Frontispiece

The geologists, the earth scientists, have given us a beautiful and elaborate picture of the planet's formation and development; they have constructed a time scheme with which they can diagram, as with an overlay, each evolutionary step in the long process. But all that, I maintain, is merely information. It is not knowledge; even less is it understanding. Knowledge and understanding, even though based on information as an essential component, require more, namely feeling, intuition, physical contact – touching and sympathy and love. It is possible for a man and a woman to know and understand one another, in this complete sense. It is possible to know, though to a lesser degree, other living things – birds, animals, plants. It is even possible to know, through love, a place, a certain landscape, a river, canyon, mesa, mountain. But knowledge – I insist – is not possible through science alone.

Edward Abbey
Abbey's Road

THESIS

THE EFFECTS OF INPUT DATA DEGRADATION ON HYDROLOGICAL MODEL PERFORMANCE FOR A SNOWMELT DOMINATED WATERSHED

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY SCOTT D. MCKIM ENTITLED THE EFFECTS OF INPUT DATA DEGRADATION ON HYDROLOGICAL MODEL PERFORMANCE FOR A SNOWMELT DOMINANT WATERSHED BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

THE EFFECTS OF INPUT DATA DEGRADATION ON HYDROLOGICAL MODEL PERFORMANCE FOR A SNOWMELT DOMINATED BASIN

The quality and quantity of hydrometeorological data used as input to a hydrologic model is varied and the output compared to observed historical flows. Temperature and precipitation data were used to feed the National Weather Service River Forecast System (NWSRFS); this hydrologic model outputs streamflow and is used daily throughout the country to forecast streamflows. NWSRFS is a lumped empirical model developed in the 1970s for the NWS and is calibrated in this study to model a portion of the snowmelt dominated Yampa River watershed in northwest Colorado. An analysis scheme is followed to capture the model's dependence on representative meteorological stations located in an around the modeled basin.

Many regions in the United States experience meteorological and hydrological data scarcity issues. Operationally this becomes important when the available data is insufficient enough to produce reliable model outputs. Similar to Tsintikidis *et al.* (2002) concluding that the installation of additional rain gauges in a modeled basin would decrease the error of precipitation measurements in the model, we sought to find if increasing data input into a model, both the quantity and quality given by site representivity, will increase the accuracy of our model runs.

The study basin was chosen for its snowmelt dominance characteristic. Mean areal precipitation and temperature values for the modeled zones are developed individually in each analysis scheme by the arrangement of stations used in each sensitivity analysis. A statistical analysis of the relative difference between model runs and archived observed values is performed in an effort to illustrate the effect of different model input data arrangements on model simulations. This study aimed at testing the tenable assertion that subtracting hydrometeorological data from a model's dataset would decrease the accuracy of forecasted stream flows from that model. Stream flows and snow water equivalence are analyzed to test the model's sensitivity to the amount of data used.

Since the NWSRFS uses predetermined weights to determine MAPs, the number of stations used does not significantly affect model output. The usage of predetermined weights maintains a consistent year-to-year MAP. Varying the MAT station configuration showed a more sizeable effect than the MAP scheme illustrated.

Though this procedure could and should be replicated for other hydroclimates and for basins with different sizes, the specific results are not transferable to other basins. The basin modeled is very heavily snowmelt dominated; this quality, as well as it size, climate, topography, and available hydrometeorological stations all influence model results; altering any of these would change the model performance.

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In Gratitude

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1. INTRODUCTION

The seasonal accumulation of snow in mountain areas of the American West accounts for a substantial portion of the West's water supply. Across much of the western United States, snowmelt is a major contributor to spring runoff, often dictating the magnitude and timing of peak annual flows. Specifically in mountainous regions, 75% of river runoff is attributed to snowmelt (Doesken and Judson, 1996); Gray and Prowse (1993) estimated that 85-90% of the annual streamflow in mountainous areas of California is provided by snowmelt. As populations continue to rise in arid regions of the American West, water supplies are at the center of many political, economic, social and environmental debates. Being able to forecast water supplies is of paramount importance as water resources in the West continue to be taxed by an ever-growing demand. Hydrologic models, requiring both meteorological and hydrological data, are often employed to forecast water supplies and stream levels throughout the nation. Such models are at the mercy of the quality of the input data that are used to feed them.

Prompted by the nation's economy being increasingly dependent on river and flood forecasting, in the late 1800s the United States Congress created a stream and river gauging program, as well as a weather observation and forecasting program. Today the National Weather Service (NWS) is responsible for issuing public weather forecasts, fire weather forecasts, aviation forecasts, and in the West together with the Natural Resource Conservation Service (NRCS), hydrological forecasts. Hydrology efforts within the NWS are divided into two main functional groups, the Weather Forecast Office (WFO) and the River Forecast Center (RFC). There are 13 RFC's in the country, each assigned to a major river basin and geographical area and together they are mandated to provide forecasts for the entire United States. Daily forecasts are issued at over 4,000 locations from hydrometeorological data inputted in a hydrologic model (NCDC, 2004).

Within the coterminous U.S., a dense network of recording stations (350 stations per 10^5km^2) provides an ample quality and quantity of continuous meteorological and hydrologic data. These data are used by NWS models to initialize meteorological and hydrological models intended to forecast future states of the atmosphere and streams. Despite advances in hydrological and meteorological modeling in past decades, models are often not sufficient in replicating natural phenomenon at different spatial and temporal scales (Singh, 1981). Inadequate quality and quantity of input data and the insufficient representation of the physical controlling processes in models contribute to operational model deficiencies (Anderson and Bates, 2001). Despite the wide usage of lumped and empirically based models, many hydrologic models used operationally today are more limited in their performance by input data than by the representation of the physical processes. The concern of insufficient input data for models is accentuated in areas with data paucity. These are primarily regions with low population density and significant topographic obstacles, preventing installation and maintenance of weather stations due to difficult access and prohibitively large costs. Examples of such areas in the United States include regions near the Continental Divide of the Rocky Mountains, the vast unpopulated regions of Alaska, and modeled areas over the oceans.

Shiklomanov *et al. (*2002) showed that gauge decline in Pan-Arctic regions resulted in a hydrologic gauge density of 9.3 gauges per 10^5 km^2 across the North American arctic area. The density of hydrometeorological stations in Alaska is much less than in the coterminous U.S., limiting the tools and clues by which forecasts can be made for Alaska. Currently Alaska has a station density of 66 stations per 10^5 km^2, which is 19% of the density across the coterminous U.S. (Shiklomanov *et al.,* 2002). Alaska is charged with making river forecasts based on much less data than the coterminous U.S. have available. It is a result of the data scarcity issue in Alaska and much of the mountain west compared to the rest of the U.S. that the idea for this study was born.

The aim of this study is to illustrate the effect that model input data has on streamflow simulations in a snowmelt dominated basin through a comparison of various model runs. Tsintikidis *et al. (*2002) and St-Hilaire *et al. (*2003) showed that denser networks more accurately quantify precipitation estimation. At some point, the rate of increase was expected to diminish with continued increase in input data. Operationally this issue of optimized data networks becomes significant with the finite financial constraints inherent in data collection and operational hydrology, and raises the question of how the operational community can gain the greatest improvement in model performance for the least amount of financial investment.

2. BACKGROUND

Hydrologic models infused with hydrometeorological data are often used to forecast river heights and streamflows. There are numerous hydrologic models in use today in the operational and academic/research communities. The U.S. Army Corps of Engineers, the United States Geological Survey, universities, and even private engineering and environmental firms have their own models suited to their interests in hydrology. Ensuring the quality of the data that is used in any hydrologic model is crucial to making accurate and reliable forecasts as the models are only as good as the data used to drive them.

The first step to developing a model or using a model is to identify the key objectives of the model. Models are then used with this objective in mind; assumptions, input parameters, data, and output are all developed. The model must then be ‘fit’ together; data must be gathered and analyzed and input parameters must be estimated. When the model is constructed, it must be validated against known natural processes. After this step, the model is usually implemented and the model results are then analyzed and the sensitivity is tested.

2.1 HYDROLOGIC MODELING

The technique and process of modeling is used by various users to better understand, forecast, and manage complex systems. Within the hydrology realm, models are an approximation of an actual hydrologic system, including inputs and outputs that are measurable hydrologic variables concerning atmospheric, land surface, and subsurface variables. Within a model, the physical basin is assumed to be constant; topography, vegetation, land cover, and digital elevation models are often included in the model structure. The structure of a model is a set(s) of equations linking the inputs and outputs. Environmental models, to include hydrologic models, are usually calculated by computers, and applying these models, a user can better understand temporal and spatial hydrologic systems by forecasting, reproducing and estimating hydrologic phenomenon. Most often models are used in a forecasting realm, to allow extrapolation across time, and in some cases space, to understand and predict situations where no measurements are available.

The duty of river forecast models is to estimate the amount of runoff a precipitation event will generate, compute the routing of the water from one forecast point to another, and to predict the flow of water at a given forecast point throughout the forecast period. In many areas the existence of snow, both on the ground and in the form of precipitation, needs to be considered by the forecaster when evaluating the potential response of the modeling system to input time series. Knowledge of the snow extent within the forecast area, both location and how much, as well as the form of recent precipitation, is required by the hydrologic forecaster. These data are available from several sources of information, such as the National Operational Hydrologic Remote

Sensing Center (NOHRSC). Like any model user, a forecaster should have a good sense of how the hydrologic modeling system is expected to respond to data inputs during various snow-related situations in which adjustments might be needed for incorrect model responses.

The most accurate modeling of snow-related processes requires a number of variables, such as incoming solar radiation, albedo, the reflective properties of surfaces, incoming long wave radiation, wind speed, vapor pressure of the air, air temperature and precipitation. Together these variables account for the physical processes that affect a snowpack. However, in general, the only readily available data (in real-time mode) are precipitation and temperature. Acquiring the other variables in a real-time mode across the United States is difficult or impossible. With this in mind, in the simulation of snow-related processes, air temperature is commonly used as an index that represents the other variables. This approach has been shown to work reasonably well (Anderson, 1968).

The process of a modeling a natural system can incorporate a few different types of models. Models with distributed parameters take advantage of being able to assign variable parameter values and have the ability to model multiple points within the basin. Lumped models assume a constant value for model parameters, and thus lack some of the heterogeneity of model parameters that actually occur in the natural system. Stochastic models involve a random variable that is used to drive process-oriented phenomenon in the model. A deterministic model has no probabilistic nature, but rather describes a system whose time evolution can be predicted exactly. Lastly, physically based models are based on actual physical explanations of natural phenomenon through mathematical calculations in the model. Empirical based models are based on developed relationships between variables and phenomenon, but have no physical basis.

2.1.1 National Weather Service River Forecast System

The National Weather Service (NWS) River Forecast Centers (RFC's) currently use the River Forecast System (NWSRFS) package as its main operational hydrologic forecast tool to make streamflow forecasts. NWSRFS is a collection of interrelated computer programs and data stores that in tandem act as a data analysis and forecast production tool. Original documentation of the initial version, developed in 1971 was published as *NOAA Technical Memorandum NWS Hydro-4, National Weather Service River Forecast System River Forecast Procedures* by the Hydrologic Research Laboratory (1971). NWSRFS is a lumped model, capable of end-to-end processing, ranging from data collection to forecast production. The NWSRFS currently serves many of the needs of the National Oceanographic and Atmospheric Administration's RFCs, which provide much of the hydrologic guidance for national public warning purposes. NWSRFS is composed of three main functional systems, the Operational Forecast System (OFS), Calibration System (CS), and the Ensemble Streamflow Prediction (ESP) System, all utilizing the same hydrologic and hydraulic models (see Figure 2-1). These models describe the equation of motion and the flow water through the hydrologic cycle, including snow processes, rainfall/runoff, and river channel routing operations.

The Calibration System exists to allow the forecaster to resolve model parameters at a forecast point. The CS runs the hydrologic models based on historical data for the forecast point. The forecaster can then compare the historical observed and simulated streamflows to make adjustments to the model parameters to match the simulated to the observed streamflows, as best as possible. It is during this process that a calibration deck is made in order to run the model. The calibration deck is a file that serves as the actual code compiled in the computer to execute, or ‘run’, the model. This file contains all the input and output data paths, internal operations and model parameters needed to run the model. See Appendix E for an example of a calibration deck file.

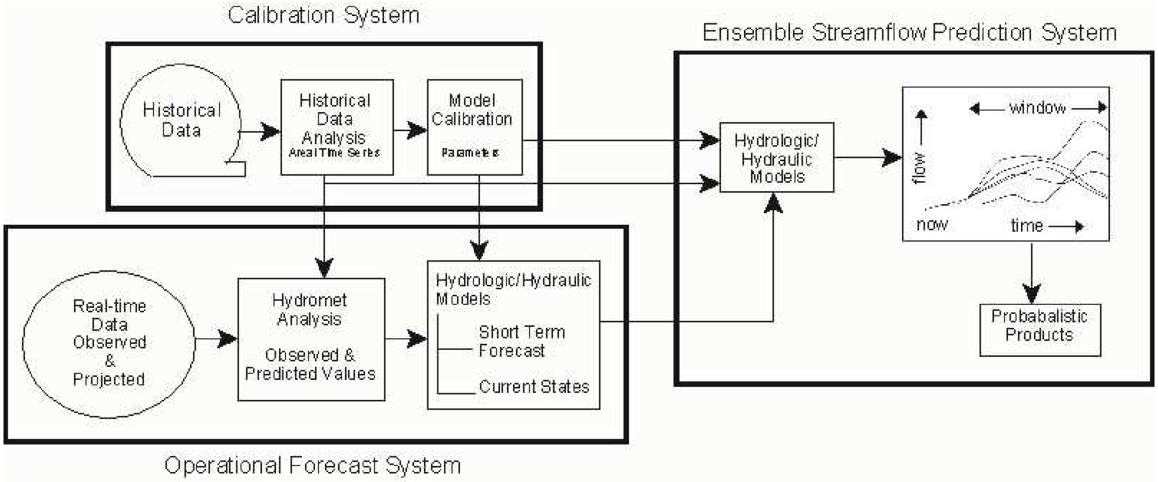

Figure 2-1. NWSRFS Functional Structure

LAG/K is a subroutine used within NWSRFS that provides a computerized solution to the Linsley *et al.* (1975) graphical routing technique. It is used as a method of storage routing between flow points on a river, and has the capability to lag flow in time and attenuate peak river flows. Both the lag in time and attenuation in peak can be set to constant or variable values (NOAA, 2002a).

The Interactive Calibration Program (ICP) is a graphical interface and display program that works with the CS. The ICP displays the observed and simulated streamflow values and can display the detailed information about the state variables of internal models, such as the NWSRFS Snow Accumulation and Ablation Model (SNOW-17), the Sacramento Soil Moisture Accounting Model (SAC-SMA), and the unit hydrograph subroutine (UNIT-HG). These models are three of many modular units within NWSRFS than can be used singly or in combination for simulating various parts of the hydrologic cycle. The detailed output option enables the user to better visualize simulated variables in the model over time, and to assist in determining reasonable parameter changes that should be made. The parameters can then be changed and the calibration rerun to display the new results.

The OFS provides short term (usually out to three days) streamflow forecasts and uses model parameters that were determined from the CS together with real-time precipitation, temperature, snow, hydrometric, and reservoir data to produce the forecasts.

The ESP system uses an ensemble technique to create probabilistic river stage forecasts for mid-long term time scales out to months in advance. Current state variables of the model determined by the OFS and historical time series for model inputs of precipitation, temperature, and potential evaporation are used to simulate streamflow for multiple forecast points. NWSRFS calculates predicted river stages and flows at forecast locations in 6-hour time intervals routinely through 24 hours, with the capability of producing 72-hour forecasts.

The quantity and placement of meteorological stations within a basin, especially mountain terrain, have a great effect on hydrologic flow simulations and predictions (Tsintikidis *et al*., 2002).

2.1.1.1 Data Requirements

NWSRFS requires only two hydrometeorological data time series to produce streamflow simulations: temperature and precipitation. Operationally this is significant because these two data types are readily available throughout the U.S. on a real-time basis. Other data, such as radiation, vapor pressure, wind and soil moisture data are not readily available, thus the NWSRFS is not more complicated and does not compute physically-based ablation.

In addition to the time series of precipitation and temperature data, some static data are used by the model components of NWSRFS to produce streamflow forecasts. The Sacramento Soil Moisture Accounting Model (SAC-SMA) requires knowledge of the porosity of the modeled area's soils to calculate infiltration and runoff. Riparian vegetation area, latitude and longitude of the basin, rain/snow elevation data, lapse rates, and elevations in the basin, among other data, are also required in NWSRFS model operations. Evapotranspiration data and consumptive use data are also utilized in the water balance calculation used to determine areal precipitation values for the modeled zones.

2.1.1.2 NWSRFS Snow Model (SNOW-17)

Since snow is dominant in the study basin being modeled (Yampa River, Colorado), the NWSRFS snow model is used extensively in this study. SNOW-17 is a snow accumulation and ablation model that exists as a subroutine within NWSRFS. While SNOW-17 is a conceptual model, each of the significant physical processes affecting snow accumulation and ablation is mathematically represented in the model (NOAA, 2003). It uses air temperature as the only index to account for energy exchanges at the snow-air interface, and requires streamflow, precipitation, and potential evapotranspiration data to run (Anderson, 1973). SNOW-17 is responsible for most of the output from NWSRFS during winter months in regions where solid precipitation is a significant part of the hydrologic cycle. This model is well documented in the NOAA Technical Memo HYDRO-17 (Anderson, 1973).

SNOW-17 is part of NWSRFS and acts as a conceptual model of the significant physical processes affecting snow accumulation and snowmelt; these pertinent physical processes are represented mathematically in the model. Figure 2-2 shows a flow chart of the model showing each of the physical processes that are included. This flow chart depicts the model's decision tree based on data inputs of temperature and precipitation and whether snow is present on the ground.

Energy exchanges across the snow-air interface are quantified by using air temperature as an index in SNOW-17. SNOW-17 has been tested in several climatic regions across the U.S., and an expected range of values for the calibration parameters was provided for a variety of conditions (Anderson, 1973).

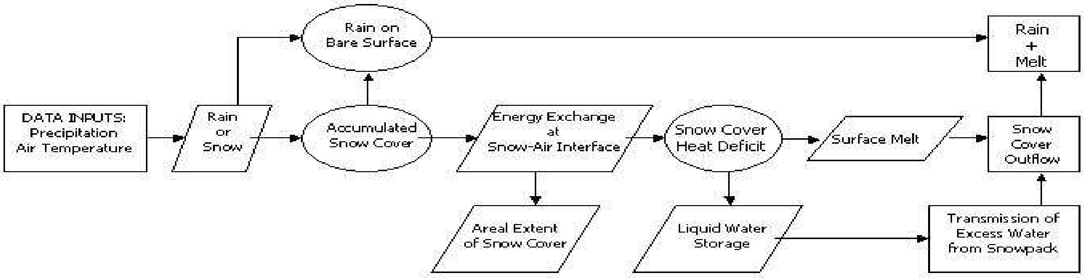

Figure 2-2. SNOW-17 Flow Chart.

2.1.2 Model Evaluation

Scientific knowledge is inherently uncertain. From the initial step of observing natural phenomenon, uncertainty is introduced by the method of measurement and possibly measurement error. When used in a model, this uncertainty and/or error will result in model error. Thus, it is expected that any attempt to reproduce past or future conditions must contain some uncertainty. Model validation must quantify the accumulated effects of both uncertainty and objective model error. Numerical simulations heighten uncertainty because of the phenomenon of non-uniqueness, i.e., when more than one model configuration may produce the same output. According to Anderson and Bates (2001), this can occur as follows:

> *a) numerically, when the possibility of more than one solution to the governing equations exists;*
>
> *b) parametrically, when a wide range of possible model inputs can potentially produce the same output; and*

c) conceptually, when more than one conceptual model may prove adequate to account for the empirical evidence.

All model simulations produce error; understanding the importance and the significance of the sources of error can assist a modeler in improving model simulations. Numerical simulations are fundamentally problematic because most problems in the earth and environmental sciences are inverse, that is, the scientific community knows the configuration of the world but often times lacks the knowledge of the processes and parameters that produce it. In this way, numerical modeling is always faced with the problem of non-uniqueness. Philosophically, it is impossible to demonstrate the truth of any proposition within a system, except in a closed system where all possible explanations and arrangements of the system are known. The natural world is not a closed system and a perfect knowledge of it is impossible. Therefore, validation and verification of model performance is philosophically impossible. A model can only be falsified (Anderson and Bates, 2001). However, our current understanding of the hydrologic system is adequate enough to run the NWSRFS and to generate statistically sound conclusions from it. The model can be calibrated and the results can be used for verification.

