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Examining the Impacts of Land-Use Change on Hydrologic Resources

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Contents

Tables

Figures

Abstract

The research community over the past several years has put a great effort into studying the potential impacts of a changing climate. But the issues that face the world today encompass greater change than just that of climate. For instance, there are changes due to population dynamics (such as migration), economics, and the way that land is used. Water resources are affected specifically by changes in climate and land use.

A water balance model developed for the purpose of examining climate change was extended to allow analysis of impacts from land-use change. In addition, it was modified so that a watershed could be modeled by multiple smaller units within the basin. Two methodologies were applied to break the basin into smaller parts: first, hydrologic boundaries of major tributaries were used, and second, a delineation based on five classes of land-use type, which included tundra, forest, rangeland, agriculture, and urban land, was created.

The model originally had three parameters which were calibrated statistically. A goal of this project was to take a step towards making these parameters physically-based in the watershed, thereby avoiding the need for statistical calibration which might allow parameters to mask interconnections in the hydrologic processes. The parameter which represents maximum soil moisture capacity was therefore set based on land-use type.

The South Platte Basin upstream of the town of Masters, Colorado was chosen as a case study basin. The study included eight sub-basins delineated by hydrologic boundaries and the five land classes mentioned previously. A climate change sensitivity analysis was performed and a hypothetical land-use scenario was analyzed. This hypothetical scenario increased the percentage of urban land and removed all agriculture. In addition, some rangeland was converted to forested land. These tests were examined individually and in a combined scenario. Results found that the land-use scenario estimated greater runoff and acted to mitigate negative effects and enhance positive impacts of climate change. The magnitude of the impact of land-use change was found to be of the same order as that of climate change, and it therefore warrants further research into possible effects of such changes.

The study clearly demonstrated the sensitivity of model results to inclusion of land-use change, and the need for further development of the hydrological model to be implemented for the Yellow River basin in North China, a water-critical region of the LUC project study area.

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O. Perrin Bowling, Kenneth M. Strzepek

1. Introduction

As the Earth's population has been growing rapidly and more stress is put on the land to support the increased population, one question that arises is how hydrologic resources will be affected. Water is essential to life, and as industrialization continues, more of the world's population becomes concentrated in urban centers, with greater stress on available water resources. Postel (1992) says "In contrast to earlier decades of unfettered damming, drilling, and diverting to gain ever greater control over water, the next generation will be marked by limits and constraints — political, economic, and ecological."

One of the recent thrusts in hydrologic modeling is the assessment of the effects of land-use and land-cover changes on water resources. These changes are the result of natural processes as well as anthropogenic influences, and they include such processes as vegetation dynamics, erosion, acidification, salinization, overgrazing, desertification, mining, urban and industrial development, conversion of lands to and from agriculture, and deforestation.

The International Institute for Applied Systems Analysis has undertaken the task of creating a model to analyze the influence of a range of socio-economic and biogeophysical driving forces on the spatial characteristics, temporal dynamics, and environmental consequences of changes in land use and land cover between 1900 and 1990 in Europe and Northern Asia. The model will be utilized to project possible changes in land use and cover between 1990 and 2050 based on assumptions of different future driving forces (Fischer *et al.*, 1996).

The work in this paper represents part of the effort to include an assessment of hydrologic resources in the IIASA model. It is clear that hydrology can both affect land use and land cover change (e.g. erosion) as well as being affected by it (e.g. the effects of deforestation on surface runoff). Thus it is an important element of the IIASA Land Use Change (LUC) Project.

Up to now, there have been many great efforts to examine potential impacts of climatic change upon water resources (see, for example, Nemec and Schaake, 1982; Nash and Gleick, 1991; Riebsame *et al.*, 1995; Jeton *et al.*, 1996; IPCC, 1996). However, there has been much less focus on the potential effects of land-use change. One purpose of this paper is to examine the magnitudes of some possible changes in land use and compare them to the potential impacts of climatic change. If they are of the same scale, then much more emphasis will need to be placed on land-use changes in the coming decades.

The impacts of socio-economic and biogeophysical driving forces are rarely limited to watershed boundaries. Portions of a catchment or catchments can experience significant change while other parts show negligible effects. Potential climatic changes in precipitation and temperature are not likely to match hydrologic boundaries either.

Because of these variations, a model which can examine the effects of change on sub-catchment-scale parts of a basin is needed. A model with a more thorough spatial distribution is more likely to represent such variations more accurately.

The question then arises: how should a watershed be divided into smaller parts? Jeton *et al.* (1996) used the concept of hydrologic response units (HRUs) in a study on two basins in the western U.S., wherein each HRU was assumed to have a homogeneous response to precipitation inputs. They differentiated HRUs based on altitude, slope, aspect, land cover, and soil type.

It was quickly realized that lack of data availability in the study regions of the LUC project would restrict the use of such a specific categorization as that used by Jeton *et al.* to divide a watershed. Therefore, it was decided to use a categorization of five land-use classes which were appropriate to the case study basin chosen: agricultural land, forests, rangeland, tundra, and impervious areas.

One problem with this kind of categorization is that many distinct areas are defined, and each one becomes a separate basin in the multi-basin model. For the Jeton *et al.* study, the model would have become intractable if each hydrologically distinct area was modeled separately. Instead, they chose to model one area for each HRU, allowing the “basins” to be constituted of noncontiguous parts. Their study did not address the impacts of modeling noncontiguous basins. Since the classification used in this paper was much coarser than that used in the Jeton *et al.* study, it was possible to model a watershed using both contiguous areas defined by hydrologic boundaries and noncontiguous areas made up of land-use classes to study the impact of the classification scheme.

This model was designed to be used in a study area that may not have abundant data. The Yellow River Basin was initially chosen as a case study because it is an important watershed within the study area of the LUC project. However, after several months it became clear that some essential data were not available. Thus, in order to properly test the model and to give some idea of the absolute data requirements, the South Platte River Basin in Colorado was chosen. These two river basins exhibit some similarities, mostly with respect to their latitude and land-use types, although the results described pertain only to the South Platte.

2. Hydrologic Modeling

Background

Hydrologic modeling originated in the latter part of the 19th century as a way to address design issues for urban sewers, land reclamation drainage systems, and reservoir spillways (Todini, 1988). Into the early 20th century, empirical formulas were the primary tool used to estimate runoff. Also during this time, the rational method, which is based on the concept of concentration time, was developed. The modified rational method, which incorporates lines of equal travel time, appeared in the 1920s. In 1932, Sherman developed the unit hydrograph concept. The 1930s and 1940s marked an emphasis on statistical analysis in models. A breakthrough occurred in the 1950s when conceptual models using systems engineering approaches were created. The search for models that were physically-based began in the 1960s. According to Todini (1988), the need for physically-based models arose due to three requirements:

- extending the use of the model to long continuous records avoiding the complexity of storm runoff and base flow separation;
- applying the model to complex watersheds with a large variety of soils, vegetation, slopes, etc.; and
- extending the model more or less without calibration to other similar catchments.

Many of the classic hydrologic models were developed during this time, such as the Stanford IV and Sacramento models. In the 1970s, the emphasis fell on modeling environmental problems, including such topics as soil erosion, soil degradation, and pollution. Real-time forecasting for use in flood warning systems arose in the late 1970s and 1980s. For a more extensive description of the history of hydrologic modeling, see Todini (1988).

Physically-Based Models

As mentioned above, the search for physically-based models to represent the dynamics of a watershed began over 30 years ago. During this time, many models which attempt to use a physical basis were developed. Also in this period, the debate about whether physical models are truly physically-based arose. This section examines some perspectives in the debate.

As described by Liggett (1990) and Beven (1989), the task of representing a basin by its physical parameters is quite complicated:

> If there is an example of a computational hydraulics problem that has been defeated by the wealth of detail necessary for a practical solution, it must be this one. We are nowhere near to describing the hydraulic properties of a watershed. (Liggett, 1990)

> The difficulties of hydrological simulation arise due to the non-linearities inherent in these [loss and routing] functions, especially in the loss function, as a result of antecedent conditions and the spatial complexities

> of the catchment topography, soils, vegetation and rainfall inputs. (Beven, 1989)

Physically-based models must capture the interworking of many different parameters. Thus a tremendous data requirement arises, which is often hard to meet — especially in many river basins in developing countries. In addition, there are many degrees of freedom in a model with a large number of parameters. Liggett (1990) states that "...many of the watershed programs require the tuning of so many knobs that they are no better than statistical black boxes." Does the inclusion of so many different parameters really make the model more accurate? Beven (1989) says "It appears that three to five parameters should be sufficient to reproduce most of the information in a hydrological record." In addition, Franchini and Pacciani (1991) state further complications of overparameterization:

> In the STANFORD IV and SACRAMENTO models, the attempt to grasp the different interactions of the various phases of the rainfall-runoff transformation within the soil is not advantageous for computational purposes; it results in a useless increase of parameters and a consequent increase in difficulty of the calibration procedure.

Beyond parameterization, there is a data issue involved. Poor data or simply a poor spatially-or temporally-distributed data set can lead to the wrong conclusions of a model's ability to estimate runoff and to complexities in optimization. Woolhiser (1996) says:

> The importance of high spatial and temporal resolution of rainfall data cannot be overemphasized. To conclude that a physically based model is a poor representation of reality when it fails to predict runoff well when the rainfall data are insufficient is akin to condemning a beam flexure formula because it fails to estimate the proper displacement when the wrong distribution of load is applied...It is also true that difficulties in the optimization of parameters will result from the poor spatial resolution of rainfall data.

In addition there is the subject of model scale and how parameters reflect that scale. Woolhiser (1996) writes:

> We would expect that when the computational scales of the physically based model and the scales of spatial variability of the real system are commensurate, the parameters would have some physical significance, provided that important mechanisms have not been ignored. However, as the system being modeled becomes too large and the computational scale becomes large relative to the scale of variability of the real system, the parameters will most certainly lose some of their significance, although there may be some regularities that can be used.

Thus it is important to have a knowledge of spatial variability within the basin under analysis, and to align the model's scale appropriately.

The next topic to be addressed is that of calibration. According to Todini (1988), any statistical calibration leads to the loss of physical meaning:

> ...if one 'calibrates' the model parameters α by means of a statistical technique based upon residuals, regardless of the physicality of the model, this is equivalent to assuming a stochastic model...thus losing a great deal of the physical meaning.

This issue will be explored more thoroughly in Chapter 4.

Finally, a perspective that seems to balance out the debate on physically-based models is that of Woolhiser (1996), who recognizes the advantages and disadvantages of both sides and notes that all models "inevitably involve distortion":

> In my opinion, the term physically based, distributed model is an imprecise term, which was originally used to describe models that are not pipe and bucket compartment models or general linear or nonlinear system models. A better approach might be to recognize that, instead of specific classes of models, we have an array, with the simpler models being higher-order abstractions of the more detailed models (Woolhiser 1975). As such, they share some common properties, but all inevitably involve distortion. The simpler models are more general and involve fewer parameters, but this generality has been purchased at the price of a less detailed description.

The following section addresses the type of model used in this paper and how it falls into the debate on a physical basis for models.

The WatBal-LUC Model

Todini (1988) separates model structures into four classes, with increasing requirements for *a priori* knowledge: (1) purely stochastic, (2) lumped integral, (3) distributed integral, and (4) distributed differential. According to Todini's descriptions, the first category is not generally used in rainfall-runoff modeling because continuity of mass can be incorporated, thus getting away from a "purely" stochastic model. In the second category, the watershed is modeled as a whole and the interactions of the system are modeled using integral forms such as the impulse response or unit hydrograph. The third category endeavors to improve on the lumped models by using smaller, subcatchment areas and combining them by matching boundary conditions. However, Todini suggests that these models can more accurately be thought of as extensions of the lumped models which are an improvement in matching spatial variability but which do not sufficiently compute fluxes internal to a basin. The fourth and last category, which does not encompass many models, uses spatial and temporal discretization and mass and momentum balances, matching boundary conditions at each time step. An example of this type of model is the Système Hydrologique Européen (SHE) developed for laboratory-scale experiments.

