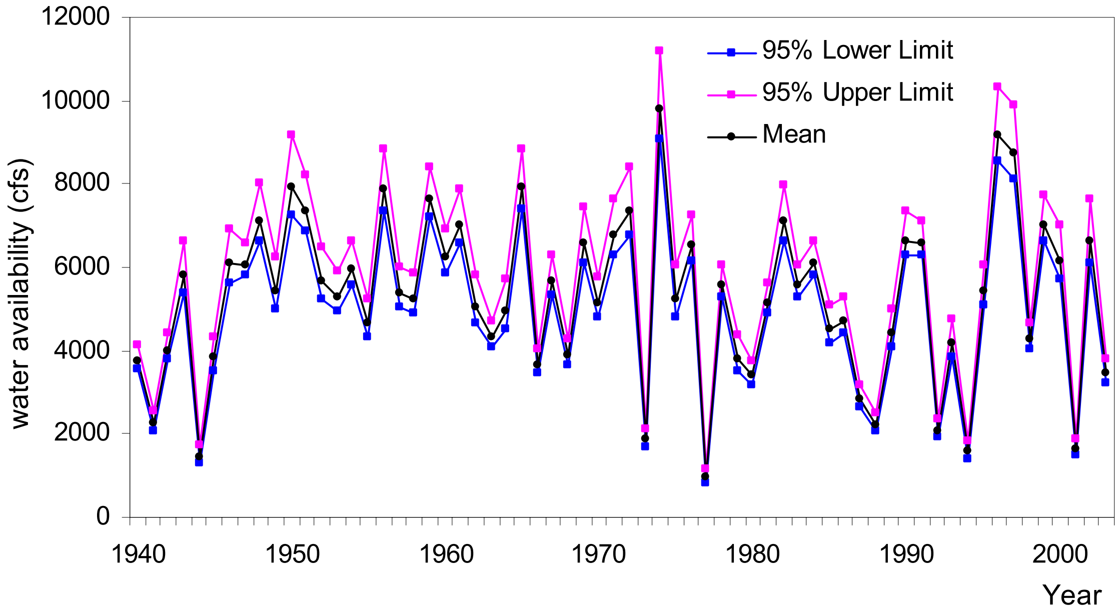


Figure 5.10 95% Confidence interval for annual water availability of the Spokane River watershed

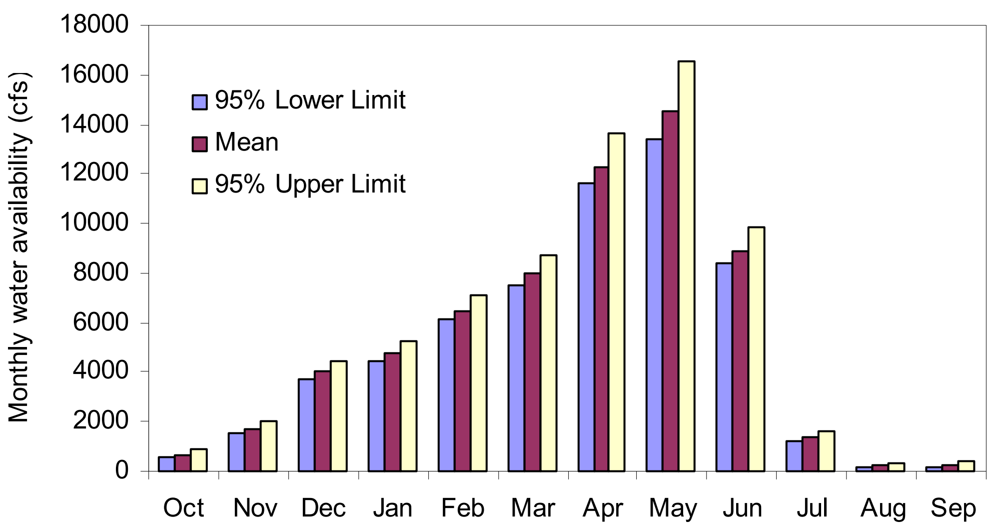


Figure 5.11 95% Confidence interval for monthly water availability of the Spokane River watershed

5.2.6 Frequency Analyses

The watershed availability is different from month to month and from year to year. Frequency analyses are useful because they can, not only supply the average water availability for a specific year and month, but also give the variances, which are important information for decision makers.

5.2.6.1 Annual water availability series

If a normal distribution was assumed (log transformation makes the situation more dire, Figure 5.12), the annual water availability frequencies could be estimated. The results were listed in Table 5.6. The normality plot of annual water availability showed (Figure 5.13) that the normal distribution was a reasonable assumption.

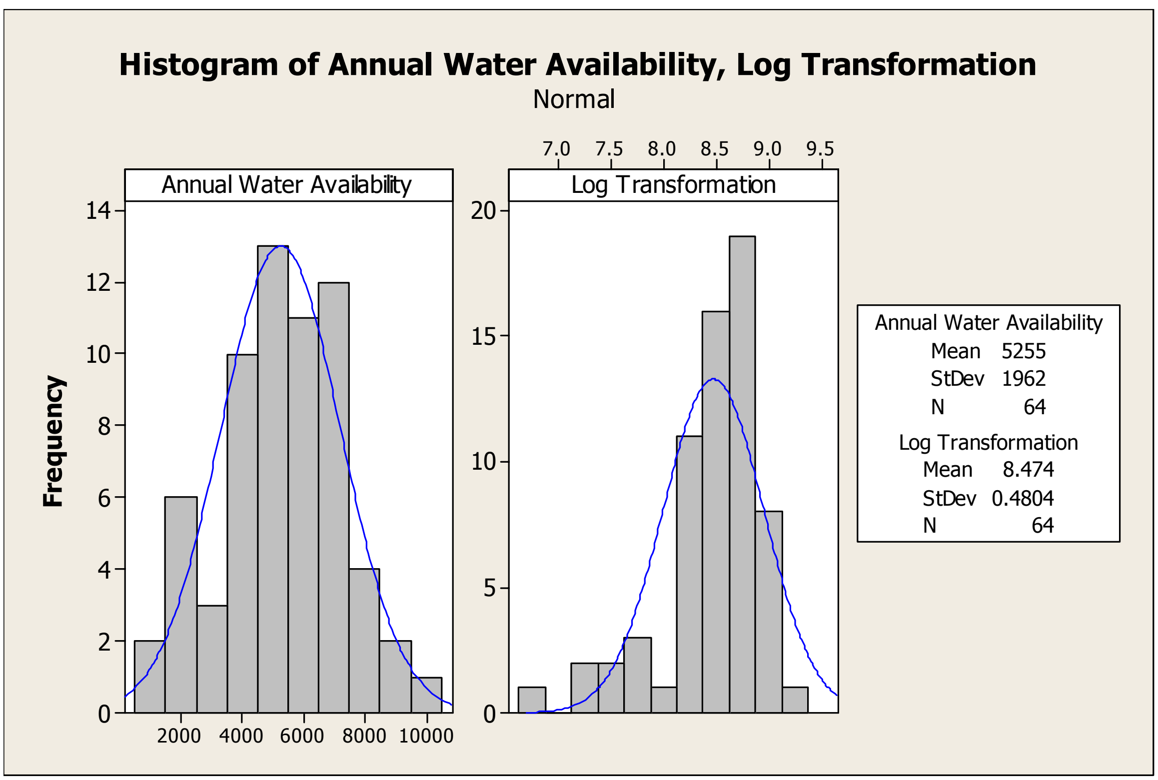


Figure 5.12 Histogram of annual water availability and its log transformation

Table 5.6 Frequency analyses of annual water availability

Frequency (%)	T(years)	Water Availability (cfs)
2	50	1226
5	20	2028
10	10	2741
20	5	3604
50	2	5255

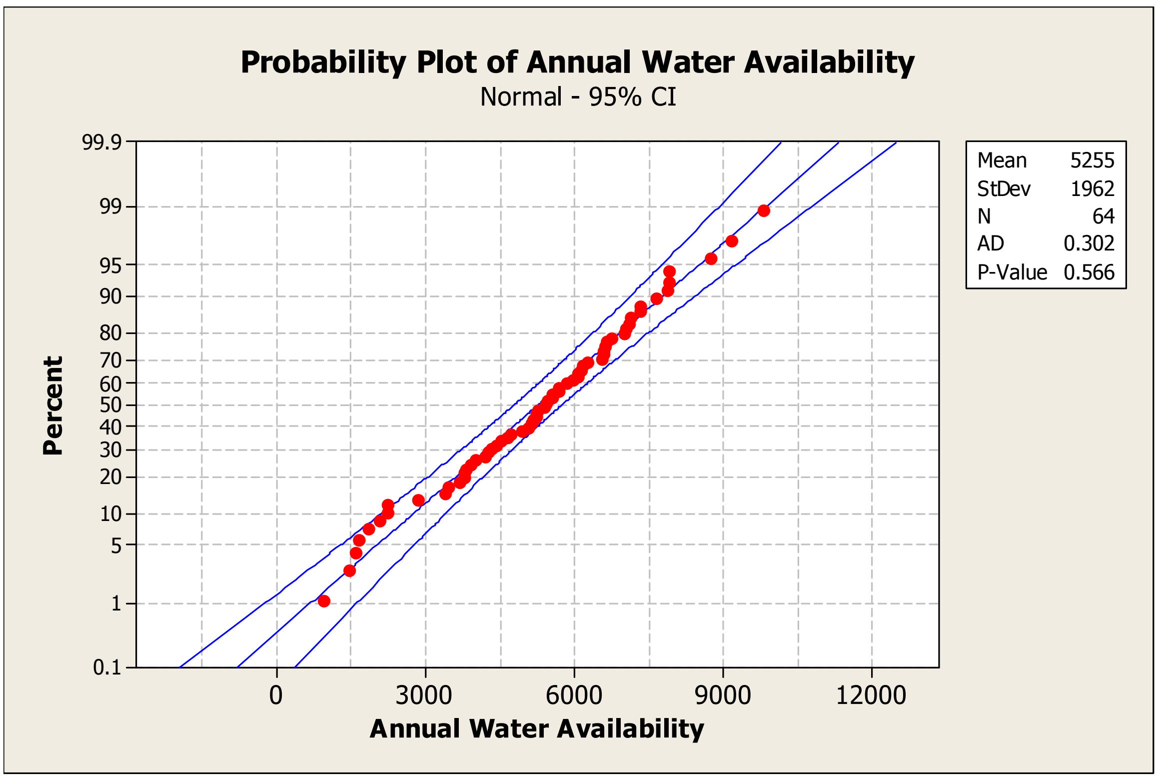


Figure 5.13 Normality plot of the annual water availability

5.2.6.2 Monthly water availability series

Due to the fact that the water availability varies significantly from month to month, the frequencies of monthly water availability are more useful for water resource planning and management, and for regional development. However, it is not suitable to use the same techniques as used for annual predictions, because monthly water availability is NOT normally distributed (Figure 5.14). If they were assumed as having normal distributions, there would be many months with monthly water availability less than zero (Table 5.7).

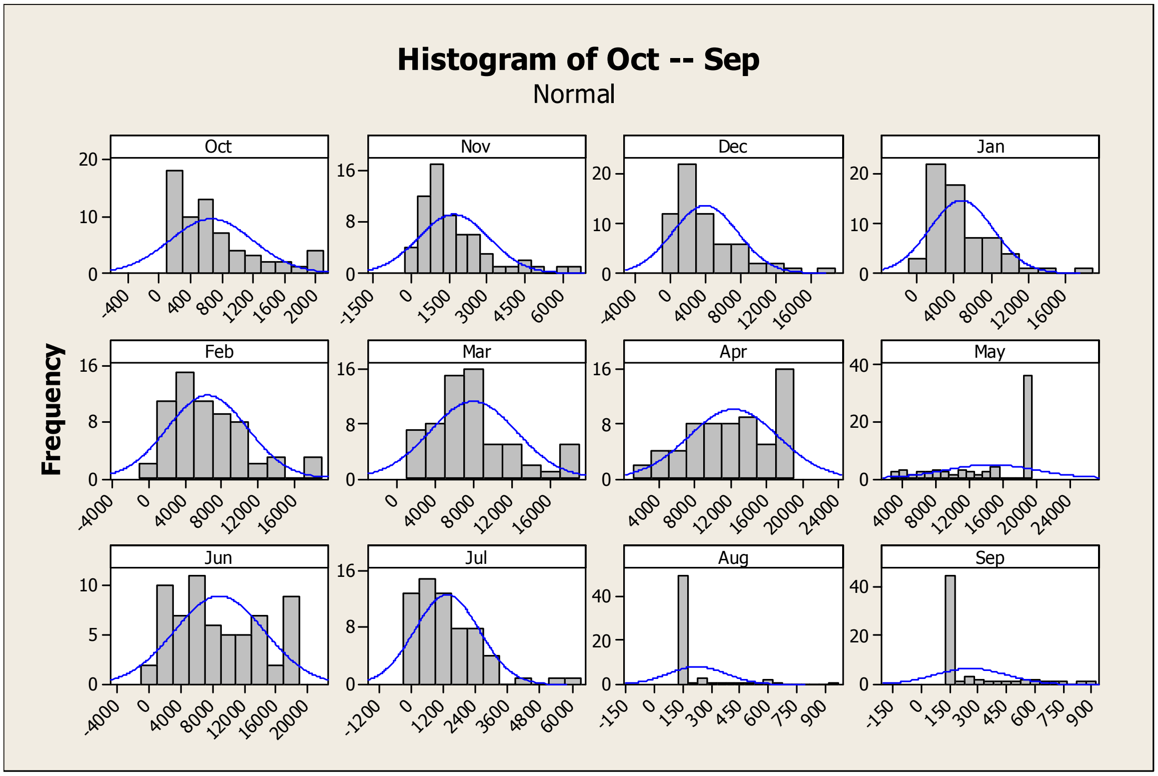


Figure 5.14 Histogram of monthly water availability

Table 5.7 Frequency analyses of monthly water availability based on normal distribution

Frequency (%)	2	5	10	20	50
Oct	<0	<0	<0	222	670
Nov	<0	<0	<0	514	1684
Dec	<0	<0	<0	859	3998
Jan	<0	<0	290	1815	4733
Feb	<0	<0	895	2811	6477
Mar	<0	538	2179	4166	7968
Apr	1984	4039	5865	8076	12306
May	3482	5678	7630	9992	14513
Jun	<0	<0	1602	4105	8894
Jul	<0	<0	<0	325	1337
Aug	<0	<0	25	93	222
Sep	<0	<0	11	96	257

Instead of using normal distribution assumptions, this doctoral research simply used the 64 years of data to compute probability by P(i)=i/n+1. The results are listed in Table 5.8. In August and September, the water availability does not change with frequencies. It reflects the fact that surface water availability is almost zero for these two months at most of years. The only available water comes for ground water.

Table 5.8 Frequency analyses of monthly water availability based on 64 year data

Frequency (%)	2	5	10	20	50
Oct	154	154	154	160	538
Nov	156	194	319	655	1227
Dec	154	260	680	1293	2583
Jan	677	1034	1542	2133	3387
Feb	162	1021	1675	2854	5541
Mar	1099	1509	2376	4689	7152
Apr	1773	3062	4915	7416	12856
May	3277	3699	5566	8103	18625
Jun	787	1269	1793	3287	7760
Jul	159	159	159	159	1045
Aug	158	158	158	158	158
Sep	157	157	157	157	157

5.3 WATER USE VERSE WATER AVAILABILITY

5.3.1 Water use estimation

5.3.1.1 Domestic water use

The total annual domestic water use for the entire watershed was estimated at about 124.58 Mgal/day in 2000. 90.7 Mgal/day was used by the Spokane County (Lane, 2000) and 33.88 Mgal/day by three counties (Benewah, Kootenai, and Shoshone) in Idaho (USGS-Idaho, 2005). The domestic water use in Idaho came from two categories: the self-supplied water withdrawal for Benewah, Kootenai, and Shoshone counties were 0.73, 4.69, and 0.53 Mgal/day and the public-supplied water withdrawal for Benewah, Kootenai, and Shoshone counties were 1.2, 24.32, and 2.41 Mgal/day.

5.3.1.2 Irrigation/Agricultural water use

The total agricultural/irrigation water use in the Spokane River watershed was 43.09 Mgal/day in 2000 from three categories of water uses: crop irrigation, golf irrigation, and aquaculture and livestock.

Total crop irrigation was 9.16, 1.16, 27.33, and 0.15 Mgal/day for Spokane, Benewah, Kootenai, and Shoshone counties, respectively in 2000 (Lane, 2000; USGS-Idaho, 2005). The total crop irrigation withdrawal then for the watershed was 37.80 Mgal/day.

The golf irrigation water use was 1.41, 0.0, 1.99, and 0.15 Mgal/day for Spokane, Benewah, Kootenai, and Shoshone counties, respectively in 2000. The total golf irrigation withdrawal then for the watershed was 3.55 Mgal/day.

Idaho (USGS-Idaho, 2005) also supplied water use data for aquaculture and livestock, which was about 1.94 Mgal/day.

5.3.1.3 Industrial water use

The total industrial water use for the entire watershed was about 45.8 Mgal/day in 2000. The industrial water uses for Spokane, Benewah, Kootenai, and Shoshone counties were 44.6, 0.32, 0.86, and 0.02 Mgal/day, respectively.

5.3.1.4 Total water use

With a final summation of all withdrawal sources, the total water use in the Spokane River watershed in 2000 was 213.47 Mgal/day, or 330.3 cfs.

5.3.2 Water availability verse water use

When water availability was estimated, the value of 350 cfs from ground-water well pumping was not included. This was almost the same amount as the current water use in the watershed. At present, the water availability seems to be enough for water use on the annual basis, even in a very dry year (T=50years). However, there are 123 months, especially August and September, when the surface water availability is essentially equal to zero. The only available water comes from the ground water. In August and September, the water use already reaches the water availability capacity in a normal year. The situation is more critical in the drought years.

5.4 CONCLUSIONS AND DISCUSSIONS

This doctoral research developed a monthly water availability model considering streamflow, instream flow, flood flow, ground water, and surface- and ground- water interaction. Statistical based methods were used to analyze the uncertainty and frequencies of monthly water availability. As a tool, this method can be applied to any other watersheds for estimating monthly water availability.

The application of this method to the Spokane River watershed indicated that the Spokane River had a serious water availability issue during summer months. There were 123 months during a 64 year period (768 months) when surface water availability equaled to zero. The only available water for these months was from the limited ground water. These months mostly occurred in August (49 out of 64 months) and September (43 out of 64 months). There were 38 years when both August and September had no surface water availability. Therefore, if fish and river habitat were to be protected during the summer, there would be insufficient water for out-stream uses, such as domestic, industry and irrigation, according to the instream flow requirement.

The 123 months were distributed over 55 years. This indicated that there was at least one month when the streamflow was less than the recommended instream flow for 86% years during our 64 year study period.

Currently, water availability could meet the water demand/water use on an annual basis. However, it is not the case for a monthly basis, because during the late summer months, the water availability only depends on limited ground-water supplies.

CHAPTER 6 MODELING IMPACTS OF CLIMATIC CHANGE ON WATER AVAILABILITY

All models are wrong. Some models are useful.
G. E. P. Box

Models are undeniably beautiful, and a man may justly be proud to be seen in their company. But they may have hidden vices. The question is, after all, not only whether they are good to look at, but whether we can live happily with them.
A. Kaplan, 1964

6.1 MONTHLY WATER BALANCE MODEL

6.1.1 Model structure

The model (Figure 6.1) has all major hydrologic processes at the watershed scale and includes seven major parts (or sub-models): (1) a rain/snow module; (2) snow accumulation and snowmelt; (3) direct runoff; (4) AE/PE; (5) soil moisture; (6) ground water; and (7) total runoff.

One distinct difference between the proposed model and existing GIS based water balance models is that the proposed model is also land use based (Figure 6.1) which computes the water balance for each 2 km × 2 km cell based on its land use and land cover categories. The model can represent the distinct hydrologic processes associated each different land use categories.

Besides the feature of land use based, there are two sub-models dealing with rain/snow and snow accumulation and snowmelt processes. These two processes are critical for the Inland Pacific Northwest region where the watersheds receive most of annual precipitation in winter months as the form of snowfall and where monthly peak flows occurs in May as a result of snowmelt.

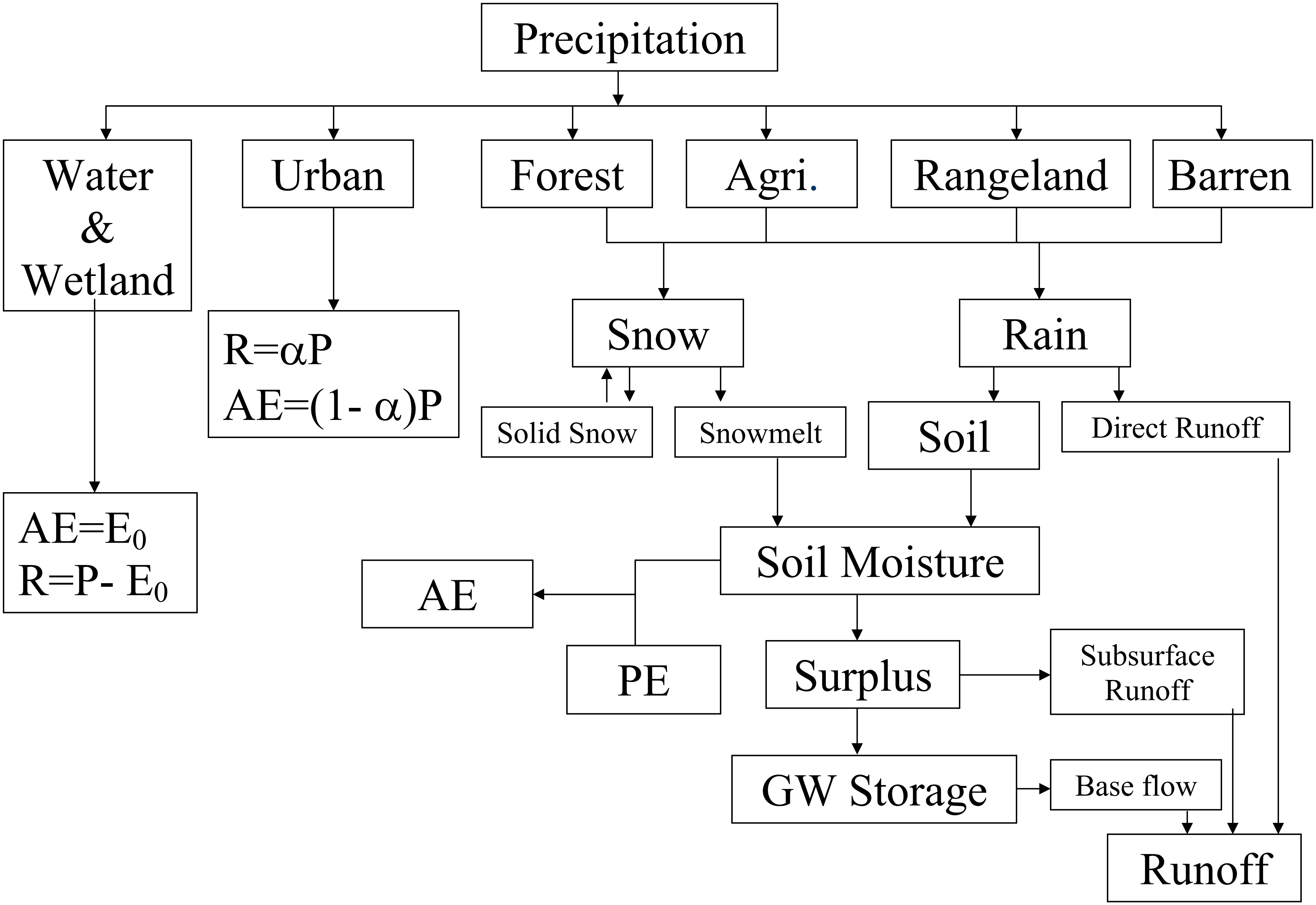


Figure 6.1 Model Structure

The main reasons why a new model was developed instead of using the existing hydrological models are (1) the Inland Pacific Northwest has a unique winter hydrology that is not reflected in most of the simple water balance models. On the other hand, the complicated process- and physical- based models may work for this region, but they require many parameters which are not available for most watersheds. Figure 6.2 shows the relationship between monthly precipitation and monthly streamflow for Spokane River watershed that indicates why most of the simple water balance models will not work for this region. (2) most existing GIS based water balance models study the impacts of climatic and land use/land cover changes separately due to models' structures.