2.1.2.1 Model Calibration

Calibration is a method of tuning the model with local historical data. A successful model calibration provides an unbiased reproduction of historical conditions. To do this, the modeler adjusts the parameters that cause the model components to mimic the hydrologic processes they were designed to represent. It is assumed after a successful model calibration, that the model then has the ability to extrapolate beyond conditions encountered in the historical period, and is valid for future time steps and forecasting, if the past is in the same statistical population as the future.

Within the calibration system of the NWSRFS, model parameters are determined and historical time series are created from streamflow and mean areal estimates of precipitation and temperature. Data used to generate the mean areal estimates are obtained from the National Climatic Data Center (NCDC, 2004) archive.

Following the establishment of the historical time series, both manual and automatic procedures are used to develop calibrated parameters for the hydrologic models used in the forecast operations. Automatic procedures generate time series based on historical data, while manual calibration adjustments are made by the modeler to alter parameters that affect the time series. An important assumption to consider in this process is whether the mean areal estimations derived from the historical gauge network are statistically similar to those derived from the operational gauge network (Johnson *et al.*, 1999).

When running a model in calibration mode, systematic errors and biases are assumed to be consistent between model runs. Likewise, the ability of a model to reproduce historical data does not translate into a capacity to predict future conditions. The process of calibration against historical data assumes the representivity of that data, and therefore assumes that the conditions they represent are on-going (Konikow and Person, 1985). For this reason, it is important to make sure that the historical data used in model calibration extends over the full range of natural variability of the system.

2.1.2.2 Model Verification

Assessing a model's performance involves the assessment of an inclusive range of testing procedures required to develop confidence. Comparing prediction with measurement requires consideration of the extent to which the following are true:

> *a) variations in the observations are explained by predictions;*
>
> *b) predictions agree with observations; and*
>
> *c) predictions provide sufficiently reliable information for them to be accepted when there are no data off of which to verify, data that can be forecasted and can be verified against (Anderson and Bates, 2001).*

For hydrologic modeling, an adequate fit test, serving as a qualitative assessment, is useful in comparing predicted and observed discharge hydrographs. When comparing hydrographs of snowmelt dominated areas, it is important to compare peaks, volume and timing between simulated and observed discharges. In snowmelt dominated areas, the annual spring slug of water in the rivers is crucial to agricultural operations and water supply planning, etc. The timing and peak of a hydrograph are quantities of a hydrograph that can be compared and are especially pertinent in snowmelt dominated basins. Snow water equivalent (SWE) is another variable that can be compared between model simulated SWE and observed SWE, as it is the driver of snowmelt and the spring hydrograph increases.

For hydrologic analysis, the coefficient of efficiency (E), also called the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970; Grunwald and Frede, 1999) is often used. It measures the fit between measured and simulated (predicted) values. The computation of E is the sum of the deviations of the observations from a linear regression line with a slope of 1. If the measured value is the same as the simulated value, E is 1. If is E is between 0 and 1, it indicates deviations between the measured and simulated values. The Nash-Sutcliffe coefficient (E) between predicted and measured values can be computed as:

$$E = (\sum_{i=1}^{n} (Q_{sim} - Q_{obs})^2 / \sum_{i=1}^{n} (Q_{obs} - \overline{Q}_{obs})^2 \qquad i = 1,2,\ldots,n$$

where Q_{sim} represents simulated runoff values and Q_{obs} represents observed runoff values.

An objective function is an aggregated measure of difference between the simulated and observed system response. Traditionally, a modeler defines an objective function and minimizes its value, a procedure usually called calibration (Wagener, 2003). Pardo-Iguzquiza (1998) used an objective function to methodically search for the appropriate number and locations of rain gauges which minimized the variance of the estimation error of areal mean rainfall events for a fictitious basin.

It should be noted that most of the study sites in the literature consider only rainfall and very few make reference to snow. Snow-dominated systems differ from rainfall-dominated systems in some fundamental ways. Snow-dominated environments usually experience a slug of runoff during the spring runoff after the snowpack ripens and starts to lose its water content. Snowpacks are viewed as water storage tanks that accumulate throughout the winter season and release their moisture over a period during melt. In contrast, rainfall-dominated basins have a more regular streamflow-runoff relationship, experiencing commensurate rises in streamflow after rainfall events.

The goal of a calibration is to match simulated and observed system behavior. Statistically, objective functions act as goodness-of-fit tests between the observed and predicted values. Different objective functions may result in different conclusions about model validity. When validating a model's output, it is critical to apply a number of tests, and to accurately justify the reasons for choosing those tests and results.

A sensitivity analysis is another technique used to analyze model performance and output. It involves changing model parameters and observing the resultant change in model output. In response to representative variation of model input parameter values and boundary conditions, the technique has the ability to determine i) that theoretically realistic model behavior has been achieved (e.g. Howes and Anderson, 1988); ii) the likely magnitude of error in a model prediction that arises from a particular parameter specification (Lane *et al.*, 1994); and iii) the parameters to which the model is most sensitive (McCuen, 1973). These parameters must therefore be given most attention in terms of acquisition.

In practice, sensitivity analysis is complicated by several factors. Models have numerous parameters and many more combinations of them. The reaction of a model to a change in a parameter is dependent on the values of other inter-related parameters. Because of this interconnection between parameters, often a relatively restricted understanding of actual sensitivity of a model is obtained. Non-linearity in model response to altered parameters is another problem. If simple, first-order assessments of sensitivity, based on direct differentiation or linear factor perturbation (e.g., Bates and Anderson, 1996) are assumed, and in fact the analytic framework of the model is non-linear, errors in sensitivity should be assumed.

Finally, knowledge of the spatial distribution of parameters must be known prior to altering them. Because of spatially distributed feedback within a model, complex spatial responses to uniform parameter perturbation can occur, and erroneously skew the output and assumed sensitivity. In mountainous regions, snow distribution exhibits unique spatial heterogeneity (Elder *et al.*, 1991; Doesken and Judson, 1996; Balk and Elder, 2000). Effects of wind distribution, accumulation, melt differences, and varying energy fluxes determine snow distribution and consequently snowmelt runoff (Winstral and Marks, 2002). At the same time that snow distribution is so variable across space, the current knowledge of snow is not consistent across scales (e.g., Blőschl, 1999). Current process-based knowledge of snow and snowpack metamorphosis is limited to the watershed/local scale, and does not scale-up to regional, continental, and global scales in heterogeneous terrain. Snow accumulation and ablation processes, soil freeze/thaw transitions, infiltration, and other hillslope scale processes are well understood; how these cumulative effects affect snow on a regional scale is not well understood (Blőschl, 1999). Therefore, snow cannot be modeled uniformly over differing scales (Deems *et al.*, in press). In general, the representation of snow processes in highly heterogeneous environments is a challenge for hydrologic modelers focusing on snow.

2.2 DATA ISSUES

2.2.1 Data Quality

When modeling hydrologic systems that require copious amounts of hydrometeorological data, it is prudent to ensure the consistency and accuracy of the data. Consistency refers to a measure of how similar the data are to its data set, including having a period of record without interruptions. Accuracy is a measure of how close the observed values are to the actual values. The better both of these values are, the more confidence can be given to the authenticity of the data set and results produced based on the data.

Point temperature and precipitation data used for this study were collected as part of the nationwide Cooperative Observer Network (COOP) and Automated Weather Observing Sites (AWOS). The COOP system accounts for over 8300 daily observations of temperature and precipitation that are measured by volunteer weather observers throughout the U.S., Pacific Islands, Puerto Rico, and the Virgin Islands (Reek *et al.*, 1992) These stations often have inconsistent records and are prone to station moves and periods of no data. Stations with the longest records at an unaltered location provide the best quality data through their consistency. There are currently over 600 AWOS sites located in the U.S. that consist of a suite of sensors which collect meteorological data and disseminate it to public and private interest groups throughout the country. Most AWOS sites are located at airports throughout the country; pilots used AWOS data for flight planning while meteorologists use the nationwide network of wind, temperature, sky conditions (overcast, broken, scattered or clear), altimeter (atmospheric pressure) and visibility data to assist in forecasts.

Errors embedded in station data get exacerbated in the process of extrapolating point data to spatial data. Mean areal estimates of temperature and precipitation are only as accurate as the point data off of which they are based.

2.2.2 Precipitation Data

It is difficult to obtain reliable spatial and representative estimations of precipitation in mountainous terrain. Large variability in space and time associated with mesoscale precipitation and uncertainties of the precipitation catch of winter storms add to the uncertainty of precipitation estimates. When calibrating NWSRFS to areas which receive considerable amounts of solid precipitation, it is important to consider precipitation gauge deficiency due to wind (Peck, 1972). Literature on this subject has been published since the mid eighteenth century. Kurtyka (1953), Israelson (1967) and Larson (1971) have each published comprehensive literature reviews containing over a thousand references in the field of precipitation measurements. More recently, WMO (1973) has published an annotated bibliography on the topic. Yang *et al.* (2000) compared catch efficiencies of different gauges for both rain and snow and found catch efficiency to be a function of the gauge design, wind speed, and air temperature. Local topography, size of the study area, type of precipitation (convective versus stratiform) and large-scale atmospheric motions and forcing affect the measurement and estimation of precipitation (Tsinitinkidis *et al.*, 2002).

The fundamental problem underlying precipitation studies is that the accuracy of the determination of the ground-truthed precipitation data ends up dictating the value of the entire study. Because of this, it is not surprising to find that the comparison of results from various studies including those listed above, show a rather wide range of catch deficiencies for any given situation. However, precipitation measurement error studies do illustrate considerable point measurements of precipitation deficiencies due to the wind. These errors tend to increase with wind speed and are much greater for solid precipitation than for liquid precipitation (Larson and Peck, 1974). Moreover, it has been shown that the most important factor in obtaining reliable precipitation measurements is proper site selection (Goodison *et al.*, 1998). A well protected site can reduce measurement errors. Gauge shields have been shown to be much more effective with snow than for rain (e.g., Goodison, 1978). No combination of gauge and shield, however, will entirely eliminate the adverse effect of wind on catch.

Chua and Bras (1982) illustrated the difficulties with estimating mean areal precipitation (MAP) in mountainous regions, and recommend the advantages of kriging to estimate MAP. Kriging was chosen in the study by Chua and Bras (1982) because of how it handled the assumptions of snowdrift and spatial dependency of precipitation influenced by orographic effects. Despite there being errors in the data from the higher mountainous elevations, the data are responsible for most of the hydrologic input into a montane basin.

Synthetic data generation is often used to study the reliability of the estimate of precipitation errors, as the lack of ground-truth data creates no absolute precipitation measurement. Tsintikidis *et al*. (2002), motivated by precipitation uncertainty which greatly affected hydrologic flow models and predictions, gradually increased the density of the real-time network in a study basin. They analyzed the differences of the precipitation estimates compared to the outputs generated from model runs with various numbers of stations used. They concluded that the installation of additional gauges would decrease the error of precipitation estimates. Tsintikidis *et al*. (2002) also showed that adding specific locations throughout the watershed substantially reduced the precipitation estimation error.

2.2.3 Snow Data

Measurements of snow characteristics are difficult to quantify, especially spatially. Larson and Peck (1974) illustrated the biases in gauge-measured precipitation caused by wind, wetting, and evaporation losses; these have been recognized as affecting all types of precipitation gauges. Such systematic errors in measurement are most pronounced during solid precipitation events (Yang *et al.,* 2002). Solid precipitation is much more difficult to measure than liquid precipitation. The World Meteorological Organization compared the catch efficiencies of many different gauges under solid precipitation events. Goodison *et al. (*1998) showed that the difficultly of measuring snow events predicated the need for standard methods of measurements.

Many tests of snow model predictions distributed over large areas are susceptible to the difficulty in quantitative evaluation due to variability in snow extent patterns and snow physical properties. Predicting runoff from a basin that is largely snow-dominated throughout the year can be difficult because of the errors associated with determining the physical snow characteristics of the basin, including depth, snow water equivalent, and spatial differences in depth caused by scour and wind-loading. In flat terrain, a plot of simulation accuracy versus number of gauges should show a clear relationship as to how simulation results deteriorate as the number of gauges is reduced. However, in the mountains it is not only the number of gauges but also their location, including elevation that will determine the simulation results. Reducing one network, e.g., temperature, while leaving the other network, precipitation, the same tested the effective representivity of each variable on the simulation results. Theoretically temperature is a more conservative data type than precipitation, i.e., it has less spatial variation. Reducing the temperature network should have less of an effect on the results than a reduction in the precipitation network by the same number of stations. While temperature primarily affects the timing of snowmelt, precipitation primarily affects the volume of snowmelt runoff.

2.2.4 Hydrologic Data

The U.S. Geological Survey is the primary body responsible for collecting and publishing hydrologic data. Motivated by navigation purposes, in 1840 the U.S. Federal Government started the systematic collection of quantitative data on water bodies. Explained by the settlement of the U.S., water resources have been measured since 1860 in the Eastern states and since the early 1900s in the West. There are currently about 25,000 stations in the hydrological network of North America with roughly 80% of these stations located in the U.S. (Shiklomanov and Rodda, 2003). These stations have various lengths of record; the Atlantic Coast of the U.S. claims the highest station densities (one station per 200 to 500km^2) and the longest periods of record, while central and western portions of the U.S. claim one station per 500 to 1000km^2 and shorter periods of record.

Precipitation collection measurements, especially solid precipitation measurements, are very susceptible to undercatch due to splashing, wetting of the funnel, and wind. Much literature exists citing the precipitation catch discrepancies between different kinds of gauges and different kinds of shields. Goodison *et al.* (1998) illustrated the differences between catch efficiencies and commented that the ideal arrangement for best estimates of "ground-truthed" data often does not exist in operational networks. The chronic problem of data deficiencies underscore the pressing importance of designing hydrologic networks in order that they can provide the maximum information for a given investment of time and money.

2.2.5 Data Network Designs

It has not been until recently in the past half century that the topic of design of meteorological and hydrological networks has been studied. In hydrological terms, a network is a system for the acquisition of hydrometeorological data. A network should "satisfy the demand made by the principle users of hydrological data for scientific and practical purposes" (Kouzel, 1969). Data acquisition is a fundamental feature in the creation of hydrologic knowledge, and it's for this reason that Rodda (1969) commented that its neglect is very surprising.

Hydrologic data have been collected in Egypt and China for thousands of years; hydrologic networks similar to those that exist today were first found in Europe and North America in the 1700 and 1800s (Rodda, 1998). Today the U.S. national network is comprised of instruments and stations, both temporary and permanent, located across the country.

In one of the earliest references to network design practices, Linsley *et al.* (1958) recommended that a standard and universal procedure for network design was impossible to achieve. Among the problems associated with creating principles by which a network should be designed include the wide range of data that need to be collected, and the changing needs of the current water forecasting methods. In recent years, a number of government agencies and industries have begun to reinvest in meteorological networks. The establishment of basic hydrological networks and the improvement of existing networks are important to provide the fundamental data needed to monitor our water resources for development and hydrological modeling. Increased meteorological station network density can be beneficial for a number of purposes, including flood forecasting.

Deficiencies in meteorological and hydrological networks are often the result of operation of non-hydrological factors, specifically, inadequate funds, shortage of observers and inaccessible sites. Within the operational hydrologic community, financial constraints are often the primary limitation of the number of hydrometeorological recording stations available within a given forecasting area. Dozier (1992) suggested that the increase in computing power in recent years has been the focus of attention of the scientific community; with such the emphasis on computers, data collection systems have eroded. In the U.S. since the mid 1970s, more than 100 stream gauging stations with records of more than 30 years are being discontinued due to lack of funding (Lanfear and Hirsch, 1999).

The greater the number of data points for any given area, the better hydrologic and weather forecasting models will perform. As the amount of input data is increased there is likely a nonlinear increase in model performance. St.-Hilaire *et al.* (2003) showed that denser networks more accurately quantify precipitation estimates. At some point, the increase in performance should diminish with increased input data. Operationally this becomes significant with the finite financial constraints inherent in operational hydrology. This raises the issue of how the operational community can gain the greatest improvement in model performance for the least amount of financial investment.

Although some networks have been designed scientifically, more often than not development of networks have been the result of *ad hoc* responses to particular problems and/or interest in observing meteorological and hydrological phenomena. In most networks that developed over time without a designed framework, the availability of observers determined the overall network. Nowadays, most meteorological and hydrological networks are automated, usurping the need for a physical human presence. For this reason, there is usually a marked correlation between population distribution and instrument density, often resulting in the poorest network where hydrological and meteorological information is needed most, i.e., in remote, heterogeneous terrain.

The optimal network of hydrologic gauges and meteorological recording stations takes into account the number and location of those sites, providing greater accuracy of actual precipitation estimation, and with minimum cost, a characteristic important to the operational hydrology community. Methods of design apply the concepts of regionalization, the concept of making decisions based on local input where local attributes of the land and knowledge dictate the decision making process. Mapping and systems analysis are often concepts used to drive the design of hydrologic gauge networks, but Rodda (1969) demonstrated that economic reasons are often the overriding force behind the design and placement of hydrological and meteorological gauges.

A procedure to optimize a rain gauge network could be considered archaic with the current spatial and temporal resolution of weather radar available. However, weather radars even today fail to provide complete coverage in the U.S. (Fassnacht *et al.*, 2001). Satellites using thermal infrared imaging have the capability of estimating rainfall amounts (Hsu *et al.*, 1999), yet the algorithms must be calibrated and validated using rain gauges networks (Petty, 1995). For radar data, Fassnacht *et al.* (1999) compared simulated runoff volumes from radar versus gridded gauge data. For these reasons rain gauge network optimization is still of practical interest.

Precipitation is the most variable water balance element over a region. Accordingly, the density of the precipitation network should be higher than the density of networks established for the observation of the other water balance elements. Especially in mountainous area, consideration of vertical zonality, steepness, and exposure of slopes should be noted when designing a precipitation network. Kouzel (1969) showed that the error in averaging over an area decreases with the increase in period of averaging for the same network density (a decrease in the distance averaged over).

Pardo-Iguzguiza (1998) used a variance reduction method to search for the appropriate number of precipitation gauges and their locations which minimize the variance of the estimation error for areal mean rainfall events. As expected, Pardo-Iguzguiza (1998) found that a given objective function can be minimized indefinitely by increasing the number of points indefinitely, but noted that the gain is not uniform. When the number of data points is low, the addition of a point considerably reduced the estimation variance. Yet when the number is high, one additional point did not greatly reduce the estimation variance. The optimal number of gauges can be chosen when the slope between the number of points and estimation variance begins to diminish.

2.3 OBJECTIVES

NWSRFS was run in calibration mode on a portion of the Yampa River in northwest Colorado. With the available temperature and precipitation data in and near the watershed, it was possible to vary the quantity and representivity of model input data, ranging from a very dense network to a sparse network, and including geographic arrangements. Running a hydrologic model on this basin with a sparse network of meteorological data would mimic the situation that is present in many mountainous areas throughout the U.S. where snowmelt is the dominant hydrological feature, and where few meteorological data are available. Using the NWSRFS for the streamflow forecast points utilizes a currently operational model that is calibrated with historical data for the modeled watershed. The focus of this study is the quantification of the combined quantity and quality of the input data on hydrological model output.

3. STUDY AREA AND DATA DESCRIPTION

The study area encompasses the 847 km^2 Yampa River watershed below Stage Coach Reservoir and upstream of the USGS gauge in Steamboat Springs in northwestern Colorado, USA (Figure 3-1). The town of Steamboat Springs and the accompanying ski resort are located within the study basin. The most common land-use within the basin is agriculture. Land cover in the montane areas is coniferous and aspen while the non-agricultural rangeland is grass and shrubs, such as sage.

