Global Climate Change Response Program, Water Yield in Semiarid Environment Under Projected Climate Change

United States Department of the Interior

Follow this and additional works at: https://digitalcommons.usu.edu/govdocs_water

Part of the Water Resource Management Commons

Recommended Citation


This Report is brought to you for free and open access by the U.S. Government Documents (Utah Regional Depository) at DigitalCommons@USU. It has been accepted for inclusion in Water by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.
This paper presents the practical application of a distributed parameter climate-vegetation hydrologic model (CVHM) and its ability to simulate hydrologic response under existing conditions and under assumed CO₂-induced climate and vegetation change. Applying the model to the Weber River basin provided a basis for determining the impacts of climate change on the hydrologic response. By using a "what if" scenario, the model included the changes in plant transpiration rates and in vegetation cover under a CO₂-altered climate change and the effects of these changes on water yield.

The results of applying this model to the Weber River basin suggest significant but less severe impacts of climate change on water yield than previous studies in the Western United States have indicated. A decrease in annual runoff of 15 to 20 percent could be possible for cases of warming associated with decreased precipitation. In most cases, projected changes in monthly flows are relatively greater than corresponding changes in annual flows. Increase in winter and early spring runoff may lead to increased flooding in the early half of the spring.

Interpretation of the model results must be tempered with the fact that limited data of one water year were used for model calibration. However, the results do provide preliminary indications as to how the monthly, seasonal, and annual water supplies in the Weber River basin could be altered as a result of climate change.
GLOBAL CLIMATE CHANGE RESPONSE PROGRAM

WATER YIELD IN SEMIARID ENVIRONMENT UNDER PROJECTED CLIMATE CHANGE

J. Paul Riley
Alok K. Sikka
Ashutosh S. Linaye
Robert W. Gunderson
Gail E. Bingham
Roger D. Hansen

Utah Center for Water Resources Research
Utah Water Research Laboratory
Utah State University
Logan, Utah 84322-8200

FEBRUARY 1996

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PROVO AREA OFFICE
PROVO, UTAH

MISSION STATEMENTS

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. Administration.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.
Global climate change is a change in the climate of the earth occurring either naturally or as a result of human influence. Of particular concern is "anthropogenic" global warming, which is a warming of the Earth's atmosphere caused by the influence of humans on the natural environment. Anthropogenic global warming is the result of an increase in atmospheric concentrations of carbon dioxide, methane, chlorofluorocarbons, and other "greenhouse" gases, which trap additional heat in the atmosphere. The increase in greenhouse gases is caused by the consumption of fossil fuels (coal, petroleum, and natural gas), land use modification, and the release of agricultural and industrial gases into the atmosphere.

Global climate change may threaten water-dependent ecosystems unless adequate preparations are taken. It has the potential to affect water demands, water supplies, and water management. It could affect the quantity and seasonal timing of precipitation and runoff and the severity of storms, floods, and droughts.

The Bureau of Reclamation (Reclamation) supplies municipal water to 25 million people in the 17 Western States, provides irrigation water for 10 million acres of farmland, and operates 52 hydroelectric facilities which generate approximately 48 billion kilowatthours of electricity annually, making Reclamation the Nation's 11th largest electric utility. In addition, Reclamation facilities provide flood control, recreation, fish and wildlife enhancement, and environmental management.

Because Reclamation has the responsibility to wisely manage water resources while ensuring that associated environmental assets are preserved, the impacts of global climate change on water resources and environmental assets need to be identified, and appropriate responses need to be studied.

Of concern are the impacts on agriculture, municipal and industrial water supplies, hydroelectric power generation, water quality, fisheries, wetlands, riparian communities, and recreation. Also of concern are the impacts on reservoir operations, flood control, drought management, and distribution of water for beneficial uses.

The Global Climate Change Response Program, a multiyear Reclamation research program, is designed to study the potential impacts of global climate change in the 17 Western States and to determine the impacts on water demands, water supplies, and water management. This program will endeavor to develop strategies and responses to deal with these impacts through a broad range of technical studies and research activities and projects.

**ABSTRACT**

This paper presents the practical application of a distributed parameter climate vegetation hydrologic model (CVHM) and its ability to simulate hydrologic response under existing conditions and under assumed CO2-induced climate and vegetation change. Applying the model to the Weber River basin provided a basis for determining the impacts of climate change on the hydrologic response. By using a "what if" scenario this model included the changes in plant transpiration rates and in vegetation cover under a CO2-altered climate change and the effects of these changes on water yield.

The results of applying this model to the Weber River basin suggest significant but less severe impacts of climate change on water yield than previous studies in the Western United States have indicated. A decrease in annual runoff of 15 to 20 percent could be possible for cases of warming associated with decreased precipitation. In most cases, projected changes in monthly flows are relatively greater than corresponding changes in annual flows with monthly peak runoff shifting from May to March or April. Increase in winter and early spring runoff may lead to increased flooding in the early half of the spring as a result of warming combined with precipitation increases of more than 10 percent.

Interpretation of the model results must be tempered with the fact that limited data of one water year were used for model calibration, and the sensitivity analyses results are based on the assumed scenarios, all of which may not be internally consistent. However, the results do provide preliminary indications as to how the monthly, seasonal, and annual water supplies in the Weber River basin could be altered as a result of climate change.
ACRONYMS AND ABBREVIATIONS

AET actual evapotranspiration
ANNE interactive data management system
BAS baseflow
BST base temperature
BZ current available soil moisture in the lower zone
BZMX maximum available water holding capacity of the lower soil zone
CARD canopy average radiation per unit LAI
CC canopy conductance; stomatal conductance
CD-ROM Compact Disk-Read Only Memory
CCMX maximum canopy stomatal conductance
CTW snow sublimation rate factor
CVHM Climate Vegetation Hydrologic Model
DEM Digital Elevation Model
DRCOR rainfall correction factor
DSCOR snowfall correction factor
ES actual soil evaporation
ESP potential soil evaporation
ET evapotranspiration
EXCS infiltration to the soil root zone in excess of field capacity
EXT species dependent light extinction coefficient
FAC LAI factor
FCV Fuzzy c-Varieties
GCCRP Global Climate Change Response Program
GCM general circulation models
GIS geographic information system
GRU grouped response unit
GW groundwater storage
HCF humidity correction factor
HRU hydrologic response unit
IRMB Royal Meteorologic Institute of Belgium
ITEND end of the active transpiration period
ITST beginning of the active transpiration period
L (LAI) leaf area index
LAI leaf area index
NDVI normalized difference vegetation index
MIPS Map and Image Processing System
NRCS Natural Resource Conservation Service
NWSRFS National Weather Service River Forecast System