WatBal-LUC[1], the model employed in this paper, falls generally into the second category, although it represents a basin in a distributed fashion by subcatchment areas. It does not belong in the third category (nominally) because it does not consider boundary conditions between sub-basin areas.

The original WatBal model, of which WatBal-LUC is an extension, used three calibration parameters which were calibrated statistically by minimizing residuals (see Chapter 3 for a description of the model). One goal of the research in this paper was to take a first step towards establishing a physical basis for those parameters, eventually being able to estimate runoff without any calibration and thereby allowing basins without runoff gauges to be analyzed. To accomplish this task, one of the three parameters was established *a priori*, and the other two were statistically calibrated.

One of the main aims of this project was to use the model to estimate impacts of land-use change. As described by Beven (1989), such a task needs a physically-based model:

> There are some hydrological problems demanding predictions which at present can only be provided by physically-based models...Predicting the effects of land-use changes is a particular example that has often been used to justify the effort of developing physically-based models.

Though the WatBal-LUC model tested here is only partially physically-based, the parameter which was set *a priori* reflects the type of land use, and, as will be shown in Chapter 6, the model was able to capture specific impacts of land-use change.

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[1] The name WatBal-LUC is derived from the Land Use Change (LUC) Project at the International Institute for Applied Systems Analysis (Vienna, Austria), for which WatBal-LUC was created.

3. Incorporating Land Use in a Monthly Water Balance Model

The Conceptual Model

The water balance model employed for this paper is an extension and modification of the WatBal model (Yates, 1996). WatBal was created as a tool for modeling the response of river basins to potential climate change. The framework was developed by Kaczmarek and Krasuski (1991), and elements of their approach were adapted by Yates (1996). The model uses a simple, lumped-storage approach with a small number of parameters. WatBal is a lumped conceptual model that represents storage by a single "bucket" with precipitation input and outputs of evapotranspiration, surface runoff, subsurface runoff, and baseflow (see Figure 3.1).

It was desired to develop a model which could predict the runoff response over an entire river basin by using smaller, sub-catchment-scale areas and then calibrating the runoff to historical measurements at the mouth of the basin. WatBal- LUC is the model extension which was developed for this purpose. It was written in Visual Basic and combined with a genetic algorithm for calibration.

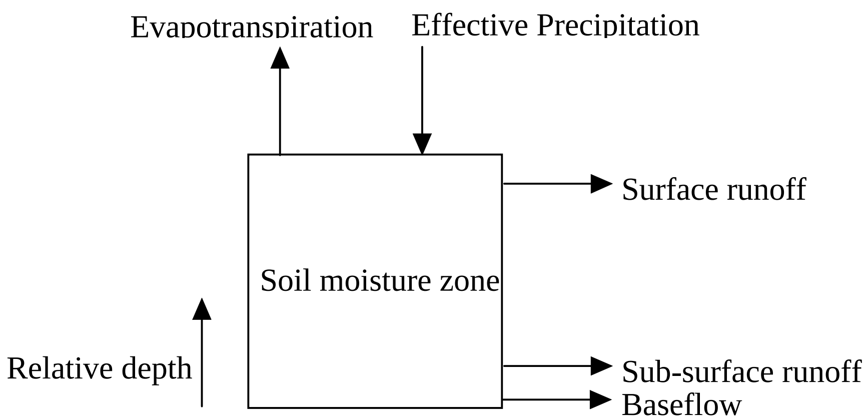


Figure 3.1 *Storage "bucket" used in the WatBal model (after Yates, 1996).*

Model Equations

The mass balance in the model is represented by the following differential equation (Yates, 1996):

$$S_{\max}\frac{dz}{dt} = P_{eff}(t) - R_{uns}(z,t) - R_{sat}(z,t) - R_b - E(PET,z,t) \qquad (3.1)$$

where S_{max} ≡ maximum storage capacity

z ≡ relative storage ($0 \le z \le 1$)

P_{eff} ≡ effective precipitation

R_{uns} ≡ unsaturated zone runoff

R_{sat} ≡ saturated zone runoff

R_b ≡ baseflow

E ≡ evaporation.

WatBal-LUC uses a separate differential equation for each sub-basin. There are two parameters for each sub-catchment which are changed during the iterative calibration procedure: α and ε. These coefficients are used in the saturated and unsaturated zone runoff equations given below, which are elements of the principle governing differential equation (Eq. 3.1). Note that the unsaturated zone component is considered to encompass overland flow; therefore all precipitation is assumed to infiltrate the soil matrix, if only slightly.

$$R_{sat} = \alpha z^{\gamma} \qquad (3.2)$$

$$R_{uns} = \begin{cases} z^{\varepsilon}(P_{eff} - R_b), & P_{eff} > R_b \\ 0, & P_{eff} \le R_b \end{cases} \qquad (3.3)$$

Model Inputs

Input data required for driving the model are monthly values of mean minimum and maximum temperature, of precipitation and relative humidity, duration of sunshine, and windspeed, for estimating potential evapotranspiration (PET) according to the Penman-Monteith model. A study by Niemann *et al.* (1994), which used the WatBal model, examined the impacts of using long-term average data instead of a time series for climate change analysis, and found that there was almost no difference in the results. Therefore, in the analysis that follows, long-term average data were used. Monthly runoff values at the mouth of the basin are needed for calibration. Additionally, monthly temperatures are required to compute precipitation adjustment due to snowmelt, a process which has a crucial impact on the hydrology of some river basins.

Snowmelt Sub-Model

An important component of the hydrologic cycle for some basins is snowmelt. WatBal-LUC computes an "adjusted" effective precipitation with a temperature index snowmelt model, using the following equations:

$$P_{eff,i} = mf_i (A_{i-1} + P_{m,i}) \tag{3.4}$$

where

$$mf_i = \begin{cases} 0 & for T_i \le T_s \\ 1 & for T_i \ge T_l \\ \dfrac{T_i - T_s}{T_l - T_s} & for T_s \le T_i \le T_l \end{cases} \tag{3.5}$$

and

$$A_i = (1 - mf_i)(A_{i-1} + P_{m,i}) \tag{3.6}$$

where mf_i ≡ melt factor in month i

A_i ≡ snow accumulation in month i

$P_{m,i}$ ≡ observed precipitation in month i

$P_{eff,i}$ ≡ effective precipitation in month i

T_s ≡ freezing temperature

T_l ≡ melting temperature.

T_i ≡ mean monthly temperature.

Yates (1996) notes that the WatBal model was quite sensitive to the values used to define the threshold temperatures in the East River, which is a tributary of the Gunnison River in Colorado. His conclusion was affirmed by this analysis on the South Platte River, also in Colorado. Specifically, it was determined that (1) using temperatures that are too cold simulates an early melt and causes the peak runoff to be too low (Fig. 3.2a); (2) using temperatures that are too warm predicts a late melt and the observed hydrograph peak is missed (Fig. 3.2b); (3) using a range between the solid and liquid threshold temperatures that is too small results in a larger slope for the rise of the modeled hydrograph (Fig. 3.2c); and (4) using too large a range simulates a smaller slope for the hydrograph rise and a diminished peak runoff (Fig. 3.2d). The last option also incorporates the effects of using temperatures that are too cold or too warm, by shifting the peak early or late. Figure 3.2e shows an example of properly adjusted temperature indices.

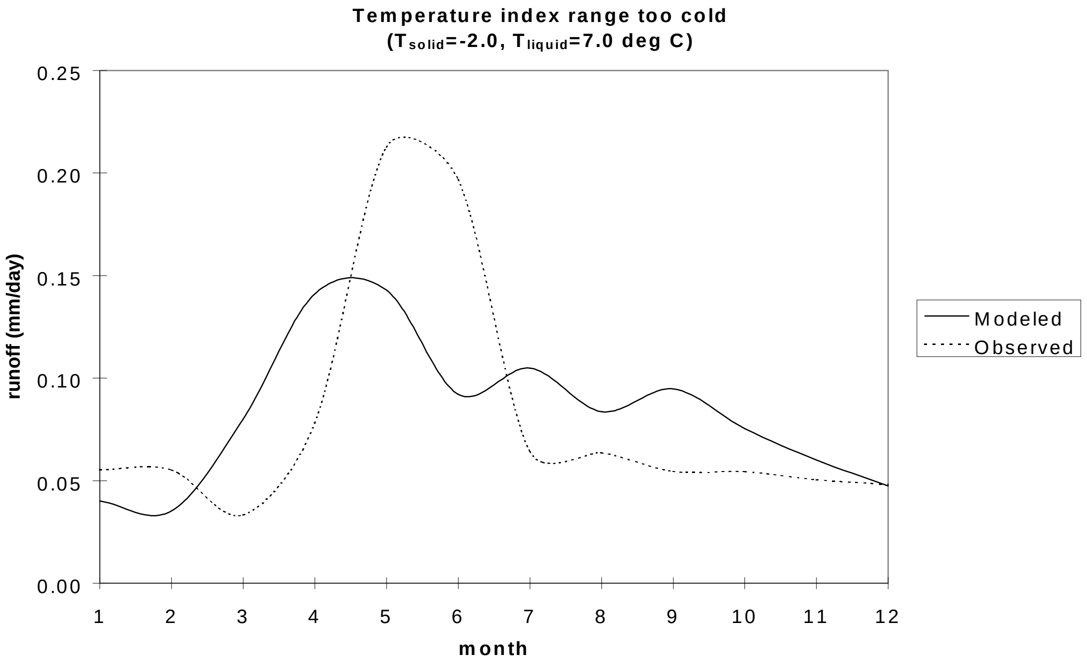


Figure 3.2a. *Example of using temperature indices that are too cold in the snowmelt model.*

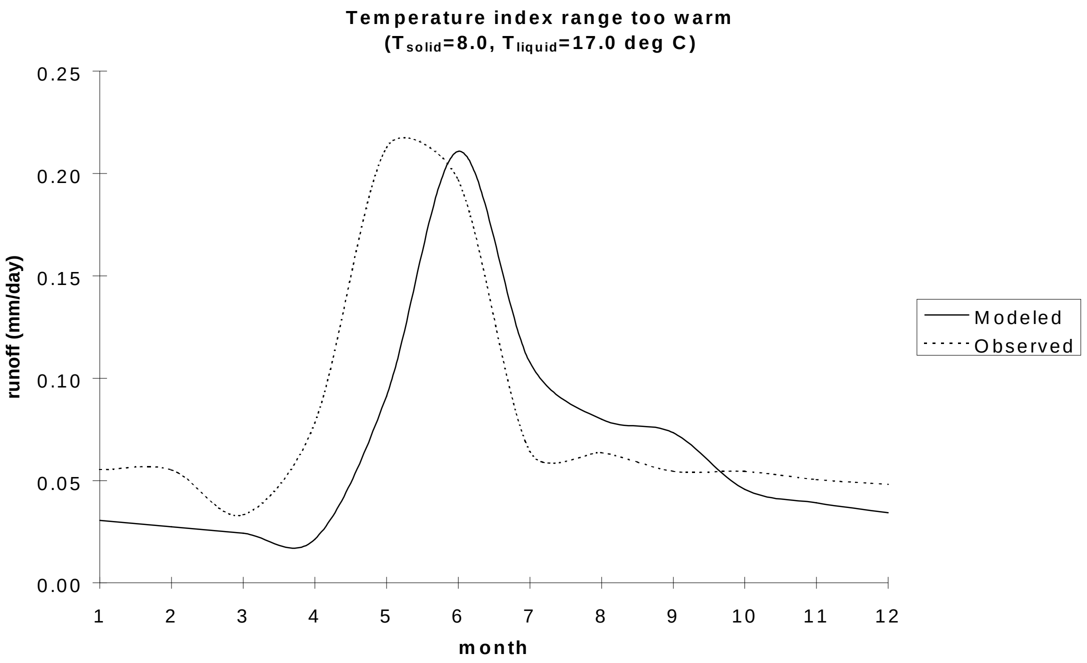


Figure 3.2b. *Example of using temperature indices that are too warm in the snowmelt model.*