The Yampa River watershed is a snowmelt dominated system and was chosen for its mountainous terrain (ranging from 2042 to 3042m). The region experiences heavy winter precipitation. In places snow depths reach up to 508 cm (200 in) annually, and it has a relatively dense network of both meteorological and hydrologic recording stations. Average peak SWE at the Tower SNOTEL site is 1350 mm (53 in). Mean annual precipitation values peak at 1270mm (as measured in snow surveys) in the mountainous portion, making it one of the wettest locales in Colorado. The lower elevations in the basin receive about 580mm (at the Steamboat Springs station) of precipitation each year. There are numerous diversions present in this stretch of the river, but all are believed to have return flow to the Yampa River basin (Colorado Division of Water Resources, pers.

comm., 2004). A consumptive use operation is used in the model to account for net loss from these diversions.

For operational hydrologic forecasting purposes, the area in the model is divided into three zones based on elevation. Each zone, as per its elevation, has different parameters in the subroutines of NWSRFS. This elevation split in the model is especially pertinent due to the hydrologically distinct regimes at different elevations in the study basin. The upper zone encompasses the elevation range from 3048m to 3228m with an area of 35 km^2, the middle zone from 2591m to 3047m (373 km^2), and the lower zone from 2053m to 2590m (391 km^2).

The storms that typically affect the study basin originate over the Pacific; by the time the storms get to western Colorado, they are usually moisture-starved and produce a dry, continental snowpack. The wintertime Pacific High climatologically located west of Baja California acts to steer storms zonally west to east across the western U.S. A large area of cold high pressure over the northern inter-mountain west and southern Canadian Prairie Provinces helps to enhance this climatologically winter zonal flow. Because of this predominant zonal flow, excellent conditions for orographic enhancement of precipitation events occur. The upper zone of the basin forms the western side of the north/south trending continental divide. As storm systems are forced up and over the topographic barrier, they cool and enhance the condensation of moisture. As the rising saturated air condenses, latent heat is liberated by the condensing vapor and both the temperature and dew point temperature decrease moist-adiabatically, the lapse rate of a saturated parcel of air. It is for this reason that a trend in increased precipitation with stations closer to the divide is seen. Of the 18 stations in the study area (Figure 3-1 and

Table 3-1), only five are located high enough to receive more winter precipitation than summer precipitation. It should be noted that most of the meteorological stations are not hydrologically significant in the Yampa River basin, meaning the meteorological data of most of the stations does not accurately represent the meteorological conditions of the modeled area. This is a result of most the stations not being at the same elevation of the basin.

The basin is characterized as a blend of the Dfb, Dfc and H climate types in Koppen's Classification System (Koppen, 1954). In the lower elevations of the basin, summers are mild with one to three months having average temperatures greater than 10C (50F). The coldest months average below -3C (26.6F). Precipitation in these lower regions occurs uniformly throughout the year. As the elevation increases in the basin, summers become cooler and winters much more severe. In the highest sections of the basin, the climate is very complex depending on elevation and exposure. The highest snowfall amounts in Colorado are found in the highest reaches of the study basin. The highest part of the watershed immediately contributing to the Yampa River flow at Steamboat Springs, CO, is characterized as an alpine region, with much of the land area being above treeline. Such regions in the intermountain west are important hydrologically, even though they encompass only a small fraction of the area. Montane regions with snow-dominated hydrology are a major source of water for runoff, groundwater recharge, and agriculture purposes.

Temperature and precipitation data used for this study were collected at hourly and daily time intervals from COOP stations, AWOS sites, and SNOTEL stations in and around the basin. Data archives are available from 1915 for this region; however, most

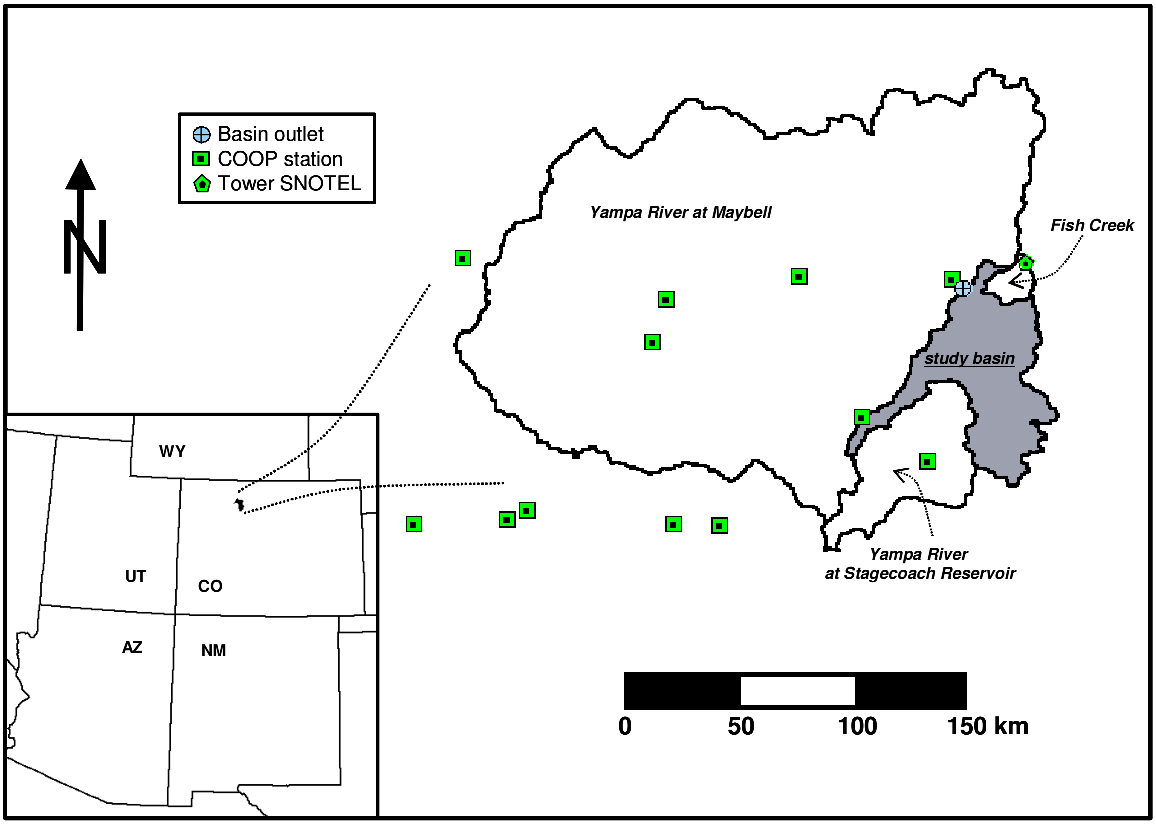

Figure 3-1. Study site map.

Table 3-1. Summary of hydrometeorological stations (NWS COOP stations). POR is the period of record for the maximum temperature (max temp), minimum temperature (min temp), and precipitation (precip).

Station	Station Number	Latitude	Longitude	Elevation (ft)	max temp POR	min temp POR	Precip POR	Avg annual Temp (F)
Craig	05 1928	40.53	107.55	6280	05/77 - 08/02	08/48 - 07/75, 06/76 - 10/76	8/48 - 06/75	42.3
Dinosaur NM	05 2286	40.25	108.97	5920	06/65 - 08/02	06/65 - 08/02	06/65 - 12/99	47.2
Meeker 3 W	05 5484	40.02	107.97	6180	01/48 - 09/70, 01/93 - 08/02	01/48 - 09/70	8/48 - 10/70, 05/93 - 12/99	44.6
Craig 4 SW	05 1932	40.45	107.58	6440	05/77 - 08/02	01/48 - 09/70, 01/93 - 08/02	5/77 - 08/02	43.2
Hayden	05 3867	40.50	107.25	6440	01/48 - 08/02	01/48 - 08/02	01/48 - 08/02	42.6
Browns Park	05 1017	40.80	108.92	5354	04/66 - 07/97	04/66 - 07/97	4/66 - 07/97	45.3
Little Hills	05 5048	40.00	108.20	6140	08/48 - 09/91	08/48 - 06/88, 12/88 - 09/91	8/48 - 9/91	42.4
Marvine	05 5408	40.02	107.55	7200	10/99 - 07/01	09/64 - 10/71, 10/99 - 07/01	08/48 - 10/71, 10/99 - 08/01	40.6
Marvine Ranch	05 5414	40.02	107.43	7800	07/72 - 08/98	07/72 - 08/98	07/72 - 08/98	36.6
Massadona	05 5422	40.28	108.6	6185	01/86 - 08/02	01/86 - 08/02	01/86 - 08/02	45.9
Maybell	05 5446	40.52	108.10	5908	03/83 - 08/02	03/83 - 08/02	03/83 - 08/02	42.3
Pyramid	05 6797	40.23	107.08	8009	N/A	N/A	08/48 - 08/02	
Rangely 1E	05 6832	40.08	108.77	5290	06/50 - 08/02	01/48 - 08/02	06/50 - 08/02	47.5
Steamboat Springs	05 7936	40.50	106.87	6636	01/48 - 08/02	01/48 - 08/02	01/48 - 08/02	39.2
Yampa	05 9265	40.15	106.92	7890	06/64 - 08/02	06/64 - 08/02	08/48 - 08/02	39.4
Tower SNOTEL	06J29S	40.54	106.68	10500	08/86 – 08/02	08/86 – 08/02	08/81 – 08/02	31.0

western water resources applications restrict their historical data analysis and model calibrations to the period with SNOTEL data (Anderson, pers. comm., 2003). Time series showing a hydrologic variable plotted against time generated using pre-SNOTEL networks are statistically very different than those generated after SNOTEL data were available because most SNOTEL data sites are located at high elevations, which have very different precipitation and temperature regimes than lower elevations. The inter-mountain west did not have many high-elevation weather stations prior to the installation of the SNOTEL sites in the 1960s.

Temperature and precipitation data were collected from stations in the Yampa River basin that have continuously reliable and available archives. Fifteen stations were deemed appropriate to be used to develop the mean areal values based on consistency of recording, i.e., period of record, missing data and station moves (see Table 3-1). Three stations used are located in the basin while the remaining 12 stations are located near the basin (Figure 3-1). To better capture the montane hydrology of the higher elevations of the study area, SNOTEL data was added to the station data used to drive the mean areal estimates of temperature and precipitation. The Tower SNOTEL site located in the highest reaches of the study basin receives on average 1450 mm (57 in) of precipitation annually, more than twice as much as the next COOP station used in this study. Therefore this station is meteorologically distinct and thus significant. Similarly, Cooley (1986) showed that using SNOTEL data in NWSRFS could improve forecast results.

Based on the periods or records available from meteorological stations and USGS streamflow gauges (Table 3-1), the time frame modeled covered over 17 years, starting in

October of 1984 and terminating in December of 2001. Because of snowmelt dominance in the basin, baseflow occurs throughout most of year; it's only during the snowmelt season that basin's hydrograph experiences any significant amplitude. See Figure 3-2 for observed daily hydrographs for a wet year and a dry year, respectively.

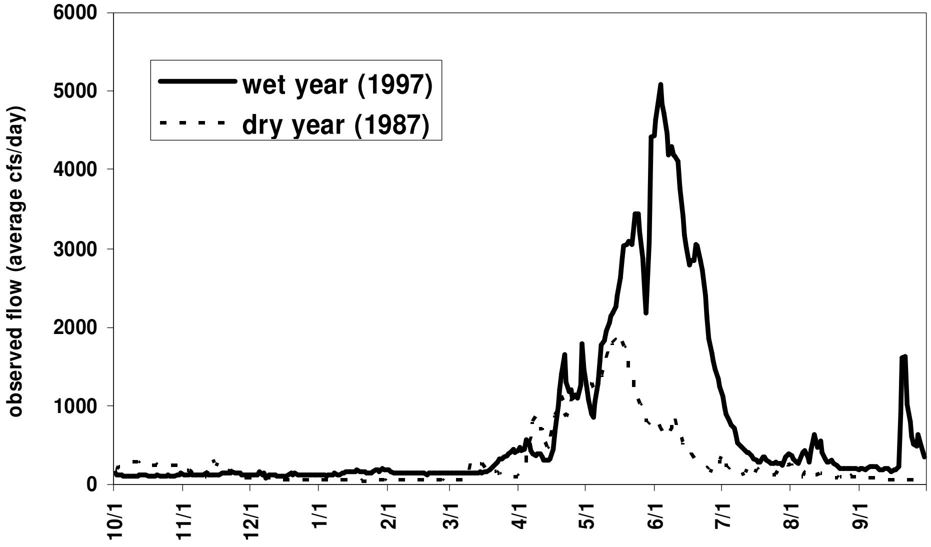

Figure 3-2. A typical wet (1997) and dry (1987) year annual hydrograph recorded from the Steamboat Springs gage on the Yampa River.

4. METHODS

This study involved ingesting hydrometeorological data into the NWSRFS. The model was run stand-alone off of the RFC network, in calibration mode to produce simulated time series stream runoff. The focus of this study is the comparison of these simulations with observed streamflows, and attributing accuracy of the simulations to the nexus of quantity and quality of data used in the model.

4.1 MODEL CALIBRATION

The purpose of a model calibration is to produce an unbiased reproduction of historical conditions with an ability to extrapolate beyond conditions encountered in the historical period. A successful calibration assigns values to parameters that cause model components to mimic the hydrologic processes they were designed to represent. Most of the model parameters used in the calibration were taken from the current values used at the Colorado Basin River Forecast Center (CBRFC) in their definition of the Yampa River. A segment definition in NWSRFS is a file that contains parameters describing the specific segment of the river. Among these parameters are values describing evaporation rates, soil moisture, typical rain/snow elevations, snowmelt characteristics, unit hydrograph parameters, and lag and attenuation values for routing.

After the temperature and precipitation data were assimilated into the NWSRFS, it was hoped that the model parameters CBRFC used in their segment definition would produce a good calibration. Differences in calculated water balance, MATs, and station weights in this study's model calibration did necessitate altering some of CBRFC's parameters. Adjustments were made primarily to SNOW-17 parameters.

The process of model calibration involved obtaining temperature, precipitation, and observed runoff data from stations in and near the Yampa River watershed. From these meteorological stations, the entire period of record for the daily and hourly minimum and maximum temperature, and daily precipitation data was retrieved. After the raw data were obtained, data were formatted for use in the model, and quality controlled to correct for missing data, data anomalies, and station moves. The end product of both the temperature and precipitation data procedures was the creation of a 6-hr time series for the period of record that coincided with all the stations; this time frame became the period over which the model was run in calibration.

4.1.1 Temperature Data

Temperature data were retrieved through the NOAA Hydrologic Data Systems Historical Data Browser (NOAA, 2004). This system retrieves data from the National Climatic Data Center and assembles it in a form usable by NWSRFS. The Temperature-Elevation Plotting Program (TAPLOT) within NWSRFS develops synthetic monthly means for fictitious stations at representative elevations in each of the three elevation zones based on nearby stations using inverse-distance weighting schemes. NWSRFS generates 6-hour MAT time series with monthly maximums and minimums for each station and the dummy stations, i.e., stations at the mean elevation of each of the three zones. See Appendix A for an example MAT file.

The quality and consistency of the temperature data were analyzed through the double mass technique necessitating the omission of some stations and corrections made to others (see Appendix B). Double mass analysis compares cumulative values at similar locations, and is used to determine corrections to hydrometeorological data to account for changes in data collection procedures or other local conditions. The double mass analysis tool within NWSRFS was used to perform the consistency checks and produced the correction factors used in subsequent processing.

Since there are no representative high-elevation stations in the watershed, average maximum and minimum temperatures were plotted against station elevations to estimate maximum and minimum temperatures at higher elevations by extrapolating lapse rates to the mean zone elevations. Mean areal temperatures (MAT) were then calculated as time series for each subbasin by an automated subroutine with NWSRFS. See Appendix A and D for the MAP and MAT files, as well as Figure 2-1 for the NWSRFS structure. SNOTEL temperature data was not used to assist in temperature determination of the upper zone. Upper zone temperatures determined using SNOTEL temperatures created erroneous lapse rates. See Figure 4-1 for mean monthly maximum and minimum temperatures based on different station configurations.

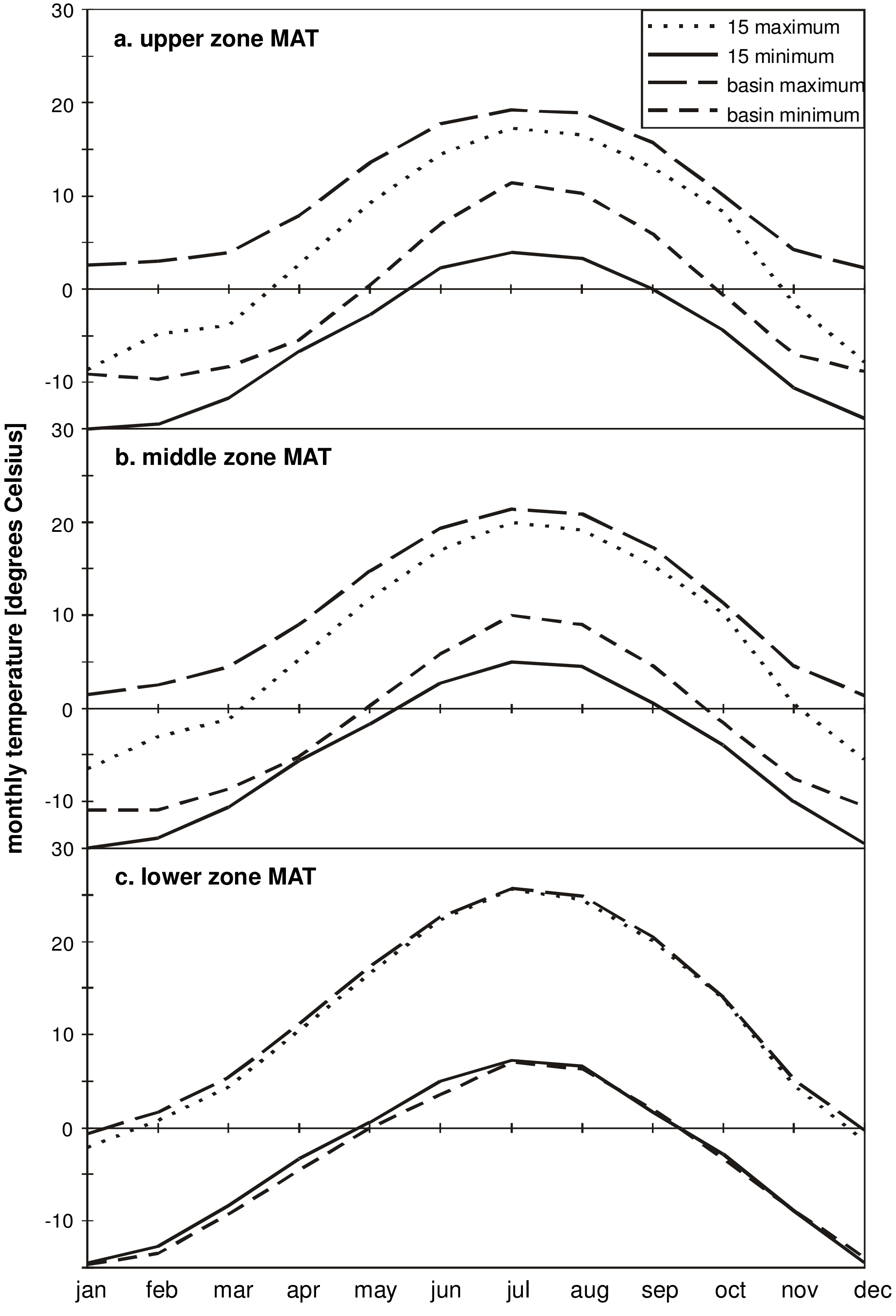

Figure 4-1. Mean monthly maximum and minimum temperatures based on the 15-station arrangement versus the basin simulation (stations located within the watershed boundary) for the a) upper zone, b) middle zone, and c) lower zone.

4.1.2 Precipitation Data

Precipitation data from 15 precipitation gauge locations were used as input into the mean areal precipitation analysis. Only three of the stations were located in the basin; the remaining 12 stations are located within approximately 100 miles of the basin**.** The Yampa River basin above Steamboat Springs is mountainous, claiming the Continental Divide as much of its eastern boundary. All of the precipitation gauge locations used for the MAP analysis are located in the lower zone of the basin with the exception of the Tower SNOTEL site, located in the upper zone of the watershed. Is as typical for precipitation measurement, most observations are made in the lower elevations where people live, while the greatest precipitation falls in higher elevations, that are often more hydrologically significant.