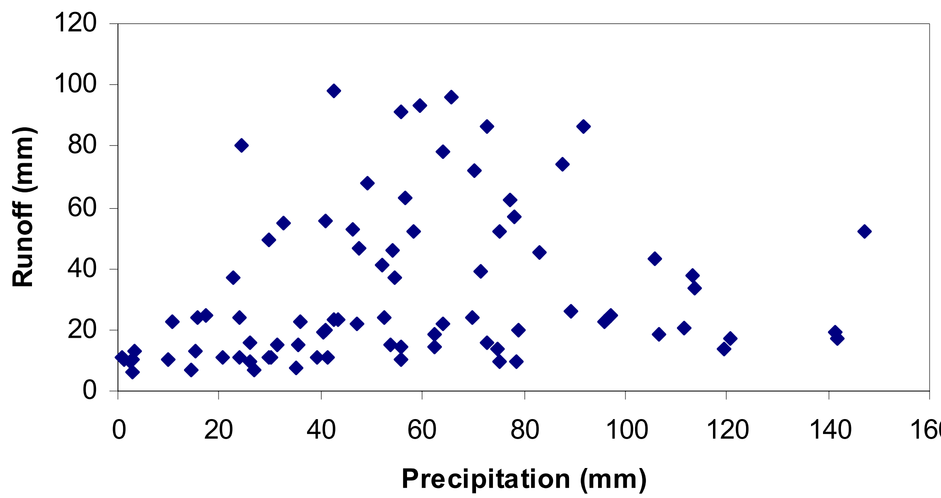


Figure 6.2 Monthly precipitation-runoff relationship of the Spokane River watershed

6.1.2 Snow Percentage

The proportion of precipitation falling as rain and snow is essential for modeling the mass balance of seasonal snow cover (Semadeni-Davis, 1997) and for correct runoff model performance (WMO, 1986). This is especially important for the Spokane River watershed, where snow accumulation and snowmelt processes are critical for runoff generation. So the first step in developing a simulation model is to determine the snow percentage as monthly total precipitation. However, it is not easy to set a threshold temperature that determines whether precipitation was rain or snow (Knight et al, 2001). Previous studies have shown that rain could occur at a mean monthly temperature of -10^{o}C and snow at +10^{o}C (Lauscher, 1954; Knight et al, 2001). The snow percentage is often estimated as a linear relationship with monthly air temperature (Knight et al, 2001). For example, Legates (1988) developed the following equation which was adopted by Knight et al (2001) to develop a water balance model for the Struma River:

$$\text{Percent Snow}=100/(1.35^{T}*1.61+1) \qquad (6.1)$$

Where T is the monthly mean temperature in ^{0}C.

Semadeni-Davis (1997) used a piece-wise linear function on the data from their Swiss investigation:

$$\%S = \begin{cases} 0 & T_{air} > 12.2 \\ -4.5T + 55 & -10 \le T_{air} \le 12.22 \\ 100 & < -10 \end{cases} \qquad (6.2)$$

Application of the Semadeni-Davis work based on 13/15 meteorological station (Appendix B) data within Spokane River watershed (Figure 6.3) showed that a piece-wise function was better than a simple linear function.

The model based on this graph was:

$$\%S = \begin{cases} 0 & T > 53^{o}F \\ -0.66T + 33.6 & 38.5^{o}F \le T \le 53^{o}F \\ -3.29T + 139.27 & T < 38.5^{0}F \end{cases} \qquad (6.3)$$

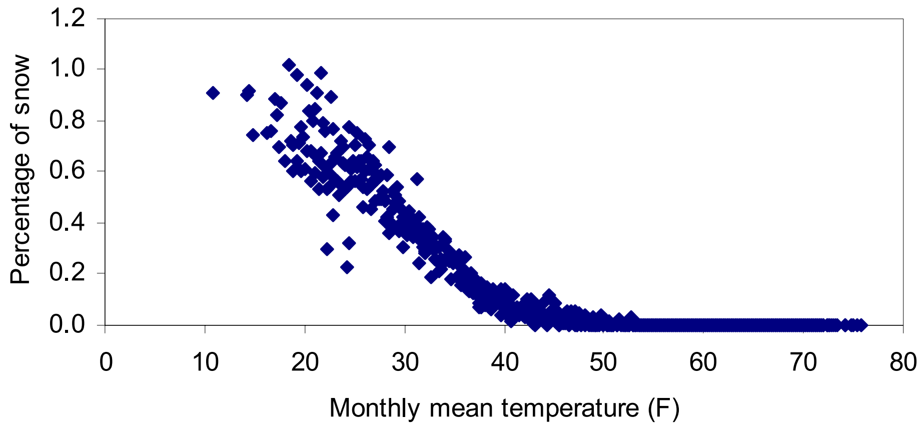


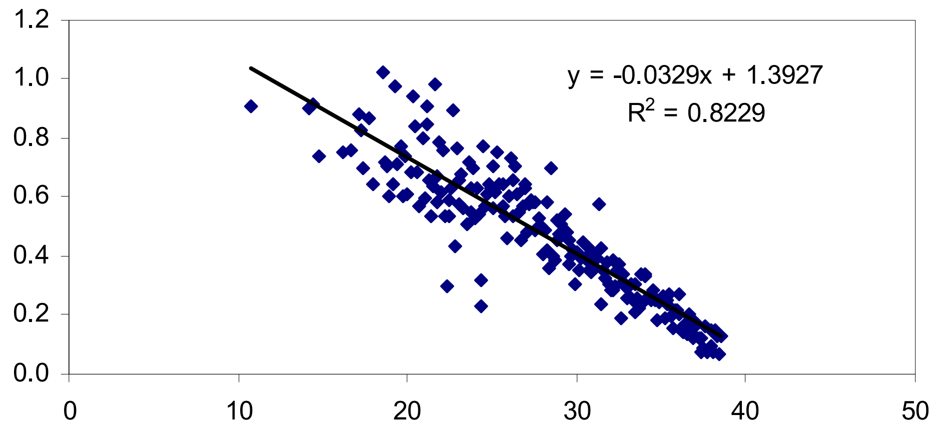
Figure 6.3 Percentage of snow as a function of monthly mean temperature

The detailed regression line and equation for the monthly mean temperature lower than 53°F are shown in Figure 6.4.

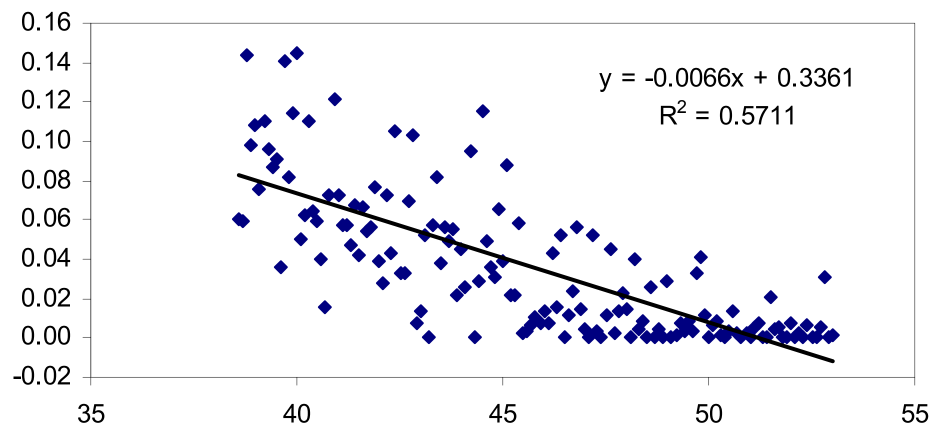
6.1.3 Snowmelt model

Basically, there are two categories of snowmelt models: energy balance models and temperature-index models, although Dingman (2002) added a third category which he described as a "hybrid approach" and Brooks and Boll (2004) split the energy balance into two categories: a simple mass and energy balance model and a complex mass and energy balance model.

Within this doctoral research, a temperature-index approach was used to estimate the snow accumulation and melt. This approach was similar to many other watershed-scale water balance models, such as the Snowmelt Runoff Model (SRM) (Martinec et al, 1994), the HBV model (Bergstrom, 1995) and the RHINEFLOW model (Kwadijk, 1993). The main reason for the choice of this particular approach was that energy models usually require extensive input data which are not available at most watersheds. This is also the reason some process- and physical- based hydrological models, such as TOPMODEL, SWAT, and AGNPS, also use a temperature-index model instead of energy models,.



(a)



(b)

Figure 6.4 Relationship between percentage of snow and monthly mean temperature in the Spokane River watershed
a: T<38.5°F
b: 38.5°F <T<53.0°F

Walter et al (2005), though, tried to use an energy balance model with the same input data as the temperature-index model, but it still requires complex computations and many assumptions.

The advantages of temperature index models are that they often give estimates that are comparable with those determined by the energy balance model, and that the temperature is variable that is easy to measure, extrapolate, and forecast (Maidment, 1993).

The simplest and most common expression of temperature index snowmelt model is:

$$M = M_f (T_i - T_b) \qquad (6.4)$$

Where

M is the depth of melted water produced in a selected time interval (mm/month in this case);

M_f is the melt factor that usually has a unit of mm/^{o}C/day. However, this unit has been converted within this doctoral research to the unit (mm/^{o}C/month) because the model has a time step of a month;

T_i is index air temperature (^{o}F or ^{o}C); and

T_b is the threshold temperature.

The most frequently used values for T_i and T_b are mean daily temperature and 0^{o}C (32^{o}F), respectively. Therefore, the calculation is often referred to as the *degree-day method*. However, for the purposes of this doctoral research a monthly mean daily temperature for T_i and 0^{o}C (32^{o}F) for T_b were used.

The degree-day coefficient implicitly represents all terms of the energy budget that account for the mass balance of a snow pack, and is therefore highly variable over time (Melloh, 1999). For this reason, several models allow the M_f to vary in time, instead of using a constant value. Martince et al (1994) recommended increasing M_f twice a month to account for lower albedo, higher aerodynamic roughness, and higher liquid water content as the snowpack ages. In the HBV model, season- and weather-dependent degree-day factors were tested, but without much success (Lindstrom et al, 1997; Dankers, 2002). The melting rate may also differ among vegetation types. Several models such as HBV and the Semi-distributed Land Use-Based Runoff Processes (SLURP) model (Kite, 1995) have therefore been applied with different snowmelt rates for several land use classes (Kite and Kouwen, 1992). This is exactly the case of this doctoral research as the present model is a land use based water balance model. The M_f values used in this model are different for each of the land use and land cover types.

6.1.4 Potential Evapotranspiration (*PE*)

PE is the rate of evapotranspiration from a surface or vegetation canopy with no limitation due to water availability (Beven, 2000). There exist a multitude of methods for the estimation of potential evapotranspiration *PE* and free water evaporation *E*, which can be grouped into five categories, as follows (Xu and Singh, 2002): (1) water budget (Guitjens, 1982); (2) mass-transfer (Harbeck, 1962); (3) combination (Penman, 1948); (4) radiation (Priestley and Taylor, 1972); and (5) temperature-based (Thornthwaite, 1948; Blaney-Criddle, 1950). The availability of many equations for determining evaporation, the varied data types required, and the wide range of expertise needed to use the various equations make it difficult to select the most appropriate evaporation method for a given study. This in turn reflects the complicated process of evapotranspiration.

An inter-comparison of a variety of methods for estimating potential evapotranspiration rate is provided by Federer et al (1996) and by Xu and Singh (2002). The basic conclusion is that the best simple physical-based method for estimating *PE* is the Penman-Monteith equation.

However, considering the main interest in the impacts of climatic change on water availability, this doctoral research prefers to estimate potential evapotranspiration with monthly mean air temperature. Thus three popular temperature-based *PE* equations were compared with the Penman-Monteith equation in terms of suitability to the Spokane River watershed.

6.1.4.1 Penman-Monteith Equation

The FAO Penman-Monteith method for calculating reference evapotranspiration ET_0 can be expressed as (Allen et al, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (6.5)$$

Where

ET_0 = reference evapotranspiration (mm/day);

R_n = net radiation at the crop surface (MJ/m^2 day);

G = soil heat flux density (MJ/m^2 day);

T = mean daily air temperature at 2 m height (^{o}C);

u_2 = wind speed at 2 m height (m/s);

e_s = saturation vapor pressure (kPa);

e_a = actual vapor pressure (kPa);

es - ea = saturation vapor pressure deficit (kPa);

Δ = slope vapor pressure curve (kPa/^{o}C); and

γ = psychrometric constant (kPa/^{o}C).

Apart from site location, the FAO Penman-Monteith equation requires air temperature, humidity, radiation, and wind speed data for daily, weekly, ten-day or monthly calculations. The computation of all terms in (6.5) required for the calculation of the reference evapotranspiration followed the method and procedure given in Chapter 3 of the FAO paper No. 56 (Allen et al, 1998). For the purpose of completeness, some important equations are briefly summarized below.

(1) Latent Heat of Vaporization (λ)

$$\lambda = 2.501 - (2.361 \times 10^{-3})T_a \qquad (6.6)$$

Where

λ = latent heat of vaporization (MJ/kg); and

T_a = air temperature (^oC).

(2) Atmospheric Pressure (P)

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad (6.7)$$

Where

P = atmospheric pressure (kPa) at elevation z (m).

(3) Saturation Vapor Pressure (e_s)

$$e_s(T_a) = 0.611\exp\left(\frac{17.27T_a}{T_a + 237.3}\right) \qquad (6.8)$$

Where

$e_s(T_a)$ = Saturation vapor pressure function (kPa); and

T_a = air temperature (^oC).

(4) Actual Vapor Pressure (e_a)

$$e_a(T_d) = 0.611\exp\left(\frac{17.27T_d}{T_d + 237.3}\right) \qquad (6.9)$$

Where

$e_a(T_d)$ = actual vapor pressure function (kPa); and

T_d = dew point temperature (^oC).

(5) Slope Vapor Pressure Curve (Δ)

$$\Delta = \frac{4098 e_s(T_a)}{(T_a + 237.3)^2} = \frac{2504 \exp\left(\frac{17.27 T_a}{T_a + 237.3}\right)}{(T_a + 237.3)^2} \tag{6.10}$$

Where

Δ = slope vapour pressure curve (kPa/^oC); and

T_a = air temperature (^oC)

(6) Psychrometric Constant (γ)

$$\gamma = \frac{C_p P}{\varepsilon \lambda} \times 10^{-3} = 0.00163 \frac{P}{\lambda} \tag{6.11}$$

Where

γ = psychrometric constant (kPa/^oC);

C_p = specific heat of moist air, 1.013 (kJ/kg ^oC);

P = atmospheric pressure (kPa);

ε = ratio molecular weight of water vapor/dry air, 0.622; and

λ = latent heat of vaporization (MJ/kg).

(7) ShortWave Radiation on a Clear-Sky Day (R_{so})

The calculation of R_{so} is required for computing net long wave radiation. A good approximation for R_{so} according to FAO (Allen et al, 1998), for daily and hourly periods is:

$$R_{so} = (0.75 + 2 \times 10^{-5} z) R_a \qquad (6.12)$$

Where

R_{so} is the short wave radiation on a clear-sky day (MJ/m^2 day);

z = station elevation (m); and

R_a = extraterrestrial radiation (MJ/m^2 day).

(8) Extraterrestrial Radiation for Daily Periods (R_a)

The extraterrestrial radiation, R_a, for each day of the year and for different latitudes is estimated from the solar constant, the solar declination, and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\varpi_s) \right] \qquad (6.13)$$

Where

R_a = extraterrestrial radiation (MJ/m^2 day);

G_{sc} = solar constant, 0.0820 (MJ/m^2 min);

d_r = inverse relative distance Earth–Sun;

ω_s = sunset hour angle;

φ = latitude (rad); and

δ = solar decimation.

The equations for calculating d_r, ω_s φ, and δ are given in Chapter 3 of FAO paper No. 56 (Allen et al, 1998).

(9) Net Solar or Net Shortwave Radiation (R_{ns})

The net shortwave radiation resulted from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - \alpha) R_s \qquad (6.14)$$

Where

R_{ns} = net solar or shortwave radiation (MJ/m^2 day);

α = albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop (dimensionless); and

R_s = the incoming solar radiation (MJ/m^2 day).

(10) Net Long-wave Radiation (R_{nl})

The net outgoing long-wave radiation is calculated by:

$$R_{nl} = \sigma\left[\frac{T_{\min,K}^4 + T_{\max,K}^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \qquad (6.15)$$

Where

R_{nl} = net outgoing long-wave radiation (MJ/m^2 day);

σ = Stefan-Boltzmann constant (4.903×10.9 MJ/K^4 m^2 day);

$T_{\max,K}$ = maximum absolute temperature during the 24 hr period;

$T_{\min,K}$ = minimum absolute temperature during the 24 hr period;

e_a = actual vapor pressure (kPa);

R_s / R_{so} = relative shortwave radiation (limited to ≤ 1.0);

R_s = measured solar radiation (MJ/m^2 day); and

R_{so} = calculated (Equation 5.12) clear-sky radiation (MJ/m^2 day).

(11) Net Radiation (R_n)

The net radiation (R_n) is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net long-wave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \qquad (6.16)$$

(12) Soil Heat Flux (G)

For vegetation covered surfaces and the calculation time steps are 24 hr or longer, below is the calculation procedure as proposed by FAO (Allen et al, 1998), based on the idea that the soil temperature follows air temperature:

$$G = c_s \frac{T_i - T_{i-1}}{\Delta t} \Delta z \qquad (6.17)$$

Where

G = soil heat flux (MJ/m2 day);

c_s = soil heat capacity (MJ/m^3 ^{o}C);

T_i = air temperature at time i (^{o}C);

T_{i-1} = air temperature at time i-1 (^{o}C);

Δt = length of time interval (day); and

Δz = effective soil depth (m), which for a time interval of one or few days is about 0.10–0.20 m.

Different equations are proposed by Allen et al, (1998) in calculating G depending on the computation time periods.

6.1.4.2 Thornthwaite Equation

The Thornthwaite method of estimating potential evapotranspiration (*PE*) (Thornthwaite and Maither, 1955; 1957) is based on air temperature and day length only. Expressed on a monthly basis it reads (Ward and Robinson, 1990; Sellinger, 1996):

$$PE = 16 \times d_i \left[\frac{10T_i}{I} \right]^a \qquad (6.18)$$

Where

PE is the monthly potential evapotranspiration (mm/month);

d_i is the day length correction factor;

T_i is the monthly mean air temperature (^oC);

I is the heat index; and

a is a cubic function of I, namely:

$$a = 0.49 + 0.0179I - 7.71*10^{-5}I^2 + 6.75*10^{-7}I^3 \quad (6.19)$$

The day length correction factor, d_i, is estimated (Rosenberg et al, 1983) by:

$$d_i = \left[\frac{L_i}{12}\right] \times \left[\frac{N_i}{30}\right] \quad (6.20)$$

Where

L_i is mean actual day length (hour); and

N_i is the number of days in a given month.

The heat index, I, which is the summation of the monthly heat indexes:

$$I = \sum_{i=1}^{12} \left[\frac{T_i}{5}\right]^{1.514} \quad (6.21)$$

Thornwaite and Mather (1957) recommend using the day length correction factor for 50^oN and higher latitudes.

The Thornwaite method requires only temperature and hours of daylight. These two variables are relatively easy to obtain. Consequently, it has been applied in many studies to a wide range of climatological conditions, often with reliable results (Penman, 1956; Perira and Camargo, 1989; Dankers, 2002). Poorer results, though, can be expected over very short periods of time (when mean temperature is not a suitable measure of incoming radiation) and in environments with rapidly changing air temperature and humidity resulting from advection effects, such as the British Isles (Ward and Robinson, 1990; Dankers, 2002).

6.1.4.3 Blaney-Criddle Equation

The Blaney-Criddle (1950) procedure for estimating ET is well known in the western U.S.A. and has been also used extensively throughout the world (Singh, 1989). The usual form of the Blaney-Criddle equation converted to metric units is written as:

$$ET = kp(0.46Ta + 8.13) \qquad (6.22)$$

Where

ET = potential evapotranspiration from a reference crop, in mm, for the period in which p is expressed;

Ta = mean temperature in ^{o}C;

p = percentage of total daytime hours for the used period (daily or monthly) out of total daytime hours of the year (365×12); and

k = monthly consumptive use coefficient, depending on vegetation type, location and season. For the growing season (May to October), k varies, for example, from 0.5 for an orange tree to 1.2 for various forms of dense natural vegetation.

Following the recommendation of Blaney and Criddle (1950), in the first stage of the comparative study, values of 0.85 and 0.45 were used for the growing season (April to September) and the non-growing season (October to March), respectively.

6.1.4.4 Hargreaves Method

Hargreaves and Samani (1982; 1985) proposed several improvements to the Hargreaves (1975) equation for estimating grass-related reference ET (mm/day). One of its popular forms (Xu and Singh, 2002) is:

$$ET = aR_aTD^{1/2}(T_a + 17.8) \qquad (6.23)$$

Where

a = 0.0023 is a coefficient;

TD = the difference between maximum and minimum daily temperature in ^{o}C;

R_a = the extraterrestrial radiation expressed in equivalent evaporation units; and

Ta is the mean daily or monthly air temperature depending the computation period.

For a given latitude and day, R_a is obtained from tables or may be calculated using Equation (6.13). The only variables for a given location and time period is the daily/monthly mean, maximum and minimum air temperatures. Therefore, the Hargreaves method is essentially a temperature-based method.

6.1.4.5 Results of PE estimations

Data from the Spokane International Airport were used to test three *PE* estimation methods. It was found the all three temperature-based methods underestimated *PE* for the Spokane region when compared with results from the Penman-Monteith equation (Figure 6.5).

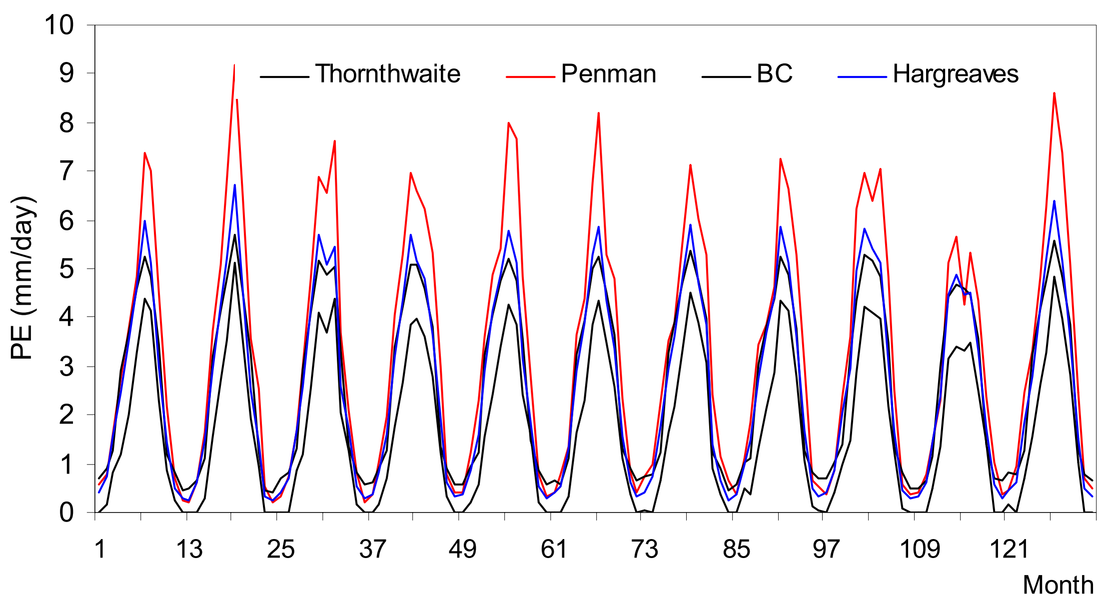


Figure 6.5 Comparisons of three temperature-based methods for estimating PE at Spokane International Airport station with Penman-Monteith equation (1984–1994)

However, the regression analyses indicated that the *PE* estimations by these three methods have good regression relationships with Penman-Monteith estimates (Figure 6.6).

The main concern with the Thornthwaite method is that it could not deal with negative monthly temperatures. Since there are two to three months in the Spokane River watershed when the monthly mean of daily temperature is below zero, the Thornthwaite method was eliminated from this doctoral research.