ACRONYMS AND ABBREVIATIONS—continued

P precipitation
PM Penman-Monteith
PPT total daily precipitation on HRU in m/day
PPT-PTN net interception
PRMS Precipitation Runoff Modeling System
PTN net precipitation at the ground surface
PWEQV simulated depth of snow water equivalent
RA aerodynamic resistance
RACT radiation threshold
RADEP evaporation depth
RAS subsurface or interflow
RC canopy resistance to water vapor per unit LAI
RCB baseflow recession constant
RCF interflow routing coefficient
Reclamation United States Bureau of Reclamation
RECHR current available soil moisture in the upper zone
REM maximum available water-holding capacity of the upper or recharge soil zone
RES subsurface reservoir inflow
RNO net radiation above canopy
RNS average net radiation at soil surface
RSEP flow from a subsurface reservoir to a ground-water reservoir
SALB surface albedo
SC a threshold value of the soil moisture for canopy conductance computations
SCX-SCN maximum and minimum runoff contributing areas
SEP seepage rate
SHE Système Hydrologique Européen
SMLT snowmelt
SMAV current available soil moisture in the soil profile (upper and lower zones)
SMA maximum available water holding capacity of the soil profile (upper and lower zones)
SNEV snow evaporation or sublimation
SRX maximum infiltration capacity
SWRD daily incoming shortwave radiation
T temperature
TLX-TLN maximum and minimum temperature lapse rates
TLX-TLM maximum and minimum monthly temperature lapse rates
TXAJ maximum air temperatures
TNAJ minimum air temperatures
### ACRONYMS AND ABBREVIATIONS—continued

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>thematic mapper</td>
</tr>
<tr>
<td>TRAN</td>
<td>transpiration</td>
</tr>
<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geologic Survey</td>
</tr>
<tr>
<td>USU</td>
<td>Utah State University</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator coordinates</td>
</tr>
<tr>
<td>VPD</td>
<td>vapor pressure deficit</td>
</tr>
<tr>
<td>WK</td>
<td>a critical level of soil moisture above which actual and potential soil evaporation are equal</td>
</tr>
<tr>
<td>WL</td>
<td>critical low soil moisture level below which soil evaporation is assumed to be negligible</td>
</tr>
<tr>
<td>XIN</td>
<td>current depth of interception</td>
</tr>
<tr>
<td>XINCF</td>
<td>interception coefficient in m/unit LAI</td>
</tr>
<tr>
<td>XINCFR</td>
<td>storage coefficient for rain</td>
</tr>
<tr>
<td>XINCFS</td>
<td>storage coefficient for snow</td>
</tr>
<tr>
<td>XINLOS</td>
<td>loss from interception storage by evaporation</td>
</tr>
</tbody>
</table>
Chapter I.—Introduction

Document purpo se

Study purpo se

Chapter II.—A watershed model for evaluating the hydrologic effects of climate change on vegetated watersheds

Background and related issues

Development of the model

Meteorological driving inputs

Canopy interception and evaporation

Soil evaporation and transpiration scheme

Partitioning of radiation energy

Actual soil evaporation

Transpiration

LAI variations during growing season

Soil moisture and infiltration

Streamflow or water yield

Parameter and data requirements

Model calibration

Chapter III.—An interactive graphics fuzzy clustering procedure for partitioning a watershed into hydrologic response units for distributed parameter modeling

Background

Fuzzy c-Varieties pattern recognition

Principal component models

Influence coefficients

Equations of FCV algorithms

Watershed partitioning

Definition and criteria

Procedure

Chapter IV.—Modeling the effects of climate change on the hydrologic response of the Causey watershed

Description of study watershed

Data/rasters preparation

Partitioning the watershed into hydrologic response units

Chapter V.—Modeling of Weber River Basin for determining the hydrologic implications of climate change

The study area

Hydrologic response unit delineation

Parameter estimation

Model calibration

Application of climate change scenarios to the Weber River Basin

Climate change impact

Climate change scenarios

Sensitivity studies

Results and discussion

Results of the CVHM calibration for the six gauged watersheds

Results of climate change on individual watersheds

Impacts of the climate change scenarios on Weber River outflows

Chapter VI.—Conclusions

Bibliography

TABLES

Table

1. Selected soil and vegetation parameters for different HRUs used in simulations

2. Assumed climate change scenarios for the Causey watershed
TABLES—continued

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Effect of climate change on runoff and actual evapotranspiration for the Causey watershed</td>
<td>39</td>
</tr>
<tr>
<td>4. Response of the six gauged watersheds to various climate change scenarios</td>
<td>50</td>
</tr>
<tr>
<td>5. Average response of the watersheds to each of the climate change scenarios</td>
<td>51</td>
</tr>
<tr>
<td>6. The effects of climate change temperature scenarios on water shortages to demand areas within Weber River Basin</td>
<td>54</td>
</tr>
<tr>
<td>7. The effects of climate change precipitation scenarios on water shortages to demand areas within Weber River Basin</td>
<td>55</td>
</tr>
<tr>
<td>8. The effects of climate change dual scenarios on water shortages to demand areas within Weber River Basin</td>
<td>56</td>
</tr>
<tr>
<td>9. The effects of climate change multiple parameter scenarios on water shortages to demand areas within Weber River Basin</td>
<td>57</td>
</tr>
<tr>
<td>10. The effects of climate change scenarios on spills to the Great Salt Lake</td>
<td>58</td>
</tr>
</tbody>
</table>

FIGURES—continued

<table>
<thead>
<tr>
<th>Figure</th>
<th>Following page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Hydrologic response units (HRUs) of the Causey watershed</td>
<td>32</td>
</tr>
<tr>
<td>6. Overlay of HRUs on vegetation type and soil moisture holding capacity</td>
<td>36</td>
</tr>
<tr>
<td>7. Comparison of observed and simulated streamflow hydrographs of the Causey watershed for water year 1989</td>
<td>36</td>
</tr>
<tr>
<td>8. Mass curve of observed and simulated flows of the Causey watershed for water year 1989</td>
<td>36</td>
</tr>
<tr>
<td>9. Observed and simulated depth of snow water equivalent of the Causey watershed for water year 1989</td>
<td>36</td>
</tr>
<tr>
<td>10. Simulated monthly flows of Causey watershed illustrating the effects of climate change on timings of peak flow</td>
<td>40</td>
</tr>
<tr>
<td>11. Simulated monthly flows of the Causey watershed illustrating changes in monthly flow volumes</td>
<td>40</td>
</tr>
<tr>
<td>12. Changes in annual and seasonal flows of the Causey watershed under different climate change scenarios</td>
<td>40</td>
</tr>
<tr>
<td>13. Study area: Weber River Basin</td>
<td>44</td>
</tr>
<tr>
<td>14. Hydrologic response units (HRUs): Chalk Creek watershed</td>
<td>44</td>
</tr>
<tr>
<td>15. Hydrologic response units (HRUs): Lost Creek watershed</td>
<td>44</td>
</tr>
<tr>
<td>16. Hydrologic response units (HRUs): East Canyon Creek watershed</td>
<td>44</td>
</tr>
<tr>
<td>17. Hydrologic response units (HRUs): Smith and Morehouse Creek watershed</td>
<td>44</td>
</tr>
<tr>
<td>18. Hydrologic response units (HRUs): Wheeler Creek watershed</td>
<td>44</td>
</tr>
<tr>
<td>19. Schematic diagram of flows in Weber River Simulation Model</td>
<td>46</td>
</tr>
<tr>
<td>20. Model calibration for the Chalk Creek watershed</td>
<td>48</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>21.</td>
<td>Model calibration for the Lost Creek watershed</td>
</tr>
<tr>
<td>22.</td>
<td>Model calibration for the East Canyon Creek watershed</td>
</tr>
<tr>
<td>23.</td>
<td>The effects of climate change temperature scenarios on spills to the Great Salt Lake</td>
</tr>
<tr>
<td>24.</td>
<td>The effects of climate change precipitation scenarios on spills to the Great Salt Lake</td>
</tr>
<tr>
<td>25.</td>
<td>The effects of climate change dual parameter scenarios on spills to the Great Salt Lake</td>
</tr>
</tbody>
</table>
Chapter I

INTRODUCTION

DOCUMENT PURPOSE

This report summarizes work accomplished during a 4-year investigation, "Water Yield in Semiarid Environment Under Projected Climate Change." This study was funded through the United States Bureau of Reclamation's (Reclamation) Global Climate Change Response Program (GCGRP) and cost shared by Utah State University (USU). A majority of the work was accomplished at USU, with Dr. J. Paul Riley serving as the principal investigator. Also participating were Dr. Gail E. Bingham and Dr. Robert W. Gunderson. Dr. Alok K. Sikka's doctoral dissertation (1993) and Ashutosh S. Limaye's masters thesis (1994) provide a more detailed description of the investigation's methodology. Dr. Roger Hansen was Reclamation's project coordinator.