Precipitation data were used to determine mean annual precipitation for each zone. Appendix D contains a MAP file. Missing data and extraneous values were all corrected using subroutines within NWSRFS designed to assist the user in determining the validity of the data. This precipitation data, combined with the hourly and daily precipitation values, generated 6-hour time series.

4.1.3 Runoff Data

All daily runoff data were obtained from the Historical Data Browser, which directly obtains data from the USGS gauge network and is utilized by NWSRFS users to get the data into a usable format by the NWSRFS. Knowing the daily runoff from the inlet and outlet of the basin on the Yampa River, Stagecoach Reservoir and on the Yampa River at Steamboat Springs gauge, respectively, runoff for the modeled watershed was determined. Daily runoff data are calculated as the mean flow measured during the day. The periods of record for the gauges are included in Appendix C. The historical runoff data form the streamflow time series which simulated model runs are compared to in the analysis portion of the study.

4.1.4 Water Balance

The water balance approach to hydrologic analysis is an accounting of the inputs and outputs of water. For a complete discussion of the water balance performed for this study see Appendix C. The significant variables in this water balance are precipitation, evapotranspiration and runoff, and the water balance procedure aimed at a “best-guess” value for each variable for each zone of the modeled basin. Once these variables were determined, the baseline MAP arrangement was created, off of which subsequent analysis was based. It is acknowledged that uncertainties in each of these variables will preclude us from knowing for sure the “true” values. These are best guesses and help produce a baseline MAP.

Evaporation is an important sink in the water balance of this basin. Evaporation data were acquired from the University of Nevada’s Desert Research Institute (DRI, 2004) and runoff data were acquired from the United States Geological Survey (USGS, 2004) provides runoff data. Precipitation variation over an area must be determined to gain knowledge of the hydrology of an area. Precipitation, aside from areal radar estimates, is measured at point values. For most hydrologic applications, use of precipitation data requires an ability to estimate the value at other points. Many areal analysis methods exist, including isohyets and Thiessen polygons, all involving inferences concerning the depth of precipitation at all points in the area of interest. The areal analysis technique used within NWSRFS is a formulation that produces an estimate of the precipitation at a point as a function of surrounding points. The method is based on an inverse distance-weighting scheme. This technique can never result in a point estimate that is greater than the largest amount observed or less than the smallest amount observed (NOAA, 1996). MAP time series were calculated for each subbasin.

Precipitation-elevation Regression Independent Slopes Model (PRISM) data were used to calculate precipitation in each subbasin. PRISM information helps hydrologists to better assess the water balance at a watershed scale since it provides special precipitation data that is lacking in point station observations (Daly et. al., 1994). An important component of a hydrologic model calibration is preparation of MAP time series and when a basin is divided into elevation zones, an MAP time series must be created for each zone. PRISM is used to determine areal zonal precipitation as well as the distribution of precipitation with elevation. A Geographic Information System (GIS) was used to spatially determine precipitation amounts for each zone in the watershed. See Figure 4 and Appendix I for GIS procedures.

Once both the MAT and MAP time series were developed, a calibration deck was made containing the MAT and MAPs for each subbasin, and observed runoff time series for the basin, collectively run through the models of NWSRFS. The output from running the calibration program produces a time series hydrograph of observed versus simulated runoff. Results and analysis were based on the time series hydrograph statistics produced by NWSRFS. For a complete process description of the water balance, see Appendix C.

4.1.5 Model Parameter Adjustments

Parameters within SNOW-17 provide flexibility in the calibration of NWSRFS to adjust precipitation. As mentioned above, there are gauge catch deficiencies when measuring precipitation, especially solid precipitation. The PXADJ parameter is used to adjust precipitation input to the model and is the ratio of average areal precipitation to the precipitation input. If good estimates are made for mean basin precipitation, PXADJ has been found to be relatively unimportant, and is set equal to one. Another parameter that can be used to adjust streamflow in solid precipitation areas is the snow correction factor (SCF). SCF is part of the snow accumulation and ablation model and adjusts solid precipitation. SCF is highly dependent point-wise on gauge exposure, wind speeds, gauge/shield configurations and storm type. Anderson (1973) found that SCF has a significant effect on snowpack runoff volumes. For this study, SCF was increased to reduce the overall snow accumulation in the basin. Lastly, the melt factor parameter MFMAX was lowered to delay the peak snowmelt runoff, in essence broadening the hydrograph.

4.2 SENSITIVITY SCHEME

Running many instances of the calibration deck with the differing station MAP and MAT configurations was the main focus of this study. The main bulk of the sensitivity scheme is designed around how well the model can capture wintertime precipitation, the most hydrologically significant aspect of the basin's hydrograph. Parameters within the calibration deck remained constant, so what errors were present in the parameters themselves were present in all model runs. It is for this reason that the relative differences between model runs, and not the absolute difference between the simulated and observed values was of importance. Each model run was compared to the initial model run that was developed with the most available data.

The determination of mean areal precipitation values in the modeled area is the main goal of model calibration in NWSRFS. To do this station weights need to be determined; how much a station is weighted is a variable of the final MAP used in the model. In addition to determining station weights within the model, other variables that are calibrated in this process include evaporation rates, rain-snow elevations within each zone, soil moisture values, and areal extents of snow as a function of elevation. The first execution of the model included running the model with the richest data set available; all fifteen stations in the basin were used to determine the baseline MAP and subsequent simulated streamflow.

The deterioration of the dense network was based on changing the density of the stations and the distribution of the stations based on location characteristics including elevation, proximity to the basin and other stations, high and low precipitation stations, and exposure to major storm tracks. A sparse network with only low elevation stations would mimic the situation in many data sparse, mountainous regions in the U.S.; many high elevation sites with snow dominated climates, despite being so hydrologically significant, often lack hydrometeorological stations. Due to the hydrologic dominance of snow in the Yampa River basin, model runs including stations at higher altitude were expected to perform better. Model runs using these stations were expected to better capture the orographic nature of the winter-dominated annual precipitation.

4.2.1 Geographic Snow Dependence Sensitivity

The first scheme employed in this study was developed to test the sensitivity of the model simulations to the stations with a predominance of solid wintertime precipitation. It was believed that since the basin is so heavily snowmelt dominated that model runs incorporating more of these representative stations would perform well.

The first model run (Scheme A) under this scheme involves running the model with input data from the six stations with the highest annual average precipitation. These stations include the Tower SNOTEL site (1453 mm / 57.20 in), Marvine Ranch (647 mm / 25.49 in), Steamboat Springs (606 mm / 23.85 in), Marvine (539 mm / 21.23 in), Pyramid (526 mm / 20.72 in), and Hamilton (474 mm / 18.66 in). The schemes are summarized in Table 4-1. This station configuration, in addition to having the highest average annual precipitation, claimed the stations with the most winter average precipitation and the six highest stations in elevation in the basin. The second plan under this scheme (Scheme B) was to run the model with the five stations having the lowest annual average precipitation. Stations in this configuration include Browns Park (213 mm / 8.37 in), Rangely (10.34 mm / 10.34 in), Dinosaur (279 mm / 10.98 in), Maybell (313 mm / 12.34 in), and Massadona (334 mm / 13.15 in).

In general for this basin, the further east you are in this basin, the higher the elevation trend, and this also corresponds to increased precipitation. Most of the modeled area is higher in elevation than the surrounding area where many of the meteorological stations are located. To analyze how the model responds to input data from stations in close proximity to the study basin, Scheme C is run which incorporates the three stations that are located within the basin boundaries. This configuration was designed to test how well the model resolves the hydrometeorology of the basin using only stations that geographically represent the basin, i.e., stations located within the watershed boundary. Scheme D takes this one step further and uses data from the six closest stations to the basin, including the three stations located in the basin. The Tower SNOTEL site, Steamboat Springs and Yampa are the three stations located within the basin, while Hayden, Craig and Hamilton are added to these three to make up the six closest station configuration.

Table 4-1. Summary of snow-dependence modeling schemes.

Scheme	Conditions	Stations	Precipitation (in)
A	highest annual average precipitation	Tower (SNOTEL)	57.2
		Marvine Ranch	25.5
		Steamboat Springs	23.9
		Marvine Ranch	21.2
		Pyramid	20.7
		Hamilton	18.7
B	lowest annual average precipitation	Browns Park	8.4
		Rangely	10.3
		Dinosaur	11
		Maybell	12.3
		Massadona	13.2
C	in the basin	Tower SNOTEL	57.2
		Steamboat Springs	23.9
		Hamilton	18.7
D	closest to the basin	Tower SNOTEL	57.2
		Steamboat Springs	23.9
		Hamilton	18.7
		Yampa	15.6
		Hayden	16.9
		Craig	15.4

4.2.2 Model sensitivity to the quantity of stations

The sensitivity scheme employed for this study was used to illustrate the varying degrees of model output based on differing arrangements of input scenarios that readily exist in the operational realm. The second scheme was run to measure how sensitive the model was to the number of stations used to initialize the model.

4.2.2.1 Snow Hydrology

The initial model run under this second scheme was executed using all fifteen stations to form the baseline. Each subsequent model run used one less station in the MAP determination. Stations were eliminated based on how far they were from the modeled basin; the farthest stations were eliminated first. This scheme was followed until there was one station remaining. The model was run twice with one station, the first using Steamboat Springs as the lone station, and the next using the Tower SNOTEL site as the one station.

4.2.2.2 Rainfall Event Sensitivity

To further test the model's sensitivity to the quantity of stations being used to drive the model, two specific rainfall events were analyzed. Due to the nature of determining the weights for station used in the water balance procedure, it was thought that the model might respond differently to rainfall events than to snowfall events. Two rainfall events, identified as producing marked increases in the observed hydrograph, occurred over a portion of the basin on 15 September 1997 through 18 September 1997 and the end of

May 1997 during the height of snowmelt runoff. These two events were used to test the sensitivity of the model response to specific rainfall events on discharge simulation.

This scheme was developed to test the response to rainfall events. The preceding scheme may not produce marked yearly MAP changes, and thus no marked streamflow runoff differences. It would be expected that greater changes would occur in specific rainfall events, and possibly less effect in the snowmelt dominated basin.

4.2.3 Mean Areal Temperature Sensitivity

To diagnose how sensitive the model is to the changing of MATs, the model was run with varying scenarios used to determine different MATs. It was believed changing MATs might be more significant for the simulation of snowmelt timing than changing MAPs would be. Temperature, and thus the modeled MATs, primarily controls the timing of snowmelt.

The base model run was compared with a model run having its MATs developed without the inclusion of the Tower SNOTEL station data. MATs are developed by plotting mean monthly maximum and minimum temperatures for each zone versus their elevation. A trendline is then fit to the points. The equation defining this trendline is then used to solve for temperatures at the elevations of the three zones being modeled.

The second plan varying MAT development utilizes only the COOP stations data within the basin, i.e., Steamboat Springs and Yampa. The lapse rates that determine the MATs for this station arrangement are based on two points, and thus are at the mercy of the specific stations used. Tower temperature time series were not used to better replicate the situation of not having any high-elevation representative stations that is present in many montane watersheds.

4.3 SENSITIVITY EVALUATION

Observed data were used to compare with the simulated results. The degree of similarity between observed and simulated plots, given current constraints in available data-lacking regions, was used to assess the appropriateness of the sampling configuration.

The absolute variance of estimation is not as important as the relative value between different alternatives for different configurations of sampling data. Statistically, an objective function can be minimized indefinitely simply by increasing the number of points indefinitely (Pardo-Iguzquiza, 1998). The gain achieved through a decreased variance is not uniform though. When the number of points is low, one additional point implies a considerable reduction in the estimation variance, but when the number of points is high, one additional point does not greatly reduce the estimation variance. The optimal number of gauges can be chosen when the slope of a graph of sampling points versus estimation variance begins to diminish (Pardo-Iguzquiza, 1998).

The quality of the simulated streamflow hydrographs was assessed for how close they were to the observed streamflow hydrographs. The timing, peak, cumulative volume, Nash-Sutcliffe efficiency parameter and percent bias were used to assess the quality of the hydrographs. Simulations and observed time series were compared subjectively to assess the timing of the peak hydrograph. The rising and recessional limbs of the simulation hydrographs were compared to the shape of the observed hydrograph. Timing of the spring hydrograph is often critical to agricultural interests to capture the first snowmelt. Peak flows were compared between observed and simulated model runs. Because of the snow is primary driver of the hydrograph, simulated and observed SWE were compared.

5. RESULTS

5.1 MODEL CALIBRATION

The model calibration process produced the best possible simulation results from NWSRFS using the best available data. Since the hydrograph is snowmelt driven, base flow occurs for eight months of the year. This calibration focused on accurately resolving the four high flow months of the year: April, May, June and July.

The water balance procedure described in section 4.1.4 was the first step of this process and provided much of the knowledge and hydrologic understanding required for the rest of the calibration process. The calibration included many iterative steps of varying the water balance numbers, the SNOW-17 parameters and the weights of the stations used. Table 5-1 displays the calibration results. Monthly percent biases, measured between observed and simulated monthly means, were lowered to agree within one percent bias of the high-flow months. The SCF parameters in SNOW-17 were altered to 1.33, 1.23, and 1.18 for the upper, middle and lower zones, respectively. MFMAX parameters were changed to 0.82 for all zones, while MFMIN was maintained at 0.20 for all zones. MFMAX and MFMIN are melt factors within the SNOW-17 model that dictate the amount of daily melt that is possible throughout the year.

The calibration of the model involved using the temperature and precipitation data of 15 stations in and around the basin. The double-mass technique was used to assess the quality of the data and to make any necessary changes (see Appendix B). Areal precipitation amounts were determined to be 1200, 980, and 646 mm (47.10 in, 38.57 in and 25.44 in), for the upper, middle and lower zones, respectively. See Appendix A and C for a list of the MAT and MAP files determined for the base run, respectively.

5.1 SENSITIVITY SCHEME RESULTS

5.1.1 Geographic Snow Dependence Sensitivity Results

Scheme A involved running the model with the stations having the highest annual average precipitation, which are also the stations with the highest average winter precipitation and the highest elevation in the basin. This simulation produced negative biases compared to the baseline run for every month. Observed and modeled streamflows were correlated from 01 April through 21 July of the modeled period; the Nash-Sutcliffe coefficient for this scheme was 0.71 showing very good correlation. In general, the model performed well using the stations of Scheme A. Figures 6 and 7 show the Apr-Jul hydrographs of the observed and modeled streamflows. Compared to the rest Schemes B, C, and D, Scheme A performed the best (see Figures 8 and 9)

Scheme B set up a model configuration of stations believed to poorly represent the precipitation pattern in the basin. Scheme B performed poorly compared to Schemes A, C, and D. Total volume (entire year) was 83% of observed and the Nash-Sutcliffe parameter for Apr-Jul flows is –1.43. Figures 10 and 11 show the observed vs. simulated hydrographs of Scheme B.

The simulation for Scheme C captured 83% of the observed accumulated flow and has a Nash-Sutcliffe coefficient of Apr-Jul flows is 0.681. This scheme performed remarkably similarly to Scheme A. Figure 12 shows the results from Scheme C simulation.

Scheme D, which used the six closest stations to the basin to develop the MAP values, showed equally good results as Scheme A and C. The Nash-Sutcliffe coefficient As is common with all four snow-dependence schemes, the simulated hydrograph is too late in rising and to quick to return to baseflow. The Nash-Sutcliffe parameter for this simulation is 0.607, and the simulated accumulated flow is 85% of observed. Figure 13 displays the results for this scheme.

Figure 8 shows the SWE time series for this scheme along with the SWE time series from the Rabbit Ears SNOTEL site. The Rabbit Ears SWE time series was included to give a second comparison to the modeled SWE time series. It should be noted that the Tower SNOTEL site has on average 25% more peak SWE (1350 mm / 53 in) than any other gauged site in the Colorado Basin, including Alta in Utah and Wolf Creek in the San Juan Mountains of Colorado.

5.2.2 Station Quantity Sensitivity Results

The number of stations used to determine model MAP values and subsequently streamflow simulations were incrementally decreased until there was only one station remaining. Figure 9 shows selected hydrograph plots resulting from this study. The fourteen-station configuration produced very different simulations than the baseline run containing fifteen stations. The peak is lower, total accumulated runoff is 81% of observed, and despite the timing being a bit off, both the rising and receding limbs are uniform in their error. The Nash-Sutcliffe efficiency parameter for the fourteen-station configuration is 0.84. It is noted that although the MAPs produced by the 'upr' and 'mid' zones are less than those determined by the water balance, the 'lwr' zone MAP is higher than the water balance determined value.

There was little noticeable difference between the 13-, 12-, 11-, 10- and nine-station configuration simulation results. These arrangements show less accuracy than the previous fourteen-station run. The accumulated flows are 78%, 79%, 82%, 79% and 80% of observed while the Nash-Sutcliffe efficiency parameters show a similar trend: 0.81, 0.81, 0.81, 0.80, 0.81, for the 13-, 12- and 11-, 10- and nine-station arrangements, respectively; the peak is very poorly resolved and all monthly biases are negative. The MAPs produced in these arrangements are less than the MAPs determined by the water balance procedure for all three zones.

Simulations between the eight- to five-station arrangements show a similar trend of increasing accuracy in the model simulation. Peak flows increase from the eight-station configuration value of 42.9 cubic meters per second per day ($m^3/s/d$) through 44.3 cmsd, 45.7cmsd to 46.6cmsd for the five-station arrangement. Accordingly, accumulated total flows also increase with a decrease in the number of stations used from eight to five: 79%, 82%, 84%, and 86% for the eight-, seven-, six- and five-station configurations, respectively. Nash-Sutcliffe parameters reflect the same increasing trend. As can be expected, the modeled MAPs for all the zones increase throughout these station runs. The eight- and seven-station arrangements accurately resolve MAPs for each of their three zones, while the six- and five-station model runs overestimate MAPs for all of their zones. All four of these model runs start to peak late and recede a bit too soon, congruous with all the model runs thus far presented.

The four-, three- and two-station configurations show a sequential increase in peakflows and a noticeable shifting of the simulation hydrograph to later in the month of May. Relative bias differences between observed and simulated flows increase to a positive bias during the later high-flow months of June and July while the negative early high-flow bias of April decreases even more. Simulated MAPs for these three model runs all exceed the water balance-determined MAPs. Nash-Sutcliffe parameters are uniform around 0.84 for these model runs.

The one-station arrangement using Steamboat Springs produced a relatively poor simulation. The Nash-Sutcliffe parameter for this run was the lowest seen in all the simulations. Simulated accumulated flows were 78% of observed, also the lowest encountered. The simulated hydrograph is shifted later in the season, producing a poorly timed rising limb but had a reasonable receding limb. Modeled MAPs were lower than the water balance determined values for the upper and middle zones; the lower zone simulated MAP was accurate.

Aside from scheme ‘B’ in the snow-dependence portion of the analysis, the one-station configuration containing the Tower SNOTEL site produced the highest Nash-Sutcliffe parameter. Much of this simulation’s rising and receding limbs of the hydrograph match the observed hydrograph. The simulated peak flow is greater than the observed flow while preserving the accurate timing of the snowmelt. Simulated MAPs are very precise compared to the water balanced produced MAP values.

A plot of the SWE time series for the 14-, seven-, and one-station configurations are plotted against the observed SWE of the Rabbit and Tower SNOTEL sites in Figure 10. It is difficult to attribute accuracy to certain arrangements from this chart since the observed SWE values for the three model zones are not known. The SNOTEL time series do give us a rough estimate of whether the simulated SWE time series are acceptable.

5.2.2.1 Rainfall Event Sensitivity Results

This scheme was developed to assess whether there was a marked difference in specific rainfall-induced hydrograph simulations, as compared to snowfall determination. A greater change in specific rainfall events hydrographs is expected.

The results from the first rainfall event of 14 May through 11 June 1997 clearly show a decrease in simulation accuracy with fewer stations used (Figure 5-8). The baseflow deviated from the observed flow by a 9% bias; the six-station and two-station arrangements had increased biases of 12% and 21%, respectively.

The second rainfall event analyzed has a different characteristic from the first rainfall event analyzed above. The 18 September through 22 September 1997 event occurred during a time of baseflow on the hydrograph and thus had no snowmelt effects. The base simulation of the hydrograph illustrate that the model does not accurately resolve the streamflow during the baseflow months (Figure 5-9). The base simulation has a 39% bias over this period, and the six- and two-station arrangements have percent biases of -40% and -53%, respectively.