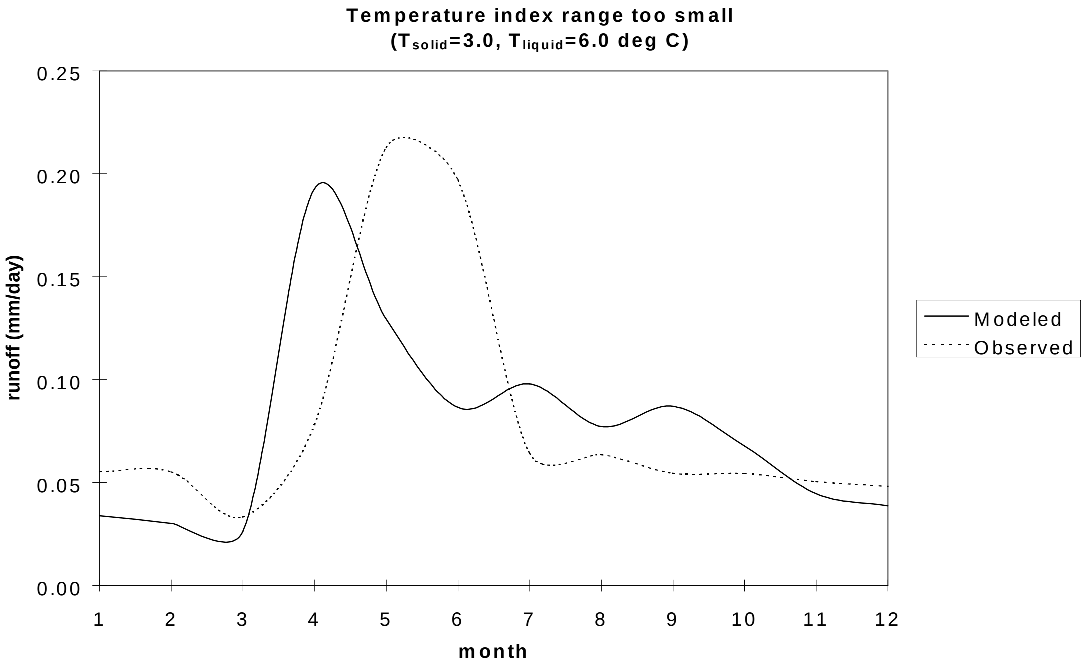


Figure 3.2c. *Example of using a temperature index range that is too small in the snowmelt model.*

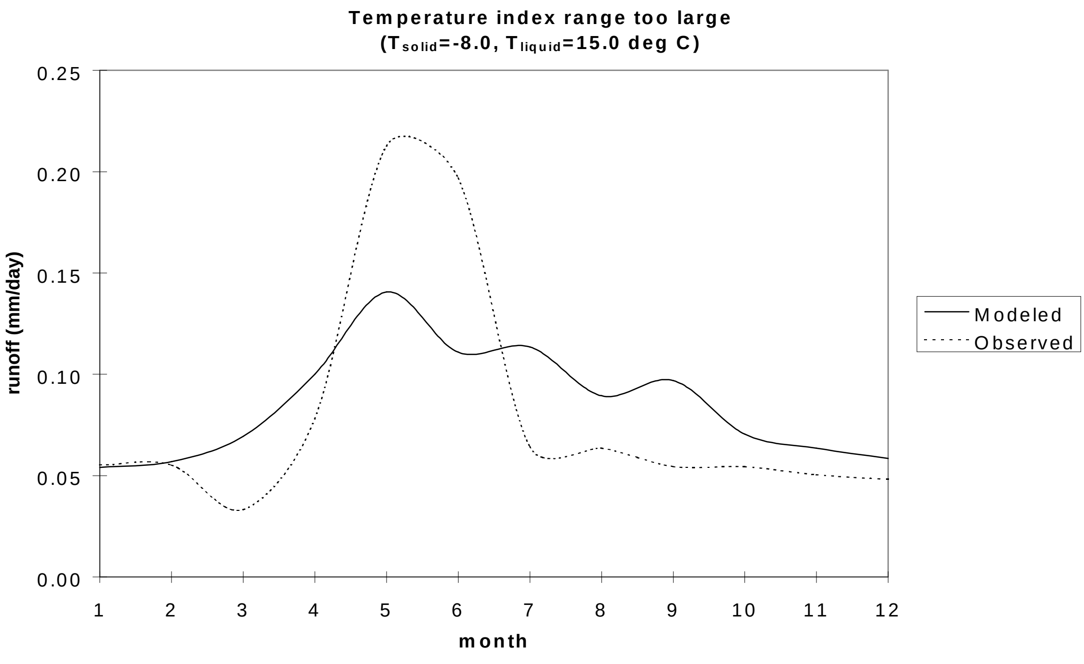


Figure 3.2d. *Example of using a temperature index range that is too large in the snowmelt model.*

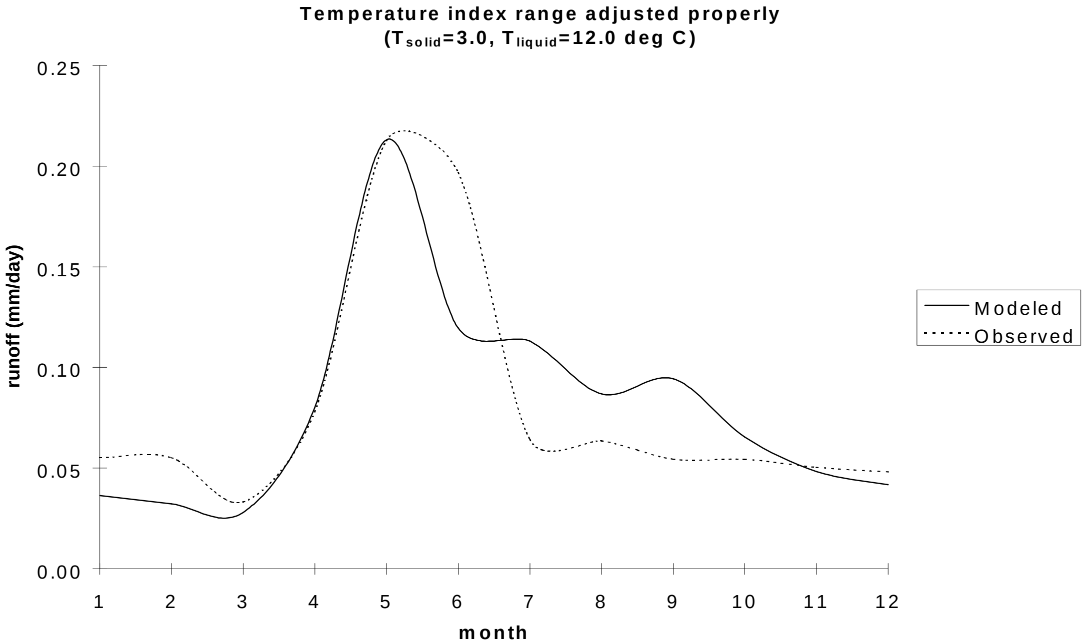


Figure 3.2e. *Example of using a temperature index range that is properly adjusted in the snowmelt model.*

Model Parameters

One difference between the original WatBal and WatBal-LUC is that S_{max}, the parameter that defines the storage "bucket" size of a basin, is a calibrated coefficient in the former model. It was suggested that this parameter could be assigned values based on land-use type, and thus could be physically-based. Though statistical calibration was needed for ε and α, assigning S_{max} physically was a step towards making the model completely based on physical parameters, which will be undertaken with further research towards the goal of using the model on ungauged basins. It should be noted that the values assigned to this parameter in the South Platte River study were determined by the author’s judgment in conference with colleagues, and to some degree by making successive runs of the model with differing parameter values. More research needs to be undertaken on the values given to the S_{max} parameter.

It was decided that within the LUC project potential evapotranspiration would be estimated by the Penman-Monteith equation (FAO, 1992).

Next, the albedo for use in determining PET was chosen from ranges suggested by Shuttleworth (1993) based on land-use type. The values used for albedo are shown in Table 3.1.

Table 3.1. *Assignment of maximum soil moisture capacity and albedo to land-use types*[*)].

Land-use Type	S_{max} (mm)	albedo
Urban	500	0.10
Tundra	800	0.50
Rangeland	1500	0.23
Forest	2000	0.13
Agriculture	2500	0.23

*) The values used in Table 3.1 are under review and should be taken as indicative only.

Lastly, it is recommended by Yates (1996) to determine the baseflow value from the 95th percentile low flow in the runoff data series.

Alternative Approaches to Incorporating Land Use

Because this research project involved examining changes to land use, a subdivision of the watershed into units that could reflect the land use was desirable. A similar hydrologic and climate change study was performed by Jeton *et al.* (1996) for two river basins in the Sierra Nevada, USA. They separated the catchments into segments based on altitude, slope, aspect, land cover, and soil type. Such a designation of hydrologically homogenous zones led to a large number of distinct areas that would have been difficult to model as individual basins. Therefore, Jeton *et al. (1996)* modeled each distinct class as a unit, even though the class could be (and was) made up of areas from different locations in the basin. In other words, the classes could be noncontiguous.

In this project, homogeneous areas with respect to hydrology and climatology were distinguished by land-use type. This classification led to a smaller number of distinct areas, but, as in the Jeton *et al.* study, the areas were allowed to be constituted of noncontiguous parts. The coarser classification scheme decreased data requirements and also allowed comparison with an analysis that used a basin separated into units based on hydrologic boundaries (such as tributary basins).

To demonstrate how a catchment was divided for the model, Figure 3.3 shows a schematization of a hypothetical river basin. For simplicity, the hydrologic basins (Fig. 3.3a) are represented by triangles. Suppose Basins 1 and 3 are tributaries to the main basin (2). Figure 3.3b shows the same conceptual watershed divided into land classes. Suppose this basin starts in mountains (tundra) and continues through a forested area onto plains that are used for grazing. Figures 3.3c-d show hypothetical temperature and precipitation distributions, respectively.