STUDY PURPOSE

Projected scenarios of climate change are likely to have serious impacts on water supply, quality, and demand in arid and semiarid regions. These changes may have ramifications for making decisions on water allocations and water rights in the future (Nash and Gleick, 1991). Even a marginal change in the average annual runoff from a change in climate can lead to a widening of the gap between water supply and water demand. For this reason, a quantitative assessment of climate change impacts on water resources assumes an urgent priority in water-short regions such as the semiarid Western United States.

General Circulation Models (GCM) are capable of generating specific climatic scenarios for given input parameters, such as atmospheric CO$_2$ levels. However, the hydrologic input parameters provided by the GCMs represent average values for large areas, often with little or no relevance to specific regions or drainage basins. Until a realistic linkage between GCMs and hydrologic models can be achieved, climatic scenario-based analyses with hydrologic models represent the most satisfactory procedure for evaluating the possible effects of climate changes on runoff from watersheds.

Although these scenarios cannot be regarded as reliable predictions of future conditions, they can be expected to provide insights into regional or basin vulnerabilities (Nash and Gleick, 1991). The hydrologic impacts of climate change have commonly been studied using the off-line approach of driving hydrologic models by climatic data obtained either from GCM based or assumed hypothetical climate-change scenarios. The types of models used include:

- Statistical and empirical models (Schwarz, 1977; Stockton and Boggess, 1979; Revelle and Waggoner, 1983; Hargreaves et al., 1992)

- Simple water balance models such as Thornthwaite's model (Cohen, 1986; Flaschka et al., 1987; Gleick 1987; Sikka and Narayana, 1988)

- Conceptual watershed hydrologic models (Nemec and Schanke, 1982, Bultot et al., 1988; Lettenmaier et al., 1988; Schake, 1990; Nash and Gleick, 1991)

Most of these models are either empirical or lumped parameter models. For this reason, these models do not consider the spatial variability of physical watershed characteristics and climatic input variables.

In addition, previous climate-change runoff studies involving hydrologic models have included temperature and precipitation changes without explicitly including the effects of both the short and long term vegetation changes which occur. Vegetation properties such as stomatal conductance, leaf area index (LAI), and water use efficiency change with alterations in both climate and enhanced levels of CO$_2$ (Eamus and Jarvis, 1989; Eamus, 1991; Rosenberg et al., 1990). This study focuses on a procedure: for determining the effects of both precipitation and temperature changes on the hydrology of the semiarid Causey watershed in northern Utah. Although limited data were available, the purpose of the study was to demonstrate the modelling procedure and its application. Subsequently, the model is applied to the six other watersheds at the headwaters of the Weber basin (Limaye, 1994).
Chapter II

A WATERSHED MODEL FOR EVALUATING
THE HYDROLOGIC EFFECTS OF CLIMATE CHANGE
ON VEGETATED WATERSHEDS

Continued efforts have been made to study the influence of climate change on hydrology using both the on-line and the off-line approaches. The on-line approach directly uses and interprets the hydrologic outputs obtained from the general circulation models (GCM) which represent large scale area average values often with little relevance to drainage basins. Alternatively, the off-line approach involves employing hydrologic models at the watershed scale driven by climatic data obtained either directly from GCM outputs or from hypothetical or GCM-based scenarios of climate change (Nemec and Schaake, 1982; Lettenmaier et al., 1988; Gleick, 1986; Nash and Gleick 1991; Arnell, 1992a and b). Shifts in vegetation and corresponding changes in stomatal conductance, biomass, and leaf area index (LAI) result from changes in climate and altered levels of CO₂ in the atmosphere (Eamus and Jarvis, 1989; Neilson et al., 1989; Rosenberg et al., 1990; Eamus, 1991; Argen et al., 1991).

Previous studies considered the effect of changes in CO₂ levels on stomatal resistance and evapotranspiration (ET) (Idso and Brazel, 1984, and Gifford, 1988) and neglected the effect on plant size or LAI. The focus of this chapter is the development of a model employing a distributed watershed modeling approach to include the effect of climate change and the resulting vegetation changes. A biophysical approach for simulating actual evapotranspiration (AET) from a naturally vegetated watershed is developed and incorporated into an existing hydrologic model to develop a Climate Vegetation Hydrologic Model (CVHM). Under this concept, a watershed that is partitioned into a mosaic of units based on characteristics such as soils, vegetation, slope, aspect, and elevation is used to provide distributed parameter modeling capability (Leavesley and Stannard, 1990; Sikka, 1993). Each unit, called a hydrologic response unit (HRU), is considered homogeneous in its hydrologic response. The Precipitation Runoff Modeling System (PRMS) of the United States Geologic Survey (USGS) (Leavesley et al., 1983) was taken as the base model for modifications. Calibration of the model to the Causey watershed, a subwatershed in the Weber River Basin, is also presented in this chapter. Chapter V presents the application of the model for evaluating the impacts of potential climate and resulting vegetation changes on the hydrology of Weber River Basin.
BACKGROUND AND RELATED ISSUES

There are a number of issues, widely discussed in the literature, which must be considered for a change in hydrology study (Klemes, 1985; World Meteorological Organization, 1987; Dooge, 1989; Lettenmaier et al., 1988; Nash and Gleick, 1991; Waggoner, 1990; Argen et al., 1991). Some of these issues are discussed in the following paragraphs.

The Thornthwaite Water Balance Model and conceptual watershed hydrologic models have been employed primarily in simulating the effects of climate change on hydrology. Four specific models are used in climate impact studies:

1. The Soil Moisture Accounting Model (commonly known as the Sacramento Model) of the National Weather Service River Forecast System (NWSRFS) (Nemec and Schaake, 1982; Lettenmaier et al., 1988; Nash and Gleick, 1991)
2. IRMB (Royal Meteorological Institute of Belgium) (Bultot et al., 1988)
3. PROSPER (Yeakley et al., 1990)
4. PRMS (Leavesley et al., 1983; Hay et al., 1993)

A review of hydrologic models used in climate impact studies is available in Sikka (1993).

One of the basic issues is the appropriateness of such models for simulating climate change impact because most of these models were developed to accomplish other objectives, such as flood flow simulation, streamflow forecasting, reservoir design, and operation. Most of these models do not consider changes in vegetation characteristics, such as LAI, stomatal conductance, and transpiration rates under a CO₂-altered climate, and the effects of these changes on runoff. Models such as Système Hydrologique Européen (SHE) (Abbott et al., 1986b) can be viewed as comprehensive models to investigate the rainfall-runoff process. However, the data and computing requirements for models of this type are very extensive (Kite and Kouwen, 1992).