5.2.3 Mean Areal Temperature Sensitivity

When MATs were developed without using the Tower SNOTEL station, model results were negligibly different than the base model run. Trendlines used to determine lapse rate equations were very similar to temperatures developed from lapse rates generated by the inclusion of the Tower site. It is noted that correlations between trendlines defining lapse rates were much higher for maximum temperatures than they were for minimum temperatures. Moreover, correlations were highest during the warmest months of the year within the maximum data set. It is likely that minimum temperatures and lower maximum temperatures during cooler months are more influenced by microclimate such as the presence of drainage flows, local vegetation, nearby development and topographic parameters such as elevation and aspect.

The second MAT scheme developed was based on the stations only within in the basin in which very few stations are present, but those that were used were quasi-representative of the modeled basin. This scheme produced MATs based off of Steamboat Springs and Yampa temperature records. It is noted that in this case during some of the winter months, Steamboat Springs, the higher elevation of the two stations, actually has a higher average minimum and maximum temperature. This then produces a lapse rate that increases temperature with elevation, the opposite of what occurs in nature except for very cold climates or in temperature inversions. From this alone, it can be expected that model results using this scheme will be inaccurate. Compared with the base model run using fifteens stations, the percent biases systemically increased as the elevation rose. This is expected since most of the stations are located in the lower elevation range, and as lapse rates extrapolate up to the middle and upper zones, the errors will grow. The upper zone biases were 38% and 65% for the maximum and minimum time series; the middle and lower zones had biases of 23% and 42% and 3% and -3% for the maximum and minimum monthly averages. This second MAT scheme produced predictable model results. Because many of the lapse rates were increasing with temperature as the elevation was increased, artificially high MATs were produced for many of the months for the three zones. The amount of precipitation in the basin was the same as the model's base run after the calibration. However, because the zones were artificially warm, the snow melted out much sooner than observed. March, April and early may have high positive biases reflecting this early melt-off. Because so much is melted off early, there isn't enough to water in the streams in late May, June and July, creating large negative biases during these months. Figures 5-10a,b, and c show the different monthly mean maximum and minimum temperatures used to drive the model with the 15-station configuration compared with the base simulation means.

It is difficult to assign degrees of accuracy to the SWE simulations because there are no observed SWE values for the specific zones from which to compare. Both the Tower and Rabbit Ears SNOTEL sites provide an acceptable judge as to the rough accuracy of the simulation. It can be seen, based off of the SNOTEL data, that timing of accumulation and extinction of the snowpack are in general good agreement. It is stressed that SWE can be highly variable depending on elevation, aspect, slope and local vegetation.

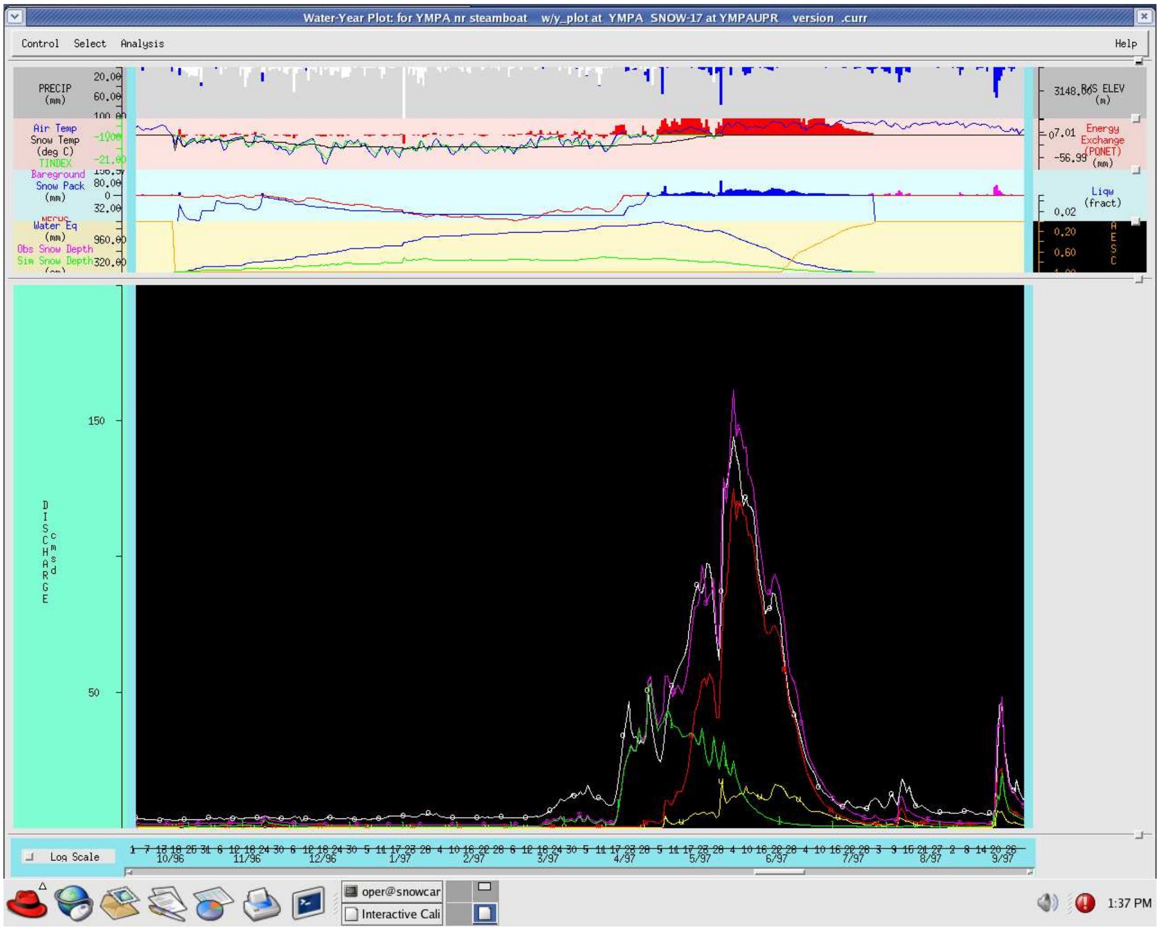

Figure 5-1. Calibration results taken from the NWSRFS screen.

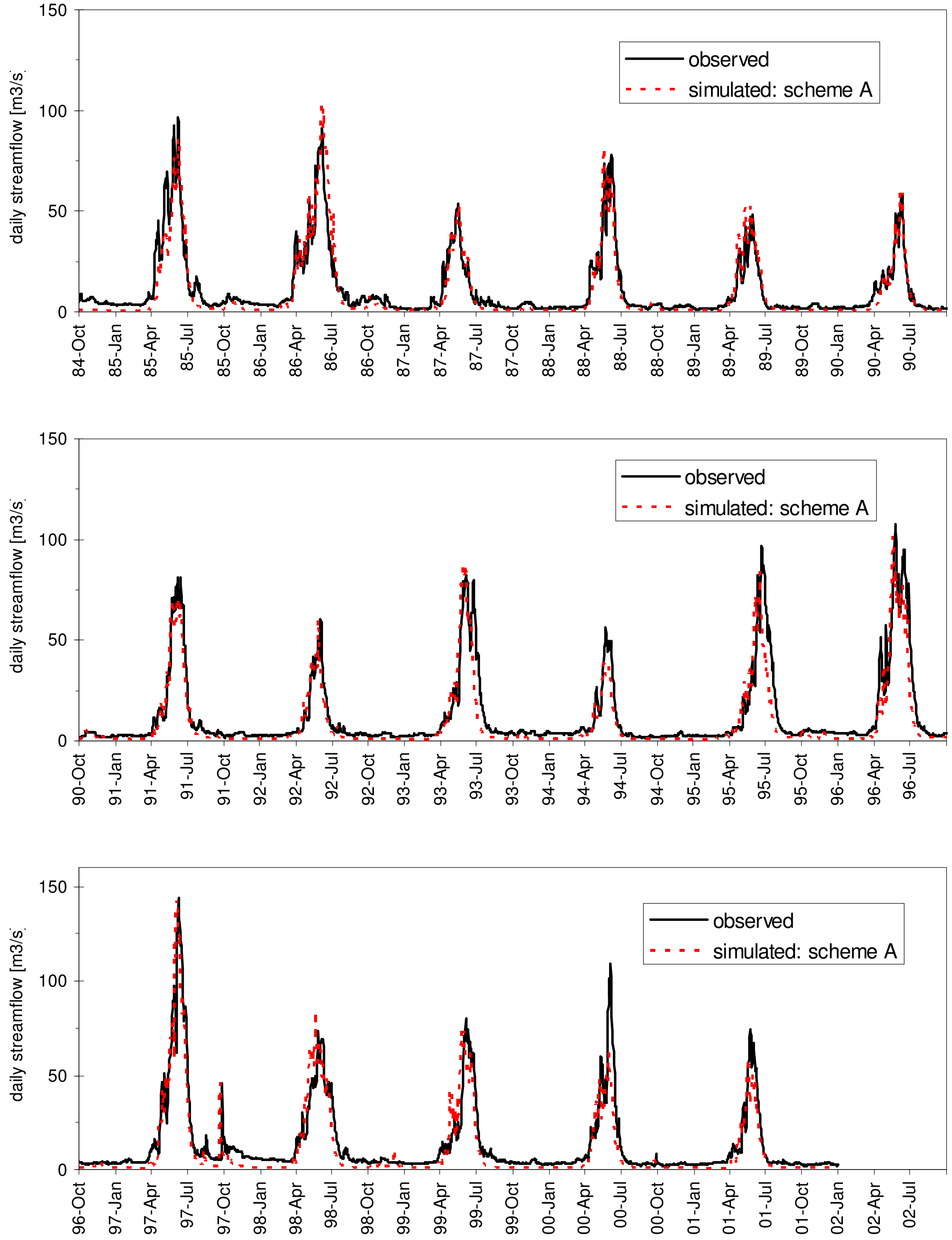

Figure 5-2. Simulated scheme A and observed hydrographs for water years a) 1985 to 1990, b) 1991 to 1996, and 1997 to 2001.

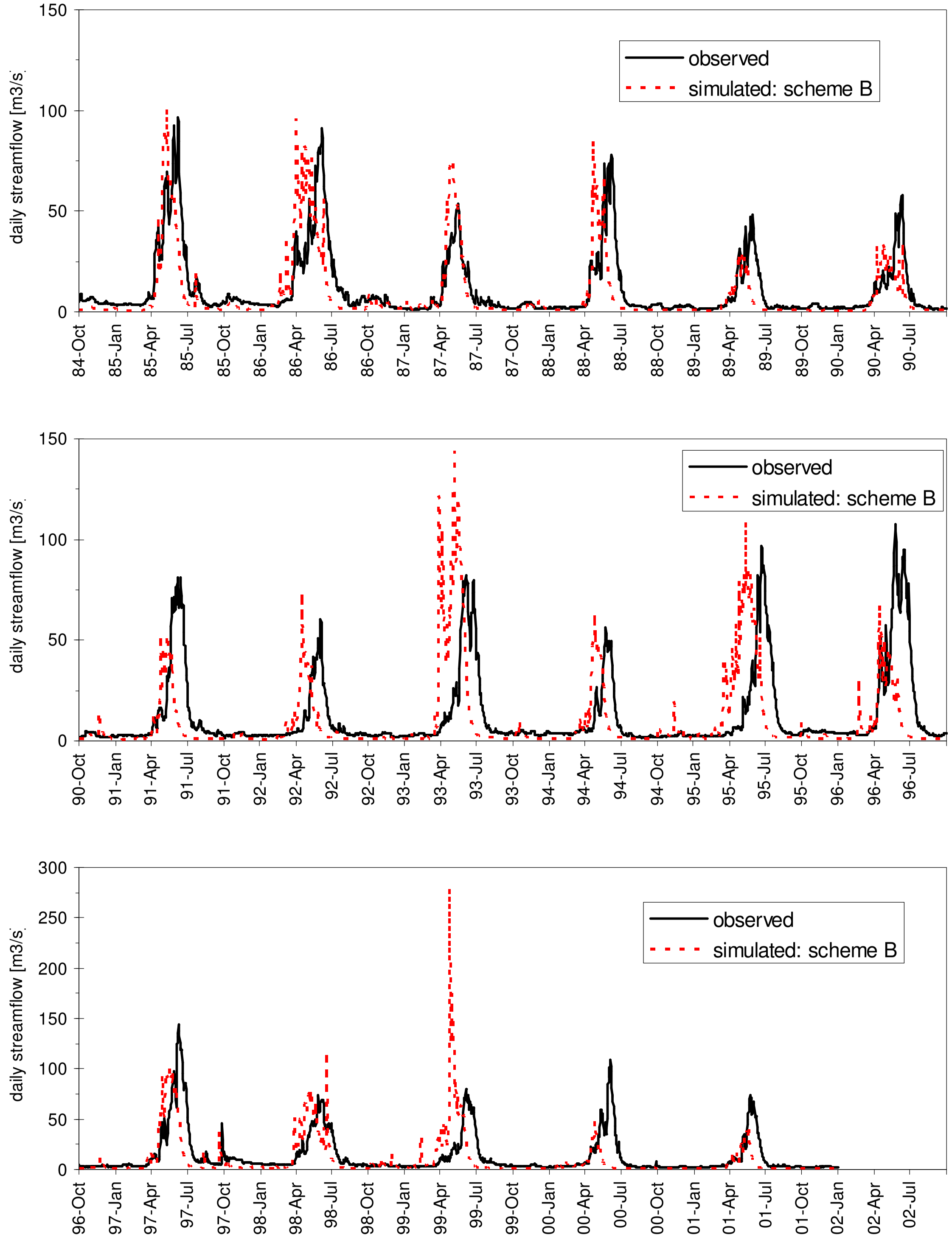

Figure 5-3. Simulated scheme B and observed hydrographs for water years a) 1985 to 1990, b) 1991 to 1996, and 1997 to 2001.

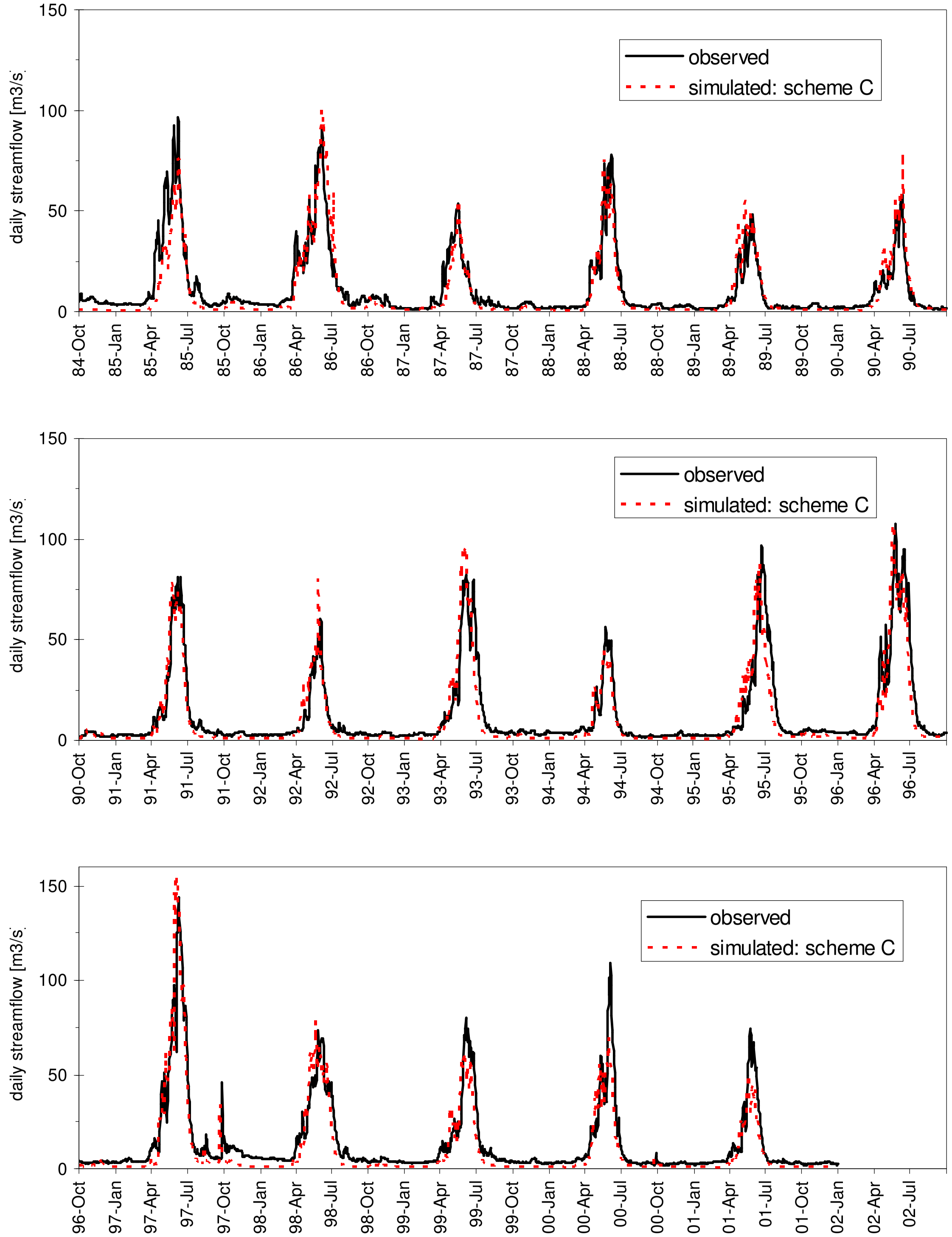

Figure 5-4. Simulated scheme C and observed hydrographs for water years a) 1985 to 1990, b) 1991 to 1996, and 1997 to 2001.

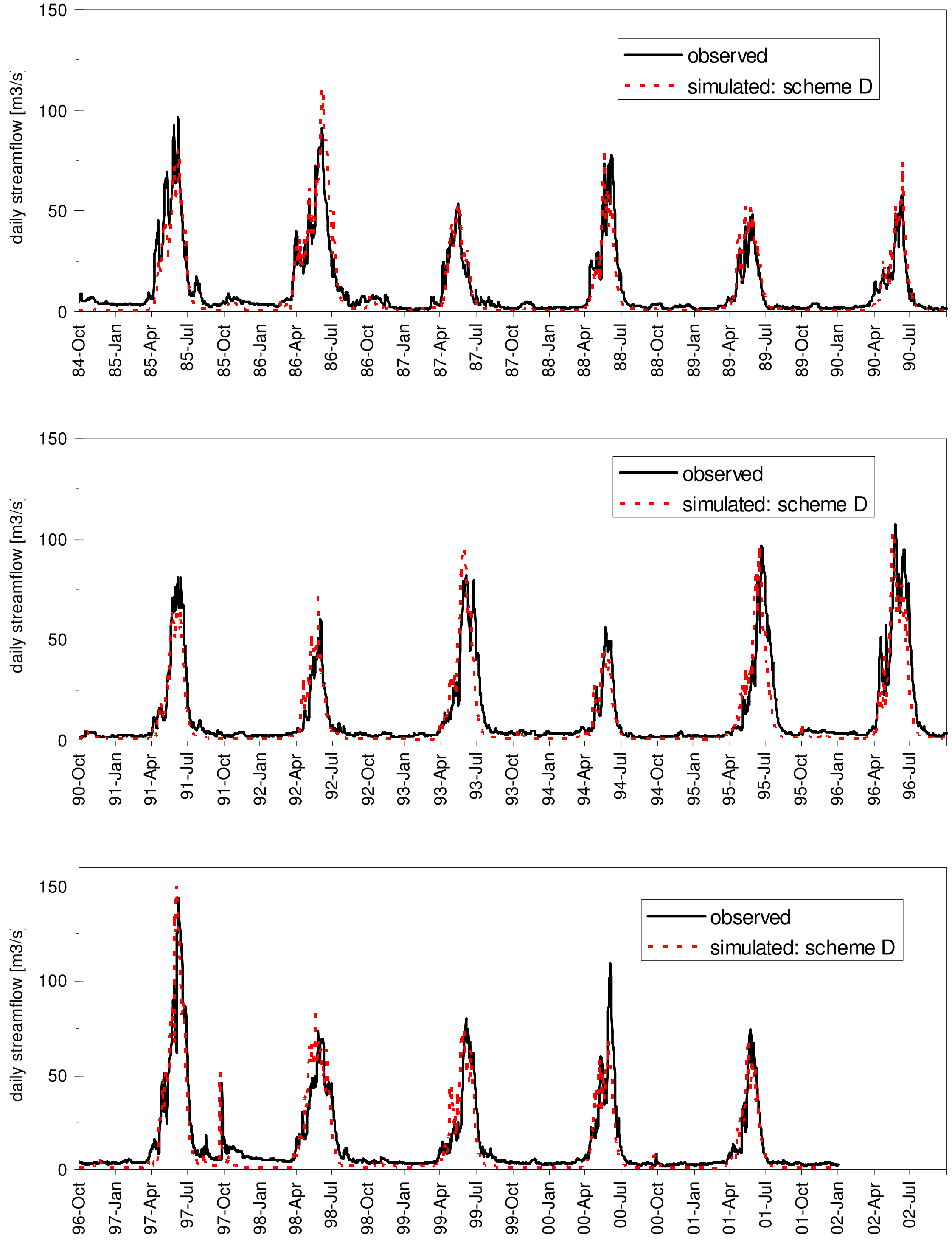

Figure 5-5. Simulated scheme D and observed hydrographs for water years a) 1985 to 1990, b) 1991 to 1996, and 1997 to 2001.