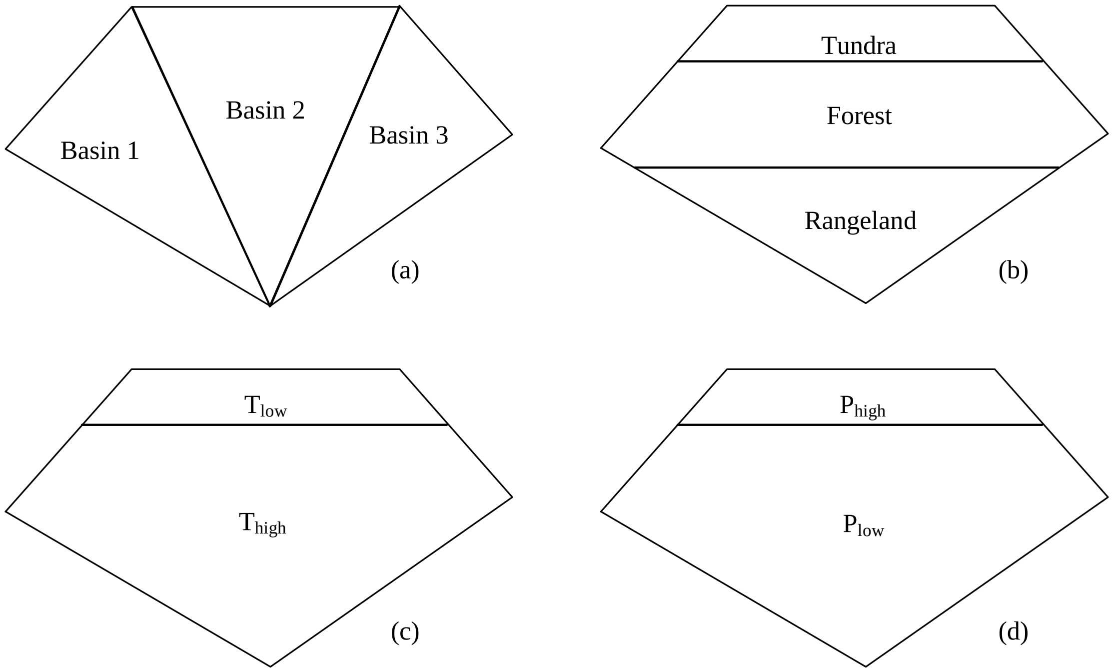


Figure 3.3. *Schematization of a simple basin showing (a) three sub-basins divided by watershed boundaries, (b) three land-use classes in the basin, (c) areas of similar temperature, and (d) areas of similar precipitation.*

Each of the sub-basins, whether divided by hydrologic boundaries or into hydroclimatologically homogeneous classes, has a water balance that can be represented by the governing differential equation (Eq. 3.1). The Geographic Information System (GIS) is used to determine single monthly values of the climate variables such as temperature, precipitation, and relative humidity which represent a whole section of the basin. Figures 3.3c-d were drawn to show that land classes tend to mimic topography. It can be seen from Figure 3.3 that the temperature and precipitation values for the land classes will be more homogeneous than those for the hydrologic sub-basins, which will be an areal-weighted average of the high and low temperatures and precipitations. The lapse rate for temperature, which describes how temperature generally decreases with altitude, is given as approximately 9.8°C/km for the dry adiabatic lapse rate (Chow *et al.*, 1988). It is clear then that a watershed which encompasses a diversity of elevations will tend to be represented by an overpredicted temperature. Additionally, if a temperature index model is being used to estimate snowmelt, the overpredicted temperatures will cause the model to simulate snowmelt sooner, giving an early peak to the hydrograph. This facet was compensated for by adjusting the temperature indices until the peak matched, as described previously.

Other climatic variables are affected by elevation and are therefore impacted by which kind of delineation scheme is used: for example, specific humidity decreases with elevation while wind velocity tends to increase with elevation (Chow *et al.*, 1988). Consider also potential evapotranspiration, which generally increases with temperature. PET is a non-linear function of specific humidity and temperature, among other variables.

The maximum soil moisture capacity, S_{max}, was set based on land cover type as shown in Table 3.1. As with the other variables, S_{max} in the model is constant for a given land class and is an areal-weighted average in the hydrologic sub-basins. It is easy to see that in a basin with diverse land classes, the average values used for the hydrologic sub-basins would cause those basins to be less responsive to changes in land use (assuming the changes did not alter the relative diversity of land classes). This response will be demonstrated further in Chapter 5, which discusses the case study basin.

4. Model Calibration

Background

Many different techniques have been applied to calibrate models, from simple heuristics to complex mathematical algorithms. Some of these techniques are described below.

Two of the simplest types of search techniques are blind search and heuristic search (Fulp, 1988). A blind search methodically tests a tree of possible alternatives until the solution is found. This type of search is cumbersome, in that as the number of calibration parameters increases, the number of nodes in the tree grows exponentially. A heuristic search improves on a blind search by providing direction through the tree from a heuristic function, thereby allowing the search to avoid sampling the entire tree.

Singh (1988) provides a thorough summary of many types of parameter estimation. These methods include the method of moments, the method of cumulants, the graphical method, the method of incomplete means, the method of probability weighted moments, the method of mixed moments, maximum likelihood estimation, the least squares method, constrained parameter estimation, Bayesian estimation, various optimization methods, regression and correlation, and the method of principle of maximum entropy.

Calibration of the WatBal-LUC Model

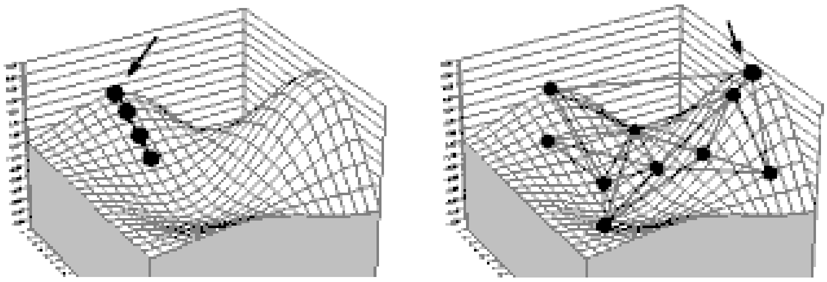
The original WatBal model, which focused on an entire basin, used a heuristic method to calibrate three parameters: it tested each parameter separately, determining whether an increase in that value would increase or decrease the curve fit. It would then proceed to increase or decrease the parameter based upon the results of that test. Each parameter was tested in turn, and the model was calibrated.

Because the WatBal-LUC model was designed to model a catchment as several sub-basins, it was quickly realized that a change in the calibration routine would be necessary. Although the S_{max} parameter was no longer being calibrated, each sub-basin had two calibration parameters, which meant that a watershed with 8 sub-basins would have a model with 16 parameters to be estimated. Using the heuristic method in the original model would require giving preference to specific parameters (for example, was it better to calibrate all the epsilons first, and then the alphas, or to calibrate both parameters from the first sub-basin, then both from the second, and so on?). Also this type of routine was largely dependent on the initial guesses given to the parameters. It could easily get caught at a local optimum instead of finding the true global optimum. Lastly, with many parameters to be estimated, this type of solution technique could quickly become intractable.

The next attempt to find a way to calibrate the model was a non-linear least squares routine. The method uses a Taylor series expansion of the function being calibrated (Singh, 1988), which is the differential water balance equation for the WatBal-LUC model (see Eq. 3.1). This method produced many complications in the calibration process, which were thought to be due to getting caught at local optima. After many attempts to incorporate the routine, it was decided to use a genetic algorithm.

Genetic algorithms were invented by John Holland of the University of Michigan in the 1970s (Antonoff, 1991). The technique borrows language and concepts from genetics: there is a population of organisms, and the organisms reproduce and are subject to random mutations. The concept of “survival of the fittest” applies in that the organisms which do not produce good results are cast out of the population, leaving the organisms which can better solve the problem to reproduce. By using a population of organisms, many possible solutions can be examined within a short time, and by adding a factor of randomness (“mutation”), the solution is more likely to achieve a global optimum. Figure 4.1 shows an example (from Axcélis, Inc.) of how the global optimum is pinpointed through the random mutation.

The genetic algorithm software used is called Evolver (by Axcélis, Inc.). For the hydrologic model, a population of 100 organisms was used. The genetic algorithm was programmed to create the population while keeping the values for ε and α within a specified range (0.1-10.0). It then tested each organism for its “fitness” by running it through a routine that calculated the sum of the squares of the residuals between the observed and predicted runoff values.



(a) (b)

Figure 4.1. *Example showing how (a) many routines, when starting at the lowest point, would "climb" the lower hill and report its top as the maximum, while (b) a genetic algorithm, with its random "mutation" factor, thoroughly samples the solution space and quickly determines the true global optimum. (figures from Axcélis, 1996)*

Then, the organisms were ranked and the half which fit the least well were discarded. The half that remained were duplicated (to bring the population back up to 100 organisms), and then they were subjected to the process called "cross-over" which is similar to reproduction. In this process, the organisms pair off at random and each gives part of its information to the children. For instance, in modeling 4 sub-basins, each organism has information about 8 parameters, so when they pair off, the children receive 4 parameter values from each parent.[2] Additionally at this time, some of the organisms were subjected to an adjustable mutation rate, which adds a random value to the set of parameter values. The mutation process allows a more thorough sampling of the entire solution space, so that a true global optimum can be found. Next, each of the new organisms was tested for fitness, and the process cycled again as described above. The algorithm was programmed to finish after finding an optimal solution and unsuccessfully trying to improve on it 1000 times.

[2] This is an adjustable ratio between 0 and 1. If it is set at either extreme, the child becomes a clone of one parent or the other. For the hydrologic model, a ratio of 0.5 was used, indicating 50% information from each parent.

5. Case Studies

One of the main goals of the design of the WatBal-LUC model was to use as few parameters as possible. This facet allows a more wide application of the model to areas that do not have a variety of data easily available, especially developing countries. The main focus area of the LUC Project includes Russia, China, and Mongolia. Data on the Yellow River Basin were being prepared for a case study until it became clear that the data available were not sufficient, and that greater efforts would have to be expended in retrieving these data from sources within China. Therefore, in order to thoroughly test the model, it was decided to use a case study basin in the United States: that of the South Platte River in Colorado, where plentiful data were available.

South Platte River

The South Platte River begins in the Rocky Mountains southwest of Denver, Colorado, and flows north and east towards Nebraska. This study examined the basin upstream of the town of Masters, Colorado, which is approximately 200 km (125 miles) upstream of the point where the South Platte flows into Nebraska. The basin includes a range of land-use types, which have been aggregated to include agriculture, forests, grasslands, tundra, and impervious areas. The basin is located at approximately 40°N latitude.

The basin area of approximately 31,500 km^2 was divided into 8 contiguous areas based on hydrologic boundaries delineated by the USGS and shown in Figure 5.1. These areas include the upper basin, the confluence of the North Fork of the South Platte with the main stem, Clear Creek, Boulder/St. Vrain Creeks, Big Thompson River, Cache la Poudre River, Lone Tree and Crow Creeks, and the main basin.

Data on land use was acquired from the United States Geological Survey (DOI / USGS, 1986) in the form of digital maps, which were then used in the GIS to produce the input necessary for the model. Figures 5.2 and 5.3 show the land use in the South Platte Basin as acquired from the USGS with some aggregation of classes and as digitized to represent the five classes in the study, respectively. The approximate size of each of these areas is given in Table 5.1. The distribution of each of the eight hydrologic sub-basins into land-use types is presented in Table 5.2. Digitization left some areas unaccounted for, as can be seen in Figure 5.3; however, at least 90% of all areas were included.

Table 5.1. *Division of South Platte Basin into land-use areas.*

Land-use Type	Area (km^2)
Urban	816
Tundra	1326
Rangeland	10330
Forest	9746
Agriculture	6970

Table 5.2. *Division of land use to each hydrologic sub-basin, given as percentages of sub-basin area.*

	Land-use Type				
Basin	Urban	Tundra	Rangeland	Forest	Agriculture
North S. Platte	1.8	0.0	73.8	2.4	22.0
Cache la Poudre	0.6	4.7	24.7	39.4	30.7
Main Basin	5.2	0.0	42.8	0.0	52.0
Big Thompson	0.7	9.4	8.5	51.1	30.3
Boulder / St. Vrain	1.0	9.0	5.1	46.7	38.2
Clear Creek	11.1	23.1	11.6	52.5	1.7
North Fork	4.8	3.0	22.6	69.6	0.1
Upper S. Platte	0.0	5.8	51.8	40.9	1.5

The values for the maximum soil moisture capacity, S_{max}, for the hydrologic sub-basins were calculated as areal weightings of the values assigned to land classes. These values are presented in Table 5.3, which shows that they range between the values given to rangeland and forest areas. They do not vary much, considering that the range given to land classes spans from 500 mm to 2500 mm.