The Blaney-Criddle model separated the computation results into two groups. This is because only two values for the monthly consumptive use coefficient were used. Xu and Sight (2002) introduced a third value for March, April, and September. Nichols et al (2004) tried different values for every 15 days. This doctoral research adjusted the value for every month and the model results showed considerable improvement (Figure 6.7). The modified consumptive use coefficients range from 0.30 to 1.19 (Table 6.1), which are smaller than that 0.32–1.38 of the Middle Rio Grande and 0.32–1.37 (April 15 to Oct 31) of New Mexico State University (Nichol et al, 2004).

Table 6.1 Modified K value for Blaney-Criddle model

Month	Modified K value
Jan	0.30
Feb	0.49
Mar	0.70
Apr	0.90
May	0.99
Jun	1.07
Jul	1.18
Aug	1.19
Sep	1.11
Oct	0.86
Nov	0.44
Dec	0.30

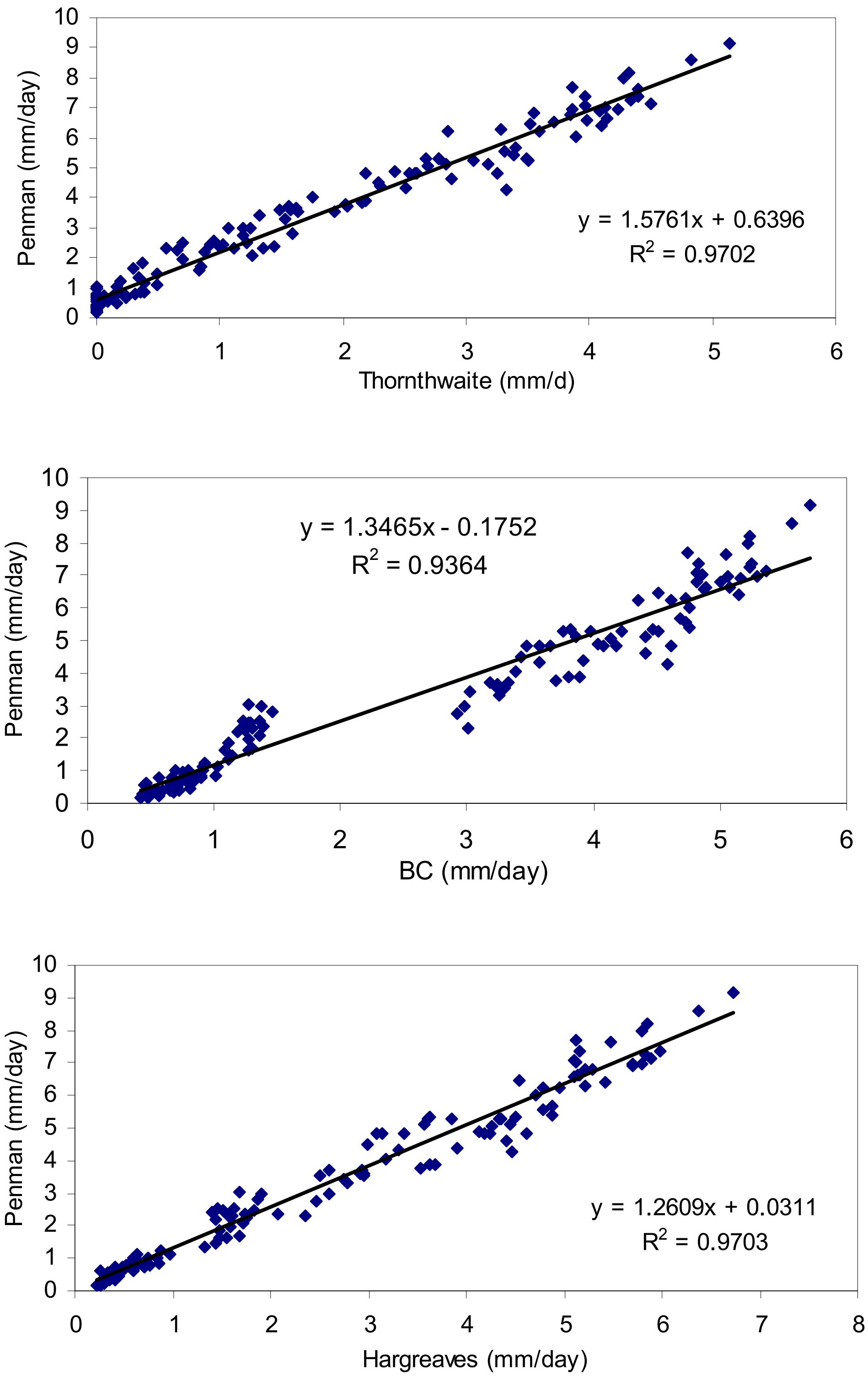


Figure 6.6 Relationships between three temperature-based methods for estimating PE and Penman-Monteith equation

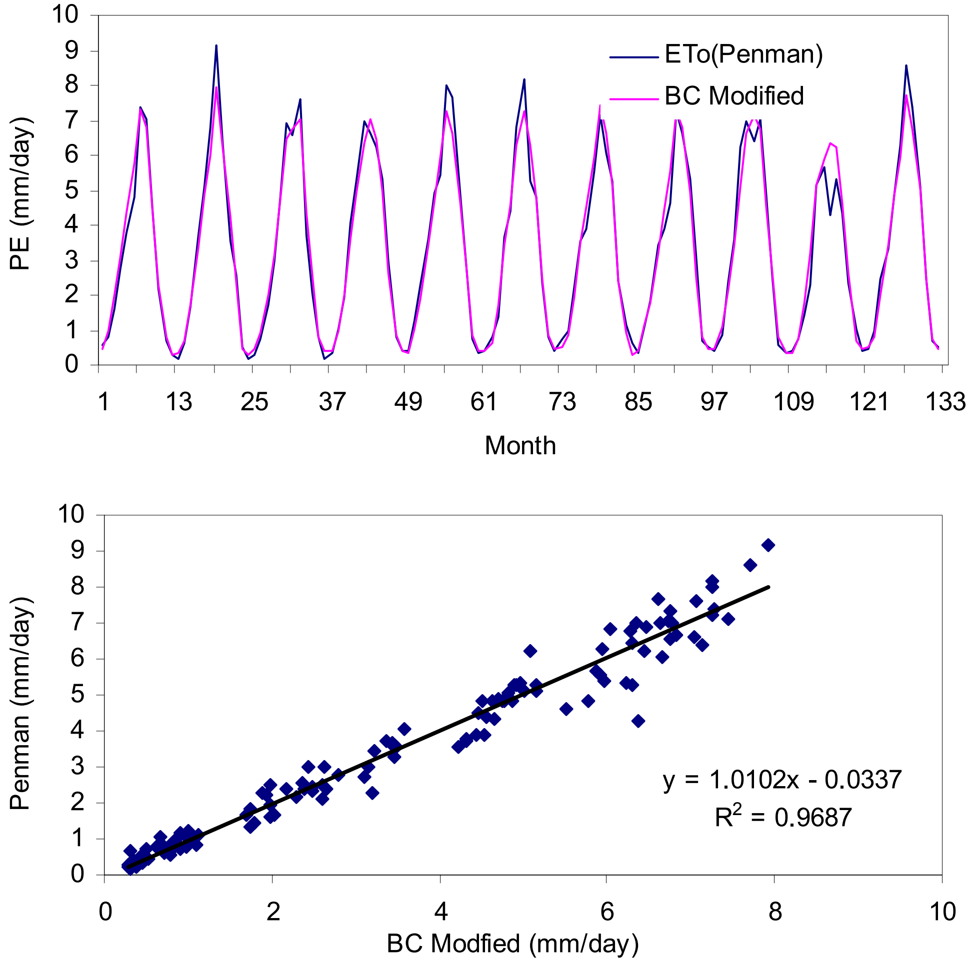


Figure 6.7 Potential Evapotranspiration estimation by the modified Blaney-Criddle model and Penman-Monteith Equation

The Hargreaves method was calibrated the parameter, *a*, by minimizing the least square error (Xu and Singh, 2002), i.e.:

$$OF = \sum_{t=1}^{N} \left(E_{t,Pen} - E_{t,comp}\right)^2 = \text{minimize SSQ} \qquad (6.24)$$

Where

OF is the objective function which should be minimized;

$E_{t,Pen}$ is the *PE* computed by Penaman-Monteith method for the *t*th month;

$E_{t,comp}$ is the *PE* estimated by Hargreaves method for the *t*th month; and

N is the total simulation months.

The calibrated results indicated that *a*=0.0029 has the lowest least square error for the Spokane River watershed (Figure 6.8).

The calibrated Hargreaves model has a good estimate of *PE* with R^2=0.9702 and the regression line between *PE* from the calibrated Hargreaves model and that from Penman-Monteith equation is very close to a 1:1 line (Figure 6.9).

Since it considers radiation and its model results were a better fit with the Penman-Monteith equation, the Hargreaves model was adopted within this doctoral research for the water balance model.

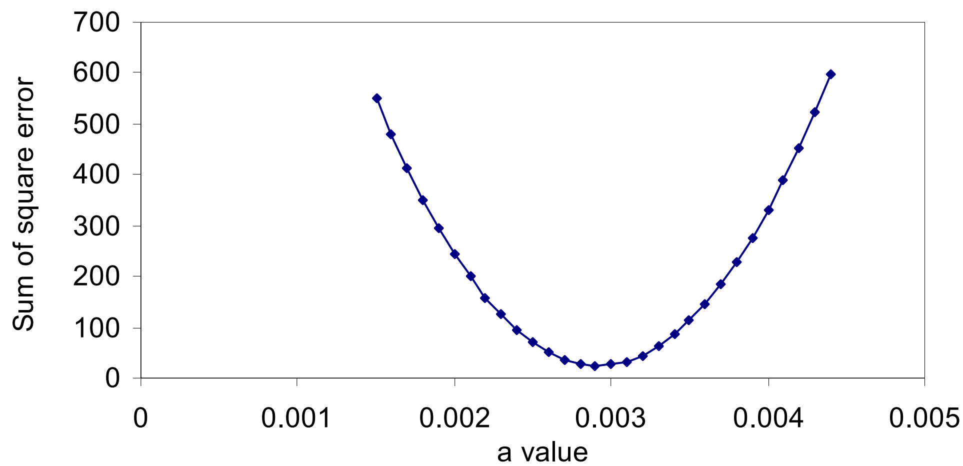


Figure 6.8 Calibration of parameter *a* for the Hargreaves method

6.1.4.6 PE coefficients for different land use types

The Potential Evapotranspiration estimated was based on standard conditions which are in reference to crops grown in large fields under excellent agronomic and soil water conditions. The crop/forest/wetland/water surface evapotranspirations differ distinctly from the reference evapotranspiration, as the ground cover, canopy properties

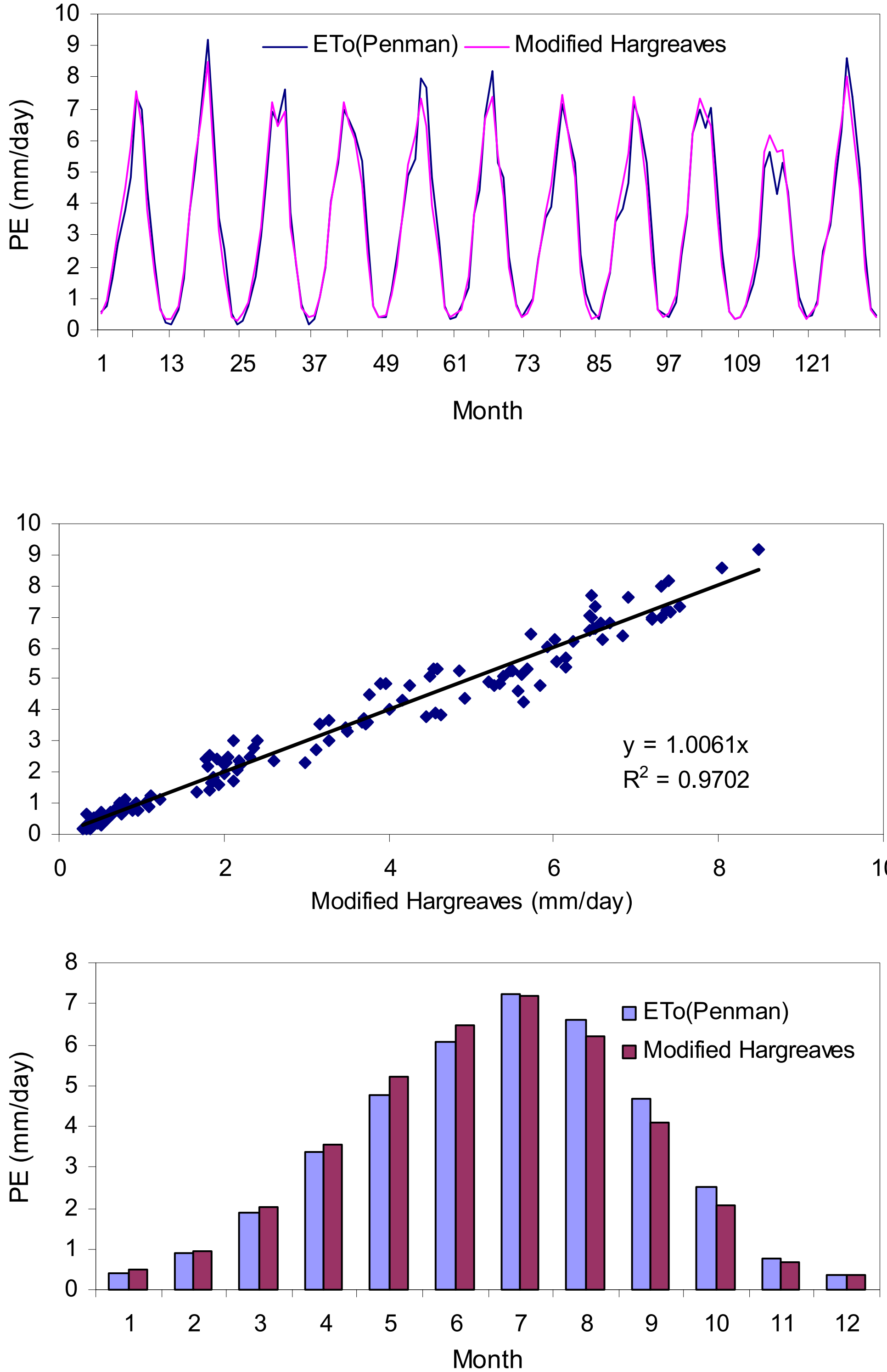


Figure 6.9 Potential Evapotranspiration estimation by the modified Hargreaves model and Penman-Monteith Equation
(Above: monthly time series, Middle: relationship, Bottom, monthly distributions)

and aerodynamic resistance of the crops are different from referred grass. This doctoral research estimated the *PE* for different land use types based on a crop coefficient approach (Allen et al, 1998), i.e.

$$ETc = Kc \cdot ET_0 \qquad (6.25)$$

Where

ETc is the crop evapotranspiration [mm/d]. The "crop" here could be grassland, forest, agricultural, wetland, barren land and water body;

Kc is crop coefficient [dimensionless]; and

ET_0 is the reference crop evapotranspiration [mm/d]. In this research, it is the *PE* computation results from the modified Hargreaves model.

For various land use, the *Kc* are obtained from Allen et al (1998) and Choi et al (2001) and are listed in Table 6.2.

Table 6.2 Crop coefficients for various land uses of the Spokane River watershed

	Forest[1]	Agricultural[2]	Rangeland	Water[3]	Wetland	Barren Land
Jan	0.50	0.4	0.9	1.2525	0.95	0.25
Feb	0.57	0.4	0.9	1.2525	0.95	0.25
Mar	0.67	0.9	0.9	0.6525	0.95	0.25
Apr	0.67	1.15	1	0.6525	0.95	0.25
May	0.77	1.15	1	0.6525	1.2	0.25
Jun	0.80	1.15	1	0.6525	1.2	0.25
Jul	0.80	1.15	1.05	0.6525	1.2	0.25
Aug	0.80	0.58	1.05	0.6525	1.2	0.25
Sep	0.67	0.27	1	1.2525	1.2	0.25
Oct	0.57	0.4	0.9	1.2525	0.8	0.25
Nov	0.50	0.4	0.9	1.2525	0.95	0.25
Dec	0.40	0.4	0.9	1.2525	0.95	0.25

1. The average value of Conifer, Deciduous, and Mixed forest from Choi et al (2001).
2. Based on winter wheat from Allen et al (1998).
3. Water depth >5m from Allen et al (1998).

6.1.5 Direct Runoff

Direct Runoff (*DR*) is caused by and directly following a rainfall or snowmelt event. It is a quick response from the surface flow to precipitation and snowmelt during storms events.

The easiest and most popular method to estimate *DR* is assuming it is a portion of precipitation. For example, Gleick (1987a) assumed *DR* was 20% of precipitation from February to September, 10% from October to November, and 30% from December to January when he developed a water balance model for climate impacts assessment for the Sacramento Basin. However, considering that *DR* is highly related to impervious areas, which is related to land use, this doctoral research adopted the Curve-Number (*CN*) method (US Soil Conservation Service, 1986) to incorporate the land use factor. The formula was developed by Ferguson (1996) and used by Knight et al (2001) as:

$$DR = -0.095 + 0.208\, P/S^{0.66} \qquad (6.26)$$

$$S = (1000/CN) - 10 \qquad (6.27)$$

Where

CN is the Curve-Number (*CN*) for that specific cell based on land use/land cover type;

S is the potential maximum retention after runoff begins; and

P is the monthly precipitation.

The soil type in the Spokane River watershed is silt loam and loam, so it falls into soil type B of the *CN* table. The Maidment (1993) was used to obtain the *CN* values while Table 5.5.1 and Table 9.4.2 are preliminary references.

6.1.6 Actual Evapotranspiration (*AE*)

Actual Evapotranspiration (*AE*) is a function of Potential Evaporation (*PE*) and Soil Available Moisture (*SM*). It is calculated by using Thornthwaite's accounting method (Thornthwaite and Mather, 1955; Knight et al, 2001), in which vegetation and soil moisture deficit indices are employed to simulate asymptotic soil moisture depletion. As Mather (1997) reiterated, *AE* depends on stored moisture in the soil, the type of vegetation coverage, as well as on climatic factors. Thus two step calculations were necessary to estimate monthly *AE* (Knight et al, 2001). The soil available moisture for the month was first calculated by:

$$SM_t = SN_t + SM_{t-1} + (P_t - DR_t) \qquad (6.28)$$

Where

SM of a given month (SM_t) is the sum of snowmelt (SN_t), rainfall that goes into soil (P_t-DR_t), and soil moisture retained from the previous month (SM_{t-1}).

Usually estimated using soil texture and vegetation rooting depth, the field capacity of soil (*FC*) was estimated from vegetation cover and standard tables using the land cover maps (Dunne and Leopold, 1978; Knight et al, 2001). This research simply took the values of Knight et al (2001) and compared them with several existing water balance models.

The soil moisture deficit was then combined to compute *AE* for each month. If there is less moisture in the soil than *FC*, *AE* is proportionately less than *PE* as:

If $SM_t >= FC$, $AE = PE$ (6.29)

If $SM_t < FC$, $AE = PE\ (SM_t/FC)$ (6.30)

After estimating *AE*, the remaining soil moisture was derived by deducting *AE* from *SM*, which will become potential runoff.

$$SM_t = SN_t + (P_t - DR_t) + SM_{t-1} - AE \qquad (6.31)$$

6.1.7 Soil Moisture Surplus and subsurface flow

The next step is to determine the proportion of soil moisture that contributes to runoff. Because not all moisture surplus moves from ground to surface water immediately, nor does runoff move instantly downstream, an assumption was required with regard to the proportion of available water that would actually run off in a given month (Knight et al, 2001). However, if soil moisture surplus is less than maximum soil water content (*MaxS*), there is no subsurface and ground water produced in the specific month. However, ground water from the previous month could still contribute to the streamflow as base flow.

If $SM_t > MaxS$, then $S_t = SM_t - MaxS$ (6.32)

If $SM_t <= MaxS$, then $S_t = 0$ (6.33)

Where

S*t* is the soil moisture surplus for month *t*.

A portion of the soil moisture surplus (S_t) converts into subsurface flow as:

$$Q_{Sub} = K_1 * S_t \qquad (6.34)$$

While the rest of it percolates into ground-water storage.

$$Percolation = (1-K_1) * S_t \qquad (6.35)$$

6.1.8 Ground-water Storage and GW Flow

The ground-water flow is assumed to be:

$$GW_t = K_2 * (G_{t-1}) \qquad (6.36)$$

Where

G_{t-1} is the ground-water storage for the previous month. This means a lag of one month for ground water is considered and K_2 is a coefficient.

The ground-water storage would then be:

$$G_t=G_{t-1}+ (1-K_1)*S_t-K_2*G_{t-1} \quad (6.37)$$

6.1.9 Model outputs

By the end of the simulation for a specific month *t*, the various parameters outputs would be:

The total monthly runoff: $R=DR_t + K_1*S_t + K_2*(G_{t-1})$

The actual evaporation: AE

The snow depth (SWE): $SW_t = \%S*P_t-SN_t$

The soil moisture: $Min\ (SN_t + (P_t-DR_t) + SM_{t-1}-AE, MaxS)$

The ground-water storage: $Gt-1+ (1-K_1)*S_t-K_2*G_{t-1}$

Most of these parameters would be the initial value for the simulation of next month.

6.2 MODEL APPLICATIONS

6.2.1 Models results and discussions

The model that consists of the above equations was coded with Microsoft Visual Basic. The 1984–1991 monthly precipitation and temperature data were prepared and interpolated into each 2 km × 2 km cell using ArcGIS Geostatistical Analyst. Visual Basic was adopted because it is a language that is embedded into Microsoft Excel and ArcGIS, and thus the program could be coupled into these two popular softwares when necessary. The model results are discussed in the following sections.

6.2.1.1 Spatial distribution

The spatial distribution of annual runoff is highly related to the annual precipitation spatial distribution (Figure 6.10). The southwest corner of the watershed generates less than 100 mm runoff annually and the eastern portion of the watershed can produce more than 900 mm annually. Water bodies and wetlands usually have negative runoff generation because the potential evapotranspiration is larger than the precipitation (Figure 6.10)

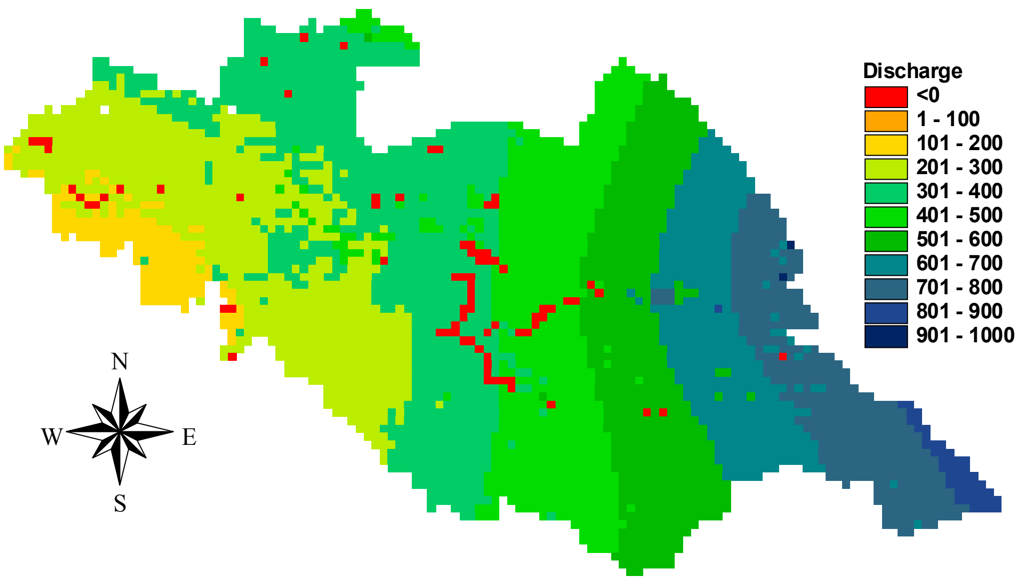


Figure 6.10 Annual runoff spatial distribution of the Spokane River watershed

6.2.1.2 Time Series Runoff

Monthly time series runoff in the Spokane River watershed is shown in Figure 6.11. Direct visual inspection indicates that the model has an acceptable fit with the observed data with degree of fit improving over time. This might be due to the initial soil moisture and ground-water conditions, which are extremely difficult to accurately retrieve. Further optimization may produce a better fit, but it is beyond the scope of this doctoral research.