Another important issue is the inclusion of potential changes in vegetation resulting from rising levels of CO₂. One of the predictions of forest response to climate change at the regional level is the shift of vegetation zones in latitude and elevation (Neilson et al., 1989). Changes in plant leaf area, stomatal conductance, photosynthesis, and growth rates are also expected to result from increased atmospheric CO₂ levels (Eamus and Jarvis, 1989; Rosenberg et al., 1990; Eamus, 1991; Argen et al., 1991). The results from growth chamber and greenhouse studies tend to suggest an increase in plant sizes and a 20 to 40 percent decrease in maximum canopy stomatal conductance (CCMX) from increased levels of atmospheric CO₂. Idso and Brazel (1984) attribute increases in runoff to stomatal regulation induced by elevated levels of CO₂, while Gifford (1988) reports that leaf area increased to compensate for the reduction in water consumption, maintaining constant regional evapotranspiration.

It appears that the hydrologic implications of climate change cannot be realistically assessed without taking into account CO₂-induced changes in vegetation. Rosenberg et al. (1990) suggest that changes in canopy resistance caused by both stomatal resistance and leaf area cannot be excluded from consideration as a modifier of climate change effects. The Penman-Monteith (PM) equation addresses this deficiency only when it is coupled with a procedure for reflecting soil moisture effects on stomatal resistance and is linked with an appropriate hydrologic water-balance model. Saugier and Katerji (1991) also conclude that under these conditions the PM equation is a sound approach for estimating evapotranspiration from vegetated surfaces.

Another major issue is the question of bringing spatial variability into the modeling process to reflect heterogeneity in soils, vegetation, and topography on a watershed scale. Larson et al. (1982) state that averaging a certain parameter 'averages' (implicitly) the process being represented. Abott et al. (1986a) also note that the ability to model spatial variations in watershed parameters is becoming increasingly necessary, not only for applied studies but also for improving the understanding of catchment processes. Conventional lumped parameter watershed models may produce reasonable results, but, because of the distributed nature of climatic inputs and physical watershed parameters, they are often inappropriate for studying the effects of climate change, land use, and vegetation changes on watershed hydrology (Kite and Kouwen 1992; Sikka 1993; Abbott et al., 1986a).

The model developed for this study uses the PM equation for transpiration and incorporates LAI and stomatal conductance to reflect the effects of vegetation on hydrologic components for evaluating the hydrologic impacts of climate change in a "what if" mode. This distributed parameter model has a capability to incorporate variations in soils, vegetation, and topography by changing parameters in respective HRUs.
DEVELOPMENT OF THE MODEL

The CVIfM is a deterministic, physical-process based, distributed-parameter hydrologic model with a daily time step for simulating hydrologic responses of vegetated mountain watersheds. LAI is used as a surrogate of vegetation structure to compute energy and mass exchange. This model was developed by incorporating changes in the soil vegetation climate schemes into the daily version of the Precipitation Runoff Modeling System (PRMS) of the U.S. Geological Survey (Leavesley et al., 1983). The watershed is partitioned into subunits, called hydrologic response units (HRU), to provide a distributed parameter capability. HRUs are assumed to be homogeneous in their hydrologic response. The general structure of the PRMS model was kept as a base, and modifications were made in the components dealing with interception, soil evaporation (ES), transpiration, soil moisture, and subsurface flow. The interactive data management system (ANNIE) of the PRMS was used. This interactive system allows users to input data from a variety of sources, and those data are reformatted by ANNIE to a system compatible file structure.

A flowchart of the model is shown in figure 1. Water and energy balances are computed daily for each HRU, and the weighted sum of their responses on a unit area basis produces an overall watershed response. The model is based on the mass water balance equation. State variables such as available soil moisture, snow water equivalent, subsurface and groundwater storage are given the initial conditions. The model treats vegetation canopy as proportional to the LAI (the area of leaves per unit area of ground). Depending upon air temperature, precipitation occurs as rain, snow, or a mixture of both. Interception is computed as a function of LAI and net precipitation (PTN) at the ground surface is computed as precipitation (PPT) less interception. Available radiation energy (incoming shortwave radiation) is partitioned in such a way that potential radiation energy is available first for evaporating canopy-intercepted water, and the rest of it is divided between soil evaporation (ES) and transpiration (TRAN) based on the LAI and the species dependent light extinction coefficient (EXT). A portion of unused ES energy in dry soils is added to the canopy radiation for transpiration.

A two-layer, soil-moisture submodel is used in the PRMS model. ES is assumed to take place only from the upper soil layer, with the potential soil evaporation (ESP) being limited by the available soil water in this layer. The soil profile depth depends upon the effective root zone depth of the predominant vegetation type in the HRU. Transpiration is assumed to take place from the entire soil profile depth depending on the relative moisture availability in the upper and lower soil layers. Actual transpiration is computed using the PM equation. To account for soil moisture depletion, the PM equation is linked with the soil moisture balance model to increase the canopy

---

Figure 1.—Schematic diagram of climate-vegetation-hydrologic model.
resistance term for depleting soil moisture. The humidity, temperature, and radiation corrections are also made while computing canopy resistance. Soil moisture is updated daily after correcting for ES, transpiration, surface runoff, infiltration, and drainage. Values of LAI are kept constant during the nonactive transpiration period, but changed during the active transpiration period.

Significant changes in LAI occur for deciduous vegetation during the growing season. Snowmelt (SMLT) is modelled by an energy balance scheme for two 12-hour periods in a day. Infiltration from rain-on-snow is treated as snowmelt if the snow pack is not depleted and as rain if the snow pack is depleted. Infiltration in excess of the field capacity of the root zone soil profile (EXCS) is routed to subsurface and groundwater reservoirs. Streamflow is computed as the total of surface runoff, subsurface or interflow (RAS), and baseflow (BAS). The details of individual model components are described in the following sections.

**Meteorological Driving Inputs**

The PRMS model is driven by the daily climatic data of precipitation, maximum and minimum air temperatures, and solar radiation. These daily meteorologic inputs of the base station are adjusted for slope, aspect, and elevation to compute their values for each distributed unit, HRU, using temperature-lapse rates, slope-aspect corrections, and precipitation-correction factors. This process is discussed later in Model Calibration and the details are found in Leavesley et al. (1983). Vapor pressure and absolute humidity are computed in the model from the relationship of air temperature to saturation vapor pressure (Murray, 1967; and Federer and Lash, 1978). Average daylight temperature for transpiration calculations is computed in the model from maximum and minimum air temperatures (Running et al., 1987). Due to lack of wind data, reasonable values for canopy aerodynamic resistance (RA) were used for a forest watershed. Observed daily shortwave radiation is also adjusted to estimate the daily incoming shortwave radiation (SWRD) received on the slope-aspect combination of each HRU (Leavesley et al., 1983). In the absence of solar radiation data, values are estimated by PRMS from daily air temperature data.

**Canopy Interception and Evaporation**

Interception of throughfall is related to LAI, and interception loss from evaporation (XINLOS) is limited by a function of incoming shortwave radiation. Several studies have concluded that a linear decrease in throughfall from 95 percent at LAI of 1, to 83 percent at LAI of 9 is a reasonable description of interception (Woodward, 1987). The interception is computed as a function of LAI based on the interception storage coefficient for the predominant vegetation on the HRU. Net precipitation reaching the ground surface (PTN) in each HRU on a day with precipitation is computed as:

$$\text{PTN} = \text{PPT} - (\text{XINCF} \cdot \text{LAI} - \text{XIN})$$

where:

- PTN = net precipitation reaching the ground surface in m/day
- PPT = total daily precipitation depth on HRU in m/day
- XINCF = interception coefficient in m/unit LAI
- XIN = current depth of interception, in m

Depending on the occurrence of rain or snow, the model assigns appropriate values of the interception coefficient, XINCFR for rain and XINCFS for snow.