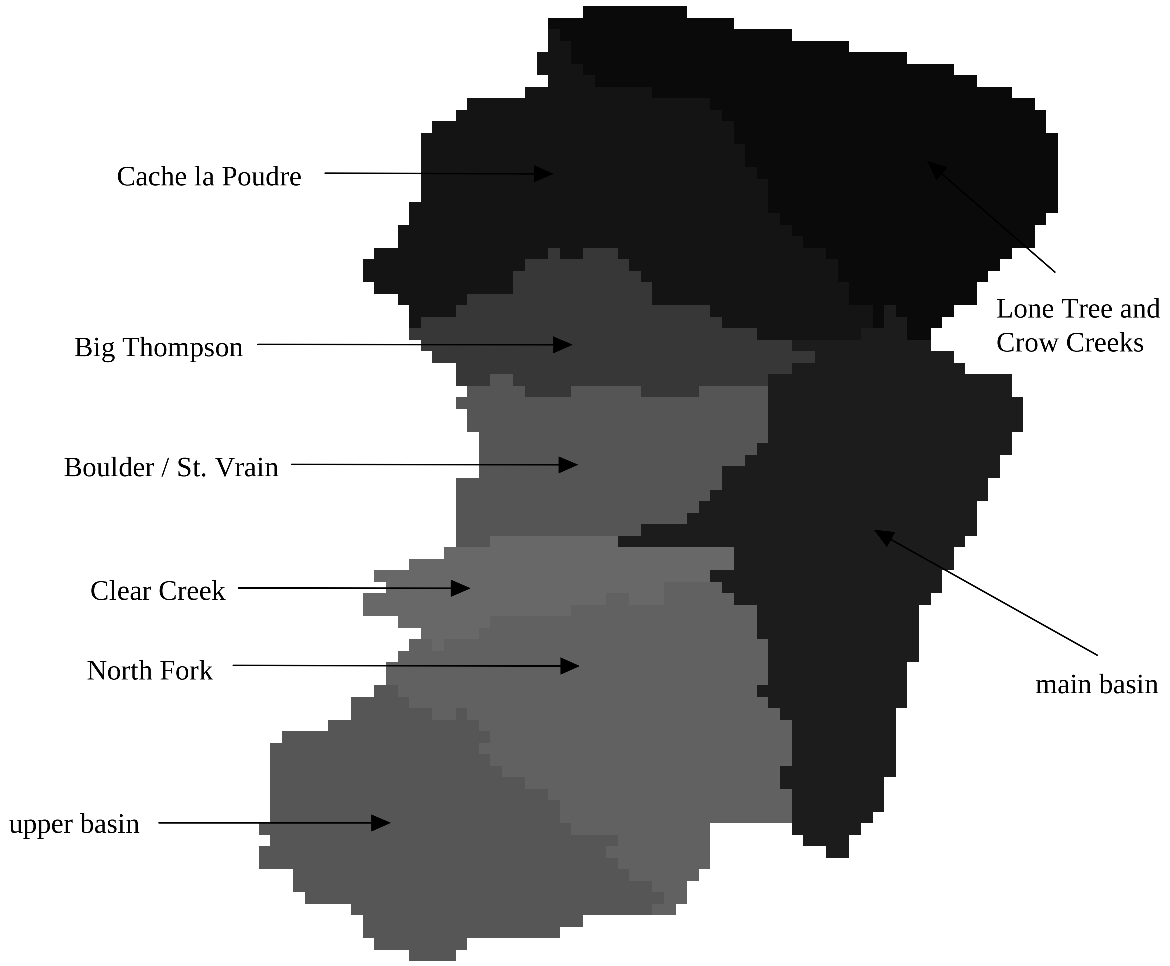


Figure 5.1. *Hydrologic sub-basins according to USGS delineation.*

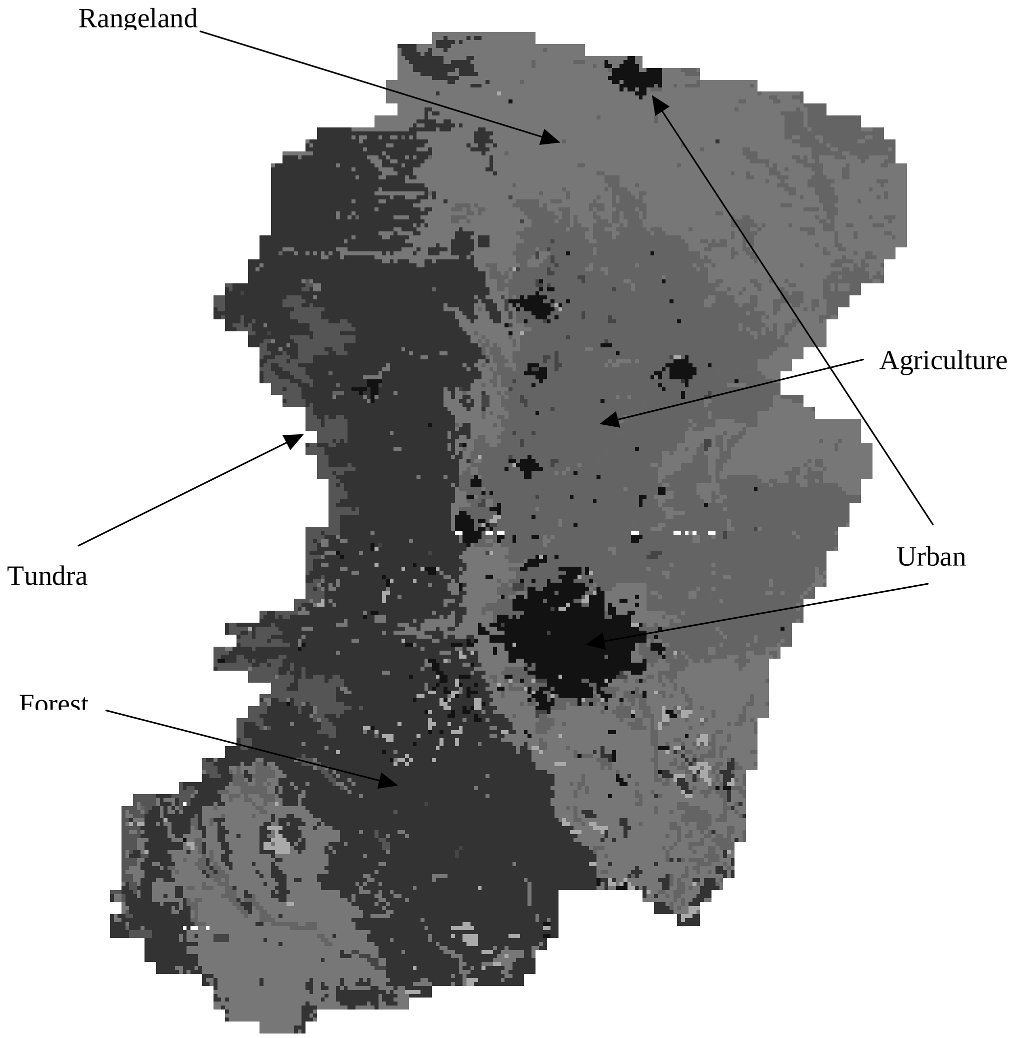


Figure 5.2. *Land-Use from USGS digital maps with some class aggregations*.

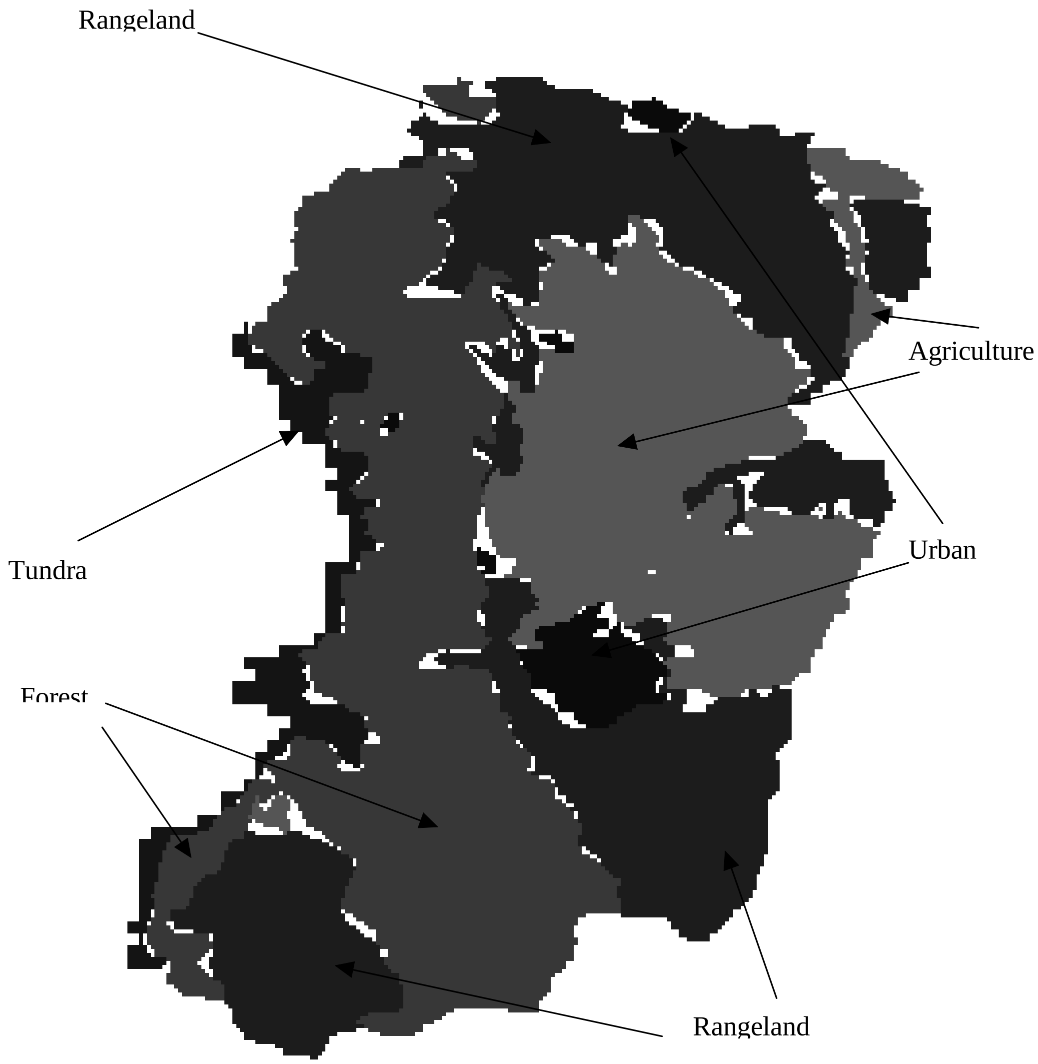


Figure 5.3. *Land-use digitized into the five land classes.*

Table 5.3. *Areal-weighted average* S_{max} *values for the hydrologic sub-basins.*

Hydrologic Sub-Basin	S_{max} (mm)
North S. Platte	1714
Cache la Poudre	1965
Main Basin	1968
Big Thompson	1985
Boulder / St. Vrain	2042
Clear Creek	1506
North Fork	1780
Upper S. Platte	1679

The model was calibrated using flow data at Masters available from the United States Geological Survey (USGS). Daily discharge data were given from December of 1976 to September of 1988. The long-term average discharge for each month was computed and then used for calibration. Precipitation and temperature data were obtained from the Global Historical Climatology Network of NOAA (Vose *et al.*, 1992). There were approximately 40 climate stations which were used in a GIS to obtain interpolated images of precipitation and temperature data. These images could then be overlaid by the sub-basin image to determine average precipitation and temperature data for each month over each sub-basin. Further climate data, including relative humidity, windspeed, and number of hours of sunshine in a day, were obtained from the Leemans and Cramer (1991) database for the calculation of potential evapotranspiration according to the Penman-Monteith method. The Leemans and Cramer database provides values for the climate parameters on a 0.5° latitude by 0.5° longitude grid. These values were again used to obtain interpolated images in the GIS which then provided a way to determine average monthly values per sub-basin.