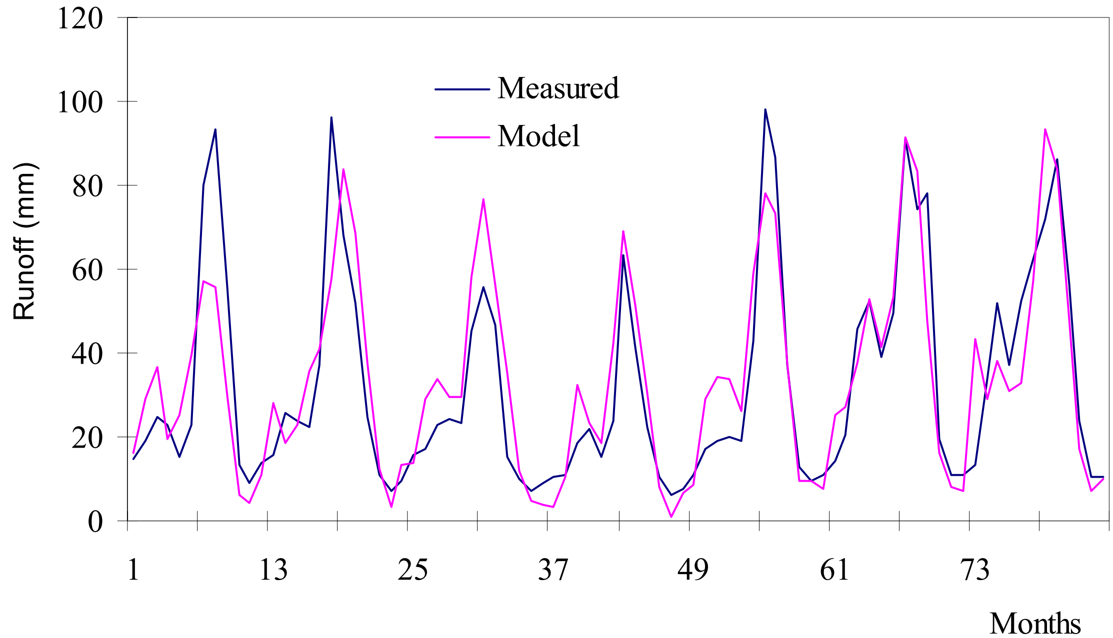


Figure 6.11 Model and measured monthly streamflow in the Spokane River watershed

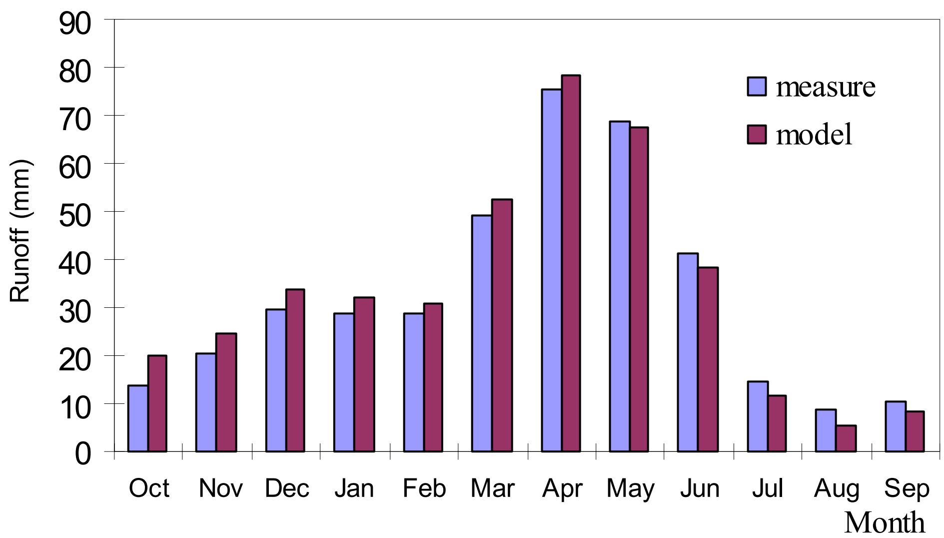


Figure 6.12 Monthly average comparison of model and measured streamflow for Spokane River watershed

From the monthly average point of view, the model results and observed data are consistent (Figure 6.12).

6.2.2 Model efficiency analyses

Seven methods were used in this doctoral research to justify the model performance. Since each of the methods has its own advantages and disadvantages, it is hard to conclude which one is the best method to use.

The first criterion is the correlation and correlation-based measures (correlation coefficient r, and the coefficient of determination R^2). This kind of indicator has been widely used to evaluate the "goodness-of-fit" of hydrological models. However, these measures are oversensitive to extreme values and are insensitive to additive and proportional differences between model predictions and observations (Legates, 1999; Morgen and Quinton, 2001).

The second criterion used in this doctoral research is the Nash–Sutcliffe efficiency criterion (Nash and Sutcliffe, 1970), which is probably the most popular indicator used by hydrologists. The coefficient of efficiency (EF) is defined by (Nash and Sutcliffe, 1970):

$$EF = 1 - \frac{\sum_i \left(Q_i - \hat{Q}_i\right)^2}{\sum_i \left(Q_i - \overline{Q}\right)^2} \qquad (6.38)$$

Where

Q_i is the observed streamflow for *i*th time period;

$\hat{Q}_i$ is the simulated streamflow for *i*th time period; and

$\overline{Q}$ is the mean value of observed streamflow for entire simulation period.

The value of *EF* is always expected to approach unity for a good simulation of the observed runoff series. The coefficient of efficiency (*EF*) represents an improvement over the coefficient of determination for model evaluation purposes in that it is sensitive to differences in the observed and model simulated means and variances. Because of the squared differences, however, *EF*, as R^2, is overly sensitive to extreme values.

The third efficiency criterion used is the relative error of the volumetric fit between the observed runoff series and the simulated series, which is defined by:

$$RE = \frac{\sum_i \left(Q_i - \hat{Q}_i\right)}{\sum_i Q_i} \qquad (6.39)$$

The value of *RE* is expected to be close to zero for a good simulation of the total volume of the observed runoff series. The *RE* is an average scenario that underestimates the effects of extreme error and therefore is not a recommended method. For example, in one month the difference between observed and simulated runoff depth is 200 mm and another month is -200mm then a value of zero of *RE* could result, but still be a very poor model performance.

The fourth criterion applied is the relative error between the observed maximum monthly runoff and the simulated maximum monthly runoff within the whole series, which is denoted by RE_m, with

$$RE_m = \frac{Q_m - \hat{Q}_m}{Q_m} \qquad (6.40)$$

Where Q_m and $\hat{Q}_m$ represent the observed maximum monthly runoff and the simulated maximum monthly runoff, respectively. This indicator emphasis the maximum runoff and may be a good indicator for flood predication, but is not suitable for overall model performance justifications.

The fifth criterion is the index of agreement developed by Willmott (1981) and is defined by:

$$d = 1.0 - \frac{\sum_i \left(Q_i - \hat{Q}_i\right)^2}{\sum_i \left(\left|\hat{Q}_i - \overline{Q}\right| + \left|Q_i - \overline{Q}\right|\right)^2} \qquad (6.41)$$

This is similar to the Nash–Sutcliffe efficiency criterion (*EF*) as it is also sensitive to extreme values due to the squared differences.

The sixth criterion used in this doctoral research was the Root Mean Square Error (RMSE). The problem with this criterion is that it is not a standardized model. The RMSE=50 might be a good model and RMSE=5 might be a poor model depending on the physical process, magnitude of streamflow, and simulation period. The primary use of this indicator is for comparing different models for the same simulation processes: the smaller the RMSE, the better the model.

$$RMSE = \left[\frac{\sum_i \left(Q_i - \hat{Q}_i\right)^2}{n}\right]^{1/2} \qquad (6.42)$$

The RMSE sometimes is used together with additional supporting information (e.g., a comparison between the observed and simulated mean, standard deviations and maximum error) because they can provide an evaluation of the error in the units of the variables (Legates, 1999).

The last criterion is a comprehensive criterion, which includes more than one indicator. It was used by Mazvimavi (2003) and is based upon on work by Lorup et al

(1998) and Schulze and Smithers (1995). A simulation model is acceptable if the simulation monthly flows satisfy the following conditions:

i) The difference between the mean of observed and that of simulated flows is within ±10% range;

ii) The difference between the standard deviation of observed flows and that of simulation flows is within the ±15% range;

iii) Coefficient of efficiency (EF) >0.7; and

iv) An acceptable agreement between the flow duration curves of observed and simulated flows based on visual inspection.

The results for these seven criteria applied to our model results are shown in Table 6.3. There are no "pass" values for the first six criteria, but the model seems to have an acceptable fit based on these values: coefficient of determination R^2=0.7564, the Nash–Sutcliffe coefficient of efficiency is 0.75, the relative error is -3.7%, the relative error for maximum monthly runoff is 5.0%, the index of agreement if 0.9295, the RMSE=12.52. The model indeed satisfied all the required conditions from seventh criterion.

Table 6.3 Model Efficiency Assessment Results

Number of Criteria	Indicators
1	R^2=0.7564 and r=0.8697
2	EF=0.75
3	RE=-3.7%
4	RE_m=5.0%
5	d=0.9295
6	RMSE=12.52
7	Difference in mean 3.70% Difference in standard deviation -6.80% Coefficient of efficiency 0.75 Agreement by visual inspection

6.3 IMPACTS OF CLIMATIC CHANGES ON WATER AVAILABILITY AS SIMULATED USING THE WATER BALANCE MODEL

Basically, there are two methods for studying the impacts of future climatic change on water availability. One is to make some hypothetical scenarios, such as precipitation changes for P_1, P_2, …, P_m and mean temperature changes for T_1, T_2, …, T_n. Then the hydrological models could be re-run $m*n$ times using different precipitation and temperature combinations to obtain the discharge (water availability) responses to each of the hypothetical climatic scenarios. The advantage of this method is to present the general relationship between hydrological regime and climatic conditions. The disadvantage of this method is that it does not reflect the future climatic scenarios of the studied watershed itself thus the result may not be very helpful for watershed management. In addition, from a technical aspect, the changes of precipitation and temperature vary from month to month and a fixed change value for all months might not reflect the reality. In contrast to this hypothetical scenario is a General Circulation Models (GCMs) scenario where, future watershed climatic conditions are obtained from the outputs of GCMs. Theoretically, climatic simulations from GCMs could be used directly as input into hydrological models, which, in turn, could be used to evaluate the impacts of climatic change on hydrological and water resources (Guo et al, 2002). However, there are two major practical challenges: (1) the outputs of different GCMs are not consistent and even opposite in direction of precipitation for some watersheds, and (2) there are differences in spatial and temporal scales between GCMs and hydrological models. There exist different methods to downscale the GCMs results for hydrological usages; however, different downscaling methods could provide different spatial distributions of precipitation and temperature for the specific watershed while using the same GCM result. Because of these two challenges, there are uncertainties about the future climatic scenario from GCM results. Thus, for this doctoral research, both methods, hypothetical and GCMs scenarios, were used and compared to study the impacts of climatic change on water availability in the Spokane River watershed.

6.3.1 Hypothetical scenarios

Various hypothetical climatic change scenarios have been adopted and climate predictions for future global warming have been standardized (Loaiciga et al, 1996). The general procedure for estimating the impacts of hypothetical climate change on hydrological behavior has the following four steps (Xu, 1999). First is to determine the parameters of a hydrological model in the study watershed using current climatic input and observed river flows for model validation. Second is to perturb the historical time series of climatic data according to some climate change scenarios. Third is to simulate the hydrological characteristics of the watershed under the perturbed climate using the calibrated hydrological models. Fourth is to compare the model simulation of the current and possible future hydrological characteristics.

This thesis research effort followed these four steps and studied the impacts of climatic change on hydrological regimes with twenty-five climatic scenarios, i.e. five precipitation change scenarios: -20%, -10%, no change, +10%, and +20%, and five temperature change scenarios: no change, +0.5°C, +1.0°C, +1.5°C, and +2.0°C.

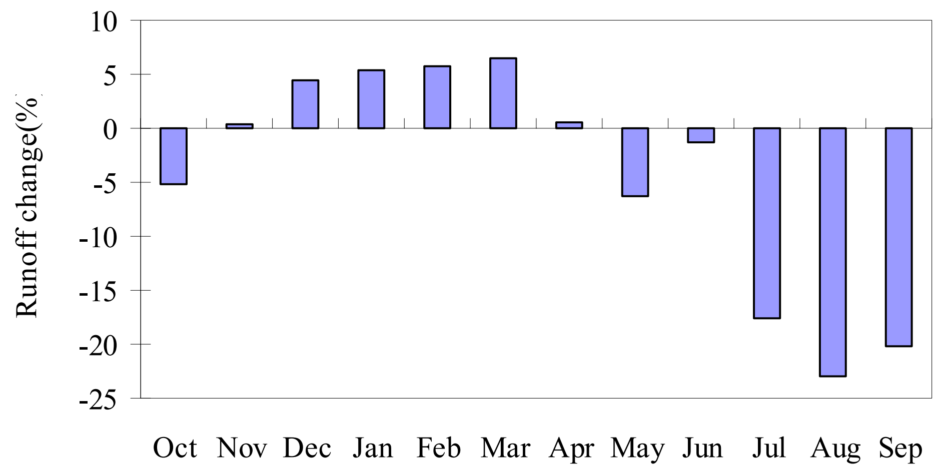
The results indicated that the streamflow was more sensitive to precipitation variation than to temperature increase (Table 6.4). This is consistent with the IPCC report (McCarthy et al, 2001) that found that the projected runoff change largely follows the projected change in precipitation. Two major conclusions that can be drawn from the results are that: (1) the streamflow change percentage is usually larger than that of precipitation — a 10% precipitation change usually results in 13–14% change in streamflow, and (2) temperature change also affects the streamflow, although its magnitude is smaller than the precipitation.

Table 6.4 Streamflow responses to climatic changes (%)

	P-20%	**P-10%**	**P+0%**	**P+10%**	**P+20%**
T+0	-26.5	-13.3	0.0	13.3	26.7
T+0.5	-26.6	-13.3	0.1	13.5	26.9
T+1.0	-26.8	-13.4	0.0	13.5	26.9
T+1.5	-27.0	-13.6	-0.2	13.3	26.9
T+2.0	-27.3	-13.9	-0.4	13.1	26.7

The above discussion is in relation to annual streamflow responses against precipitation and temperature changes. Discussion is also needed for monthly streamflow responses to temperature change as Spokane River watershed has a monthly streamflow variation, and summer is the critical period for the watershed. The simulation results indicated that the monthly streamflow distribution was more sensitive to temperature change than annual streamflow was. If the precipitation remains the same, a 2^{o}C increase in temperature may only lead to a 0.4% decrease in annual streamflow, but it could produce 20–25% streamflow decreases in July, August and September (Figure 6.13) and 5% increases for the Winter and Spring seasons (December, January, February, and March). This would bring more critical water problems to the Spokane River watershed as summer low-flow already is a serious issue.

The responses of the absolute amount of runoff follow along the same trend as percentage change (Figure 6.13). The winter months (December, January and February) are expected to receive 200 cfs more runoff. The first snow-melt flow peak is expected



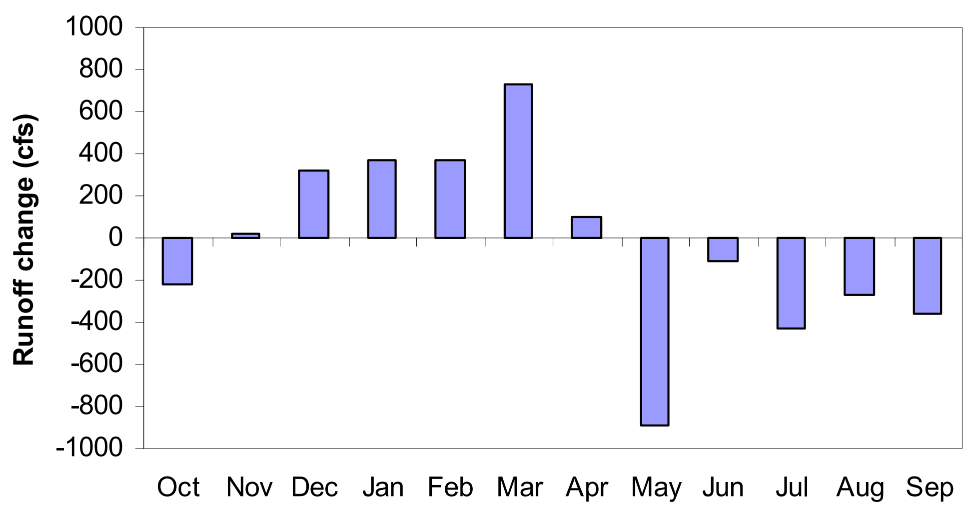


Figure 6.13 Monthly streamflow responses to temperature change

(precipitation remains the same)

Above: percentage change. Below: Absolute amount change to shift from May to March, which is expected to receive about 600 cfs more in monthly runoff. The largest runoff decrease happens in May as a portion of the snow-melt has advanced to March. The runoff is expected to decrease almost 1000 cfs for May. The streamflow is expected to reduce about 200–400 cfs for July, August, and September.

The average snow depths are sensitive to both precipitation and temperature changes (Figure 6.14). The change of snow depths resulting from a temperature increase is the main reason for the changes in the seasonal streamflow.

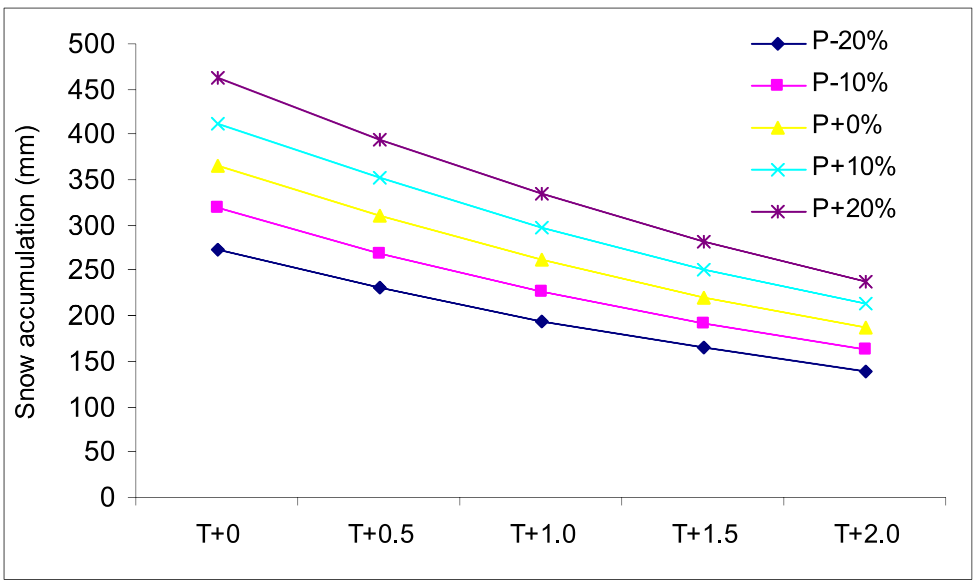


Figure 6.14 Snow accumulation responses to climatic change

6.3.2 GCMs output scenarios

Many GCMs have been used to simulate global climatic change and the results from different GCMs may give quite different predications about future climate for a specific watershed. Figure 6.15 shows the global average temperature and precipitation changes for the nineteen Coupled Model Intercomparison Project (CMIP2) simulations.

At the time of CO_2 doubling at year 70, the 20-year average (years 61 to 80) global mean temperature change as predication from these models is 1.1 to 3.1°C with an average of 1.8°C and a standard deviation of 0.4°C. At the same time, the 20-year average (years 61 to 80) percentage change of global mean precipitation from these models ranges from 0.2 to 5.6% with an average of 2.5% and a standard deviation of 1.5%.

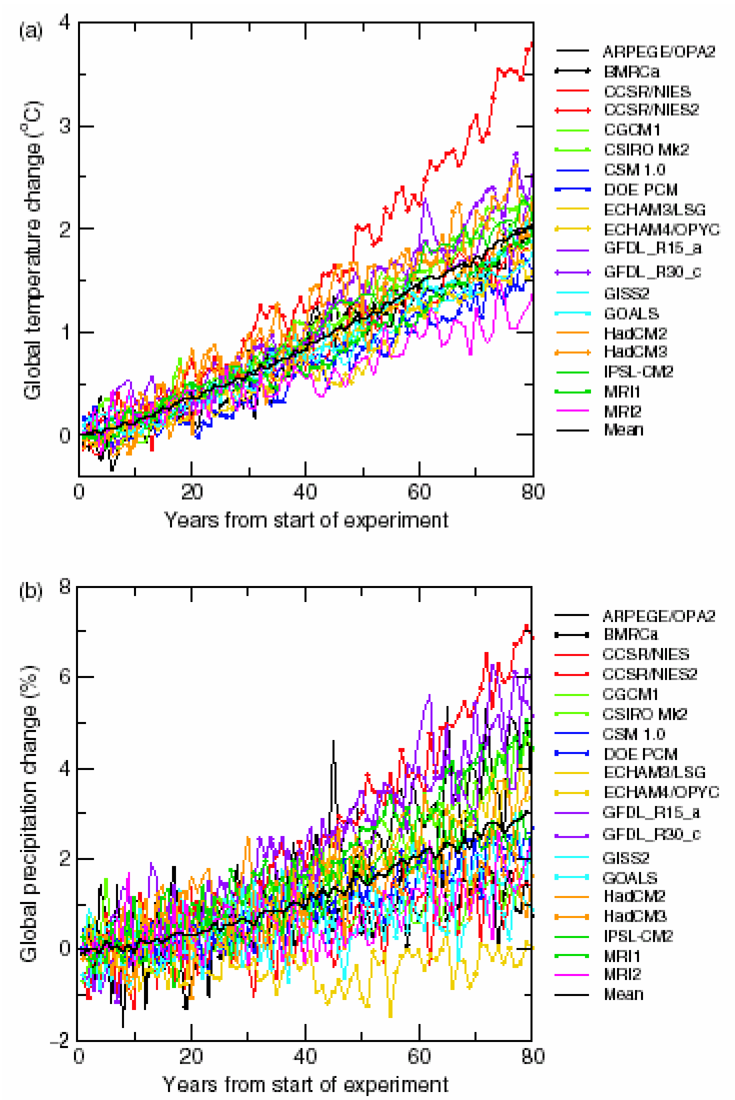


Figure 6.15The time evolution of the globally averaged
(a) temperature change relative to the control run of the CMIP2 (Coupled Model Intercomparison Project) simulations (Unit: °C).
(b) precipitation change (Unit: %)
(Houghton et al, 2001)

This is the global average value and the variation for a specific watershed would be larger than these average values.

After the appropriate GCMs model were chosen for the studied watershed, GCM results need to be downscaled into hydrological scales, which are smaller scales in both spatial and temporal aspects than GCMs. Even if GCMs in the future are run at high resolution there will remain the need to “downscale” the results from such models to individual sites or localities for impact studies (Wilby and Wigley, 1997).

There are basically two methods to downscale the GCM results: (1) a statistical-based method and (2) a regional climate model based method. A statistical-based method builds the statistical relationship between a large-scale climatic predictor variable and/or circulation characteristics with station-scale meteorological series. The basic assumption of the statistical methods, and one often criticized, is the invariance of the stochastic parameters under changed climate. In spite of this, the statistical downscaling approach is starting to provide hydrologically useful regional algorithms (Xu, 1999) and is playing an important role in translating global climate change scenarios to more regional impact assessments (Grotch and MacCracken, 1991; von Storch et al, 1993; Wilby and Wigley, 1997; Xu, 1999). Wilby and Wigley (1997) further classified the statistical methods into three categories: (1) regression method, (2) weather pattern approaches, and (3) stochastic weather generators. Each of these approaches has its own advantages and disadvantages.

Regional climate model based methods extract small-scale information from large-scale GCM data by developing and using limited area models (LAMs) or regional climate models (RCMs). This method is described as dynamic downscaling by Xu (1999) and as limited-area climate models by Wilby and Wigley (1997). This method has been applied with relative success to numerous watersheds (Giorgi, 1990; Giorgi and Mearns, 1991; Pielke et al, 1991; Giorgi et al, 1990; 1994; Jones et al, 1995; Mearns et al, 1995; Jenkins and Barron, 1997).

The main shortcomings of this method are that: (1) it requires considerable computing resources and is as expensive as to run a global GCM; (2) the model results are useful for only a specific study watershed and can not be transferred to a different watershed; and (3) these models still cannot meet the needs of spatially explicit models of ecosystems or hydrological systems and further downscaling is still needed.