If sufficient energy is available for soil surface evaporation, loss from interception storage by evaporation (XINLOS) becomes equal to net interception (PTN). Otherwise, evaporation is limited to the evaporation depth (RADEP) from a free water surface. This quantity is computed from available radiation by the following relationship:

$$\text{RADEP} = \text{SWRD} \cdot (1.0 - \text{SALB}) / 2.5E+6$$

where:

- SWRD = daily incoming shortwave radiation, in KJ/m²/day
- SALB = surface albedo
- 2.5E+6 = KJ/m² converted into evaporation depth in m, using latent heat of vaporization

If current depth of interception (XIN) at the end of day is not depleted in one day, the remainder is carried over to the next day. Intercepted snow is assumed to sublime at a rate that is expressed as a percentage (CTW) of the free-water evaporation rate. Intercepted snow is also removed by melting and adding to snowpack or soil surface as PTN when the energy balance for a 12-hr period (assumed 0600 to 1800 hrs) is positive. This computation involves using the energy balance scheme of PRMS, which requires replacing cover density with LAI.
Soil Evaporation and Transpiration Scheme

In this study, vegetation is broadly categorized as evergreen/conifers, deciduous, shrubs and grasses, and mixed vegetation.

Uniform depth of canopy, as defined by LAI, is divided into a number of horizontal layers. In order to compute average canopy transpiration, leaf level measurements or estimates from unit LAI are scaled up to whole canopy average responses. Soil evaporation (ES) and loss from interception storage by evaporation (XINLOS) and transpiration (TRAN) by plants are modeled separately and summed to compute actual evapotranspiration (AET). Partitioning of radiation energy and the computation of ES and transpiration are described below.

Partitioning of Radiation Energy

The incoming shortwave radiation available after evaporating canopy interception is partitioned between the canopy and the soil surface or snowpack using a form of Beer’s light attenuation law as a function of LAI (which defines the depth travelled in the medium) and the species dependent light extinction coefficient. This law is used to approximate the light profile within leaves and in plant canopies (Jones, 1983; Monteith and Unsworth, 1990). The average net radiation at the soil surface (RNS) is computed as:

\[
RNS = \text{RNO} \exp^{-\text{EXT} \cdot \text{LAI}}
\]  

(3)

where:

- \(\text{RNO}\) = net radiation above canopy (i.e., corrected for albedo) in KJ/m²/day
- \(\text{LAI}\) = leaf area index
- \(\text{EXT}\) = light extinction coefficient (dimensionless)

This equation is commonly used, and still remains the simplest and most reasonable model of light penetration within a canopy (Jones, 1983).

The canopy average radiation per unit LAI (CARD) in KJ/m²/day is obtained as:

\[
\text{CARD} = \text{RNO} \left[ \frac{1 - \exp\left( -\text{LAI} \cdot \text{EXT} \right)}{\text{LAI}} \right]
\]  

(4)

Actual Soil Evaporation

When the soil surface below the canopy is freely evaporating the potential soil evaporation rate (ESP) is determined using a modified version of the Penman equation, which was proposed by Ritchie (1972):

\[
\text{ESP} = \frac{\text{esp}}{\text{\Delta} \cdot \gamma} \cdot \text{RNS}
\]  

(5)

where:

- \(\text{ESP}\) = potential soil evaporation, mm/day
- \(\Delta\) = slope of saturation vapor pressure curve at mean air temperature, mbar/°C
- \(\gamma\) = psychrometric constant, mbar/°C
- \(\text{RNS}\) = average net radiation at soil surface below canopy, mm/day. (RNS from Eq (3) is converted into mm/day using this equation.)

Actual soil evaporation is calculated as a function of ESP and available soil moisture in the upper soil layer. Until a critical level of soil moisture (WK) is reached, ESP and ES are assumed to be equal. Below the WK soil moisture level, ESP is scaled down as a linear function of the ratio of current available soil moisture (RECHR) to maximum available water holding capacity (REMX) of the upper soil layer to compute ES. At and beyond a critical low soil moisture level (WL), ES is assumed to be zero as in the case of very dry soils. To perform these computations the ratio of RECHR to REMX is compared with WK and WL on a daily basis.

For drier soils, a portion of the radiation required for the ESP demand is not used. The unused portion of the radiation is assumed to be re-emitted from the soil and added to the net canopy average radiation per unit LAI for transpiration. In this study, the LAI fraction was assumed to be 20 percent. Thus, a 100-percent energy transfer was assumed to occur for canopies with LAI values of 5 or more. Saxton et al. (1974) assumed a 100-percent transfer for denser canopies with over 60 percent cover. This second order effect causes an increase in the evaporative demand for transpiration as soil dries out. This effect provides a feedback between transpiration and soil evaporation, which is more pronounced in semiarid and arid environments, especially those with low values of LAI. The remaining soil evaporation energy is considered to have been used by other energy sinks. During times when snowpack exists, soil evaporation is not computed, and the RNS is used to sublimate or evaporate snow (SNEV). SNEV is assumed to occur at a rate that is
expressed as a percentage (CTW) of the potential free-water evaporation rate for the radiation rate reaching the surface (Leavesley et al., 1983). This rate is assumed to vary between 50 and 75 percent, depending upon the climate.

Transpiration

Actual transpiration (TRAN) from vegetation canopies is computed using the Penman-Monteith (PM) equation with a resistance term (Monteith, 1965). The equation used is:

\[
TRAN = \frac{(\Delta \cdot CARD) + (CP \cdot DA \cdot VPD \cdot RA)}{(\Delta + y(1 - RC / RA)) + \lambda} \cdot LAI \cdot DAIL
\]

where:
- TRAN = canopy transpiration, mm/day
- CARD = average canopy net radiation per unit LAI, W/m² (obtained by converting KJ/m²/day into W/m²)
- CP = specific heat of air, J/Kg/°C
- DA = density of air, Kg/m³
- VPD = vapor pressure deficit from canopy to air, mbar
- RA = canopy aerodynamic resistance per unit LAI, s/m
- RC = canopy resistance to water vapor per unit LAI, s/m
- \(\Delta\) = psychrometric constant, mbar/°C
- \(\lambda\) = latent heat of vaporization of water, J/Kg
- LAI = leaf area index
- DAIL = daylength, s/day

Canopy conductance (CC=1/RC) is computed as a summation of the stomatal conductance of the leaves in each of the leaf layers, with LAI being a measure of the number of leaf layers in the canopy and assuming that leaves contribute in parallel in each of the layers. The maximum canopy stomatal conductance (CCMX) for the given plant type in a particular HRU, given as model parameter, is corrected for environmental factors such as soil moisture deficit, vapor pressure deficit, temperature, and radiation, based on the nonlinear scheme suggested by Jarvis (1976) and used by Running and Coughlan (1988), Dolman (1988), Massman and Kaufmann (1991).

The equation is given as:

\[
CC = CCMX \cdot f(D, f(e), f(t), f(I))
\]

where \(f(D), f(e), f(t), \) and \(f(I)\) are the response functions for, respectively, soil moisture deficit, vapor pressure deficit, temperature, and radiation. These functions are either developed from measured data or carefully used based on the literature values.