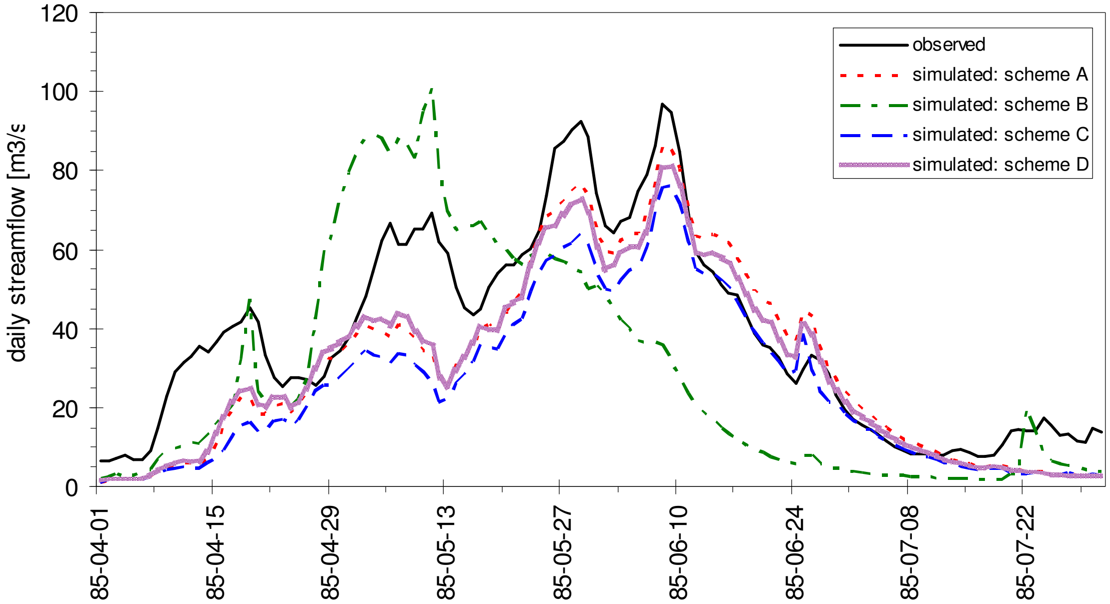

Figure 5-6. Simulated (schemes A to D) and observed discharge for April through July 1985.

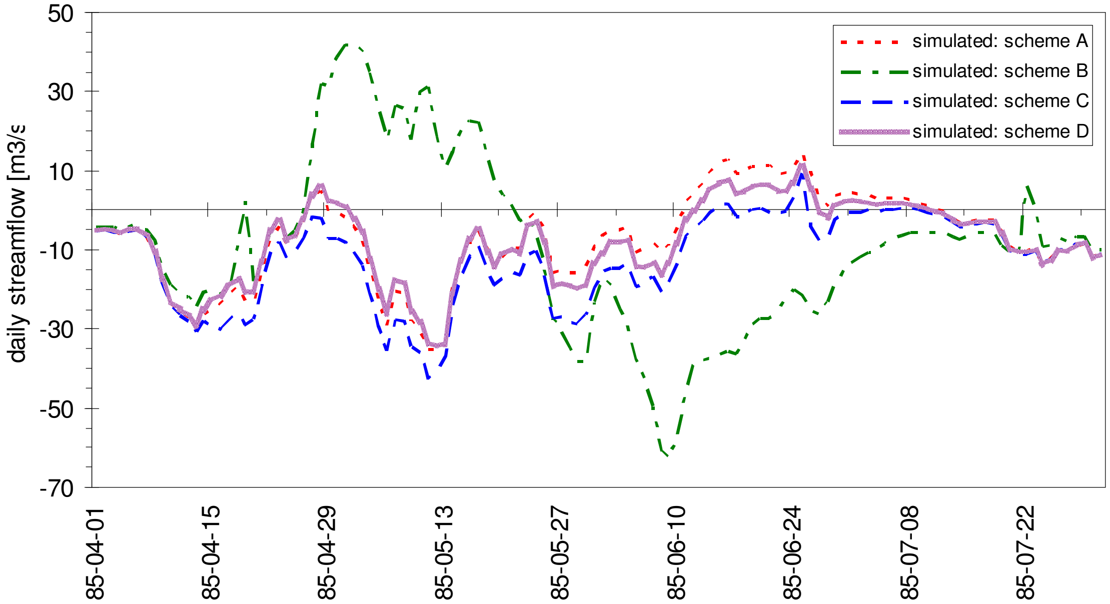

Figure 5-7. The difference between simulated (scheme A to D) and observed discharge for April through July 1985.

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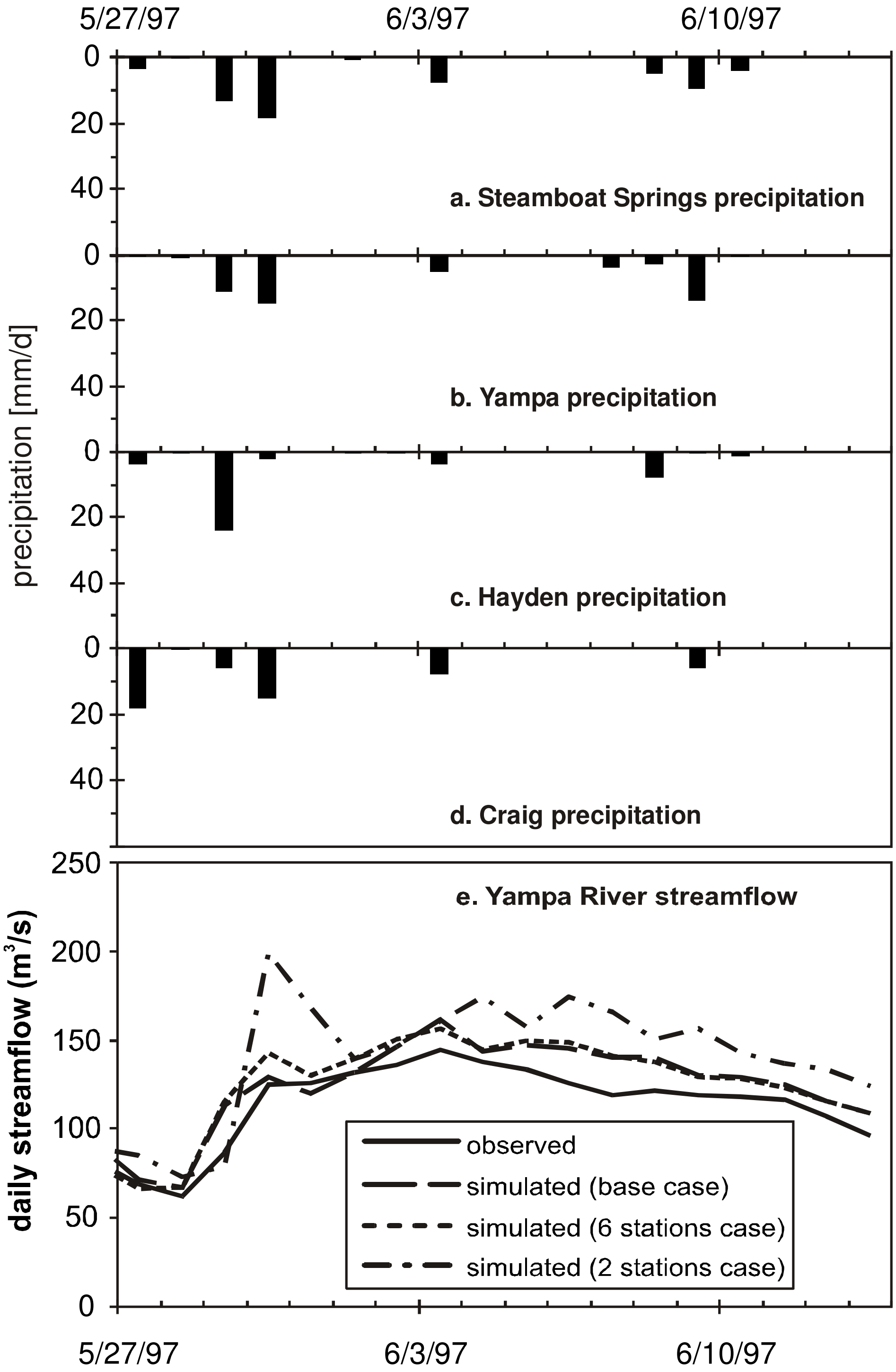

Figure 5-8. Precipitation at four stations and simulated streamflow for Storm 1.

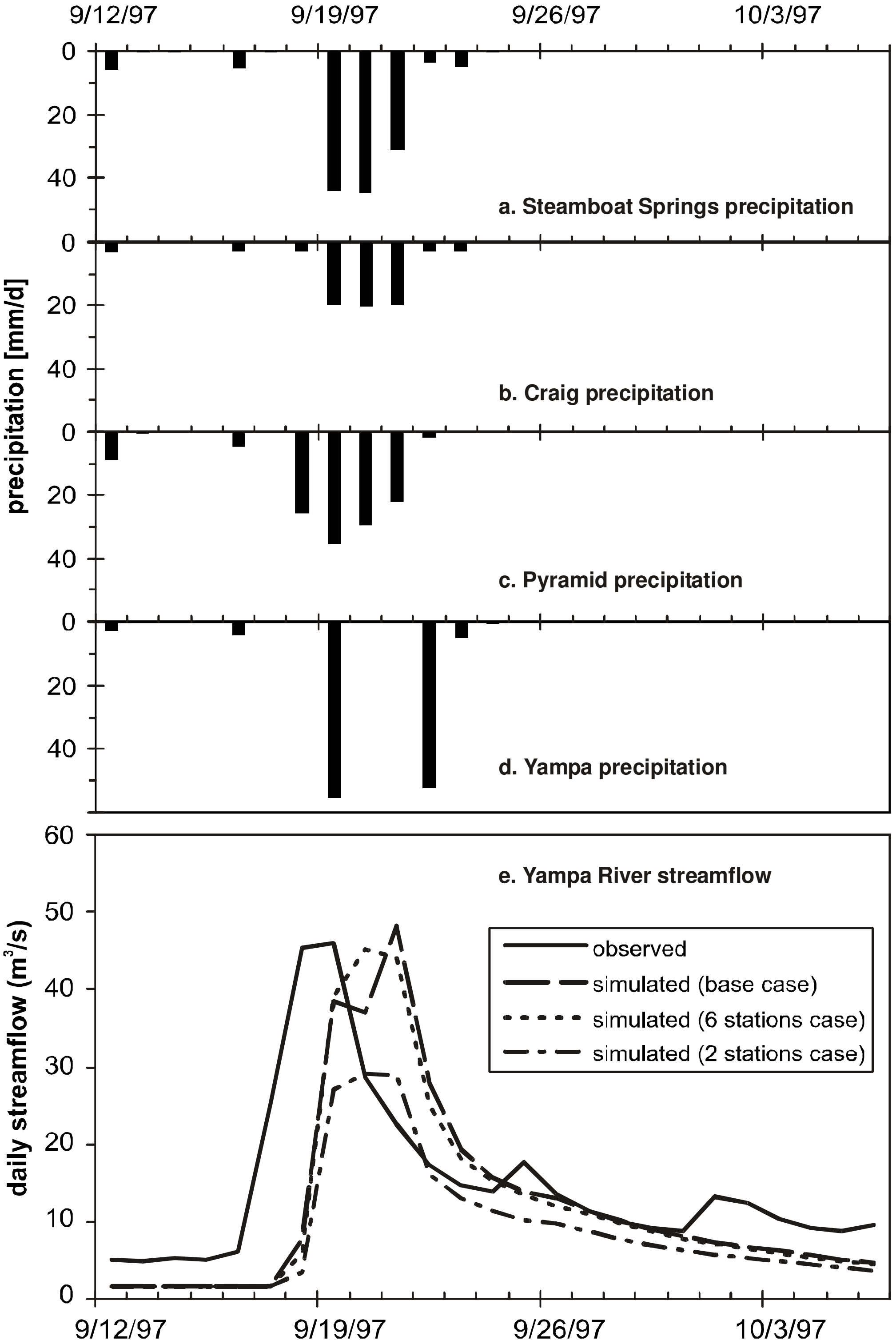

Figure 5-9. Precipitation at four stations and simulated streamflow for Storm 2.

6. DISCUSSION

The snow-dominated climate of the modeled area has a profound effect on the hydrology of the basin. Located just west of the Continental Divide, the modeled basin is subject to many winter storms that drop large amounts of snow before rising up and over the topographic barrier. Many differing arrangements of data within NWSRFS were aimed to understand the sensitivity of the model to input arrangements with varying levels of hydrological representivity. Many of the results were as expected. However, because of the ratio-dependence of the way NWSRFS determines MAPs and the way the water balance and station weights are produced, some of the results were not expected.

The base calibration was not perfect in replicating observed historical streamflows (see Appendix H.) However, the high-flow months were in very good agreement with the historic observed flows. Therefore, the subsequent analyses of the sensitivity schemes were based on relative differences and were not a function of the error entrained in the original calibration.

6.1 SNOW DEPENDENT SCHEME

The best results were produced using the proximity plan of scheme D where the six closest stations to the basin were used to drive this model run; the simulation captured the peak and much of the rising and receding limbs very accurately. This shows that NWSRFS can be run effectively with only a few stations that are representative of the basin. More important than the proximity, all these stations represented varying hydrological significances to this basin. The elevation increases dramatically in the eastern part of the basin, and the closer to this elevation increase the station is located, the better it captures the hydrology that is indicative of the basin as a whole. Eliminating the nine stations farther to the west eliminated stations that receive less than half the annual precipitation of any portion of the modeled basin receives. These outlying stations are hydrologically unrepresentative of the modeled basin.

Scheme C produced similarly good results using just the three stations located within the boundary of the modeled basin. Neither the peak of the hydrograph nor the rising limb were as accurately modeled as the preceding schemes.

The station weighting scheme and the way MAPs are determined in NWSRFS tended to smooth the large-scale variations in hydrological representivity of the stations and reduce the actual heterogeneity of the basin's precipitation regime. A significant problem arises in situations where the basin being modeled is mountainous, and where most of the precipitation gauges are located in the lower elevations of the basin. In situations such as this, areal estimates of precipitation are usually low since there are few if any precipitation gauges being employed that actually represent the montane portions of the basin. Thus scheme 'A', that employs the highest precipitation sites in the area, did not perform as well as expected. This scheme was believed to produce the best simulations as it contains the most hydrologically significant stations in the basin. This simulation produced the worst results of the snow dependence schemes. It is believed using a different model with does not have an areal distributed precipitation scheme would produce better results.

6.2 RAINFALL EVENTS

It was believed that the sensitivity of the model to long-term simulated hydrology of the basin would not be as large as it would be for specific rainfall events. In mountainous environments, NWSRFS usually uses predetermined weights to calculate MAPs for the model zones. These weights are a function of user-assigned relative weights that translate into actual weights based on mean annual precipitation for each subbasin, as determined in the water balance. By decreasing the number of stations used, the actual weights will be changing, but the subbasin yearly precipitation totals will ultimately be similar in each run since they are tied to the estimated long-term MAPs for each subbasin.

Changing the number of stations used, and thus the value by which stations are weighed, should affect the short-term precipitation since there are not long-term dependencies involved in the short-term MAP determination, and thus the streamflow simulation. Changing the number of stations used to drive the model run should only affect rainfall response, though much more so than snowmelt response because snowmelt is lagged until spring, and doesn't show up in the hydrograph until spring, often long after the snowfall occurred. In this way, snowmelt becomes more a function of snowmelt.

MAPs did have a significant effect on the simulation hydrograph when only a few stations were used. In these lower-configuration setups, often the storms incident to the basin only contributed rainfall to a select few stations. Despite the MAP configuration hydrograph having a good volume agreement with the observed flows, individual storms often did not perform well in the model depending on whether the weighted stations actually received precipitation from a given storm. This is a potential problem with using only a few stations, especially in locations where the precipitation is very orographically-oriented and often convective in the summer. Distributed physically-based models most likely would perform better in such situations.

6.3 MEAN AREAL TEMPERATURE

The MAT scheme was employed to illustrate whether MATs may be more significant for snowmelt simulation than MAPs were. As seen previously, altering MAP configurations didn't alter the model output simulation averaged over a long (multi-year) time scale very significantly. This occurred because of the correction ratio used to determine station weights used in the MAP file. A ratio of mean basin precipitation to the collective station precipitation determined through the weighting and MAP process adjusts the station configuration precipitation amount to the long-term average precipitation as determined by the waterbalance.

A ratio of one would take away the model's bias to artificially adjust station precipitation weights to long-term climatic averages observed for the watershed. To see how the model would perform without this bias, the above-mentioned ratio (mean basin precipitation to station precipitation) was manually adjusted to 1. Model results were much more predictable. Scheme A, which included the stations with the highest annual precipitation, slightly over simulated results on a monthly, yearly, and period of record scale. It is noted that the heavy dominance of snowfall in the basin is significant enough for the model to use the best results under Scheme A. Scheme B employing the stations with the least amount of precipitation severely underestimated streamflows. It is noted that the aim of this study was to test the sensitivity of NWSRFS to the input of different input data using the current procedure for determining station weights through the water balance approach. Altering the ratio to a value of 1 is not consistent with the procedure used by RFCs in their determination of station weights.

Differing MAT configurations changed the simulation hydrograph much more than did the MAPs. Snowmelt, despite ultimately being a precipitation-related event, hydrologically is often more of a temperature-sensitive function. In this way, snowfall is often lagged until the spring when temperature controls the release of the stored winter precipitation. It is for this reason that a greater response was seen from varying MATs than from varying MAPs in this snowmelt-dominated basin.

6.4 FUTURE WORK

This study revealed several directions for future work. A relatively large snowmelt dominated basin was used to test changes in model output based on varying precipitation and temperature datasets that are the input into the NWSRFS model. On average there was limited change in model output with varying MAPs, yet larger differences were modeled when individual storms were analyzed and the actual streamflow hydrograph was examined. Due to the large size of the basin, the small model response was in part a function of the hydrograph being dampened by the size of the basin. As river length and basin area increase, streamflow tends to be more attenuated, especially for snowmelt dominated regimes or localized intense rainfall. This issue of scale could be examined by modeling the smaller 69 km^2 (27 mi^2) Fish Creek Basin adjacent to and encompassed by the upper zone of the Yampa River at Steamboat region. This basin is very mountainous and includes the Tower SNOTEL site, which receives the largest recorded quantity of snowfall in the entire Colorado River basin. Runoff volumes would be more sensitive to accumulated snowfall, and streamflow would be more responsive to localized rainfall events.