The University of Washington's Climate Impacts Group (UW-CIC) has projected changes (Table 6.5) for the Pacific Northwest by using eight coupled global-atmosphere climate models: CCSR, CGCM1, CSIRO, ECHAM4/OPYC, GFDL, HadCM2, HadCM3, and NCAR PCM3 (Mote et al, 2003). The models assume an annual increase in equivalent carbon dioxide concentrations of approximately 1% per year. Changes are benchmarked from the average for the decade of the 1990s.

Table 6.5 Changes in PNW climate from eight climate models for the 2020s and 2040s (from the 1990s)

	Temperature change	**Precipitation Change**	
	Annual	Oct–Mar	Apr–Sept
2020s			
Low	+ 0.9ºF (0.5ºC)	+2%	- 4%
Average	+ 2.7ºF (1.5ºC)	+8%	+4%
High	+ 4.7ºF (2.6ºC)	+18%	+14%
2040s			
Low	+ 2.7ºF (1.5ºC)	-2%	- 7%
Average	+ 4.1ºF (2.3ºC)	+9%	+2 %
High	+ 5.8ºF (3.2ºC)	+22%	+9%

The UW-CIC also developed the climatic change streamflow scenarios using four global coupled atmosphere-ocean GCMs (HadCM2, HadCM3, ECHAM4, and PCM3) and a composite climatic change scenario that averages the results of the four individual model scenarios (Figure 6.16).

The detailed information for these composite scenarios averaged for 2020s and 2040s scenarios are listed as Table 6.6. Note that each calendar month in the climate time series used to drive the hydrologic model has exactly the same changes in temperature and precipitation. For the composite 2020s scenario, for example, all of the Januaries have their monthly total precipitation multiplied by 1.036825 and the monthly average temperature is increased by 1.906325 ^{o}C.

Table 6.6 Future climatic change scenarios for the Pacific Northwest based on four GCMs

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Composite 2020 Scenario (Jan–Dec)

Precipitation Multiplier:
1.036825 1.084375 1.0869 1.0915 0.972325 0.932075 1.00015 1.103725 1.111725 1.157425 1.081975 1.058

Delta T (^{o}C):
1.906325 1.4577 1.704225 1.428225 1.563475 2.029575 1.91775 2.1494 1.878025 1.0973 1.18355 1.9682

Composite 2040 Scenario (Jan–Dec)

Precipitation Multiplier:
1.01155 1.126125 1.10845 1.0258 1.085575 0.914975 0.95625 0.922525 0.860875 1.05705 1.0224 1.08525

Delta T (^{o}C):
2.380175 2.5935 2.643375 1.90895 1.192 2.27435 2.6922 3.02325 2.0624 2.13265 1.630275 2.5659

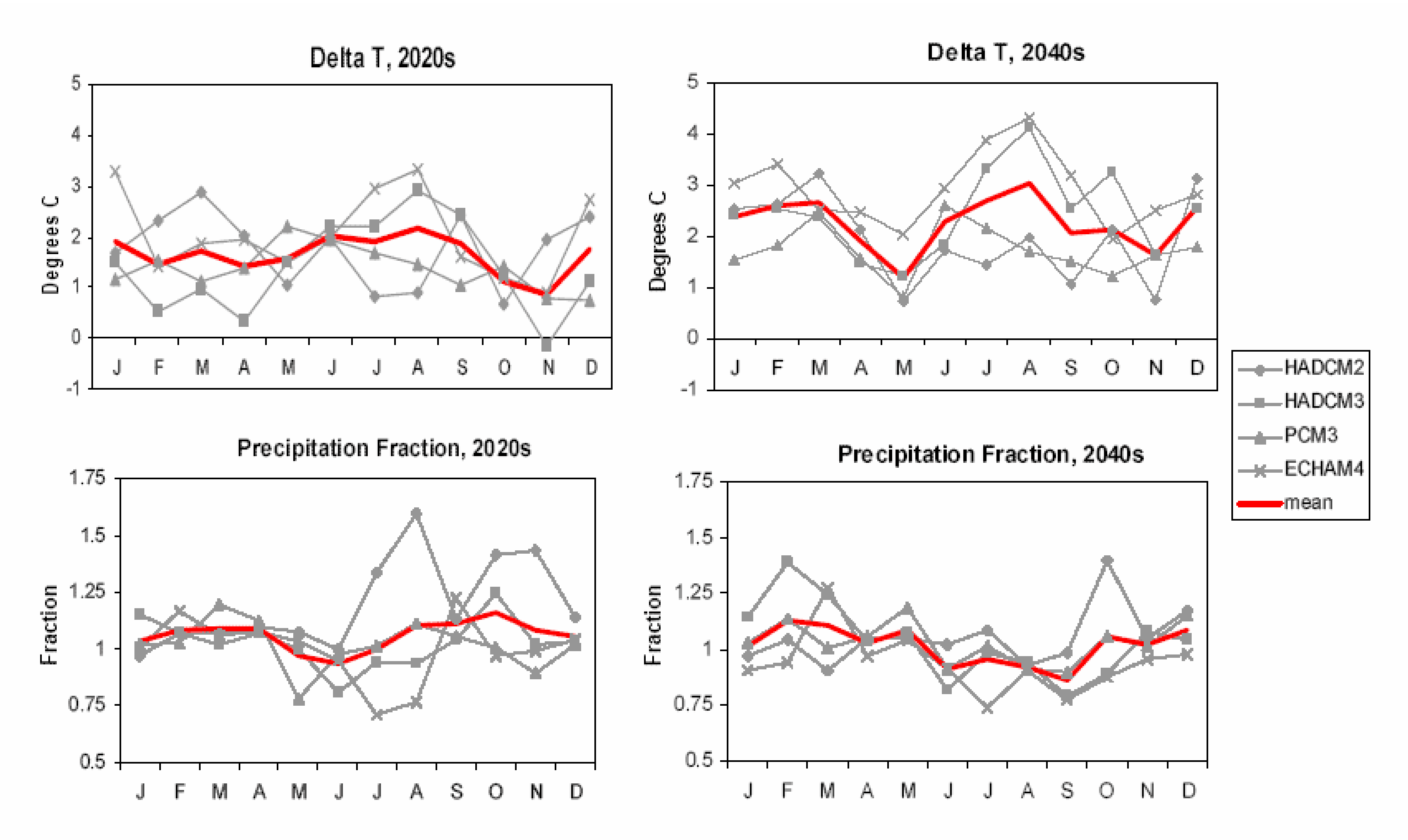


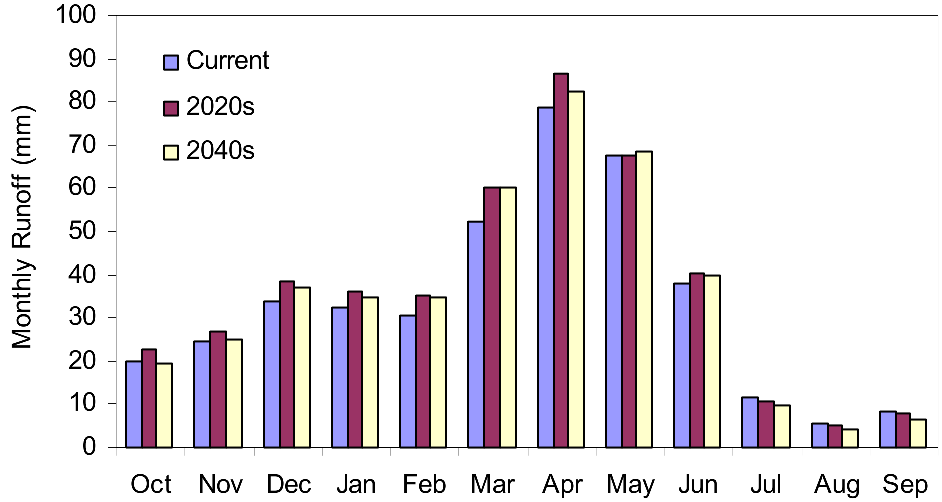
Figure 6.16 Future climatic change scenarios for Pacific Northwest based on four GCMs (http://www.cses.washington.edu/cig/fpt/ccstreamflowtool/sftmethods.shtml)

In this doctoral research, the monthly water balance model was run again for these two scenarios listed in Table 6.6 and the results indicated that the annual streamflow will increase by 8.6% for the 2020s scenario and increase by 4.8% for the 2040s scenario. However, there are distinct differences among the months (Figure 6.17). For example, the streamflow for July, August, and September will decrease by 4.9–7.0% and 14.4–24.6% in both scenarios, respectively, thus bringing rise to critical water availability concern in the Spokane River watershed as low-flow in summer is already a critical problem.

The snow depths are more sensitive to global warming than is streamflow. The snow depths would decreases for all months (Figure 6.18) except July, August and September when there are no snow-pack at all at any location in the Spokane River watershed. The spatial average of snow depth reduces from 83 mm to 53 mm for February in the 2040s climatic scenario.

6.4 IMPACTS OF LAND USE/LAND COVER CHANGE ON WATER AVAILABILITY

Since the monthly water balance mode developed in this doctoral research simulates the hydrological process at each individual cell depending on the land use type, it can simulate the hydrological responses to climatic change and land use/land cover change simultaneously. If detailed city and county land use plans for the next 20–30 years were available, future land use/land cover change scenarios for the watershed could be used to study the impacts of land use on hydrological regimes and water availability (Figure 6.19). Unfortunately, a future land use planning map for the Spokane River



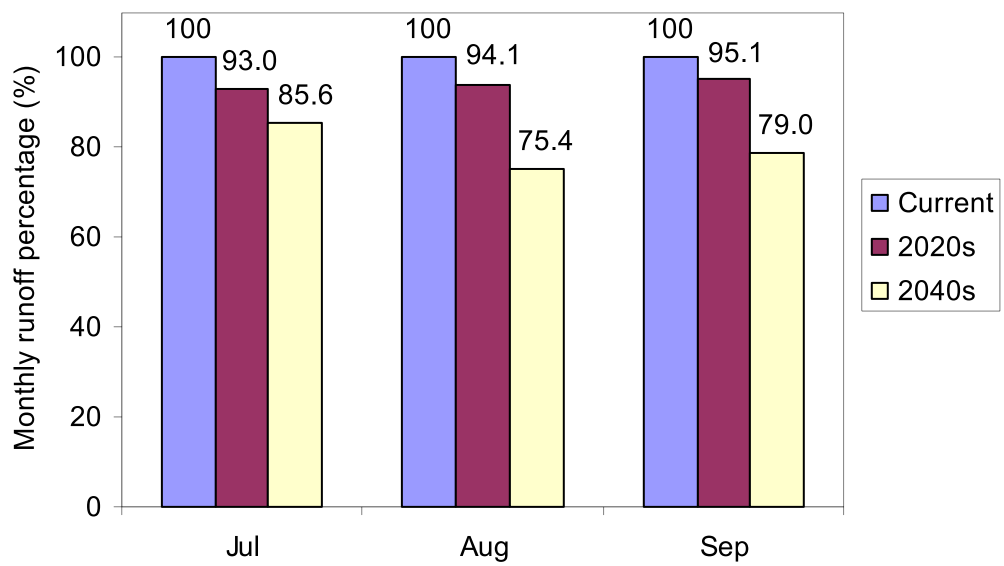


Figure 6.17 Monthly streamflow changes under 2020s and 2040s climatic scenarios

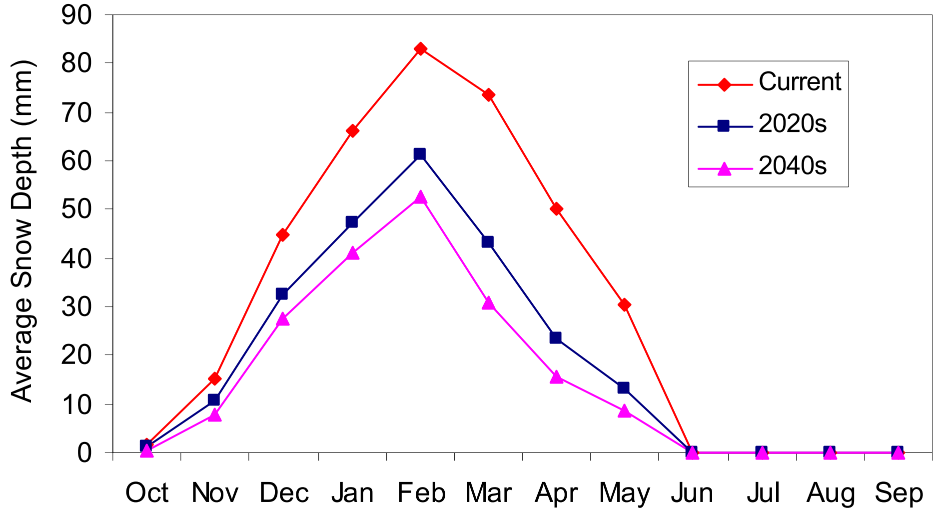


Figure 6.18 Average monthly snow depth for 2020s and 2040s

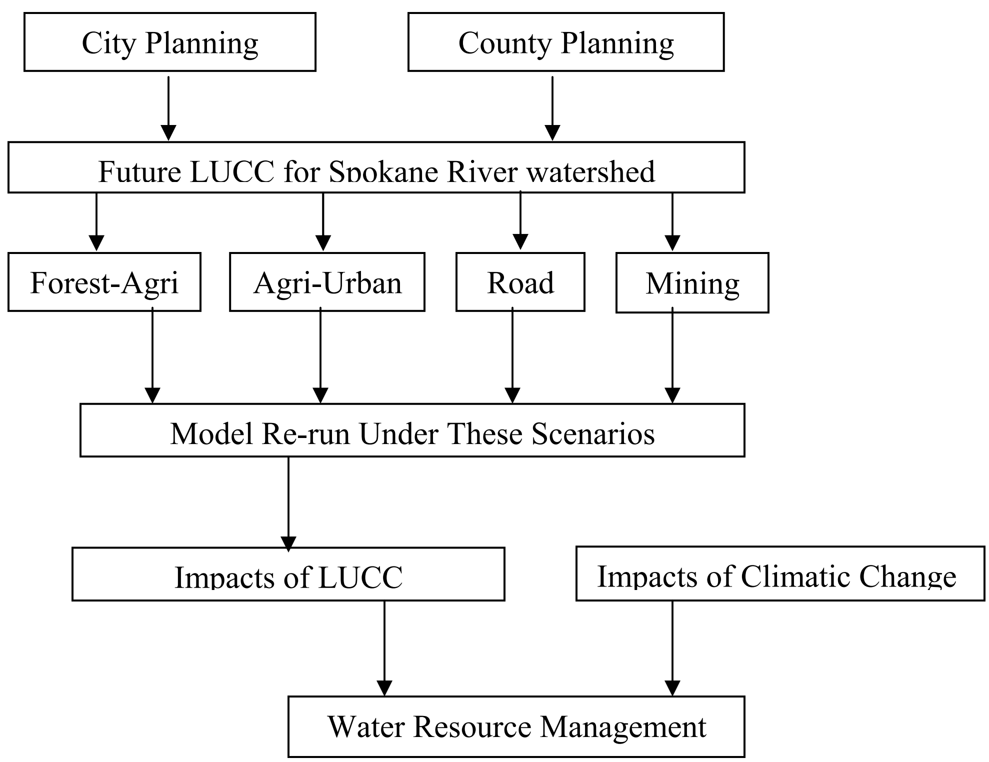


Figure 6.19 General steps of land use hydrological impacts study

watershed was not available, so this doctoral research did not run the scenarios to study the impacts of land use/land cover changes on watershed water availability.

6.5 CONCLUSIONS AND DISCUSSIONS

A GIS and land use based monthly water balance model was developed in this doctoral research. The model has all major hydrologic processes at watershed scale and includes seven major parts (or sub-models): (1) a rain/snow module; (2) snow accumulation and snowmelt; (3) direct runoff; (4) AE/PE; (5) soil moisture; (6) ground water; and (7) total runoff. The model requires only limited data and gives reasonable and acceptable results. The model was written in Visual Basic language and could be easily merged into Microsoft Excel and ArcGIS when necessary, both of which use Visual Basic as their internal language and Excel provides a user friendly interface with data and ArcGIS can display the results in a visual spatial distribution.

Application of this model to study the impacts of climatic change on hydrological regime in the Spokane River watershed resulted in useful information. (1) The streamflow was more sensitive to precipitation variation than to temperature increase. A 10% precipitation change usually results in a 13–14% change in streamflow for the Spokane River watershed. This is consistent with existing research results and general understanding of runoff generation (Arnell, 2002; McCarthy et al, 2001). (2) The temperature change also affects the streamflow. The monthly streamflow is more sensitive to temperature change than annual streamflow is. If the precipitation remains the same, a 2^{o}C increase in temperature may only lead to a 0.4% decrease in annual streamflow, but produce 20–25% streamflow decreases in July, August and September and 5% increases for December, January, February, and March. This would bring more critical water problems for the Spokane River watershed as summer low-flow already is a serious issue for watershed management. (3) Based on the GCM downscaling data from the University of Washington's Climate Impacts Group, the monthly water balance model indicated that the annual runoff would increase by 8.6% and 4.8% for 2020s and 2040s scenarios, respectively. However, there were distinct differences between months with the streamflow for July, August, and September decreasing by 4.9–7.0% and 14.4–24.6% in both scenarios. This would bring critical water availability problems for the Spokane River watershed in the future climatic warming scenarios.

CHAPTER 7 GEOSTATISTICAL ANALYSES OF IMPACTS OF CLIMATIC CHANGES WITH HISTORICAL DATA

Even the most physically-based models, however, cannot reflect the true complexity and heterogeneity of the processes occurring in the filed. Catchment hydrology is still very much an empirical science.

George Hornberger et al, 1985

7.1 INTRODUCTION

Numerous studies have simulated the sensitivity of streamflow to climatic changes for watersheds all over the world (Yates and Strzepek, 1998; McCarthy et al, 2001; Sankarasubramanian and Vogel, 2001; Arnell, 2002). A challenging issue, however, is how to verify the model results in the future climatic change scenarios as there are no "measured" data available. The best available techniques might be analyzing their historical records (Risbey and Entekhabi, 1996). They addressed this issue with the observed historical data and presented their results in contour format by using the adjustable tension continuous curvature surface grid algorithm proposed by Smith and Wessel (1990).

This study modified the methodology developed by Risbey and Entekhabi (1996) by using an ArcGIS Geostatistical Analyst to estimate the impacts of climatic change on regional hydrological regimes and to verify the monthly water balance model results.

7.2 METHODS

For each year, the annual departures for runoff, precipitation, and temperature were calculated and plotted in precipitation-temperature planes based on the methodology of Risbey and Entekhabi (1996). Each point in the plane represents observed data of one year. The contour of streamflow percentage change was then interpolated by these available points. The points were transformed to a regular grid for contouring using the adjustable tension continuous curvature surface gridding algorithm of Smith and Wessel (1990). However, the interpolation algorithm of Smith and Wessel (1990) is just one of many interpolation methods. ArcGIS Geostatistical Analyst provides a comprehensive set of tools for creating surfaces from measured sample points and results could subsequently be used in GIS models for visualization, analyses, and understanding of spatial phenomena.

Geostatistical Analyst provides two groups of interpolation techniques: deterministic and geostatistical models. Both group models rely on the similarity of nearby sample points to create representative surfaces. Deterministic techniques use mathematical functions for interpolation whereas geostatistical methods rely on both statistical and mathematical methods, thus the later can be used to create surfaces and assess the uncertainty of predictions (Johnston et al, 2001). All four deterministic interpolation models available in Geostatistical Analyst (Inverse Distance Weighted (IDW), global polynomial, local polynomial, and radial basis functions (RBFs)) were used in this doctoral research. The IDW assumes that each measured point has local influence that diminishes with distance. It weighs the points closer to the prediction location greater then those farther away, hence the name — inverse distance weighted. The general formula is:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \qquad (7.1)$$

Where

$\hat{Z}(s_0)$ is the value to be predicted for location s_0;

N is the number of measured sample points surrounding the predication that will be used in the predication;

λ_i are weights assigned to each measured point that will decrease with distance; and

$Z(s_i)$ is the observed value at the location s_i.

The formula to determine the weights is as following:

$$\lambda_i = \frac{d_{i0}^{-p}}{\sum_{i=1}^{N} d_{i0}^{-p}} \tag{7.2}$$

As distance (d) becomes larger, the weight is reduced by a factor of p. The quantity d_{i0} is the distance between the prediction location, s_0, and each of the measured locations, s_i.

Global polynomial interpolation fits a smooth surface that is defined by a mathematical function (a polynomial) to the input sample spatial points. The global polynomial surface changes gradually and captures coarse-scale patterns in the data. In contrast to that the global polynomial interpolation fits a polynomial to the entire surface, the local polynomial interpolation fits many polynomials, each within specified overlapping neighborhoods. RBFs are conceptually similar to fitting a rubber membrane through the measured sample values while minimizing the total curvature of the surface. The selected basis function determines how the rubber membrane will fit between the values. Detailed algorithms for each of these methods were described by Johnston et al (2001).

There are several geostatistical methods contained within ArcGIS Geostatistical Analyst, but they are all in the Kriging family. Ordinary, Simple, Universal, Probability, Indicator, and Disjunctive Kriging methods, along with their counterparts in Cokriging, are available. Not only do these Kriging methods create prediction and error surfaces, but they can also produce probability and quantile output maps depending on the needs of users. The four Kriging methods that can produce prediction maps (Ordinary, Simple, Universal, and Disjunctive) were used in this doctoral research. A simple mathematical expression for Ordinary, Simple, and Universal Kriging methods is:

$$Z(s)=\mu(s) + \varepsilon(s) \qquad (7.3)$$

Where

$Z(s)$ is the variable of interest, decomposed into a deterministic trend $\mu(s)$, and a random, autocorrelation error, $\varepsilon(s)$. The differences among the different Kriging methods are that Ordinary Kriging assumes the μ is an unknown constant, Simple Kriging assumes the μ is a known constant, and Universal Kriging assumes the μ(s) is some deterministic function. The disjunctive Kriging has a different mathematical form:

$$f(Z(s))=\mu + \varepsilon(s) \qquad (7.4)$$

Where

μ is an unknown constant; and

f(Z(s)) is some arbitrary function of $Z(s)$.

Detailed mathematical models for these methods were also described by Johnston et al (2001).

7.3 RESULTS

7.3.1 Streamflow-Precipitation-Temperature relationship

Although magnitudes and spatial patterns of the streamflow change as a function of precipitation and temperature changes differ among varied interpolation algorithms, the general result was clear. The streamflow was not only positively sensitive to precipitation, but also negatively sensitive to temperature (Figure 7.1), although the precipitation-runoff relationship was stronger than the runoff-temperature relationship. For example, a 30% precipitation increase would result in a 50% increase of runoff if the temperature was normal and only a 20–25% increase in runoff if the temperature was 3°F higher than a normal year. A 30% precipitation decrease would result in a less than 35% decrease of runoff if the temperature was normal and 60% decrease in runoff if the temperature was 3°F higher than a normal year.

Although the regression analyses indicated that temperature only improved the R^2 from 0.707 to 0.759, the role of temperature at this contour was clear. This result means the water issue in the Spokane River watershed is likely to be more critical in future scenarios of global warming. The IPCC in its Third Assessment Report (Houghton et al, 2001) states that "the globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100" and "based on recent global model simulations, it is likely that nearly all land areas will warm more rapidly than the global average, particularly, those at high northern latitudes in the cold season. Most notable of these is the warming in the northern region of North America, and northern and central Asia, which exceeds global mean warming in each model by more than 40%." This will cause serious consequences for urban water supply, agricultural production, industry development, and ecological systems in general.

7.3.2 Non-Liner Streamflow Response

An obvious feature of Figure 7.1 is that the response of streamflow to precipitation and temperature is nonlinear. For a given the precipitation increases or decreases, the percentage change in streamflow was larger than the percentage change in precipitation. The differences between runoff percentage change and precipitation percentage change varied with precipitation amount and temperature.