The model uses either of two options: (1) leaf water potential approach of Running and Coughlan (1988) or (2) simple soil water status threshold to reduce canopy conductance (CC) under depleting soil moisture.

The leaf water potential (or canopy water stress) approach uses an empirical function of predawn leaf water potential and soil water fraction. Maximum canopy conductance (CCMX) is then corrected for leaf water potential to compute canopy conductance (CC). This correction requires the values of spring minimum leaf water potential and leaf water potential at stomatal closure.

In view of the difficulty of obtaining such physiological data a simpler approach is used in this study.

This simple method is based on the premise that soil moisture status has a direct influence on stomatal conductance, which therefore, decreases as the soil dries. When available soil water in the profile (SMAV) reaches a specific threshold value (SC), the canopy conductance decreases linearly (or the resistance increases) as the soil continues to dry. This relationship is represented as:

\[
CC = \frac{CCMX \cdot (SMAV/SC)}{1 - HCF \cdot VPD}
\]

SC is a specific portion of the maximum available water holding capacity of the soil profile, including both the upper and lower zones (SMAV) in depth units. It can be taken from the literature or computed empirically based on field data (Arris and Eagleson, 1989; Dolman, 1988; Turner, 1991). Turner (1991) also suggested use of such an approach over the leaf water potential method, which requires many more plant parameters. However, for hourly transpiration estimates, Saugier and Katerji (1991) suggest that the leaf water potential approach has merit.

The CC from the above equation is then corrected for the vapor pressure deficit (VPD) by the following equation:

\[
CC = CC \cdot (1 - HCF \cdot VPD)
\]
Water Yield in Semiarid Environment
Under Projected Climate Change

where:

\[ \text{HC}\text{F} = \text{humidity correction factor, } 1/\text{mbar} \]
\[ \text{VPD} = \text{vapor pressure deficit, mbar} \]

If computed CC falls below the cuticular conductance, it is taken equal to the cuticular conductance value.

The CC computed above is then sequentially corrected for radiation. A decrease in canopy conductance is observed below some radiation threshold (RACT) value. The response of conductance to radiation is hyperbolic (Dolman, 1988; Massman and Kaufmann, 1991):

\[ CC = \text{MIN}((\text{CARD} - \text{RACT}),1.0) \] (10)

The value of CC from equation 10 is then corrected for subfreezing air temperatures (Running and Coughlan, 1988). The corrected value of CC is used to compute RC=1/CC for unit LAI. Due to lack of wind speed data, aerodynamic resistance (RA) for use in equation 6 is estimated on the basis of literature values for average wind conditions and leaf size (Lee, 1980; Running and Coughlan, 1988). Since the CO₂ diffusion is not explicitly simulated in the model, values of CCMX taken from the literature are reduced by 10 to 30 percent to simulate the direct effects of increased CO₂ concentrations on transpiration and, in turn, on runoff.

Transpiration from deciduous vegetation is computed in the model during the active growing or transpiring period. The beginning (ITST) and end (ITEND) of the active transpiration period are determined externally. ITST and ITEND are functions of air temperature, and many definitions based on minimum or average daily air temperatures exist in the literature (Sikka, 1993). In this study, weekly degree-days, the sum of positive differences between mean daily temperature and threshold temperature (4.5 °C) over a week, were used. This method is a more reliable indication of the active transpiration period than minimum temperature or mean daily methods because it gives less weight to short-term low temperature spells.

LAI Variations During Growing Season

Leaf area index, used as a variable in the model, can be varied over the active growing season. This capability is needed particularly for deciduous vegetation. The base LAI given as initial input parameter is kept constant during the nonactive transpiration period and is changed during the active growing season. From the beginning day of active transpiration until the full leaf, LAI goes up linearly from the base to some user-defined peak value. LAI remains at the peak value until the beginning of leaf color change, and thereafter it decreases linearly back to the base value where it remains until the end of the growing season. Due to lack of species-specific information, the transitions are assumed to be linear. Arris and Eagleson (1989) computed the average number of days elapsed from budbreak to full leaf as 19 days from the phenological data of yellow poplar (Liriodendron tulipifera L.) in the eastern United States. They also reported an elapsed period of about 17 days from the beginning of leaf color change (i.e., beginning of transpiration decline) to complete color change. Based on the values from the literature and expert opinions of the forest scientists working in this region, the model for this study uses the beginning of full leaf as being 30 days from the beginning date of the active transpiration period, and the beginning of leaf color change as being 20 days prior to the ending date of the transpiration season in the fall. However, these values could be easily changed for specific situations.

Soil Moisture and Infiltration

Soil moisture budgeting is accomplished through a field capacity based model, with the active soil profile depth considered as being the effective rooting depth of the predominant vegetation on an HRU. The upper soil layer, taken as 15 cm in this study, is termed the recharge zone, while the rest of soil depth is called the lower layer or discharge zone. Soil water balance is performed by the algebraic summation of moisture accretions and depletions to and from the soil profile. The difference between field capacity and wilting point of each zone defines the maximum available water-holding capacity of the zone—REMX for the recharge zone and maximum available water holding capacity (BZMX) for the lower zone. The current available water-holding capacity (i.e., the difference between the current soil moisture and wilting point) of the upper zone, the lower zone, and the entire soil profile is designated as, respectively, RECHR, BZ, and SMAV.

\[ \text{REMX} = \text{maximum available water-holding capacity of the upper or recharge soil zone} \]
\[ \text{BZMX} = \text{current maximum available water holding capacity of the lower zone} \]
\[ \text{RECHR} = \text{current available soil moisture in the upper zone} \]
\[ \text{BZ} = \text{current available soil moisture in the lower zone} \]
\[ \text{SMAV} = \text{current available soil moisture in the soil profile (upper and lower zones)} \]
Infiltration adds water to the active soil profile. The infiltration component of PRMS was adopted for this study (Leavesley et al., 1983). The subroutine computes infiltration from rain on a snow-free surface as the difference between net rainfall and surface runoff. Snowmelt infiltration is considered nonlimiting until the soil reaches field capacity. Once field capacity is reached, a daily maximum infiltration capacity (SRX) limits daily infiltration volume. Any snowmelt in excess of SRX becomes surface runoff. For rain on snow, the water available for infiltration at the bottom of the pack is from snowmelt and rain. When the snowpack is depleted, all water at the surface results from rain. Infiltrated water first fills the upper or recharge zone storage before moving to the lower zone. No time distribution is given to the infiltration in this daily model. Water stored in the recharge zone until its capacity, REMX, is reached. When this situation occurs, continuing infiltration (if any) is cascaded to the lower zone. If infiltration continues after the capacity of the lower zone (BZMX) is reached, the excess quantity (EXCS) is routed to the subsurface and groundwater reservoirs.

Streamflow or Water Yield

Daily streamflow or water yield is considered to be the 24-hour volume from surface, subsurface, and base flow. No routing of streamflow is done in this daily version of the model because the travel time in a small watershed is assumed to be less than the one day time step of the model. Surface runoff, subsurface flow, base flow, and snowmelt components of PRMS were used with few modifications in the base flow and snowmelt components. These processes are not discussed in detail here, but they are fully described in Leavesley et al. (1983).