This study could be replicated for differing hydroclimates to better illustrate the sensitivity of NWSRFS to different meteorological and hydrologic realms. Coastal areas with maritime a snowpack have a much different climate than inland areas with continental snowpacks; regions with differing precipitation patterns would be expected to produce differing sensitivities within NWSRFS

Model output is not only dependent upon model input, but also model characteristics. Using other models may yield slightly different results. While the NWSRFS uses mean areal precipitation and temperature, other models use distributed meteorology, which may result in smaller averaged input meteorology. For example, the USGS Precipitation Runoff Modeling System, also a conceptual model using only precipitation and temperature assigns daily (or hourly) meteorology to individual modeling response units that may be 1 km^2 grid blocks, sub-basins, etc. These individual meteorology values can be estimated from regressions using latitude, longitude and elevation (Hay *et al.,* 2000). Obviously physically based models would yield different results. However, they require much more meteorological data which are even more scarce than precipitation and temperature.

7.0 CONCLUSIONS

Different data input sets were used to illustrate the sensitivity of a semi-distributed empirical model to the hydrometeorological data used to drive the model. NWSRFS, an operational model used by the NWS to forecast streamflows for over 4000 sites in the United States, was used to model a snowmelt-dominated basin in northwestern Colorado. The availability of reliable hydrometeorological data is an operational dilemma encountered in data-scarce regions throughout the nation. Many of the regions that experience data paucity are high alpine sites that often receive a majority of their annual precipitation in the solid phase. Such areas supply a vital source of streamflow in the form of spring snowmelt for municipalities, industries and agricultural interests. Resolving NWSRFS's sensitivity to input data is important to optimizing model simulations based on the often few stations available in and around a basin.

Since the NWSRFS uses predetermined weights to determine MAPs, the number of stations used does not significantly affect model output. The usage of predetermined weights maintains a consistent year-to-year MAP. Station weights and MAPs are developed for each scenario. However, effects are seen in short-term rainfall events. Year to year simulations show little response to varying MAP station configuration because of the ratio used to correct for unrepresentative precipitation stations. When only a few stations were used, the model was at the mercy of how well those few stations captured the given precipitation events that were incident to the basin as a whole. Average runoff volumes remained consistently well simulated over the period modeled, but specific rainfall events did not perform as well.

Changing MATs impacted the model simulations much more than MAPs did. This occurred since snowmelt dominated basins are more temperature than precipitation sensitive during the spring snowmelt runoff. NWSRFS total precipitation amounts were similar enough to observed values that the amount of water stored in the snowpack at peak accumulation was commensurate with observed values. At this point the peak and timing of the streamflow hydrograph are largely dependent on temperature to drive the melt. Varying the MAT station configuration showed a much bigger effect than the MAP scheme showed.

It is believed that though this procedure could and should be replicated for other hydroclimates and for basins with different sizes, that the specific results are not transferable to other basins. The basin modeled is very heavily snowmelt dominated. This quality, as well as it size, climate, topography, and available hydrometeorological stations all influence model results; altering any of these would change the model performance.

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APPENDIX A: MAT File

This is the file that is read by NWSRFS after the Mean Areal Temperature program is executed.

```
@A 8 1953 8 2002
        @B 0 0 ENGL MNT CTMP ,, CONS
        @C PRE
        @D ,,, OUTN ENGL west_slope SUMPT SUMP
        @E 14
        @F 'STEAMBOAT SPRINGS ' 40.50 106.87 7. 6636.
        @G 20.0 28.6 33.8 42.3 53.8 65.0 75.5 82.5 80.7 72.5 60.6 42.5 30.1
        @H 20.0 1.7 4.9 14.4 24.3 31.5 36.0 41.6 40.5 32.8 24.0 14.6 3.9
        @F 'CRAIG ' 40.53 107.55 24. 6280.
        @G 20.0 31.0 35.5 43.3 55.8 67.4 77.2 85.0 82.7 74.6 62.5 46.1 34.3
        @H 20.0 3.5 8.0 17.0 27.5 35.6 42.5 48.8 47.2 38.0 27.8 17.4 7.3
        @F 'CRAIG 4 SW ' 40.45 107.58 8. 6440.
        @G 20.0 30.8 34.9 45.7 56.9 66.2 78.0 84.5 83.0 74.3 61.3 44.0 32.8
        @H 20.0 6.8 10.6 21.2 29.0 36.7 44.0 50.1 49.0 40.2 29.5 19.2 8.9
        @F 'DINOSAUR NATL MONUMN' 40.25 108.97 17. 5920.
        @G 20.0 32.7 38.9 50.2 60.7 71.8 83.4 90.3 87.9 77.8 63.4 45.9 34.0
        @H 20.0 10.2 14.9 24.7 31.6 40.3 48.8 56.3 54.5 45.3 34.6 23.1 12.3
        @F 'HAYDEN ' 40.50 107.25 18. 6440.
        @G 20.0 30.0 34.9 43.6 57.1 68.3 78.5 85.1 82.9 74.5 62.2 44.8 32.5
        @H 20.0 5.4 8.9 18.0 27.8 35.4 42.0 47.9 46.7 38.5 28.3 18.4 8.4
        @F 'LITTLE HILLS ' 40.00 108.20 18. 6140.
        @G 20.0 37.1 41.7 47.9 58.3 68.1 79.2 85.7 83.2 75.8 64.0 48.8 38.9
        @H 20.0 3.4 8.0 16.8 23.9 31.6 38.0 45.0 43.5 33.9 23.5 14.5 5.5
        @F 'MARVINE ' 40.02 107.55 8. 7200.
        @G 20.0 35.6 37.5 42.2 53.0 63.7 74.4 81.0 77.9 68.9 59.8 46.9 36.6
        @H 20.0 7.9 10.3 14.4 24.5 31.2 36.6 41.8 41.5 34.0 26.6 17.8 10.3
        @F 'MARVINE RANCH ' 40.02 107.43 18. 7800.
        @G 20.0 35.6 37.5 42.2 53.0 63.7 74.4 81.0 77.9 68.9 59.8 46.9 36.6
        @H 20.0 .8 3.1 11.1 18.1 27.2 33.0 38.5 37.6 31.3 22.4 11.2 2.2
        @F 'MASSADONA 3 E ' 40.28 108.60 7. 6185.
        @G 20.0 32.5 37.7 49.2 57.6 68.0 79.5 85.7 83.7 74.3 61.9 44.4 33.4
        @H 20.0 10.3 14.9 24.7 31.5 40.5 49.4 56.0 54.2 45.0 33.5 21.6 11.0
        @F 'MAYBELL ' 40.52 108.10 8. 5908.
        @G 20.0 32.5 37.6 47.8 59.1 70.0 79.9 87.1 84.7 74.8 62.8 45.8 34.3
        @H 20.0 2.0 7.0 17.8 26.2 33.3 40.4 46.7 45.3 35.8 25.1 15.3 4.0
        @F 'MEEKER 3 W ' 40.02 107.97 18. 6180.
        @G 20.0 36.7 40.5 48.0 58.4 69.4 79.4 86.5 83.7 76.2 64.8 49.1 37.9
        @H 20.0 8.2 12.5 20.1 28.1 35.6 41.8 48.2 46.6 38.1 28.5 18.9 10.6
        @F 'RANGELY 1 E ' 40.08 108.77 8. 5290.
        @G 20.0 32.0 39.5 51.4 63.1 73.6 85.2 91.7 89.1 79.9 66.7 48.3 34.6
        @H 20.0 3.3 10.2 22.4 32.0 40.6 48.7 55.3 52.9 43.2 31.2 19.6 7.2
        @F 'YAMPA ' 40.15 106.92 7. 7890.
```

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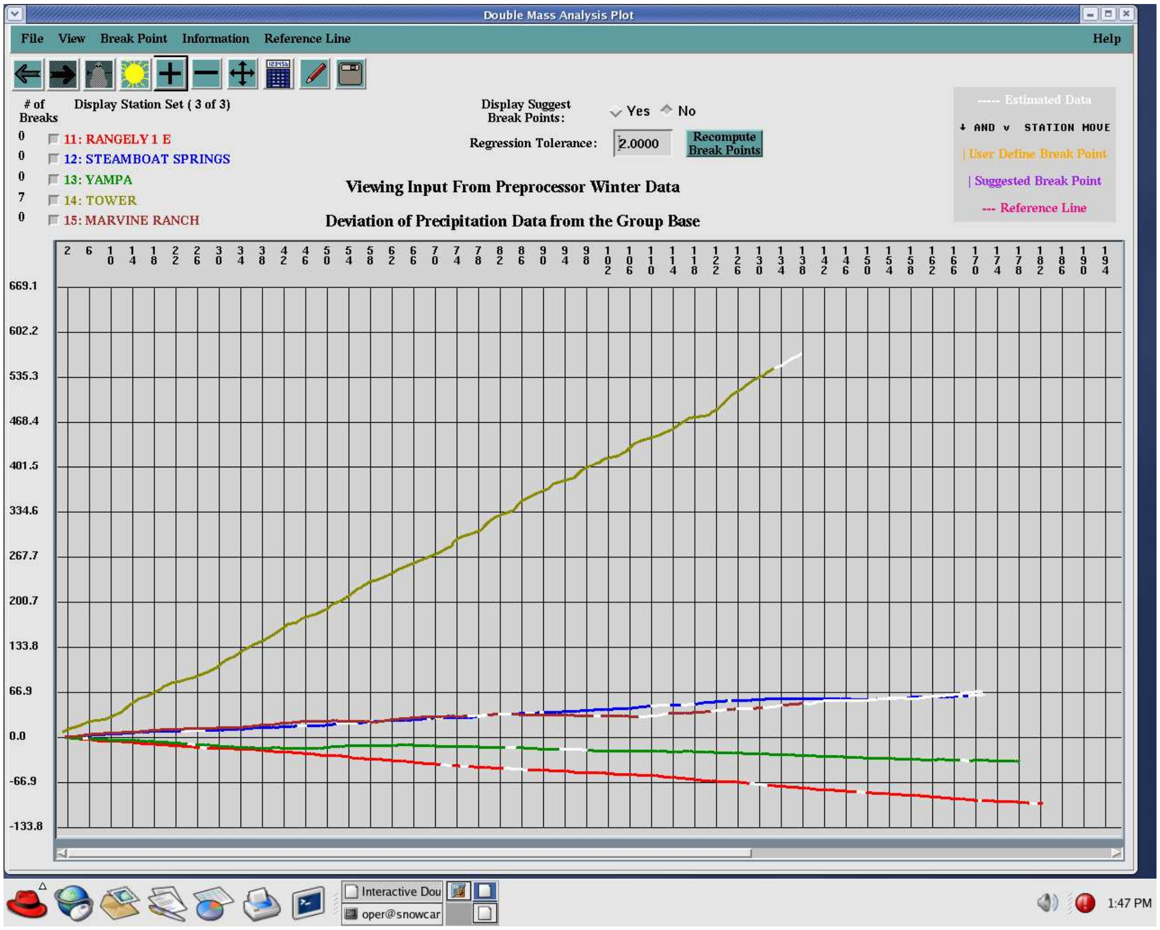
@G 20.0 31.4 35.0 41.3 51.1 61.9 71.4 77.0 75.6 68.1 57.0 41.4 32.3
@H 20.0 6.7 8.5 15.5 23.6 32.0 39.1 45.6 44.2 36.4 26.5 16.4 8.1
@F 'BROWNS PARK REFUGE ' 40.80 108.92 8. 5354.
@G 20.0 38.4 44.0 52.2 61.7 71.8 82.6 89.1 87.6 78.4 65.6 49.1 39.5
@H 20.0 7.6 12.9 21.3 27.7 35.6 41.8 46.7 44.7 36.0 26.3 17.7 9.0
@O 12 8 1953 -0.7 2.75
@O 12 8 1972 -0.6 6.35
@O 12 4 1976 0.0 1.71
@O 12 3 1984 0.0 -0.06
@O 999
@Q
TAMX CO-7936.TAMX
TAMN CO-7936.TAMN
TAMX CO-1928.TAMX
TAMN CO-1928.TAMN
TAMX CO-1932.TAMX
TAMN CO-1932.TAMN
TAMX CO-2286.TAMX
TAMN CO-2286.TAMN
TAMX CO-3867.TAMX
TAMN CO-3867.TAMN
TAMX CO-5048.TAMX
TAMN CO-5048.TAMN
TAMX CO-5408.TAMX
TAMN CO-5408.TAMN
TAMX CO-5414.TAMX
TAMN CO-5414.TAMN
TAMX CO-5422.TAMX
TAMN CO-5422.TAMN
TAMX CO-5446.TAMX
TAMN CO-5446.TAMN
TAMX CO-5484.TAMX
TAMN CO-5484.TAMN
TAMX CO-6832.TAMX
TAMN CO-6832.TAMN
TAMX CO-9265.TAMX
TAMN CO-9265.TAMN
TAMX CO-1017.TAMX
TAMN CO-1017.TAMN
@R 1 14
@S
1 2 3 4 5 6 7 8 9 10 11 12 13 14
```

APPENDIX B: Double Mass Procedure



# of Breaks	Display Station Set (3 of 3)
0	☐ 11: RANGELY 1 E
0	☐ 12: STEAMBOAT SPRINGS
0	☐ 13: YAMPA
7	☐ 14: TOWER
0	☐ 15: MARVINE RANCH

Display Suggest Break Points: ✓ Yes ◇ No

Regression Tolerance: 2.0000

The double mass procedure is used to ensure the consistency of the station data. Within NWSRFS, the Interactive Double Mass Analysis program allows the user to produce correction factors based on the graphical method of displaying the station data against a base station. Consistent plots are recognized by having straight lines throughout the period of record, whereas stations that have moves, switched instruments, or just don't have a similar meteorological regime to the rest of the stations are characterized as having choppy lines with many breaks in slope.

To correct choppy data, break points are located where the slope changes significantly, and new lines are drawn, correcting the data, based on previous slopes.

APPENDIX C: Water Balance Procedure

The goal of this water balance is to determine the mean annual precipitation values for each of the three zones (upper, middle, lower) within the drainage above the Steamboat Springs gauge on the Yampa River. A water balance is an accounting of the inputs and outputs of water. The major input of water is from precipitation and output is represented by evapotranspiration, runoff, irrigation/consumptive use; changes in groundwater contributions and changes in storage involving reservoirs can be inputs or outputs depending on their values and the basin. The geographer C. W. Thornthwaite (1899-1963) forged the water balance approach to water resource analysis. This procedure aims at a "best-guess" value for the variables describing the accounting of water within a basin. These values will go into creating the baseline MAP arrangement, off of which subsequent analysis is going to be based. Uncertainties in each of these variables will preclude us from knowing the "true" values. These are best-guesses and help produce a baseline MAP.

$$In = Out$$

$$P = RO + ET + I + \Delta G + \Delta S$$

$$P = precipitation$$

$$RO = runoff$$

$$ET = evapotranspiration$$

$$I = irrigation\_loss$$

$$\Delta G = change\_in\_groundwater\_contribution$$

$$\Delta S = change\_in\_storage\_(reservoir\_controls)$$

Runoff:
Runoff data was determined to be the most accurate variable accounted for in the water balance. Since runoff data is relatively accurate, the water balance was worked backwards from this variable. United States Geological Survey records were referenced to determine runoff amounts for the basin. There are three recording streamflow gauges in the basin, one located just downstream from the outlet at Stagecoach Reservoir on the Yampa River, another located on the Fish Creek tributary to the Yampa River, and another at the basin outlet in downtown Steamboat Springs on the Yampa River. An area-weighted average method was used to calculate the runoff from the Steamboat drainage, less the Fish Creek area and less the region upstream from the gauge below Stagecoach Reservoir. This was determined to be 14.1in.

$$RO_{drainage}(568mi^2) = RO_{stgres}(228mi^2) + RO_{stmbt}(337mi^2)$$
$$11.02(568mi^2) = 4.41(228mi^2) + RO_{stmbt}(337mi^2)$$
$$RO_{stmbt} = 15.59in$$
$$15.59(337) = 33.4(26mi^2) + 311(RO_{SB-FC})$$
$$14.1 = RO_{SB-FC}$$

Region	Runoff	Runoff (Area-wtd)	Runoff %
Ympa Upr	46	1.9	0.14
Ympa Mid	20.5	9.6	0.68
Ympa Lwr	5.1	2.5	0.18
Ympa Total	14.06	14.06	1

Evapotranspiration (ET):
The Desert Research Institute's Western Region Climate Center was referenced for pan evaporation data from around Colorado (DRI, 2004). CBRFCs segment definition provided mid-month ETD values for each month for each zone. In addition to these two sources, the Assistant Colorado State Climatologist, Nolan Doesken, suggested some evaporation numbers based on ratios associated with precipitation amounts (pers. comm.., 2004).

The DRI's WRCC data comes from standard 4ft-diamter evaporation pans that are installed aboveground, usually collocated with existing weather stations. These pans represent the ET Demand (ETD) for that particular site. Since radiation on the side walls of the pans and heat exchanges with the pan material tend to increase the evaporation totals, these values are often adjusted by multiplying the totals by 0.70 or 0.80 to more closely estimate the evaporation from naturally existing surfaces such as a shallow lake, wet soil or other moist natural surfaces. For more arid regions, and terrain with significant elevation, characteristics of the Yampa River basin, lower fractions are often used to estimate actual ET values.

No historical evaporation data exists in the Steamboat area of Colorado, so the numbers used were interpolated from nearby and comparable-setting stations in Colorado. ETD values from Grand Junction, Lake George, Grand Lake, Montrose and Denver, all stations with similar climatic regimes, were used to create an elevation vs. ETD plot. From this plot, a line fit to the curve, and ETD values were plucked off at the mean elevations of each of the three zones in the basin. The ETD amounts for upper, middle, and lower zones were 33, 39, and 53, respectively. A ratio of ET to ET-Demand, multiplied by the ET numbers, yields actual ET amounts. Actual ET is a function of the ETD, available solar radiation and water supply at the surface. Because of the aridity of the region, ET/ETD ratios have been assigned as 0.2 for each zone.

Region	ETD	ET/ETD	Actual ET
Ympa Upr	33	0.2	6.6
Ympa Mid	39	0.2	7.8
Ympa Lwr	53	0.2	10.6
Ympa Total	45.6	0.2	9.1

This value of 45.6in annually for the entire zone is similar to the 50.65in value that the CBRFC uses in their segment definition. It is also consistent with values determined for ET and ETD, according to the Colorado Assistant State Climatologist Nolan Doesken (pers. comm., 2004).

Since there is more evaporation than runoff in the lower zone, this would give persistent base flow and thus would be a losing stream.

Irrigation Loss (I):
Date for consumptive use from agricultural, industrial, and municipal sources were gathered from the Colorado Water Conservation Board's (CWCB) Consumptive Use Model. CWCB models consumptive use for every ditch on the Yampa River based on the Blaney-Criddle method. This method uses a formula describing empirically derived relationships between consumptive water use by irrigated crops and mean monthly temperature, monthly percentage of total daytime hours for the entire year and empirical coefficients that account for climatic and crop variation (USDA, 1970).

Ditch name	area (ac)	cu (ac-ft)	AF/acre	in
BAXTER DITCH	576	547	0.950	0.018
SUTTLE DITCH	672	637	0.948	0.018
WEISKOPF DITCH	77	73	0.948	0.018
WELCH & MONSON D	21	19	0.905	0.017
LOWER PLEASANT VALLEY	82	75	0.915	0.017
BEAVER CREEK D	132	99	0.750	0.014
ALPHA DITCH	312	298	0.955	0.018
ROSSI HIGHLINE DITCH	76	67	0.882	0.017
OAK DALE DITCH	108	101	0.935	0.018
OAK CREEK DITCH	141	136	0.965	0.018
BRUMBACK DITCH	64	61	0.953	0.018
LYON DITCH 2	71	67	0.944	0.018
GABIOUD DITCH	135	114	0.844	0.016
UPPER PLEASANT VALLEY	271	243	0.897	0.017
DEVER D	122	110	0.902	0.017
ADY005_YampaRabvSteambt	1484	1420	0.957	0.018
total	**4344**	**4067**	**0.915**	**0.275**

The consumptive use total of 4067 ac-ft was then converted to inches based on the area of the lower zone of the basin, and then finally to a basin-wide total.

$$4067ac - ft * 12in / ft * (1mi^2 / 640ac) / 150mi \quad = 0.508in$$

$$0.508 * 0.79 = 0.248in$$

Change in Groundwater Storage:
This is assumed to be zero for this exercise.

Change in Storage:
There is no significant storage in the modeled segment of the Yampa River.

Precipitation:
Precipitation data were gathered from Parameter-elevation Regressions on Independent Slopes Model (PRISM) data that is produced by the Spatial Climate Analysis Service at Oregon State University. PRISM precipitation climate maps are based on point precipitation data, digital elevation models and other spatial data sets. This data are produced for each state in gridded data sets.

PRISM climatological normal maps of precipitation were acquired on a monthly basis for Colorado. These maps were uploaded in a GIS environment, where the maps were clipped to the dimensions of the study basin. The PRISM maps were further split into the three elevation zones of the basin. The precipitation amounts were then area-weighted to produce a zonal PRISM values for winter and summer seasons. See below for a description of the GIS process used.

Region	**PRISM**	**PRISM (area/total)**	**Precip WY '63-'02**
Ympa Upr	65	2.25	52.6
Ympa Mid	35	1.21	28.3
Ympa Lwr	20	0.69	16.2
Ympa Total	28.94		***23.43***

The value of 23.43in was determined to be the annual basin-wide precipitation from the PRISM maps. This value was compared to the precipitation determined from the variables determined above in the water balance.

$$P = RO + ET + I + \Delta G + \Delta S$$
$$P = 14.10 + 9.1 + 0.248 + 0 + 0$$
$$P = 23.44$$

Weights:
After the precipitation data are distributed and/or estimated, mean areal precipitation is calculated by multiplying hourly precipitation values by station weights. Relative weights were assigned based on station annual and seasonal precipitation, elevation of stations, and the consistency in stations' period of record. In areas where precipitation does not show great variability with location, Theissen weights can be computed. The basin used in this study does have considerable precipitation gradients.

Precipitation amounts were divided into winter/summer amounts since much of the precipitation that falls at the higher elevation regions in the basin fall as snow in the winter. This is hydrologically significant since precipitation falling in the winter tends to be stored and doesn't contribute to streamflow till springmelt.

$$AW = (RW)*(PPT)/(\sum_{stations}(PP \ *(RW))$$

AW = Actual weight for a station in a specific season for a zone
RW = relative weight for station in a specific season for a zone
PPT = seasonal precipitation for a zone
PP = seasonal precipitation for a specific station

All relative weights had to add up to 1.0 in. for each zone for each season. Relative weights for the lower zone were based entirely on the Hayden and Yampa precipitation data, two cites similar to the area in the lower zone and with similar annual and seasonal precipitation amounts.

Relative weights for the middle and upper zones were based on a combination of stations. The most amount of precipitation fell in winter in the upper zone, with lesser amounts falling at higher elevations in the summer months.

APPENDIX D: MAP File