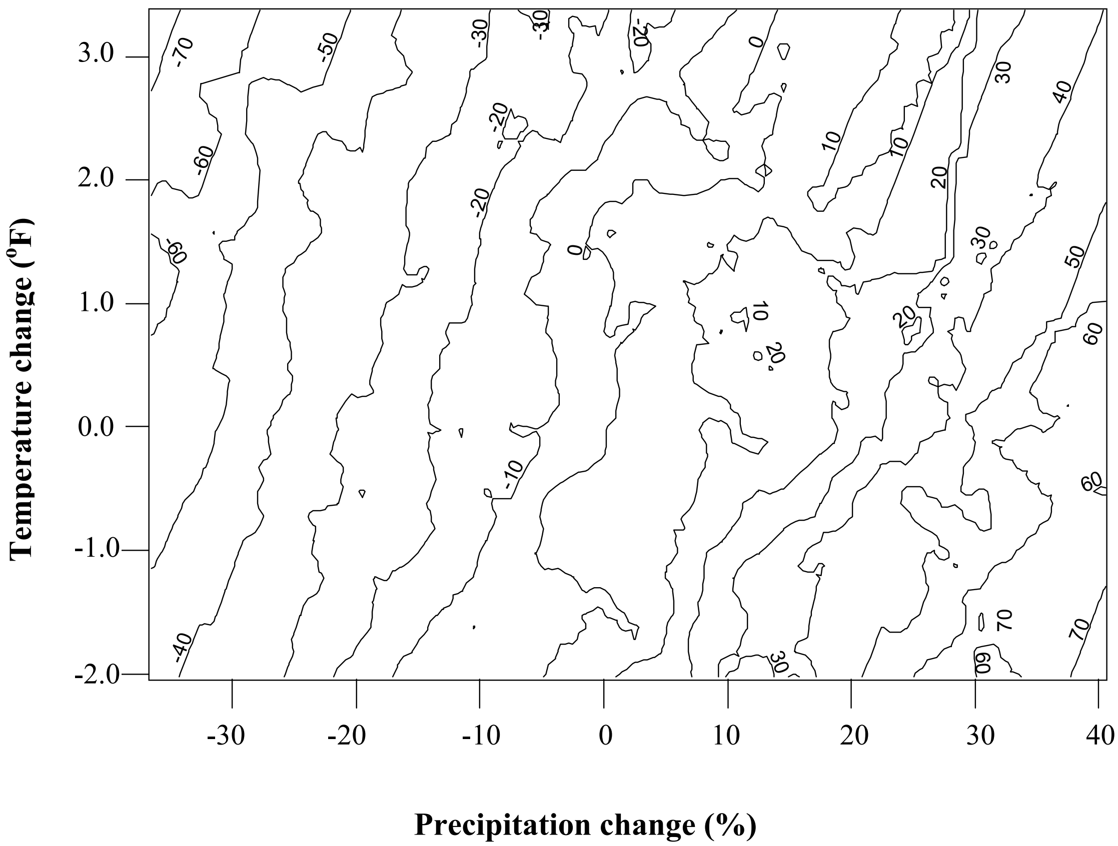


Figure 7.1 Contour plot of percentage runoff change as a function of percentage precipitation change and temperature departure in the Spokane River watershed

If the contour in Figure 7.1 was changed to the difference between runoff percentage change and precipitation percentage change, Figure 7.2 is obtained, which clearly undoes this nonlinear response.

Figure 7.3 illustrates the differences between runoff percentage change and precipitation percentage change as a function of precipitation percentage change. The larger the precipitation change, increasing or decreasing, the bigger the differences were. The general trend in the Spokane River watershed is that a 10% precipitation change

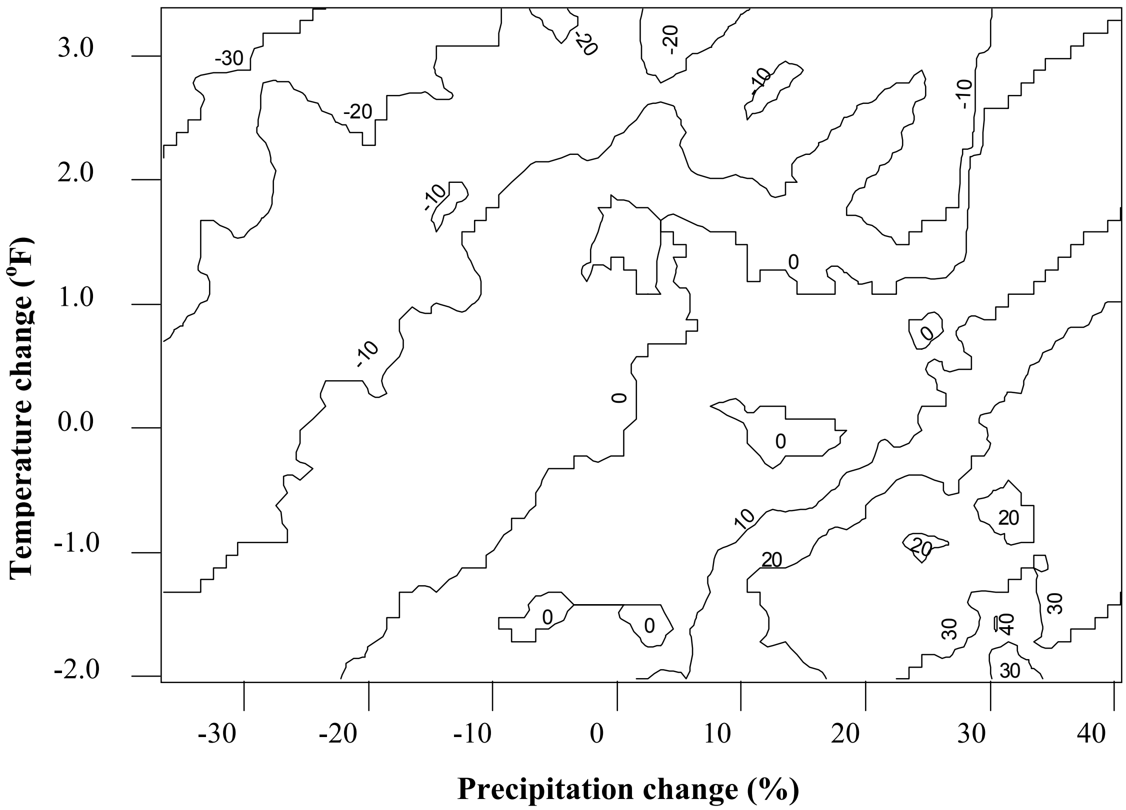


Figure 7.2 Contour plot of the difference between percentage runoff change and percentage precipitation as a function of percentage precipitation change and temperature departure in the Spokane River watershed

will result in a 15% runoff change. This is consistent with our monthly water balance model results in Chapter 6 that a 10% precipitation change will result in a 13–14% runoff change. The streamflow responses to precipitation change at Spokane River watershed was quite different from the Sacramento Basin study conducted by Risbey and Entekhabi (1996) and Yellow River study by Fu and Chen (2005). If precipitation increases, the streamflow responses at the three watersheds seem to have a similar pattern. But if the regional precipitation decreases, the streamflow responses go to different directions.

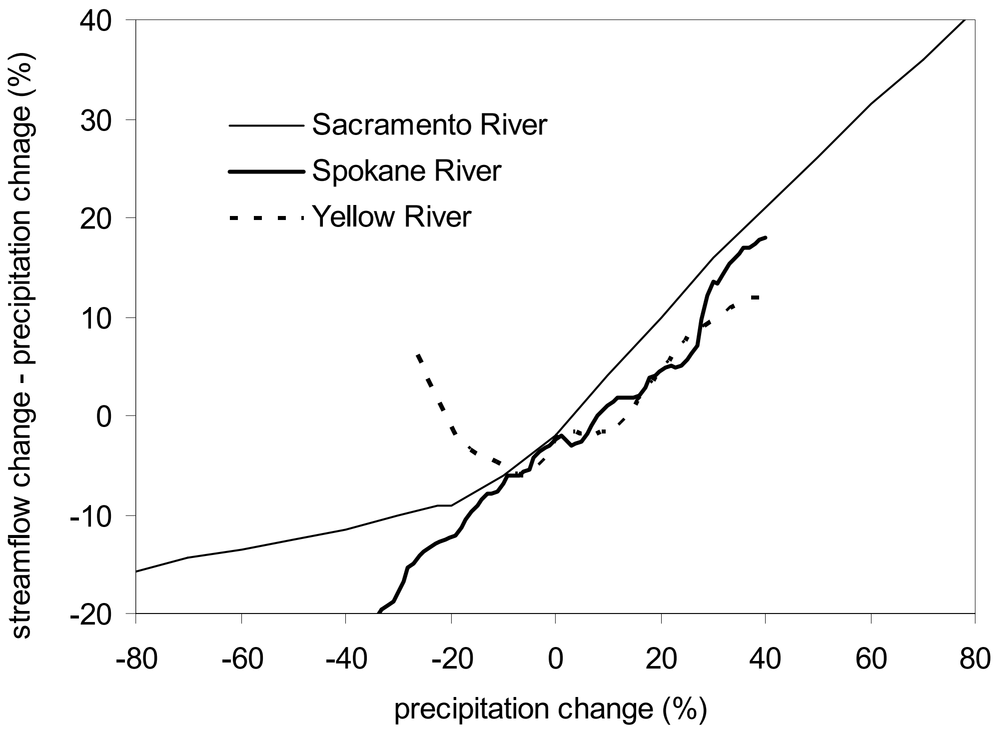


Figure 7.3 Runoff change minus precipitation change as a function of precipitation change for three watersheds

7.3.3 Model comparisons

Mathematically, the best geostatistical model is the one that has the standardized mean nearest to zero, the smallest root-mean-square predication error, the average standard error nearest the root-mean-square prediction error, and the standardized root-mean-square prediction error nearest to one (Johnston et al, 2001). Of the deterministic models, the radial basis function model produced the smallest root-mean-squares predication errors. However, this model interpolates exactly, which means the model predicts a value identical to the measured value at a sample location. The interpolation surface is not smooth. In addition, there are high-value centers in the low-value regions as the model tries to match each measured point instead of exploring the general trend among precipitation-runoff-temperature. The IDW is also an exact interpolator. The root-mean-squares of both global and local polynomial methods were close to that of Ordinary Kriging using a first order trend removal method. As illustrated in Figure 7.4 was the runoff-precipitation-temperature relation for the Spokane River watershed with global polynomial interpolation method. The contours lines were smooth, simpler, and clearer, and changed gradually compared to Figure 7.1. The changes of slopes of the contour line reveal the non-linear runoff response to precipitation and temperature. The disadvantage of polynomial interpolation techniques is that there is no assessment of prediction errors and the results may be too smooth.

Of the eight geostatistical models used, the Ordinary Kriging with first order trend removal model produced the best fit according to the aforementioned criteria. The results of the various models are summarized in Table 7.1. The Ordinary Kriging model had the second smallest root-mean-square predication errors; its average standard error was nearest the root-mean-square prediction error; and its standardized root-mean-square prediction error was nearest to one. The regular Ordinary Kriging did not remove the trend, resulting in a relatively poor interpolation. Simple Kriging assumed that the constant was known. In reality it is difficult to know this value, so any assumed-value-model will produce a relatively poor interpolation compared to Ordinary Kriging that optimizes this constant value. Universal Kriging uses a deterministic function to replace this constant. If the constant order of trend was specified, it will produce exactly the same result as the Ordinary Kriging. A first-order constant was also tested, and it did improve the interpolation. However, it was only as good as the Ordinary Kriging with first order removal and its results were not as smooth as the Ordinary Kriging with first order trend removal. Disjunctive Kriging assumed this constant was some arbitrary function. In general, Disjunctive Kriging produces better interpolation than Ordinary Kriging does. However, Disjunctive Kriging requires the bivariate normality assumption and approximations to the function. The assumptions are difficult to verify, and the solutions are mathematically and computationally complicated.

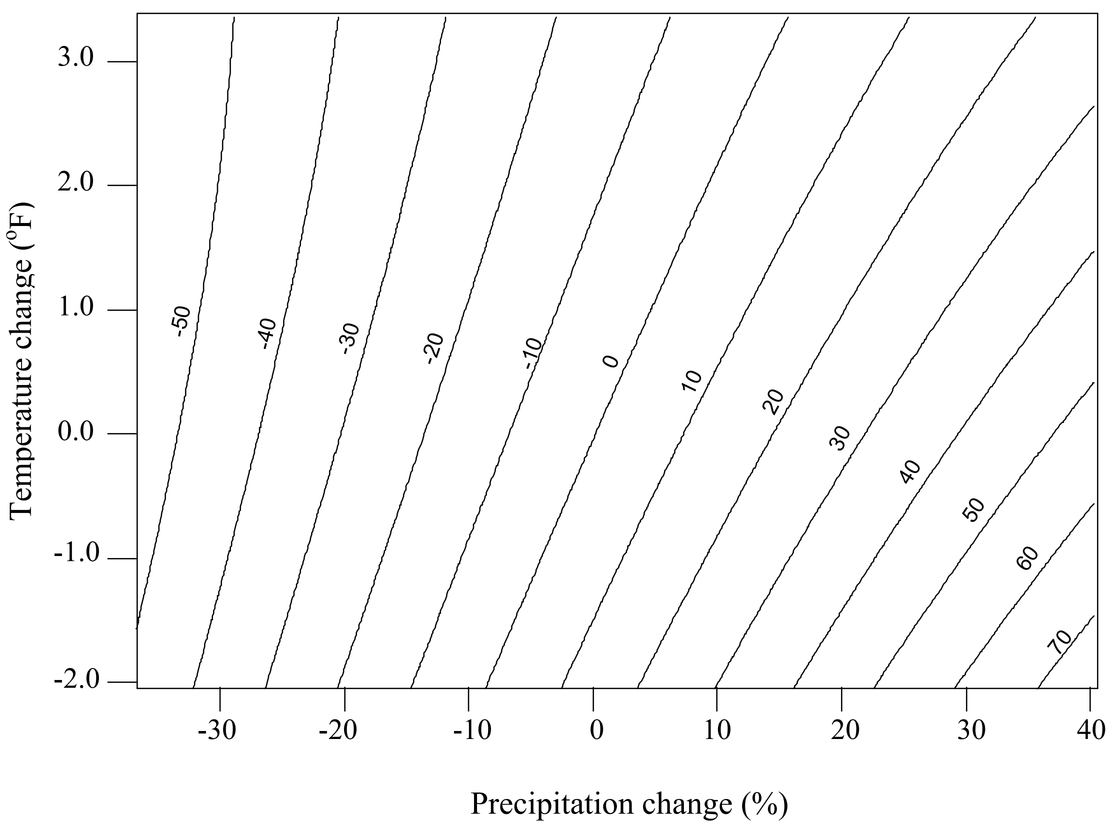


Figure 7.4 Contour plot of percentage runoff change as a function of percentage precipitation change and temperature departure for the Spokane River Basin with global polynomial interpolation method

Table 7.1 The prediction errors of different interpolation methods in ArcGIS Geostatistical Analyst

Methods	Mean	Standardiz-ed mean	root-mean-square	average standard error	standardized root-mean-square
Inverse Distance Weighted	0.0735		16.03		
Global Polynomial	0.09825		15.68		
Local Polynomial	0.1031		15.75		
Radial basis functions	0.1758		15.18		
Ordinary Kriging	0.02854	-0.004384	16.11	13.06	1.309
Ordinary Kriging with first order trend removal	0.3208	0.01975	**15.76**	**14.74**	**1.064**
Simple Kriging	0.3608	0.0113	17.44	24.51	0.7015
Universal Kriging (constant order of trend)	0.02854	-0.004384	16.11	13.06	1.309
Universal Kriging (1st order of trend)	0.2584	0.01748	17.19	15.19	1.107
Disjunctive Kriging	0.2329	0.00623	17.73	23.22	0.7516
Disjunctive Kriging with first order trend removal	1.927	0.1452	15.04	13.37	1.125

7.4 CONCLUSIONS AND DISCUSSIONS

This doctoral research modified an existing method for studying the impacts of climatic change on regional hydrological regimes with historical data by using the ArcGIS Geostatistcial Analyst. There are at least two distinct advantages of the new approach compared to its original version (Risbey and Entekhabi, 1996). First, the ArcGIS Geostatistical Analyst provides a comprehensive set of tools for creating surfaces from measured sample points compared to the adjustable tension continuous curvature surface gridding algorithm used by Risbey and Entekhabi (1996). This allows users to efficiently compare the different interpolation techniques supplied by the ArcGIS Geostatistical Analyst in order to produce the best solution. Second, the methodology can easily be applied and expanded to different watersheds and the results can subsequently be used in GIS environment for visualization and analyses.

Applications of the modified model to the Spokane River watershed indicated that a 10% precipitation change will result a 15% runoff change and that streamflow is more sensitive to precipitation than to temperature. This is consistent with the monthly water balance model results that 10% precipitation change will result in 13–14% runoff change. However, statistical methods could not be used for predicting monthly streamflow responses to climatic changes as there is a poor monthly precipitation-streamflow relationship for Spokane River watershed due to snow accumulation and snowmelt processes. Thus, a monthly water balance model is needed for studying this issue at a month time step.

CHAPTER 8 CLIMATE VARIABILITY IMPACTS (EL NIÑO ANDLA NIÑA) ON HYDROLOGICAL REGIMES

Too much water means flooding, too little and the result is drought and our planet has both in abundance.

The Water Crisis, 2004

8.1 DEFINITION OF EL NIÑO AND LA NIÑA

The term “El Niño” originally applied to an annual weak warm ocean current that ran southward along the coast of Peru and Ecuador about Christmas time and subsequently has been associated with the unusually large warming that occurs every few years and changes the local and regional ecology. Accordingly, it has been very difficult to define an El Niño event and there is no universal single definition (Trenberth, 1997). This research adopted the definition from Trenberth (1997) that “… an El Niño can be said to occur if 5-month running means of sea temperature (SST) anomalies in the Nino 3.4 region (5^{o}N–5^{o}S, 120^{o}–170^{o}W) exceed 0.4^{o}C for six months or more.”

The atmosphere component tied to El Niño is termed the “Southern Oscillation”. Scientists often call the phenomenon where the atmosphere and ocean collaborate together ENSO, short for El Niño-Southern Oscillation (Trenberth, 1997).

Based on the definition, the major events of El Niño and La Niña, the opposite event of El Niño consisting of basin-wide cooling of the tropical Pacific, are listed in Table 8.1.

Table 8.1 El Niño and La Niña Events from 1950–1997 (Trenberth, 1997)

El Niño events			La Niña events		
Begin	End	Duration (months)	Begin	End	Duration (months)
Aug 1951	Feb 1952	7	Mar 1950	Feb 1951	12
Mar 1953	Nov 1953	9	Jun 1954	Mar 1956	22
Apr 1957	Jan 1958	15	May 1956	Nov 1956	7
Jun 1963	Feb 1964	9	May 1964	Jan 1965	9
May 1965	Jun 1966	14	Jun 1970	Jan 1972	19
Sep 1968	Mar 1970	19	Jun 1973	Jun 1974	13
Apr 1972	Mar 1973	12	Sep 1974	Apr 1976	20
Aug 1976	Mar 1977	8	Sep 1984	Jun 1985	10
Jul 1977	Jan 1978	7	May 1988	Jun 1989	14
Oct 1979	Apr 1980	7	Sep 1995	Mar 1996	7
Apr 1982	Jul 1983	16			
Aug 1986	Feb 1988	19			
Mar 1991	June 1992	17			
Feb 1993	Sep 1993	8			
Jun 1994	Mar 1995	10			

8.2 IMPACTS OF EL NIÑO AND LA NIÑA ON HYDROLOGICAL REGIMES

8.2.1 Impacts on Streamflows

The observed streamflow data indicated that the El Niño and La Niña climatic pattern had an effect on the streamflow in the Spokane River watershed. Figure 8.1 shows streamflow comparisons for USGS gage 12433000, the Spokane River at Long Lake, the last USGS gage on the Spokane River. Figure 8.2 is the streamflow comparisons for USGS gage 12422500, the Spokane River at Spokane which has streamflow observation data back to 1891.

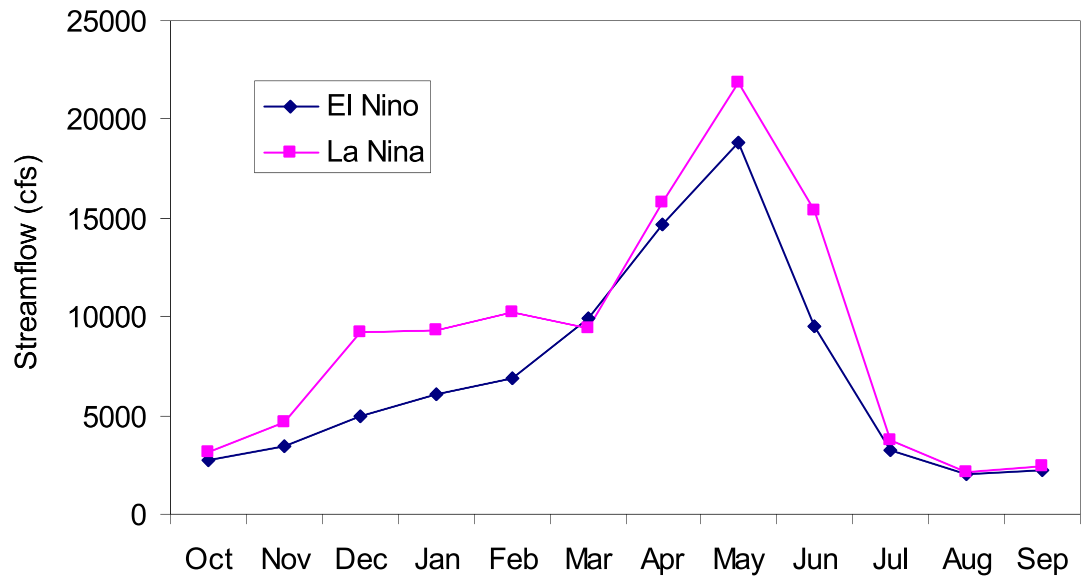


Figure 8.1 Streamflow comparisons during El Niño and La Niña events for the Spokane River at Long Lake (USGS 12433000)

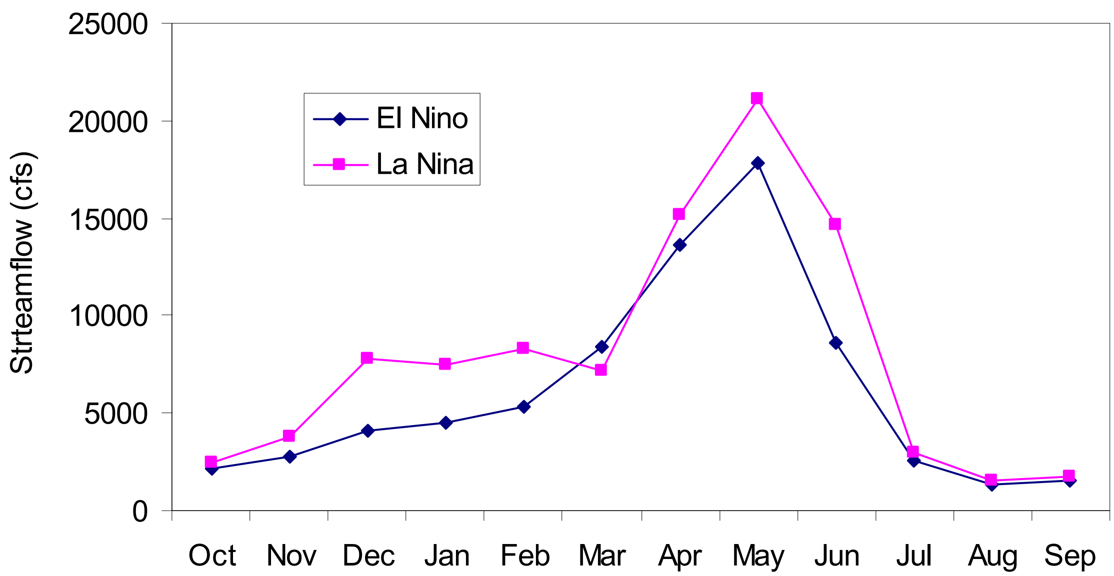


Figure 8.2 Streamflow comparisons during El Niño and La Niña events for the Spokane River at Spokane (USGS 12422500)

An overall analysis of nine USGS gages in the watershed gave a clear picture as how the El Niño and La Niña events impacted the streamflows in the Spokane River watershed (Figure 8.3). As the streamflow has great differences between large and small watersheds, the percentage of specific monthly streamflow over the long-term monthly means value was used, instead of absolute values of streamflow, for the nine-station-average scenarios. All months except March have larger streamflow during La Niña events and smaller streamflow during El Niño events (Figure 8.3).

The individual station may have larger variations than this value (Figure 8.4), but the general trend remains the same. The spatial variation of the El Niño event impacts seems smaller than that of the La Niña event impacts (Figure 8.4).