Calibration of the Model for the South Platte River Basin

The model was calibrated for two cases, that of the hydrologic sub-basins and that of the land classes. The runoff estimated from these calibrations was very similar. They are shown in Figures 5.4 and 5.5.

Two specific points are notable. First, both calibrations miss the peak slightly. It was believed that this was due to precipitation gauges being at low elevations in the basin, and this theory was tested for the land class calibration by increasing precipitation over tundra by 8% and forests by 3%. These slight increases were enough to catch the peak.

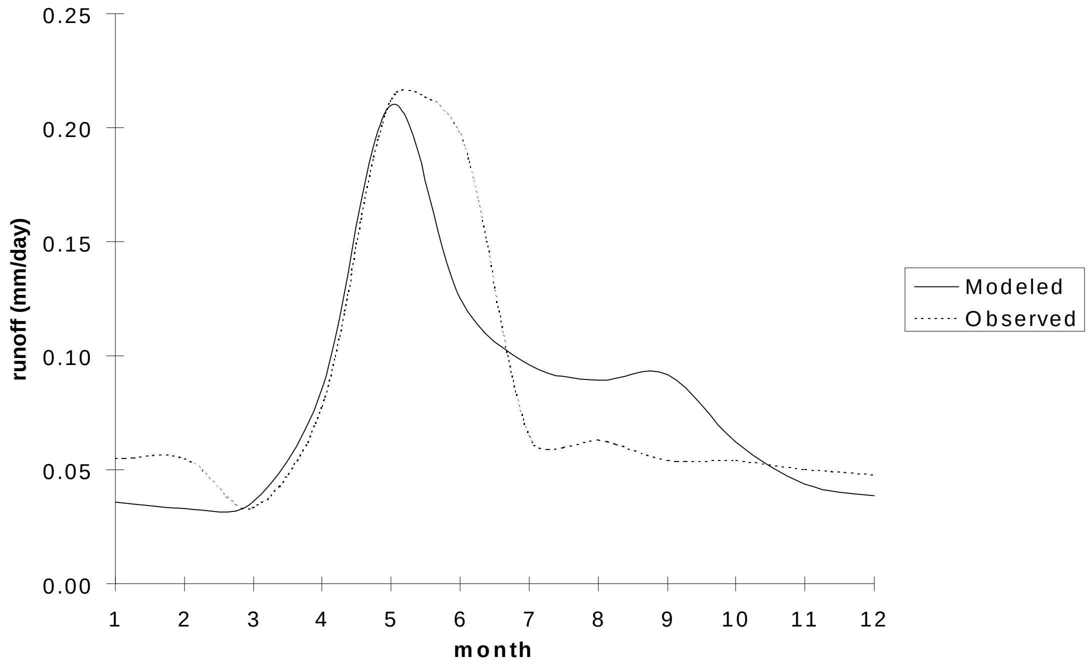


Figure 5.4. *Calibration using the eight hydrologic sub-basins.*

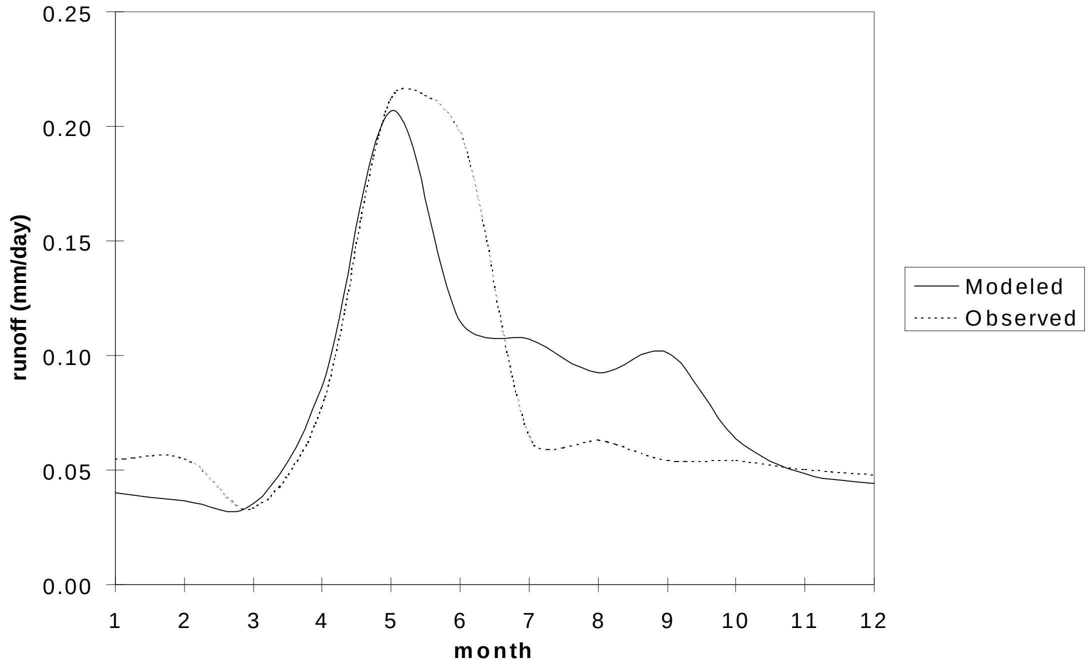


Figure 5.5. *Calibration using the five land classes*.

Second, the fall of the observed hydrographs are not followed well by the simulated hydrographs. This is due to management in the basin which was not accounted for in the model. Specifically, there are many diversions in the South Platte Basin in the growing season for irrigating agriculture. Also, the Colorado-Big Thompson Project carries water from the Colorado River in western Colorado through the mountains to the eastern plains. This water is obviously not accounted for by climatic variables, but it is included in the flow measurements at Masters. It is believed that the width of the peak on the observed hydrograph is due to this influx of water to the basin. Since this paper was intended for analysis of changes in the volume of water in the basin, and since the rise of the hydrograph was matched quite well, it was felt that the differences mentioned above were no hindrances to further analysis.

6. Changes in Climate and Land Use

According to the Intergovernmental Panel on Climate Change (IPCC, 1996), there has been an increase in atmospheric concentrations of greenhouse gases and aerosols since the beginning of the industrial era around 1750. They state that fossil fuel combustion and changes in land use (although to a smaller extent) account for anthropogenic carbon dioxide emissions, with agriculture being responsible for almost half of methane and more than two-thirds of nitrous oxide emissions generated by humans. Although experts do not yet agree on the impacts of climate change for specific regions, it is quite clear that water resources can be gravely affected by rising temperatures and changing precipitation patterns. Some areas may experience increased precipitation leading to greater flooding, while others may be faced with extreme droughts. In some snowfed basins the spring runoff peak might occur earlier in the year due to higher temperatures, thus affecting agricultural seasons. Certainly the agricultural sector could change drastically in areas that depend on irrigation for watering crops. Additionally, land-use changes, such as deforestation or converting rangeland to urban development, have the potential to impact runoff by changing the nature of a watershed.

Climate Change

Given the uncertainty in whether precipitation will increase or decrease in specific areas, one method for examining potential effects of climatic change is the use of a sensitivity analysis. This method creates several scenarios, such as an increase in temperature of 4°C with a decrease in precipitation of 20%, and analyzes the impact of each case on the runoff in a watershed. In the present analysis, three temperature scenarios (no change, +2°C, and +4°C) were combined with five precipitation scenarios (no change, ±10%, and ±20%) to make fifteen scenarios which were analyzed for each of three cases: (1) multiple basins with hydrologic boundaries, (2) multiple land-use classes, and (3) for comparison, the entire basin as a whole using the original WatBal model. The results are presented in Table 6.1.

Table 6.1. *Results for climate change sensitivity analysis, given as percentage change of annual runoff from base (T+0, P+0%) for each case.*

ΔT (°C)	ΔP (%)	Case 1	Case 2	Case 3
+0	-20	-30	-33	-33
+0	-10	-16	-17	-17
+0	0	0	0	0
+0	+10	+17	+19	+19
+0	+20	+37	+39	+40
+2	-20	-34	-38	-41
+2	-10	-21	-24	-28
+2	0	-6	-8	-13
+2	+10	+9	+9	+3
+2	+20	+27	+28	+21
+4	-20	-38	-43	-48
+4	-10	-26	-30	-36
+4	0	-12	-15	-23
+4	+10	+2	+1	-9
+4	+20	+18	+18	+6

It can be seen that Case 3, which gives the projected impacts of climate change for the basin as a whole, tends to be the most extreme case. It is notable that under the T+4/P+10 scenario, Case 3 projects a decrease of 9 percent, while the two more distributed scenarios estimate slight *increases*. An analysis of the S. Platte using the entire basin leads to the conclusion that climate change could bring about drier droughts and wetter floods than predicted with the other cases. It should be noted that with 10 or 20 percent decrease in precipitation many of the projections depict decreased flows of from 25 to almost 50 percent, which amounts to a drastic decrease in water supply. Figures 6.1a-c present the results of the three cases in graphical form.

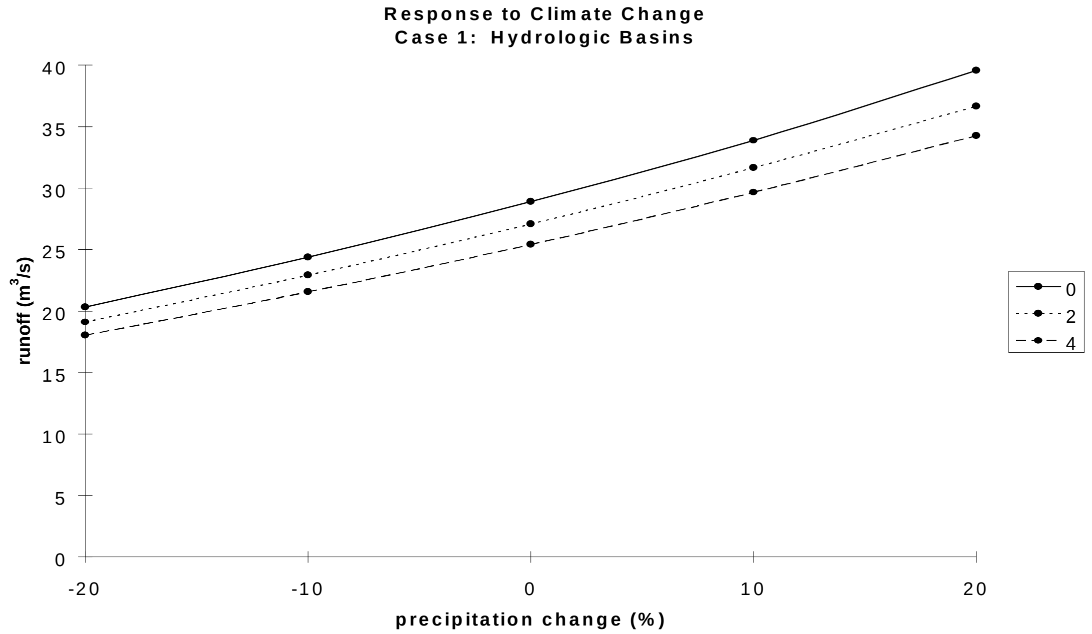


Figure 6.1a. *Results of climate change analysis for the S. Platte Basin modeled as multiple basins using hydrologic boundaries. Lines represent temperature scenarios.*