```
@A 1 1963 8 2002 IN IN ,,,
        @B 3 SEAS 0 CONT 6 ADJ SESN 11 5
        @C NORM
        @D 5 13
        @F 'ARTESIA 2 E ' 40.2300 108.9700 0.
        @G 0.65 0.67 0.79 0.87 0.63 0.56 0.53 0.90 1.03 0.91 0.53 0.71 $ 050354H
        @F 'CRAIG ' 40.5300 107.5500 0.
        @G 0.99 0.81 0.94 1.33 1.29 0.88 0.84 1.17 1.09 1.12 1.04 1.00 $ 051928H
        @F 'DINOSAUR NATL MN ' 40.2500 108.9700 0.
        @G 0.64 0.62 1.10 1.19 1.18 0.88 0.89 0.82 1.00 1.28 0.76 0.62 $ 052286H
        @F 'MEEKER 3 W ' 40.0200 107.9700 0.
        @G 1.04 1.09 1.38 1.66 1.53 1.04 1.53 1.58 1.22 1.47 1.20 1.12 $ 055484H
        @F 'MEEKER NO 2 ' 40.0300 107.9200 0.
        @G 0.87 0.80 1.56 1.61 1.45 0.97 1.43 1.40 1.45 1.42 0.99 0.99 $ 055487H
        @F 'CRAIG 4 SW ' 40.4500 107.5800 8.
        @G 0.98 1.09 1.31 1.52 1.35 1.33 1.16 1.23 1.32 1.63 1.35 1.08 $ 051932D
        @F 'HAMILTON ' 40.3700 107.6200 8.
        @G 1.26 1.35 1.75 1.94 1.88 1.23 1.37 1.46 1.59 1.82 1.49 1.52 $ 053738D
        @F 'HAYDEN ' 40.5000 107.2500 18.
        @G 1.54 1.19 1.25 1.58 1.49 1.19 1.33 1.39 1.40 1.51 1.41 1.57 $ 053867D
        @F 'BROWNS PARK ' 40.8000 108.9200 8.
        @G 0.36 0.43 0.74 0.86 1.02 0.72 0.61 0.62 1.02 1.03 0.54 0.42 $ 051017D
        @F 'LITTLE HILLS ' 40.0000 108.2000 8.
        @G 0.78 0.83 1.21 1.55 1.54 1.07 1.24 1.64 1.37 1.24 1.04 0.87 $ 055048D
        @F 'MARVINE ' 40.0200 107.5500 8.
        @G 1.83 1.67 1.85 1.84 1.72 1.28 1.68 2.01 1.95 1.87 1.60 1.93 $ 055408D
        @F 'MARVINE RANCH ' 40.0200 107.4300 8.
        @G 2.39 2.42 2.49 2.25 2.04 1.66 1.71 2.00 2.03 1.90 1.99 2.61 $ 055414D
        @F 'MASSADONA 3 E ' 40.2800 108.6000 8.
        @G 0.79 0.81 1.19 1.47 1.28 1.04 1.05 0.91 1.15 1.67 1.04 0.75 $ 055422D
        @F 'MAYBELL ' 40.5200 108.1000 8.
        @G 0.82 0.81 1.08 1.32 1.15 0.90 0.93 0.93 1.03 1.29 1.11 0.97 $ 055446D
        @F 'PYRAMID ' 40.2300 107.0800 17.
        @G 1.83 1.73 2.07 1.95 1.69 1.45 1.60 1.68 1.63 1.61 1.72 1.76 $ 056797D
        @F 'RANGELY 1 E ' 40.0800 108.7700 8.
        @G 0.55 0.61 0.92 1.03 1.03 0.77 0.91 0.95 1.11 1.21 0.69 0.56 $ 056832D
        @F 'STEAMBOAT SPRINGS ' 40.5000 106.8700 7.
        @G 2.62 2.17 2.04 2.27 2.09 1.47 1.49 1.52 1.74 1.81 2.12 2.51 $ 057936D
        @F 'YAMPA ' 40.1500 106.9200 7.
        @G 1.21 1.02 1.28 1.40 1.29 1.22 1.67 1.61 1.32 1.18 1.19 1.21 $ 059265D
        @I YMPAUPR 'YAMPA 10207' 24. MI2 steamboat stmbtupr
        @L 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.67 0.67 0. 0. 0.67 0. 0.67 0.
        0. 0. 0. 0. 0. 0. 0. 0.18 0.35 0.18 0.27 0.53 0. 0. 0.09 0. 0.18 0.
        @I YMPAMID 'YAMPA 9341' 163. MI2 steamboat stmbtmid
```

```
@L 0.23 0. 0. 0. 0. 0. 0.12 0. 0. 0. 0.12 0.58 0. 0. 0.58 0. 0.58 0.12
0. 0.19 0.47 0.2 0.2 0.1 0.18 0. 0. 0. 0. 0. 0. 0.19 0. 0.09 0.19
@I YMPALWR 'YAMPA 7590' 150. MI2 steamboat stmbtlwr
@L 0. 0. 0. 0. 0. 0. 0. 2.35 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.26
0. 0. 0. 0. 0. 0. 0. 1.3 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.14
@O S 10 5 1948 1.12
@O S 10 5 1967 1.00
@O W 15 2 1948 1.26
@O S 15 5 1948 1.30
@O S 15 9 1954 1.00
@O W 15 1 1955 0.97
@O W 15 10 1969 0.82
@O W 15 11 1977 1.00
@O S 18 5 1948 0.90
@O S 18 8 1970 0.74
@O S 18 7 1980 1.00
@O 999
@Q
CO0354HLY
CO1928HLY
CO2286HLY
CO5484HLY
CO5487HLY
CO1932DLY
CO3738DLY
CO3867DLY
CO1017DLY
CO5048DLY
CO5408DLY
CO5414DLY
CO5422DLY
CO5446DLY
CO6797DLY
CO6832DLY
CO7936DLY
CO9265DLY
@R 1 18
@S
1 9 2 6 3 7 8 10 11 15 12 13 14 4 5
16 17 18
```

APPENDIX E: Calibration Deck File

```
YMPALWR MAT 6 INPUT CARD
yampa/steamboat/stmbtlwr.MAT
YMPAUPR MAP 6 INPUT CARD
steamboat/stmbtupr.MAP06
YMPAMID MAP 6 INPUT CARD
steamboat/stmbtmid.MAP06
YMPALWR MAP 6 INPUT CARD
steamboat/stmbtlwr.MAP06
YMPA QME 24 INPUT CARD
oper/streamflow/yampa_stmbt_Q
FISH QME 24 INPUT CARD
oper/streamflow/fishcreekQ
FISH SQIN 6 INPUT CARD
oper/streamflow/FISH.sqin
STGCOACH QME 24 INPUT CARD
oper/streamflow/STGC
TOWER SNWE 24 INPUT CARD
snwe/tower.snwe
RABBIT SNWE 24 INPUT CARD
snwe/rabbit.snwe
DRYLAKE SNWE 24 INPUT CARD
snwe/drylake.snwe
COLUMB SNWE 24 INPUT CARD
snwe/columbine.snwe
YMPA SQIN 6 OUTPUT CARD
oper/ympa.sqin YMPA YMPA RIVER STM, CO
YMPA QINE 6 OUTPUT CARD
oper/ympa.qine YMPA YMPA RIVER STM, CO
YMPAUPR RSEL 6 INTERNAL
YMPAMID RSEL 6 INTERNAL
YMPALWR RSEL 6 INTERNAL
YMPAUPR SWE 24 INTERNAL
YMPAMID SWE 24 INTERNAL
YMPALWR SWE 24 INTERNAL
YMPAUPR SASC 6 INTERNAL
YMPAMID SASC 6 INTERNAL
YMPALWR SASC 6 INTERNAL
YMPAUPR RAIM 6 INTERNAL
YMPAMID RAIM 6 INTERNAL
YMPALWR RAIM 6 INTERNAL
YMPAUPR ROCL 6 INTERNAL
YMPAMID ROCL 6 INTERNAL
YMPALWR ROCL 6 INTERNAL
YMPAUPR SMZC 6 INTERNAL
```

```
YMPAMID SMZC 6 INTERNAL
YMPALWR SMZC 6 INTERNAL
YMPAUPR INFW 6 INTERNAL
YMPAMID INFW 6 INTERNAL
YMPALWR INFW 6 INTERNAL
YMPAUPR SQME 24 INTERNAL
YMPAMID SQME 24 INTERNAL
YMPALWR SQME 24 INTERNAL
YMPA SQME 24 OUTPUT
simq/ympa.txt YMPA YMPA SIMULATION
YMPAUPR SQIN 6 INTERNAL
YMPAMID SQIN 6 INTERNAL
YMPALWR SQIN 6 INTERNAL
FISHCRK SQME 24 INTERNAL
FISHCRK SQIN 1 INTERNAL
STGCOACH SQME 24 INTERNAL
STGCOACH SQIN 1 INTERNAL
END
RSNWELEV YMPAUPR
YMPAUPR RSEL 6 3.0 0.55 YMPALWR MAT 3112.
SNOW-17 YMPAUPR
UPPER 3112. 41.2 YES SUMS AVSE
6 YMPAUPR MAP 1.000 YMPAUPR RAIM
YMPAUPR MAT 6
11 10000. 10590. ENGL YMPAUPR RSEL
10023. .09 10065. .16 10098. .25 10131. .33
10144. .41 10180. .50 10193. .58 10230. .66
10302. .75 10364. .83 10426. .91
YMPAUPR SWE 24 YMPAUPR SASC 6
1.330.820 0.200.020 450. 0
0.20 0.10 0.0 1.50 0.05 0.00
0.19 0.31 0.41 0.47 0.56 0.62 0.71 0.81 0.90
RSNWELEV YMPAMID
YMPAMID RSEL 6 2.5 0.55 YMPAMID MAT 2848.
SNOW-17 YMPAMID
MID 2848. 41.2 YES SUMS AVSE
6 YMPAMID MAP 1.000 YMPAMID RAIM
YMPAMID MAT 6 2748. 0.39 0.60
11 8500. 10000. ENGL YMPAMID RSEL
8674. .08 8865. .16 9042. .25 9212. .33
9304. .41 9403. .50 9478. .58 9560. .66
9665. .75 9770. .83 9952. .91
YMPAMID SWE 24 YMPAMID SASC 6
1.230.820 0.200.020 525. 0
0.20 0.20 0.0 1.50 0.05 0.10
0.19 0.31 0.41 0.47 0.56 0.62 0.71 0.81 0.90
```

```
RSNWELEV YMPALWR
YMPALWR RSEL 6 2.0 0.55 YMPALWR MAT 2314.
SNOW-17 YMPALWR
LWR 2314. 42.0 YES SUMS AVSE
6 YMPALWR MAP 1.000 YMPALWR RAIM
YMPALWR MAT 6
11 6735. 8500. ENGL YMPALWR RSEL
6936. .08 6995. .17 7119. .25 7251. .33
7372. .41 7533. .50 7677. .58 7887. .66
8048. .75 8205. .83 8346. .91
YMPALWR SWE 24 YMPALWR SASC 6
1.180.820 0.200.0209999. 0
0.20 0.30 0.0 1.50 0.05 0.10
0.18 0.28 0.35 0.4 0.52 0.60 0.70 0.80 0.90
SAC-SMA YMPAUPR
Upper zone 6 YMPAUPR RAIM YMPAUPR INFW
YMPAUPR SASC 6 SUMS 6 6
1.00 0.650 40.0 50.00.3000.0000.1500.000 0 0.2
25.0 2.00 250. 135. 100. .120 .003 0.25 .300 0.00
0.600.801.603.205.006.807.606.604.802.801.500.80
23.0 0.0 125. 1.1 64. 130.
SAC-SMA YMPAMID
Middle Zone 6 YMPAMID RAIM YMPAMID INFW
YMPAMID SASC 6 SUMS 6 6
1.00 0.850 40.0 50.00.2500.0000.0800.000 0 0.2
30.0 2.00 225. 135. 100. .120 .003 0.25 .300 0.00
0.600.801.603.205.006.807.606.604.802.801.500.80
12.2 0.0 43. 0.0 57. 54.
SAC-SMA YMPALWR
Lower Zone 6 YMPALWR RAIM YMPALWR INFW
YMPALWR SASC 6 SUMS 6 6
1.00 0.950 40.0 40.00.2500.0000.0000.000 0 0.2
30.0 2.00 150. 100. 80. .120 .002 0.15 .300 0.00
0.600.801.603.205.006.807.606.604.802.801.500.80
6.2 0.0 3. 0.0 29. 9.
UNIT-HG YMPAUPR
YMPAUPR 13.6 2 ENGL 0.000
YMPAUPR INFW 6 YMPAUPR SQIN 6
735. 732.
UNIT-HG YMPAMID
YMPAMID 144.1 3 ENGL 0.000
YMPAMID INFW 6 YMPAMID SQIN 6
7647. 7653. 195.0
UNIT-HG YMPALWR
YMPALWR 151.0 2 ENGL 0.000
YMPALWR INFW 6 YMPALWR SQIN 6
```

```
11028. 5216.
CHANGE-T FISHC_24
FISH QME 24 FISHCRK SQME 24
CHANGE-T FISHC_1
FISHCRK SQME 24 FISHCRK SQIN 1
CHANGE-T STGC_24
STGCOACH QME 24 STGCOACH SQME 24
CHANGE-T STCG_1
STGCOACH SQME 24 STGCOACH SQIN 1
LAG/K FISH
FISHCRK SQIN 1 0 0 0 ENGL
2.000
0.000
0
LAG/K STGC
STGCOACH SQIN 1 0 0 0 ENGL
7.000
0.000
0
ADD/SUB FISH
YMPA SQIN 6 YMPA SQIN 6
MEAN-Q YMPAUPR
YMPAUPR SQIN 6 YMPAUPR SQME 24
MEAN-Q YMPAMID
YMPAMID SQIN 6 YMPAMID SQME 24
MEAN-Q YMPALWR
YMPALWR SQIN 6 YMPALWR SQME 24
MEAN-Q LWG
YMPA SQIN 6 YMPA SQME 24
ADD/SUB YMPAUPR
YMPA SQME 24 YMPAUPR SQME 24
ADD/SUB YMPAMID
YMPA SQME 24 YMPAMID SQME 24
ADD/SUB YMPALWR
YMPA SQME 24 YMPALWR SQME 24
PLOT-TS SWE
SNOW WATER EQUIV 3 1 5
ARIT 120 0 2000. 5
YMPAUPR SWE 24 YMPAUPR U
TOWER SNWE 24 TOWER T
RABBIT SNWE 24 RABBIT R
DRYLAKE SNWE 24 DRYLAKE D
COLUMB SNWE 24 COLUMBINE C
WY-PLOT YMPA
YMPA nr steamboat 5 MODS 872.8 200.
YMPA QME OBSERVED O
```

```
YMPA SQME SIMULATED S
YMPAUPR SQME SIMULATED U
YMPAMID SQME SIMULATED M
YMPALWR SQME SIMULATED L
WY-PLOT YMPA2
YMPA nr steamboat 2 MODS 872.8 200.
YMPA QME OBSERVED O
YMPA SQME SIMULATED S
STAT-QME YMPA
YMPA nr STEAMBOAT 872.8 YMPA SQME 24 YMPA QME 24 1
QUAR 3. 6. 20. 45. 75. 100.
ADJUST-Q YMPA
Yampa River nr STMBT 0 1 0
YMPA QME
YMPA SQIN 6
YMPA QINE
12
WATERBAL YMPALWR
Yampa River - lower
YMPA QME YMPA SQME 338.2 1 YES YES
YMPA mean 07590 ft 1.000 SNOW-17 YMPALWR SAC-SMA YMPALWR
WATERBAL YMPAMID
Yampa River - mid
YMPA QME YMPA SQME 338.2 1 YES YES
YMPA mean 09430 ft 1.000 SNOW-17 YMPAMID SAC-SMA YMPAMID
WATERBAL YMPAUPR
Yampa River - upper
YMPA QME YMPA SQME 338.2 1 YES YES
YMPA mean 10207 ft 1.000 SNOW-17 YMPAUPR SAC-SMA YMPAUPR
STOP
```

APPENDIX F: GIS Process

Environmental Systems Research Institute software (ESRI) ArcGIS 9.0 for Windows XP was utilized to determine seasonal PRISM precipitation values for the water balance.

ESRI Arc/INFO polygon files of montly PRISM precipitation data was initially downloaded from the Oregon State University's Oregon Climate Service at http://www.ocs.orst.edu/prism/state_products/maps.phtml?id=CO

The files were downloaded as interchange files that required extracting before further analysis could begin. In order to import the extracted interchange files in ArcGIS, the ArcToolbox/Conversion Tools/ "Import from Interchange" tool had to be used to covert the files into feature classes. In order to project these files, the feature classes had to be converted to shapefiles using ArcToolbox/Conversion Tools/ "To Shapefile". The projections were then defined to be in UTM, Zone 13N to be consistent with existing basin coverages. The final manipulation of the PRISM precipitation files was to convert the features into raster format. This was done at a scale of 200m. Despite the initial resolution of the PRISM data being at 4km scale, a 200m scale was used to better clip the precipitation data to the basin coverages.

A digital elevation model (DEM) was acquired for the state of Colorado at a resolution of ~742 sq. mi. The study basin area was isolated from the DEM using the GRIDCLIP command in ARC/INFO WORKSTATION. This DEM was then reclassified into the three elevation zones of the basin using the Spatial Analyst function. These separate elevation zones were extracted from the DEM in polygon formats. The final step involved the LATTICECLIP command in Arc/INFO, which clipped the monthly PRISM precipitation maps to the three basin zones of the study area.

The attribute tables of each of the PRISM maps for each zone and for each month were used to determine an average pixel PRISM precipitation amount. November, December, January, February, March and April zone amounts were added together to determine winter totals, while May, June, July, August, September and October values contributed to the summer season values.

These values were used to help determine the mean areal estimates of precipitation that were used to determine zonal precipitation amounts in the water balance procedure.