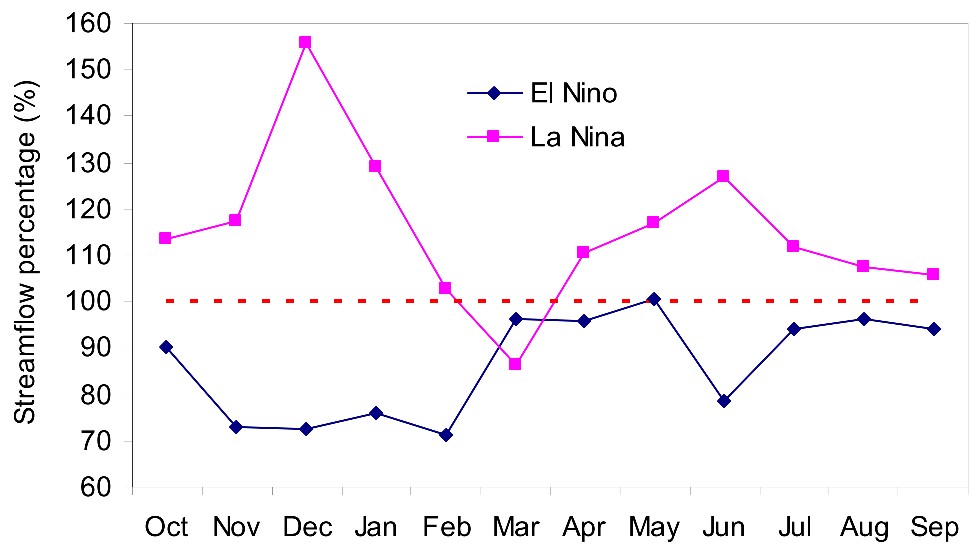


Figure 8.3 Streamflow comparisons during El Niño and La Niña events for averaging nine USGS stations

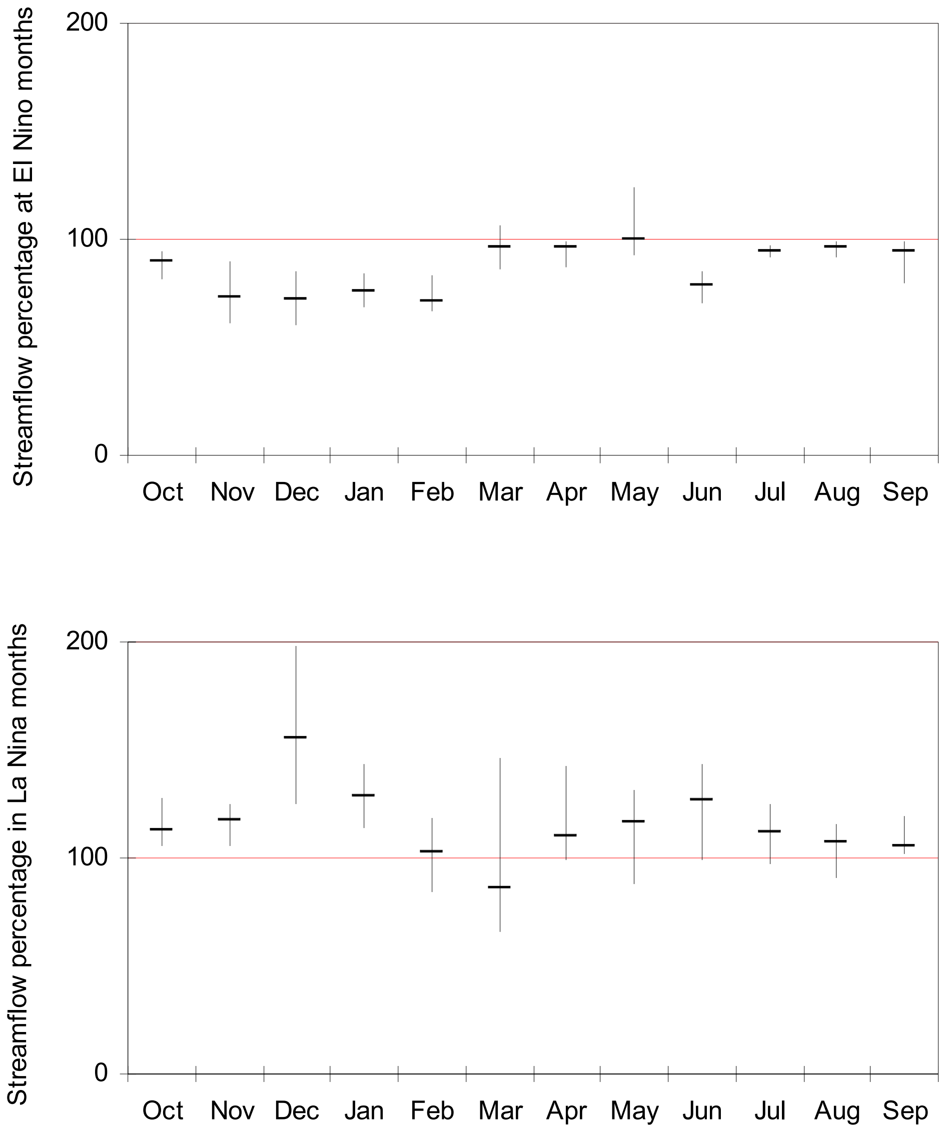


Figure 8.4 Monthly streamflow comparisons during El Niño and La Niña events for nine USGS stations

8.2.2 Impacts on Precipitation

The overall impact of El Niño and La Niña events on precipitation was significant, especially for the winter months when the watershed receives its majority of precipitation (Figure 8.5). The differences are not significant for low-rain months, such as March, April, May, June, July, August, and September (Figure 8.5).

During La Niña event months, the precipitations at majority of months and in the majority of the stations were larger than long-term average values (Figure 8.6). However, May is an exception that has not been accurately explained.

The precipitations at El Niño event months were not always below the long-term average values (Figure 8.6). However, they were indeed below the long-term average values for the winter months. This made the annual precipitation during El Niño event smaller than the long-term average (Figure 8.7) for almost all of the stations except station 107301.

The spatial variation of the impacts of El Niño and La Niña events on precipitation is generally larger than that of the impacts of El Niño and La Niña events on streamflow (Figure 8.4 and Figure 8.6).

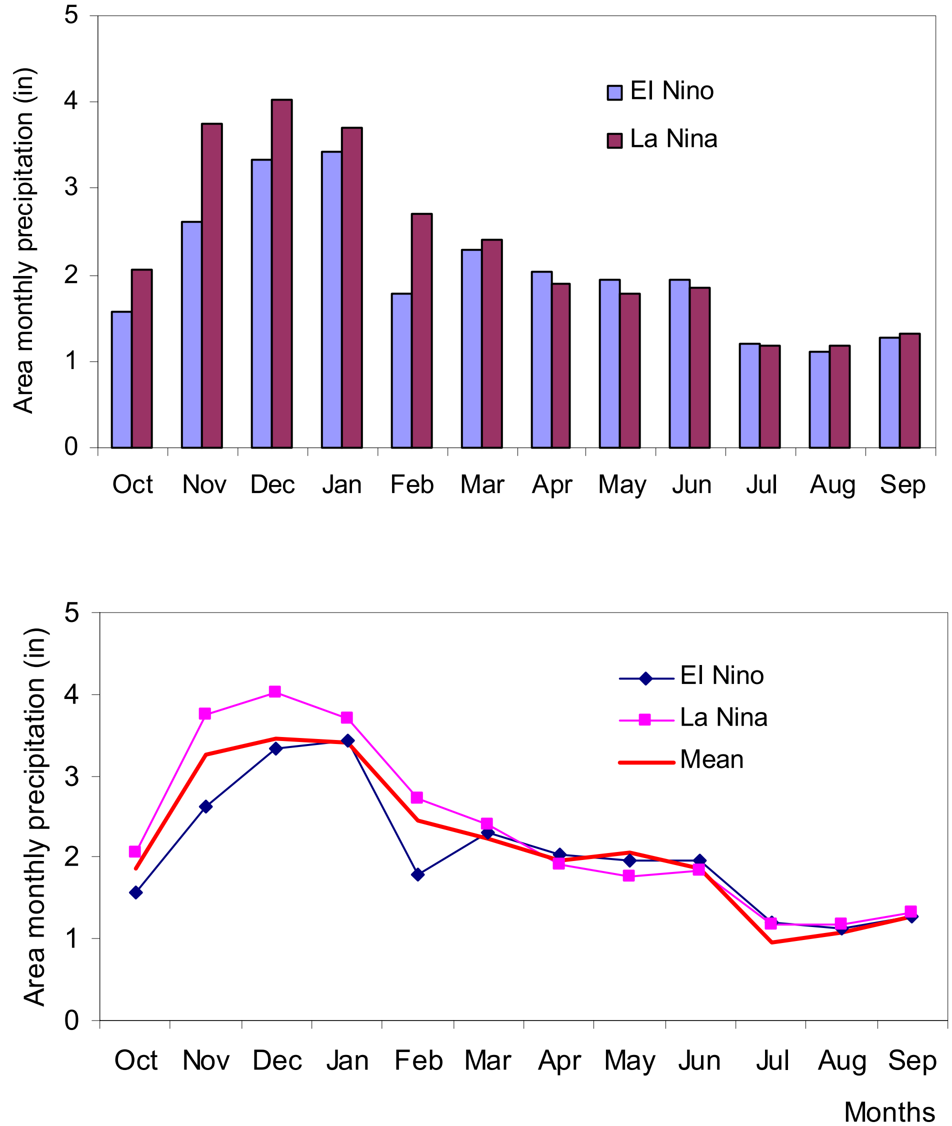


Figure 8.5 Area precipitation comparisons during El Niño and La Niña events

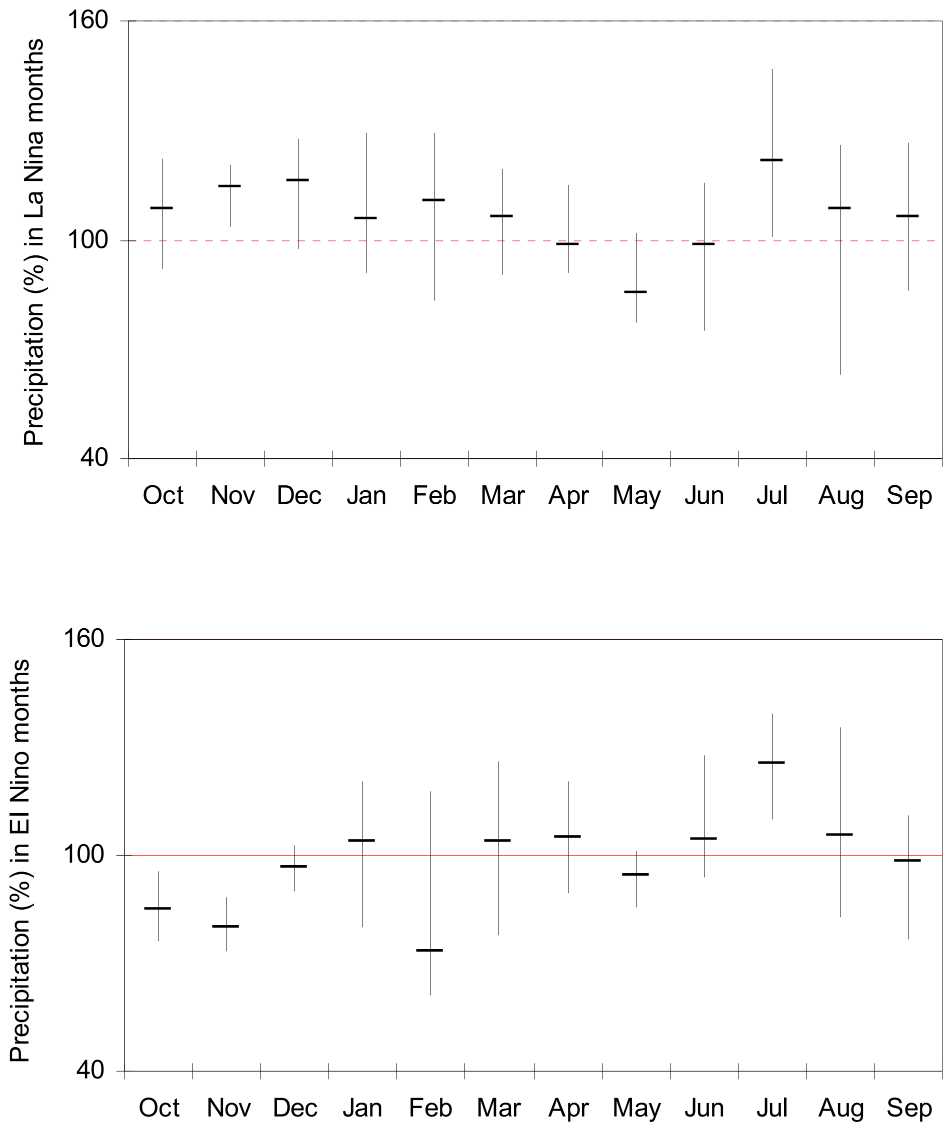


Figure 8.6 Areal precipitation during El Niño and La Niña events comparing with long-term average values

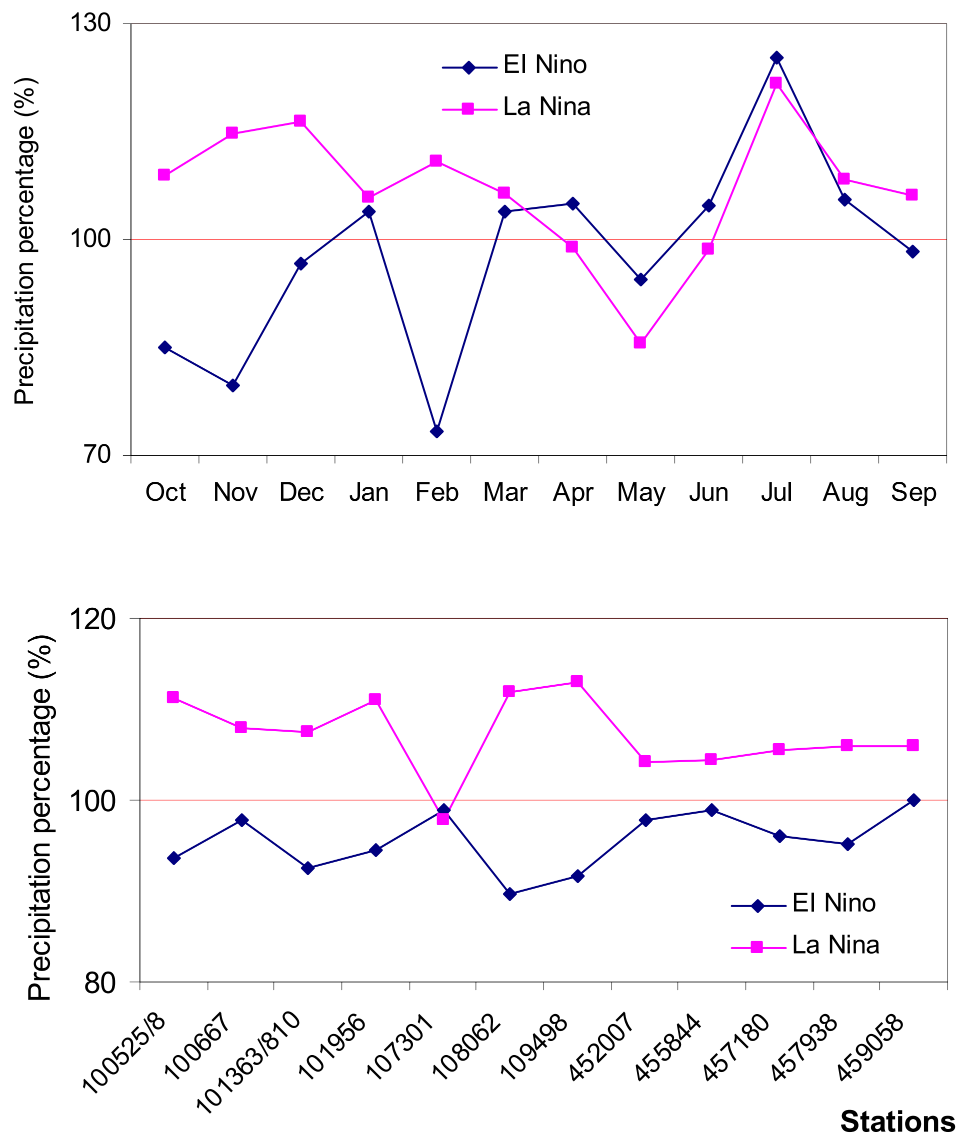


Figure 8.7 Annual precipitation during El Niño and La Niña at different stations

8.3 CONCLUSIONS AND DISCUSSIONS

The climate variability, such as El Niño and La Niña events, is one component of climatic change. However, most of climatic change impacts studies focus on global warming component only. The results of this doctoral research indicated that the El Niño and La Niña events have significant impacts on regional hydro-climatic regimes. The precipitation during La Niña event months is generally larger than that during El Niño event months for the rain-season (Oct–Feb). The differences were 25.5%, 30.0%, 19.9%, 7.9%, and 38.4% over long-term average for October, November, December, January, and February, respectively. The precipitation at other months does not reflect significant differences between El Niño and La Niña events. The areal annual precipitations (arithmetic mean of 12 to14 stations, Appendix B) were 95.6% and 107.2% during El Niño and La Niña events respectively, over long-term average.

Streamflow was more sensitive to El Niño and La Niña events than was precipitation. During El Niño events all months had a smaller streamflow than the long-term average. While during La Niña events, all months but March had a larger streamflow than the long-term average. The annual streamflow, for nine USGS station within Spokane River watershed, were 86.5% and 115.2% over long term average during El Niño and La Niña events, respectively. Since El Niño and La Niña events could be predicted about six months in advance, this conclusion would be helpful for water resources management.

CHAPTER 9 SUMMARY

As scientists we are intrigued by the possibility of assembling our knowledge into a neat package to show that we do, after all, understand our science and its complex interrelated phenomena.

W. M. Kohler, 1969

9.1 MODEL EFFORTS

Water availability is a critical issue facing us today at global, national, regional, and local scales. This doctoral research developed two models and modified one existing methodology for estimation of the water availability at watershed scale and for prediction of impacts of future climatic change on water availability.

- The water availability model concerns flood-flow, instream flow, surface water, ground water, and surface- and ground- water interaction. The application of this model to the Spokane River watershed provided a clear picture of the current water availability status. This model can be applied in other watersheds for estimating water availability.
- The monthly water balance model developed in this doctoral research is both a GIS and land use based model. The model has all major hydrologic processes at the watershed scale and includes seven sub-models. The model requires only limited data and produces reasonable and acceptable results. The model was written in Visual Basic language and could be easily merged into Microsoft Excel and ArcGIS when necessary, both of which use Visual Basic as their internal languages. In addition, Excel provides a user friendly interface with data and ArcGIS can display the results in a visual spatial distribution.

- The modified model indicated that ArcGIS Geostatistical Analyst is a useful tool for studying the climatic impacts on hydrological regimes with historical data, as it provides a comprehensive set of tools for creating surfaces from measured sample points and the model results could subsequently be used in a GIS environment for visualization and analyses.

9.2 IMPLICATION OF THE RESULTS

- The Washington State 1967 study does need to be updated as all 39 USGS streamflow stations used in this study show that there have been streamflow decreasing since 1960, although different months showed varied trends;

- The monthly average water availability in the Spokane River watershed was 5,255 cfs (148.8 cms), of which 5,094 cfs (144.2 cms), or 96.9%, was from surface water, and 753 cfs (21.3 cms), or 14.3%, was from ground water. However, 592 cfs (16.8 cms), or 11.2%, was due to the surface- and ground- water interaction and was double counted.

- There were 123 out of 768 months (64 years) with surface water availability equal to zero. The only available water for these months was limited to ground water. These critical months mostly occurred in August and September. There were 55 years when there was at least one month with zero surface water availability.

- The streamflow is more sensitive to precipitation variation than to temperature increase, because the streamflow variations over space and time are largely driven by precipitation (Arnell, 2002). The monthly water balance model indicated that a 10% precipitation change usually results in a 13–14% change in streamflow in the Spokane River watershed.

- Temperature change also affects the streamflow and this trend is more significant for the scenarios of precipitation decrease. The monthly streamflow is more sensitive to temperature change than is annual streamflow. If the precipitation remains the same, a $2^{o}C$ increase in temperature may only lead to a 0.4% decrease in annual streamflow, but produce 20–25% streamflow decreases in July, August and September and 5% increases for December, January, February, and March. This would cause more critical water problems in the Spokane River watershed as summer low-flow is already a serious issue for water resource management.
- Based on the GCM downscaling results from the University of Washington's Climate Impacts Group, the developed monthly water balance model indicated that the annual runoff would increase by 8.6% and 4.8% for the 2020s and 2040s scenarios, respectively. However, there are distinct differences between months with the streamflow for July, August, and September decreasing by 4.9–7.0% and 14.4–24.6% for both scenarios. This would cause critical water availability problems in the Spokane River watershed in the future.
- The streamflow-precipitation-temperature relationship from historical data indicated that the streamflow was sensitive to both precipitation and temperature, although the precipitation-runoff relationship was stronger than the runoff-temperature relationship. The general trend in the Spokane River watershed is that a 10% precipitation change will result in a 15% runoff change. This is consistent with results from the monthly water balance model that a 10% precipitation change would result in 13–14% runoff change. However, statistical methods could not be used for estimating monthly streamflow responses to climatic change

as there is a poor relationship between monthly precipitation and streamflow in the Spokane River watershed due to the snow accumulation and snowmelt processes. Thus, a monthly water balance model is needed for studying this issue.

- The El Niño and La Niña events have effects on the precipitation and streamflow in the Spokane River watershed. In general, the El Niño events produce a drought year (95.6% annual precipitation and 86.5% streamflow over long-term average values) while La Niña events produce a wet year (107.2% annual precipitation and 115.2% streamflow over long-term average values). The impact of El Niño and La Niña events on streamflow is more sensitive than that on precipitation.

9.3 FUTURE CONTINUOUS WORKS

9.3.1 Improvement of water availability model

(1) Ground- and surface- water interaction

Ground- and surface- water interaction is the key factor to accurately estimate water availability at a watershed scale. There are several comprehensive ground- and surface- water interaction studies in the Spokane River watershed, but their results have not been consistent. This reflects the complexity of the issue and need for further study.

(2) Water quality

This doctoral research focused on the water quantity aspect of water availability. Water quality and water environment are becoming more and more critical to almost every watershed. Thus, water quality should be included as a part of any future water availability studies.

9.3.2 Improvement of monthly water balance model

(1) Verification of each component

The monthly water balance model was tested and justified with the observed streamflow at USGS station 12433000, Spokane River at Long Lake. However, each of the components, such as soil moisture, actual evapotranspiration, snow accumulation, snowmelt, subsurface runoff, ground-water runoff (base flow), has not been justified. Justification of each of the model components would not only improve the model performance, but also increase confidence about the model application results in the climatic change scenarios.

(2) Parameter spatial distribution

The model is a GIS and land use based model. However, some of the parameters, such as, field capacity (*FC*), maximum soil content (*MaxS*), the portion of soil moisture surplus converting into subsurface (K_1), and the portion of ground water as base flow (K_2), were simply taken from existing monthly water balance models as constants. These parameters should vary with land cover, soil texture, soil depth, and geologic features. The spatial distributions of these parameters could make the model more close to physical processes.

(3) Impacts of climatic change on ground water

The focus of this doctoral research was the impacts of climatic change on streamflow, instead of watershed scale water availability. This is because the model is a surface-based water balance model, even though it has sub-surface and ground-water components. However, if one would like to further study the impacts of ground water on water availability, a comprehensive ground-water study is needed.

(4) Uncertainties of future climatic scenarios

This doctoral research simply adopted the University of Washington's Climate Impacts Group's scenarios for the future climatic scenarios. To analyze the uncertainties of these scenarios is a key task for assessing the regional water availability.