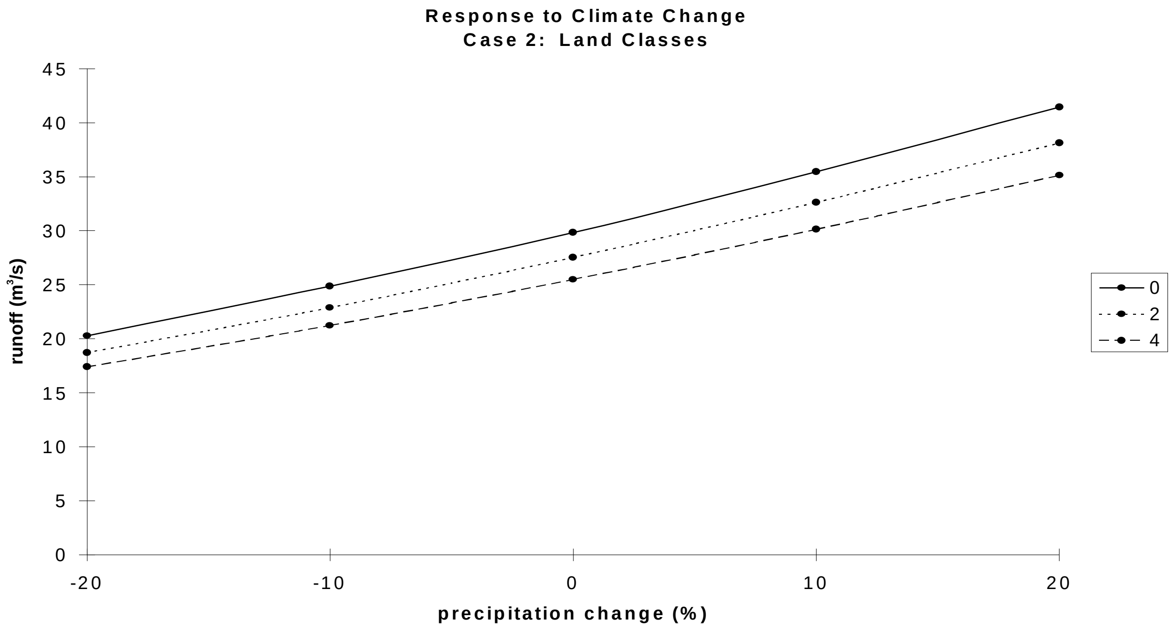


Figure 6.1b. *Results of climate change analysis for the S. Platte Basin modeled as multiple land-use classes. Lines represent temperature scenarios.*

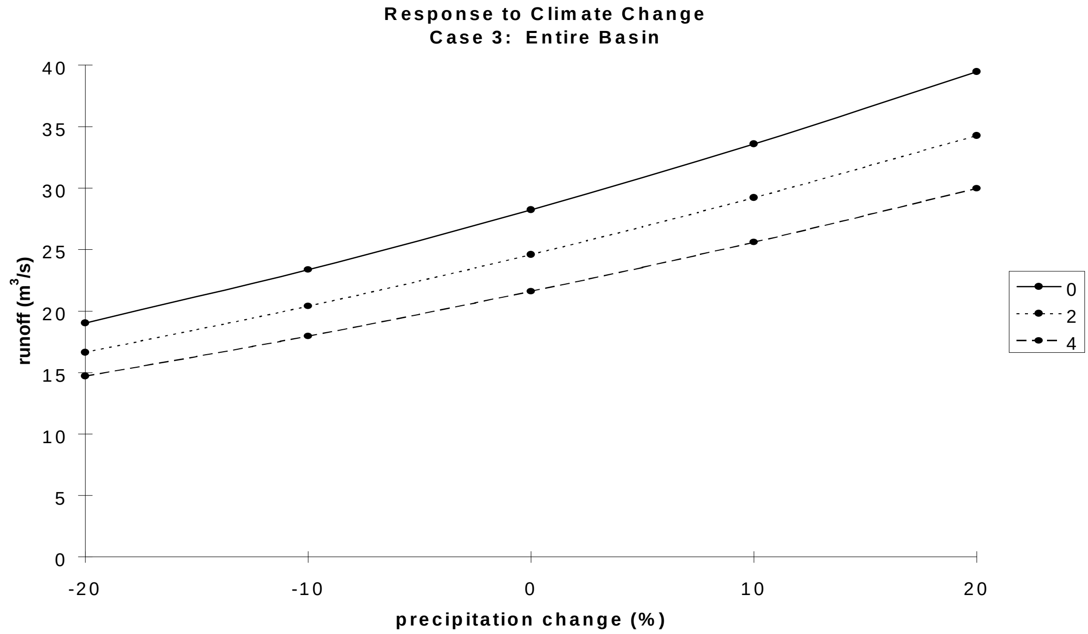


Figure 6.1c. *Results of climate change analysis for the S. Platte Basin modeled as a whole (using the original WatBal model). Lines represent temperature scenarios.*

Land-Use Change

A hypothetical scenario was developed in order to test the potential impacts of land-use change in the South Platte Basin. In this scenario, an urban corridor was created along the Front Range from Fort Collins to the southern part of the basin near Castle Rock. It was assumed that an urban area so large would put great stress on the water supply, and that irrigated agriculture would be foregone for the municipal needs of the metropolis. Thus, all agricultural land not consumed by urban development was transferred to the rangeland class. The last change made was in the South Park area southwest of Denver. Currently it is a large rangeland area which supports a small population. In the hypothetical scenario, a small core of rangeland at the center was left intact, and the rest was considered to have been re-seeded and left to become forested land. The land classes used in the hypothetical scenario are shown in Figure 6.2. The percentages of the basin area in each land class under the current and hypothetical land-use scenarios are shown in Table 6.2.

Table 6.2. *Distribution of S. Platte Basin to land classes under current and hypothetical land-use scenarios.*

Land Class	Current Scenario	Hypothetical Scenario
Urban	2.6	14.3
Tundra	4.3	4.8
Rangeland	33.1	39.3
Forest	31.3	35.6
Agriculture	22.4	0.0

Note: The percentages do not add to 100% because the digitization of land-use basins left a small part of the basin unaccounted for. The discrepancy in percentage of tundra is also due to digitizing error.

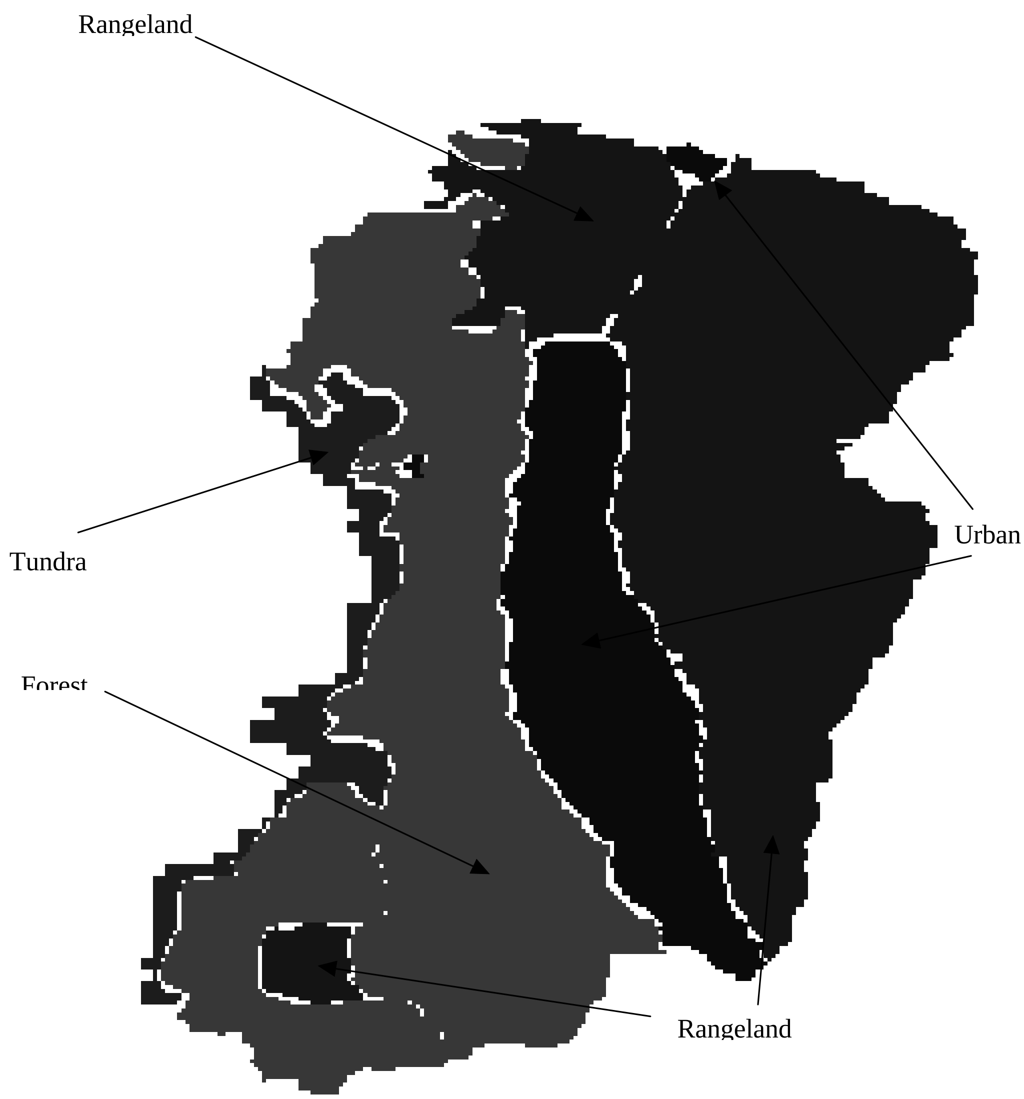


Figure 6.2. *Land-use under the hypothetical land-use change scenario.*

Table 6.3 shows the values given to S_{max} in the hydrologic sub-basins under the hypothetical scenario, as well as the values from the current scenario. Though all the values dropped (except one), they still do not span a very wide range, because many of the sub-basins are made up of several land classes.

Table 6.3. *S_{max} values under the hypothetical and current scenarios.*

Hydrologic Sub-Basin	S_{max} (mm)	
	Hypothetical	Current
North S. Platte	1494	1714
Cache la Poudre	1568	1965
Main Basin	1324	1968
Big Thompson	1407	1985
Boulder / St. Vrain	1284	2042
Clear Creek	1364	1506
North Fork	1554	1780
Upper S. Platte	1866	1679

The overall effect of the hypothetical land-use scenario is shown in Figure 6.3 for the hydrologic sub-basins (Case 1) and Figure 6.4 for the land classes (Case 2). By comparing the two figures, it can be seen that the two cases provided significantly different results. Case 1 showed almost no impact due to land-use change — some months predicted slight decreases in flow of 1 to 2%. However, the effect of land-use change on the land classes was to *increase* the runoff volume, as shown in Figure 6.4. The increase ranges from 8% in March to 25% in May. The result for the land classes is the one which makes sense intuitively, because a dramatic change in the hypothetical land-use scenario was to increase urban land from 2.6% to 14.3%. This change increased the amount of impervious land, and thus increased river runoff. Also, all agriculture was removed in the hypothetical scenario. Agricultural land had the highest S_{max}, which means it had the greatest capacity to hold water among the land class types. Therefore, decreasing the agricultural land would also tend to increase runoff.