Surface runoff from snow-free pervious HRUs is computed using the contributing-area concept (Cappus, 1960; Dickinson and Whiteley, 1970; Hewlett and Nutter, 1970). Computations are based on the assumption of either a linear or nonlinear function of antecedent soil moisture and rainfall. Surface runoff from snowmelt on a pervious HRU is the excess over daily maximum infiltration capacity (SRX) at field capacity, when moisture in the soil profile reaches field capacity. For impervious areas, snowmelt first satisfies available retention storage, and then the remaining snowmelt becomes surface runoff. Subsurface flow or seepage rate (SEP) occurs through the relatively shallow groundwater zones which conduct water to the surface channel systems. Inflow to a subsurface reservoir occurs from infiltration which is in excess of the available soil water-holding capacity (SMAX) of the soil profile. A subsurface reservoir can receive inflow from one or several HRUs, depending on the characteristics of subsurface soils and basin size. The difference between infiltration to the root zone in excess of the field capacity of the soil profile (EXCS) and the seepage (SEP) is subsurface reservoir inflow (RES). Subsurface flow is computed using either linear or non-linear reservoir routing procedures.

The snowmelt component of the PRMS model is slightly modified by replacing cover density and transmission coefficient for canopy as a function of LAI in computing shortwave and longwave net radiations. Snowpack water balance is computed daily, and the energy balance is computed twice daily for each 12-hr division (day and night). The snowpack is assumed to be a two-layered system, and snowpack depth is computed using a finite difference scheme (Riley et al., 1973). When the 12-hr energy balance is positive, it is used to melt snow.

PARAMETER AND DATA REQUIREMENTS

Application of a distributed model parameter like the one used in this study requires many site variables, model parameters, and initial conditions of the state variables to fully describe the system. Model parameters are generally descriptive and relate to specific watershed characteristics or conditions. The parameters required for each HRU, month, or single basin values are given in table 1. In principle most of the parameter values may be derived from measurements or estimates or derived empirically from the field, historic data, or relevant literature, and they need not be calibrated. Some parameter values are difficult to obtain and in such cases a reasonable initial estimate often can be made. As rightly noted by Abbott et al. (1986b), however, in practice a certain amount of calibration is generally needed because measured point values may not be representative of the spatially distributed unit. In the application of distributed models it is usually necessary to aggregate small scale physics to the HRU scale. As reported by Beven (1991) it is merely assumed that in defining a conceptual model, the same scale equations can be applied with the same parameters. Beven (1989) discusses the problems of distributed models and suggests obtaining estimates of uncertainty associated with their predictions. In view of this requirement, care must be exercised while interpreting the outputs from the model of this study.
**Table 1.** Selected soil and vegetation parameters for different HRUs used in simulations

<table>
<thead>
<tr>
<th>HRU #</th>
<th>ITST</th>
<th>XINCFS cm/LAI</th>
<th>XINCFS cm/LAI</th>
<th>CCMX m/sec</th>
<th>EXT</th>
<th>LAI</th>
<th>SMAX cm/cm</th>
<th>REMX cm/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0.013</td>
<td>0.018</td>
<td>0.004</td>
<td>0.38</td>
<td>1.14</td>
<td>0.112</td>
<td>0.112</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0.013</td>
<td>0.018</td>
<td>0.0045</td>
<td>0.38</td>
<td>1</td>
<td>0.103</td>
<td>0.106</td>
</tr>
<tr>
<td>3</td>
<td>95</td>
<td>0.006</td>
<td>0.008</td>
<td>0.004</td>
<td>0.35</td>
<td>0.92</td>
<td>0.095</td>
<td>0.095</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>0.013</td>
<td>0.016</td>
<td>0.004</td>
<td>0.38</td>
<td>1.25</td>
<td>0.094</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0.024</td>
<td>0.033</td>
<td>0.0021</td>
<td>0.47</td>
<td>1.6</td>
<td>0.098</td>
<td>0.109</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
<td>0.006</td>
<td>0.008</td>
<td>0.0045</td>
<td>0.35</td>
<td>0.6</td>
<td>0.113</td>
<td>0.113</td>
</tr>
<tr>
<td>7</td>
<td>85</td>
<td>0.006</td>
<td>0.008</td>
<td>0.0045</td>
<td>0.34</td>
<td>0.8</td>
<td>0.093</td>
<td>0.094</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>0.013</td>
<td>0.018</td>
<td>0.004</td>
<td>0.38</td>
<td>1.3</td>
<td>0.096</td>
<td>0.099</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>0.006</td>
<td>0.008</td>
<td>0.0045</td>
<td>0.35</td>
<td>1.1</td>
<td>0.092</td>
<td>0.092</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>0.013</td>
<td>0.018</td>
<td>0.004</td>
<td>0.4</td>
<td>1.3</td>
<td>0.09</td>
<td>0.092</td>
</tr>
<tr>
<td>11</td>
<td>85</td>
<td>0.006</td>
<td>0.008</td>
<td>0.0045</td>
<td>0.35</td>
<td>0.9</td>
<td>0.089</td>
<td>0.089</td>
</tr>
<tr>
<td>12</td>
<td>105</td>
<td>0.02</td>
<td>0.028</td>
<td>0.0026</td>
<td>0.45</td>
<td>2</td>
<td>0.09</td>
<td>0.106</td>
</tr>
<tr>
<td>13</td>
<td>105</td>
<td>0.016</td>
<td>0.024</td>
<td>0.0027</td>
<td>0.42</td>
<td>1.5</td>
<td>0.091</td>
<td>0.091</td>
</tr>
<tr>
<td>14</td>
<td>100</td>
<td>0.024</td>
<td>0.033</td>
<td>0.0021</td>
<td>0.48</td>
<td>2</td>
<td>0.089</td>
<td>0.091</td>
</tr>
<tr>
<td>15</td>
<td>105</td>
<td>0.02</td>
<td>0.028</td>
<td>0.0026</td>
<td>0.45</td>
<td>2.5</td>
<td>0.077</td>
<td>0.096</td>
</tr>
<tr>
<td>16</td>
<td>102</td>
<td>0.02</td>
<td>0.028</td>
<td>0.0026</td>
<td>0.45</td>
<td>2.3</td>
<td>0.092</td>
<td>0.103</td>
</tr>
<tr>
<td>17</td>
<td>100</td>
<td>0.016</td>
<td>0.024</td>
<td>0.0026</td>
<td>0.42</td>
<td>1.1</td>
<td>0.099</td>
<td>0.106</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>103</td>
<td>0.024</td>
<td>0.033</td>
<td>0.0021</td>
<td>0.47</td>
<td>1.7</td>
<td>0.113</td>
<td>0.127</td>
</tr>
</tbody>
</table>

**ITST:** Beginning of active transpiration period.

**XINCFS & XINCFS:** Interception storage for rain and snow.

**CCMX:** Maximum stomatal conductance.

**EXT:** Light extinction coefficient.

**LAI:** Leaf area index.

**REMX & SMAX:** Available water holding capacity for upper and lower soil layers.

---

**MODEL CALIBRATION**

The model contains a self calibration or self optimization capability based on either the absolute difference between the simulated and observed values or the sum of squares of the differences between the two flows. In this study, the sum of squares of the difference between the two flows was used for optimization. A groundwater recession constant and subsurface (or interflow) recession constant were input for optimization since they were found to be sensitive in the calibration process. Allowable ranges for each of the parameters were selected from the literature or other studies conducted in the surrounding area. Even after completion of the self optimizing process, some manual interventions were found necessary to bring about the required results.
Chapter III