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Appendix A Visual Basic Code

1. Loading Precipitation Data

```
Open "c:\thesis\gridtxt\fnamep.txt" For Input As #1
' fnamep.txt is a text file containing the precipitation file names for the entire simulation
period.

For i = 1 To 84   ' we simulates 84 months
Input #1, fname(i)
Next i
Close #1

For k = 1 To 84
Open fname(k) For Input As #2
  i = 1
    Do While Not EOF(2)    ' Check for end of file
      If i <= 6 Then
        Line Input #2, inputdata    ' Read line of head information, produced by ArcGIS
      Else
        For j = 1 To 125    '125 column for simulation watershed
        Input #2, pdata(k, i - 6, j)  'pdata(month, row, column)
        Next j
      End If
      i = i + 1
    Loop
Close #2   ' close the file
Next k       ' read precipitation for next month

Text5.Text = "precipitation data have been read."
```

2. Loading Temperature Data

This section is very similar with Loading precipitation data.

```
Open "c:\thesis\gridtxt\fnamet.txt" For Input As #1

For i = 1 To 84
Input #1, fname(i)
Next i
Close #1

For k = 1 To 84
Open fname(k) For Input As #2
  i = 1
    Do While Not EOF(2)    ' Check for end of file.
```

```
        If i <= 6 Then
            Line Input #2, inputdata    ' Read line of data.
        Else
            For j = 1 To 125
            Input #2, tdata(k, i - 6, j)
            Next j
        End If
        i = i + 1
    Loop
Close #2
Next k

Text5.Text = "temperature data have been read."
```

3. Loading Snowfall Information for Current scenario

```
Open "c:\thesis\gridtxt\fnames.txt" For Input As #1

For i = 1 To 84
Input #1, fname(i)
Next i
Close #1

For k = 1 To 84
Open fname(k) For Input As #2
  i = 1
    Do While Not EOF(2)    ' Check for end of file.
        If i <= 6 Then
            Line Input #2, inputdata    ' Read line of data.
        Else
            For j = 1 To 125
            Input #2, sdata(k, i - 6, j)
            Next j
        End If
        i = i + 1
    Loop
Close #2
Next k
Text5.Text = "snow data have been read."
End Sub
```

4. Loading Land Use/Land Cover Map

```
Open "c:\thesis\gridtxt\lucctxt.txt" For Input As #1
```

```
i = 1
    Do While Not EOF(1)    ' Check for end of file.
      If i <= 6 Then
        Line Input #1, inputdata    ' Read line of data.
      Else
        For j = 1 To 125
        Input #1, luccdata(i - 6, j)
        Next j
      End If
      i = i + 1
    Loop
Close #1

Text5.Text = "land use data have been read."
```

5. Setting Initial Conditions

```
MaxSS = 100#
FC = 1450#

For j = 1 To 71
  For k = 1 To 125
    soilmoisture(0, j, k) = 80
    groundwater(0, j, k) = 100
    snowacc(0, j, k) = 0#
    For i = 1 To 84
      soilmoisture(i, j, k) = 0#
      groundwater(i, j, k) = 0#
      snowacc(i, j, k) = 0#
      runoffgrid(i, j, k) = 0#
      acevap(i, j, k) = 0#
    Next i
  Next k
Next j
```

6. Units Conversions

```
For i = 1 To 84
  For j = 1 To 71
    For k = 1 To 125
      pdatam(i, j, k) = pdata(i, j, k) * 25.4 / 100   ' P is mm from HI
      tdatam(i, j, k) = (tdata(i, j, k) / 10 - 32) * 5 / 9 ' T is in C from TF
```

```
          tempvar = tdata(i, j, k) / 10
             Select Case tempvar
             Case Is > 28
             sdatam(i, j, k) = sdata(i, j, k) / 100 * 25.4
             Case Is > 20
             sdatam(i, j, k) = sdata(i, j, k) / 150 * 25.4
             Case Is > 15
             sdatam(i, j, k) = sdata(i, j, k) / 200 * 25.4
             Case Is > 10
             sdatam(i, j, k) = sdata(i, j, k) / 300 * 25.4
             Case Is > 0
             sdatam(i, j, k) = sdata(i, j, k) / 400 * 25.4
             Case Else
             sdatam(i, j, k) = sdata(i, j, k) / 500 * 25.4
             End Select

       Next k
    Next j
Next i
```

7. PE Computation

```
Racal   'call radiation computation sub-route

For i = 1 To 84  ' 84 months
   For j = 1 To 71  ' 71 rows
      For k = 1 To 125  ' 125 columns
         bb = (i + 9) Mod 12  'Our simulation is from October to September, i=1 means
                                 October
         If bb = 0 Then bb = 12
         eto(i, j, k) = 0.0029 * Ra(bb) * Diff(bb) * (tdatam(i, j, k) + 17.8) * Ndays(bb)
      Next k
   Next j
Next i
```

8. Radiation computation based on latitude and day of year

```
lati = Val(Text4.Text)  ' reading latitude

For i = 1 To 12
DR(i) = 1 + 0.033 * Cos(2 * 3.1415926 * dayJ(i) / 365)
delta(i) = 0.409 * Sin(2 * 3.1415926 * dayJ(i) / 365 - 1.39)
aa = -Tan(lati * 3.1415926 / 180) * Tan(delta(i))
ws(i) = Atn(-aa / Sqr(-aa * aa + 1)) + 2 * Atn(1)
```

```
sinsin(i) = Sin(lati * 3.1415926 / 180) * Sin(delta(i))
coscos(i) = Cos(lati * 3.1415926 / 180) * Cos(delta(i))
Ra(i) = (24 * 60 / 3.1415926) * 0.082 * DR(i) * (ws(i) * sinsin(i) + Sin(ws(i)) *
coscos(i))
Next i
```

9. Runoff from Different Land Use Types

```
For i = 1 To 84
   For j = 1 To 71
      For k = 1 To 125
         bb = (i + 9) Mod 12
            If bb = 0 Then bb = 12

         Select Case luccdata(j, k)  ‘ Land use categories

         Case 1  ‘ Urban
         runoffgrid(i, j, k) = 0.85 * pdatam(i, j, k)
         acevap(i, j, k) = 0.15 * pdatam(i, j, k)

         Case 2 ‘ Agriculture
         eto(i, j, k) = eto(i, j, k) * coag(bb)
         rungen   ‘ Go to runoff generation sub-route

         Case 3  ‘ Rangeland
         eto(i, j, k) = eto(i, j, k) * corange(bb)
         rungen

         Case 4  ‘forest
         eto(i, j, k) = eto(i, j, k) * coforest(bb)
         rungen

         Case 5 ‘water surface
         acevap(i, j, k) = eto(i, j, k) * cowater(bb)
         runoffgrid(i, j, k) = pdatam(i, j, k) - acevap(i, j, k)

         Case 6 ‘Wetland
         acevap(i, j, k) = eto(i, j, k) * cowetland(bb)
         runoffgrid(i, j, k) = pdatam(i, j, k) - acevap(i, j, k)

         Case 7 ‘Barren land
         eto(i, j, k) = eto(i, j, k) * 0.25
         rungen

         Case Else
```

```
        runoffgrid(i, j, k) = 0#
        acevap(i, j, k) = 0#

        End Select

        Next k
    Next j
Next i
```

10. Runoff Generation

```
cc = luccdata(j, k)  ‘ Land use categories

Select Case tdatam(i, j, k)   ‘Computing percentage of snow depending on temperature
Case Is > 10
sdatam(i, j, k) = 0#
Case Is > 5
sdatam(i, j, k) = (-0.015 * tdatam(i, j, k) + 0.1505) * pdatam(i, j, k)
Case Else
sdatam(i, j, k) = 0.2025 * Exp(-0.198 * tdatam(i, j, k)) * pdatam(i, j, k)
End Select

If sdatam(i, j, k) < 0 Then sdatam(i, j, k) = 0#  ‘In case formula give a percentage <0
If sdatam(i, j, k) > pdatam(i, j, k) Then sdatam(i, j, k) = pdatam(i, j, k)
                                                ‘ In case the percentage >1
rain = pdatam(i, j, k) - sdatam(i, j, k)

snowacc(i, j, k) = snowacc(i - 1, j, k) + sdatam(i, j, k)

bb = (i + 9) Mod 12
If bb = 0 Then bb = 12

If tdatam(i, j, k) > 0# Then
snowmelt = snk(bb) * tdatam(i, j, k)
Else
snowmelt = 0#
End If

If snowmelt > snowacc(i, j, k) Then
snowmelt = snowacc(i, j, k)
snowacc(i, j, k) = 0#
Else
snowacc(i, j, k) = snowacc(i, j, k) - snowmelt
End If
```

```
s = 1000 / CN(cc) – 10
DirectR = 0.208 * rain / (s ^ 0.66) - 0.095   ‘ Direct Runoff

If DirectR < 0 Then DirectR = 0 ‘In case formula give DR<0

soilmoisture(i, j, k) = soilmoisture(i - 1, j, k) + rain - DirectR + snowmelt

If soilmoisture(i, j, k) >= FC Then   ‘ Compute AE
acevap(i, j, k) = eto(i, j, k)
Else
acevap(i, j, k) = eto(i, j, k) * soilmoisture(i, j, k) / FC
End If

soilmoisture(i, j, k) = soilmoisture(i, j, k) - acevap(i, j, k)

If soilmoisture(i, j, k) > MaxSS Then   ‘ Subsurface water balance
surplus = soilmoisture(i, j, k) - MaxSS
subsurface = k1(bb) * surplus
percolation = (1 - k1(bb)) * surplus   ‘ Percolation to ground water

Else
surplus = 0#
subsurface = 0#
percolation = 0#
End If

GW = k2(bb) * groundwater(i - 1, j, k)
groundwater(i, j, k) = (1 - k2(bb)) * groundwater(i - 1, j, k) + (1 - k1(bb)) * surplus

runoffgrid(i, j, k) = DirectR + subsurface + GW
```

11. Monthly Statistical Vlaue

```
For i = 1 To 84
discharge(i) = 0#
evap(i) = 0#
snacc(i) = 0#
Next i

Ncel = 0
For j = 1 To 71
      For k = 1 To 125
         If luccdata(j, k) > 0 Then
         Ncel = Ncel + 1
         End If
```

```
        Next k
Next j

For i = 1 To 84
    aa1 = 0#
    aa2 = 0#
    aa3 = 0#

        For j = 1 To 71
            For k = 1 To 125
                If luccdata(j, k) > 0 Then
                aa1 = aa1 + runoffgrid(i, j, k)
                aa2 = aa2 + acevap(i, j, k)
                aa3 = aa3 + snowacc(i, j, k)
                End If
            Next k
        Next j
        discharge(i) = aa1 / Ncel
        evap(i) = aa2 / Ncel
        snacc(i) = aa3 / Ncel
Next i
```

12. Output Monthly Results

```
Open "c:\thesis\output\dis.txt" For Output As #2
Open "c:\thesis\output\et.txt" For Output As #3
Open "c:\thesis\output\snow.txt" For Output As #4

For i = 1 To 84
Write #2, discharge(i)
Write #3, evap(i)
Write #4, snacc(i)
Next i

Close #2
Close #3
Close #4
```

13. Output runoff, evaporation, snow accumulation, soil moisture and groundwater storage for every month at each single cell (large file size)

```
Open "c:\thesis\output\disfull.txt" For Output As #2          ‘runoff
Open "c:\thesis\output\etfull.txt" For Output As #3           ‘evaporation
Open "c:\thesis\output\snowfull.txt" For Output As #4         snow accumulation
```

```
Open "c:\thesis\output\smfull.txt" For Output As #5        'soil moisture
Open "c:\thesis\output\gwfull.txt" For Output As #6        groundwater storage

For i = 1 To 84                                            '84 months
For j = 1 To 71                                            '71 rows
For k = 1 To 125                                           '125 columns

Write #2, runoffgrid(i, j, k)
Write #3, acevap(i, j, k)
Write #4, snowacc(i, j, k)
Write #5, soilmoisture(i, j, k)
Write #6, groundwater(i, j, k)

Next k
Next j
Next i

Close #2
Close #3
Close #4
Close #5
Close #6
```

14. Main Menu for Current Scenario

```
loadp  'Loading precipitation
loadt  'Loading temperature
loads  'Loading snowfall
loadlucc  'Loading land use

Text5.Text = "initialing ..."
ini
Text5.Text = "data converting ..."
datacon
Text5.Text = "ET0 computing ..."
etocal
Text5.Text = "runoff estimating  ..."
runoff
Text5.Text = "summaring ..."
sumrunoff
Text5.Text = "outputing ..."
output
Text6.Text = "done!"
```

15. Model Run for Hypothesis Scenarios

```
Open "c:\thesis\gridtxt\fnameout.txt" For Input As #1

For mm = 1 To 5
   For nn = 1 To 5
   Input #1, ffout(mm, nn)
   Next nn
Next mm
Close #1

For mm = 1 To 5                    'Five temperature change scenarios

   For nn = 1 To 5                 'Five precipitation change scenarios

   loadp
   loadt
   loadlucc
   ini
   datacon
      For i = 1 To 84
         For j = 1 To 71
            For k = 1 To 125
               tdatam(i, j, k) = tdatam(i, j, k) + tchange(mm)          'Temperature change
               pdatam(i, j, k) = pdatam(i, j, k) * pchange(nn)          'Precipitation change

            Next k
         Next j
      Next i
   etocal
   runoff
   sumrunoff
   output2                         'Output the results for each scenario

   Next nn
Next mm

Text6.Text = "All 25 scenarios were run!!!"
```

<u>Output2</u>

```
Open "c:\thesis\output\" & ffout(mm, nn) & "dis.txt" For Output As #2
Open "c:\thesis\output\" & ffout(mm, nn) & "et.txt" For Output As #3
Open "c:\thesis\output\" & ffout(mm, nn) & "snow.txt" For Output As #4
```

```
Write #2, "T=" & tchange(mm) & " and P=" & pchange(nn)
Write #3, "T=" & tchange(mm) & " and P=" & pchange(nn)
Write #4, "T=" & tchange(mm) & " and P=" & pchange(nn)

For i = 1 To 84
Write #2, discharge(i)
Write #3, evap(i)
Write #4, snacc(i)
Next i

Close #2
Close #3
Close #4
```

16. Model run for GCM Scenarios

```
For mm = 1 To 2        'Two GCM scenarios

   loadp
   loadt
   loadlucc
   ini
   datacon
   readgcm

      For i = 1 To 84

         kkk = (i + 9) Mod 12
         If kkk = 0 Then kkk = 12

         For j = 1 To 71
            For k = 1 To 125

               tdatam(i, j, k) = tdatam(i, j, k) + tgcm(mm, kkk)       'Temperature change
               pdatam(i, j, k) = pdatam(i, j, k) * pgcm(mm, kkk)       'Precipitation change

            Next k
         Next j
      Next i

   etocal
   runoff
   sumrunoff
   output4                'Output the results foe each of GCM scenario
```

```
Next mm

Text6.Text = "Two GCM scenarios were run!!!"
```

<u>Output4</u>

```
gcmf = "c:\thesis\output\gcm" & mm & "\"

Open gcmf & "disfull.txt" For Output As #2
Open gcmf & "etfull.txt" For Output As #3
Open gcmf & "snowfull.txt" For Output As #4
Open gcmf & "smfull.txt" For Output As #5
Open gcmf & "gwfull.txt" For Output As #6

For i = 1 To 84
For j = 1 To 71
For k = 1 To 125

Write #2, runoffgrid(i, j, k)
Write #3, acevap(i, j, k)
Write #4, snowacc(i, j, k)
Write #5, soilmoisture(i, j, k)
Write #6, groundwater(i, j, k)

Next k
Next j
Next i

Close #2
Close #3
Close #4
Close #5
Close #6
```

17 Excel Program for Statistics

<u>Variables</u>

```
Dim runoff(84, 71, 125), et(84, 71, 125), sm(84, 71, 125), gw(84, 71, 125), snow(84, 71,
125)
Dim dis(71, 125), aet(71, 125), soilm(71, 125), gwater(71, 125), snowa(71, 125)
Dim luccdata(71, 125)
Dim NN(7), aa(7), Maxlucc(7), Minlucc(7)
```

Reading file

```
Open "c:\thesis\laptop\output\disfull.txt" For Input As #1  'Streamflow
Open "c:\thesis\laptop\output\etfull.txt" For Input As #2    ' AE
Open "c:\thesis\laptop\output\gwfull.txt" For Input As #3  'Ground water
Open "c:\thesis\laptop\output\snowfull.txt" For Input As #4 ' Snow accumulation
Open "c:\thesis\laptop\output\smfull.txt" For Input As #5    'Soil moisture

For i = 1 To 84 '84 months
   For j = 1 To 71 '71 rows
      For k = 1 To 125 '125 columns
         Input #1, runoff(i, j, k)
         Input #2, et(i, j, k)
         Input #3, gw(i, j, k)
         Input #4, snow(i, j, k)
         Input #5, sm(i, j, k)
      Next k
   Next j
Next i

Close #1
Close #2
Close #3
Close #4
Close #5

TextBox1.Text = "Done-reading"
```

Reading land use

```
Open "c:\thesis\laptop\GRIDTXT\lucctxt.txt" For Input As #1

For mm = 1 To 6
Line Input #1, stringtext
Next mm

For j = 1 To 71
For k = 1 To 125
Input #1, luccdata(j, k)
Next k
Next j
Close #1

' For 84 months average, spatial distribution

For j = 1 To 71
   For k = 1 To 125
      aa1 = 0#
```

```
        aa2 = 0#
        aa3 = 0#
        aa4 = 0#
        aa5 = 0#

        If luccdata(j, k) < 0 Then
        dis(j, k) = -9999
        aet(j, k) = -9999
        soilm(j, k) = -9999
        gwater(j, k) = -9999
        snowa(j, k) = -9999
        Else
        For i = 1 To 84
            aa1 = aa1 + runoff(i, j, k)
            aa2 = aa2 + et(i, j, k)
            aa3 = aa3 + gw(i, j, k)
            aa4 = aa4 + snow(i, j, k)
            aa5 = aa5 + sm(i, j, k)
        Next i
        dis(j, k) = aa1 / 7  'Annual value instead of 84 months summation
        aet(j, k) = aa2 / 7
        soilm(j, k) = aa5 / 7
        gwater(j, k) = aa3 / 7
        snowa(j, k) = aa4 / 7
        End If
    Next k
Next j
```

<u>Output</u>

```
For j = 1 To 71
    For k = 1 To 125
        Sheet1.Cells(j + 6, k) = dis(j, k)
        Sheet2.Cells(j + 6, k) = aet(j, k)
        Sheet3.Cells(j + 6, k) = soilm(j, k)
        Sheet4.Cells(j + 6, k) = gwater(j, k)
        Sheet5.Cells(j + 6, k) = snowa(j, k)
    Next k
Next j
```

<u>Average, Max and Min for each Land use</u>

```
For i = 1 To 7  ' Seven land use categories
NN(i) = 0
aa(i) = 0
```

```
Maxlucc(i) = -10000000
Minlucc(i) = 100000000
Next i

For j = 1 To 71
   For k = 1 To 125
      bb = luccdata(j, k)
      If bb > 0 Then
      NN(bb) = NN(bb) + 1
      aa(bb) = aa(bb) + snowa(j, k)
         If dis(j, k) > Maxlucc(bb) Then Maxlucc(bb) = snowa(j, k)
         If dis(j, k) < Minlucc(bb) Then Minlucc(bb) = snowa(j, k)
      End If
   Next k
Next j

For i = 1 To 7
Sheet6.Cells(i + 2, 3) = NN(i)
Sheet6.Cells(i + 2, 4) = aa(i) / NN(i)
Sheet6.Cells(i + 2, 5) = Maxlucc(i)
Sheet6.Cells(i + 2, 6) = Minlucc(i)
Next i
```

Appendix B Meteorological and streamflow stations used in this study

National Climatic Data Center (NCDC) stations used in this study

Station ID	Station name	State	County	Latitude (N)	Longitude (W)	Elevation(m)	Data Available
452007	Davenport	WA	Lincoln	47:39	-118:09	744	03/1893-current
455844	Newport	WA	Pend Oreille	48:11	-117:03	651	10/1909-current
457180	Rosalia	WA	Whitman	47:14	-117:22	732	01/1893-current
457938	Spokane International Airport	WA	Spokane	47:37	-117:32	717	08/1889-current
459058	Wellpinit	WA	Stevens	47:54	-118:00	759	08/1923-current
100525	Avery Ranger Station	ID	Shoshone	47:15	-115:48	759	12/1913-10/1968
100528	Avery Rs #2	ID	Shoshone	47:15	-115:56	729	11/1968-09/1990 04/1992-current
100667	Bayview Model Basin	ID	Kootenai	47:59	-116:34	633	04/1947-current
101363	Cabinet Gorge	ID	Bonner	48:05	-116:04	689	11/1956-current
101810	Clark Fork 1 ENE	ID	Bonner	48:09	-116:10	650	02/1912-10/1956
101956	Coeur D'Alene	ID	Kootenai	47:41	-116:48	650	08/1895-12/1925 01/1931-08/1986 11/1995-current
107188	Plummer 3 WSW	ID	Benewah	47:19	-116:58	890	02/1950-current
107301	Potlatch 3 NNE	ID	Latah	46:57	-116:53	793	03/1915-current
108062	Saint Maries 1 W	ID	Benewah	47:19	-116:35	707	04/1897-current
109498	Wallace Woodland Park	ID	Shoshone	47:29	-115:55	896	03/1941-02/2003

USGS Streamflow Stations used in this study

USGS 12433000 SPOKANE RIVER AT LONG LAKE, WA
Stevens County, Washington
Hydrologic Unit Code 17010307
Latitude 47°50'12", Longitude 117°50'25" NAD27
Drainage area 6,020.00 square miles
Gage datum 1,299.00 feet above sea level NGVD29

USGS 12422500 SPOKANE RIVER AT SPOKANE, WA
Spokane County, Washington
Hydrologic Unit Code 17010305
Latitude 47°39'34", Longitude 117°26'53" NAD27
Drainage area 4,290.00 square miles
Gage datum 1,697 feet above sea level NGVD29

USGS 12419000 SPOKANE RIVER NR POST FALLS ID
Kootenai County, Idaho
Hydrologic Unit Code 17010305
Latitude 47°42'11", Longitude 116°58'37" NAD27
Drainage area 3,840.00 square miles
Contributing drainage area 3,718.00 square miles
Gage datum 2,003. feet above sea level NGVD29

USGS 12413500 COEUR D ALENE RIVER NR CATALDO ID
Kootenai County, Idaho
Hydrologic Unit Code 17010303
Latitude 47°33'17", Longitude 116°19'23" NAD27
Drainage area 1,223.00 square miles
Contributing drainage area 1,223 square miles
Gage datum 2,100.00 feet above sea level NGVD29

USGS 12413000 NF COEUR D ALENE RIVER AT ENAVILLE ID
Shoshone County, Idaho
Hydrologic Unit Code 17010301
Latitude 47°34'08", Longitude 116°15'06" NAD27
Drainage area 895.00 square miles
Contributing drainage area 895 square miles
Gage datum 2,100. feet above sea level NGVD29

USGS 12411000 NF COEUR D ALENE R AB SHOSHONE CK NR PRICHARD ID
Shoshone County, Idaho
Hydrologic Unit Code 17010301
Latitude 47°42'26", Longitude 115°58'36" NAD27

Drainage area 335.00 square miles
Contributing drainage area 335 square miles
Gage datum 2,485.00 feet above sea level NGVD29

USGS 12415000 ST MARIES RIVER AT LOTUS ID
Benewah County, Idaho
Hydrologic Unit Code 17010304
Latitude 47°14'40", Longitude 116°37'25" NAD27
Drainage area 437.00 square miles
Contributing drainage area 437 square miles
Gage datum 2,143.36 feet above sea level NGVD29

USGS 12414500 ST JOE RIVER AT CALDER ID
Shoshone County, Idaho
Hydrologic Unit Code 17010304
Latitude 47°16'30", Longitude 116°11'15" NAD27
Drainage area 1,030.00 square miles
Contributing drainage area 1,030 square miles
Gage datum 2,096.76 feet above sea level NGVD29

USGS 12431000 LITTLE SPOKANE RIVER AT DARTFORD, WA
Spokane County, Washington
Hydrologic Unit Code 17010308
Latitude 47°47'05", Longitude 117°24'12" NAD27
Drainage area 665.00 square miles
Gage datum 1,585.62 feet above sea level NGVD29

USGS 12424000 HANGMAN CREEK AT SPOKANE, WA
Spokane County, Washington
Hydrologic Unit Code 17010306
Latitude 47°39'10", Longitude 117°26'55" NAD27
Drainage area 689.00 square miles
Gage datum 1,717.42 feet above sea level NGVD29

USGS 12420500 SPOKANE RIVER AT GREENACRES, WA
Spokane County, Washington
Hydrologic Unit Code 17010305
Latitude 47°40'39", Longitude 117°09'04" NAD27
Drainage area 4,150.00 square miles
Gage datum 1,980 feet above sea level NGVD29