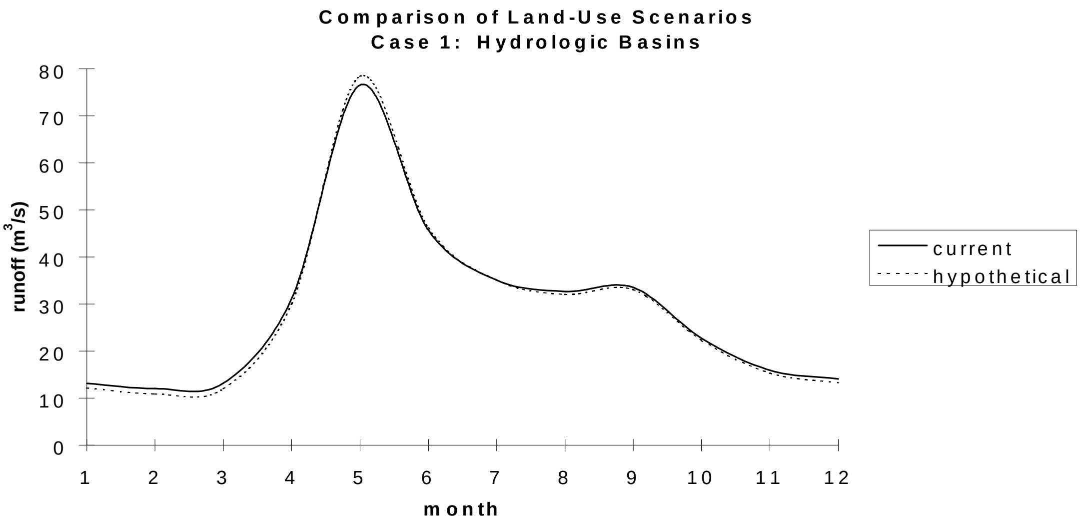


Figure 6.3. *Effect of hypothetical land-use scenario on the annual hydrograph for the hydrologic sub-basins case.*

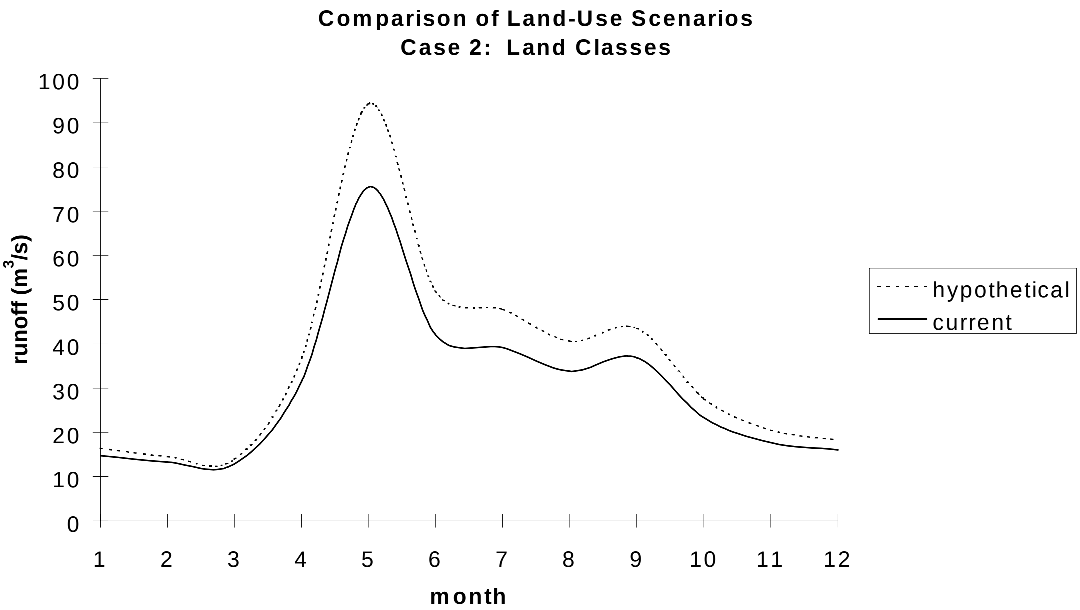


Figure 6.4. *Effect of hypothetical land-use scenario on the annual hydrograph for the land classes case.*

Land Use and Climate Change

The results of the combined scenario for model runs with the hydrologic sub-basins and the land-class basins are presented in Table 6.4, where Case 1 represents the simulations dividing the watershed according to the hydrologic sub-basins, and Case 2 represents the simulations based on a sub-division by land-cover classes. It can be seen that there is a big difference between the percentage changes in the two scenarios. Under all scenarios, Case 2 projects more water in the river. Thus, it estimates always smaller decreases or greater increases in runoff. To further show the effects of land-use change separately from climate change, Table 6.5 presents the respective differences between the combined climate/land-use change scenarios and climate change only scenarios.

Table 6.4. *Results for combined climate/land-use change scenarios, given as percentage change of annual runoff from base (T+0, P+0% under climate change only) for each case.*

ΔT (°C)	ΔP (%)	Case 1	Case 2
+0	-20	-31	-20
+0	-10	-17	-1
+0	0	-1	19
+0	+10	+15	+42
+0	+20	+35	+66
+2	-20	-35	-26
+2	-10	-22	-9
+2	0	-8	+10
+2	+10	+8	+30
+2	+20	+25	+53
+4	-20	-39	-32
+4	-10	-27	-16
+4	0	-14	+1
+4	+10	+1	+20
+4	+20	+17	+41

Table 6.5. *Land-use impact on the combined climate/land-use change scenarios, given as difference of percentage of annual runoff from base (T+0, P+0% under climate change only) for each case.*

ΔT (°C)	ΔP(%)	Case 1	Case 2
+0	-20	-1	+13
+0	-10	-1	+16
+0	0	-1	+19
+0	+10	-2	+23
+0	+20	-2	+27
+2	-20	-1	+12
+2	-10	-1	+15
+2	0	-1	+18
+2	+10	-2	+21
+2	+20	-2	+25
+4	-20	-1	+11
+4	-10	-1	+14
+4	0	-1	+17
+4	+10	-1	+20
+4	+20	-2	+23

The difference is clearly seen in Table 6.5. Case 1, which performs the analysis based on hydrologic sub-basins, predicts slight decreases to the climate change scenarios due to the effect of land-use change. However, Case 2 estimates increases due to land-use change of up to 25 percent! Based on the results of the land-use change scenario (see Figure 6.3), and based on the nature of the changes in the hypothetical land-use scenario, Case 2 gives a more plausible result: more water in the river. Thus, the analysis of the basin using hydrologic boundaries to delineate sub-basins tends to mask the effects of land-use change. This result makes sense when the layout of the South Platte Basin is considered. There are several hydrologic sub-basins that have headwaters in the mountains that flow out to the plains. These basins have similar percentages of diverse land-use types (see Table 6.6; for example, compare Boulder/St. Vrain and Big Thompson), and thus, due to averaging of parameters, they would tend to mask the effect of land-use change.

Table 6.6. *Distribution of land use by hydrologic sub-basin given as percentages of sub-basin area under hypothetical land-use scenario. Numbers in parentheses are the percentages from the current land-use situation.*

	Land-use Type			
Basin	Urban	Tundra	Range	Forest
North S. Platte	1.7 (1.8)	0.0 (0.0)	96.0 (73.8)	2.3 (2.4)
Cache la Poudre	8.8 (0.6)	5.1 (4.7)	47.8 (24.7)	38.3 (39.4)
Main Basin	17.6 (5.2)	0.0 (0.0)	85.4 (42.8)	0.0 (0.0)
Big Thompson	26.4 (0.7)	11.1 (9.4)	12.8 (8.5)	49.7 (51.1)
Boulder / St. Vrain	35.5 (1.0)	10.9 (9.0)	10.6 (5.1)	43.0 (46.7)
Clear Creek	22.7 (11.1)	24.7 (23.1)	0.0 (11.6)	52.6 (52.5)
North Fork	27.1 (4.8)	3.3 (3.0)	0.0 (22.6)	69.6 (69.6)
Upper S. Platte	0.0 (0.0)	6.9 (5.8)	10.1 (51.8)	83.0 (40.9)

A way to examine the magnitude of impacts due to land-use change is to compare it to a commensurate climate change scenario, which can be done by comparing Table 6.5 with Table 6.1. For example, the 19 percent change in runoff due to land-use change estimated for Case 2 (T+0/P+0 in Table 6.5) is comparable to the climate change scenarios in Table 6.1 of T+0/P+10 or T+4/P+20. In other words, the impact of land-use change is of the magnitude of a 10 percent increase in precipitation without any concurrent rise in temperature, or a 20 percent increase in precipitation with a 4°C rise. Other values in the two tables are also comparable. Therefore, the magnitude of land-use change is of the same order as that of climate change, and thus it appears to be an important factor to consider in making estimates of future runoff.

7. Conclusions

A statement made by Franchini and Pacciani (1991) sums up the challenge faced by hydrologic modelers that this paper has striven to meet:

> A conceptual model must balance two contrasting demands: on the one hand, to present the greatest structural simplicity, and on the other to continue to respect the physics of the problem, thereby making it possible to use prior knowledge of the geomorphological nature of the watershed in calibrating parameters. This last aspect is of fundamental importance in the regionalization phase, i.e. when watersheds without flow measurements are studied.

An aim of this research was to take a step towards making the WatBal model based completely on physical parameters, hoping that eventually the model can be used in ungauged basins.

Another goal of this analysis was to make a comparison between modeling a basin using sub-units delineated by hydrologic boundaries and modeling it using noncontiguous areas based on land-use type. The conclusion of this analysis is that nothing was lost by using noncontiguous areas; further, there was a gain in that the results were based on runoff responses from more hydroclimatologically homogeneous areas. Using average values for parameters such as S_{max} in the hydrologic sub-basins, especially when multiple land classes were present in the sub-basins, prevented the analysis from truly reflecting land-use change. Effects which can be masked when modeling with purely hydrologic boundaries are uncovered when using more hydroclimatologically homogeneous areas based on land classes, such as the impacts of the hypothetical land-use change scenario analyzed in this research effort.

The focus on climate change research is expanding and needs to continue to expand to provide a more comprehensive look at changes due to other factors, such as land use, population dynamics, and economic influences. The LUC project at IIASA is an example of a research focus that is incorporating multiple factors in its analyses. The consequences of these changes must be considered as a whole, because individual impacts may act to mitigate, worsen, or enhance the effects of other changes. In particular, it will be crucial for basin managers to consider comprehensive changes. In the example of this paper, if anticipatory policies or actions were being considered to adjust to impending impacts of climate change (for example, decreased runoff), it would be important to consider that potential land-use changes could act to mitigate the effects of the climate change and thus lessen any financial investment required to institute such policies or actions.

Further Research

A goal of this research was to turn the WatBal-LUC model into one that can be used in areas with poor data provision, specifically watersheds without gauges to indicate runoff. This paper has provided the first step in associating the calibration parameters with physical aspects of a basin by setting the maximum soil moisture capacity (S_{max}) based on land-use type. The next step or steps to be taken are to establish a physical basin connection for the other two calibration parameters: ε and α, the unsaturated zone exponent and the saturated zone coefficient, respectively. It is surmised that both parameters can be correlated to soil type (e.g. sand or clay), and ε possibly also to slope and vegetation cover.

Further, it became clear through the course of this analysis that elevation-sensitive data are quite important for basins with a large range of altitudes. In many cases, precipitation gauges and temperature stations are at low elevations in a basin, and they tend to indicate warmer temperatures and lower precipitation than actually occur at higher altitudes. In conjunction, it is important in lumped models to separate the basin with respect to differing elevations, so that the differences in temperature and precipitation can be properly reflected. In many basins, land-use type can provide such an altitude-sensitive basin delineation.

The initial tests reported here for the South Platte basin with a geographically somewhat disaggregated specification of WatBal has clearly demonstrated the importance of both altitude ranges and land-cover characteristics. It has therefore been decided to implement a hydrologic model for the Yellow River basin that will operate on a raster of 5 by 5 km (or 10 by 10 km) grid-cells at which climatic data, soil and landform attributes and land-cover data have been compiled. To the extent possible, and meaningful, the model parameterization will capture the variations in soil and sloping conditions, and land cover.

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