AN INTERACTIVE GRAPHICS FUZZY CLUSTERING PROCEDURE FOR PARTITIONING A WATERSHED INTO HYDROLOGIC RESPONSE UNITS FOR DISTRIBUTED PARAMETER MODELING

One of the major issues in watershed modeling is the question of "lumped parameter" versus "distributed parameter" hydrologic models. Bringing spatial variability into the modeling process to more accurately reflect heterogeneities in soils, vegetation, topography, and precipitation distribution on a watershed scale has become a practical possibility through advancements in remote sensing techniques and geographic information system (GIS) applications. Larson et al. (1982, p. 428) state, "Averaging a certain parameter 'averages' (implicitly) the process being represented. Because of nonlinearity and threshold values, this can lead to significant error." Huggins et al. (1977) discuss many advantages of using a distributed parameter model, but the primary reason is the potential for more accurate simulation of the runoff process. Conventional lumped hydrologic models may produce reasonable simulation results, but because of the distributed nature of climatic inputs and watershed parameters, they are often inappropriate for studying the effects of changes in climate, land use, and vegetation on the watershed hydrology (Abbott et al. 1986; Kite and Kouwen 1992; Sikka 1993). The use of a distributed watershed model is particularly more relevant to areas with steep topography and snowmelt runoff where even a small fraction of the watershed area can produce considerable changes in snowmelt runoff due to sudden changes in climatic variables.

Partitioning of watershed into spatially distributed units can be done in a number of ways, including a grid based system, hydrologic response units (HRU), subwatersheds, land classes, and elevation zones. Huggins and Monke (1968) were perhaps among the first to apply this approach which was subsequently used by Abbott et al. (1986) and many others. Grid-based models need much more data, and for large watersheds and for general predictive hydrologic studies this procedure may be computation intensive and require much effort to apply. Another approach is to partition a watershed into HRUs, either contiguous or non-contiguous, each having a particular hydrologic response in terms of a certain combination of soils, land use, elevation, slope, and aspect. Concepts from partial-area hydrology imply that catchments can be subdivided into HRUs. The concept of HRUs was used by Leavesley (1973), Rose et al. (1978), and Leavesley et al. (1983), for predicting watershed runoff, erosion, and sediment movement, and by Sikka (1993) for studying hydrologic response under the influence of climate change. The United States Geological Survey's (USGS) Precipitation-Runoff Modeling System (PRMS) and Modular Hydrologic
Modeling System (MHMS) were developed around the concept of using HRUs (Leavesley et al. 1983; Leavesley et al., 1992). Kite and Kouwen (1992) applied the concept of grouped response units (GRUs). This unit consists of a group of HRUs within a computational element. The GRUs are not necessarily contiguous but often comprise a subwatershed. The HRUs report the advantage of applying a lumped model to different land uses within subbasins by adopting this semidistributed approach. This approach is particularly applicable when stream flow gauges are available for each unit.

The land use and cover characteristics are the most important attributes in delineating HRUs and can be categorized from remotely sensed data using the technique of fuzzy pattern recognition (Leu, 1988; Lindsey, 1991). This chapter presents a new approach to partitioning watershed into hydrologic response units using digital terrain data of the Digital Elevation Model (DEM) and applying an unsupervised fuzzy pattern recognition algorithm to Landsat Thematic Mapper (TM) data in a GIS environment. Its application is also demonstrated in the Causewash watershed of Weber River Basin in Utah for hydrologic simulations using the Climate Vegetation Hydrologic Model (CVHM), described in chapter II.

BACKGROUND

The utility of remote sensing and GIS in partial area hydrology and distributed parameter modeling has been well documented and reviewed by Van De Griend and Engman (1985) and Schmugge (1987). Leavesley and Stannard (1990) used data from digital evaluation models (DEMs) to create data layers for topographic characterization and to generate data overlays of spatial coverages obtained from Landsat TM data in a GIS environment. Sasowsky and Gardner (1991) used GIS techniques to obtain parameters for a hydrologic model which simulated the runoff characteristics for various watershed configurations produced by progressive simplification of a stream network delineated from a DEM.

Using pattern recognition techniques to classify ground cover characteristics from remotely sensed data has shown promising results in a few hydrologic modeling studies (Ze Venbergen, 1985; Leu, 1988; Lindsey, 1991). Ze Venbergen (1985) employed a pattern recognition technique to classify ground cover characteristics in predicting Natural Resource Conservation Service (NRCS) curve numbers from LANDSAT/MSS data for rainfall-runoff studies. Multispectral classification is performed by either supervised or unsupervised methods based on multivariate statistical criteria.
classification of vegetation cover types and spatial distribution of soil moisture using TM data in Utah’s Tony Grove watershed. In both studies, prototypical sites were satisfactorily identified for point measurements and extrapolating point data over the watershed.

Based on the results of these studies, it appears that unsupervised pattern recognition techniques have a potential in partitioning watershed into HRUs for distributed parameter watershed modeling. FCV algorithms applied to TM satellite data in conjunction with topographic data is a new approach to partitioning a watershed into HRUs.

Fuzzy c-Varieties Pattern Recognition

The detailed description of an FCV clustering algorithm is available in Gunderson and Jacobsen (1983) and Gunderson et al. (1988). A brief description is presented here.

Let \( X = (x_1, x_2, \ldots, x_n) \) represent a finite sample of an unlabelled multispectral TM data set consisting of \( n \) measurement vectors, \( x_i \), each with \( m \) features (say 7 TM band values), \( x_i \), i.e., \( x_i = (x_{i1}, x_{i2}, \ldots, x_{im}) \). It is assumed that the measurement vectors \( x_i \) have been obtained from measurements on a collection of \( n \) objects or processes, which includes a fixed number, \( c \), of identifiable classes or categories; e.g., watershed surficial features. It is assumed that the data are unlabeled and that the vectors are allowed to have ambiguous class membership (i.e., exclusive class membership is not required). It is further assumed that each of the \( c \) classes can be satisfactorily modeled by a linear variety of the form:

\[
x = v + \sum_{j=1}^{m} \lambda_j d_j
\]

where the class center, \( v \), is a fixed vector from \( m \)-dimensional data space \( R_m \); the direction vectors, \( d_j \), form an orthonormal spanning set for \( R_m \); and, the scalars, \( \lambda_j \), are allowed to vary through the entire range of real numbers.

The objective of FCV pattern recognition can be viewed as an attempt to use the set \( X \) of unlabeled measurement vectors to infer a linear model in the form of equation 1 for each of the \( c \) classes that are assumed to be represented by the data. Equivalently, the problem is to obtain an unsupervised "best" linear fit of the data \( X \) to a given number, \( c \), of models of the form given by equation 1.

Principal Component Models

Suppose it is desired to fit all of the data \( X \) to a single linear model of the form of equation 1 (i.e., \( c=1 \)). Suppose also that the center, \( y \), is chosen as the mean of the data \( X \):

\[
v = \frac{1}{n} \sum_{k=1}^{n} x_k
\]

Let \( L \) denote a line in data space \( R_m \) through \( v \) and in the direction of the vector \( d \). After going through the derivation, Gunderson et al. (1988) obtained the following scatter matrix of \( X \) relative to the center \( v \). One way of obtaining a best linear fit to the data is to determine that line \( L \) through \( v \) which maximizes the total scatter which led to the maximization problem:

\[
\text{maximize} (d' S d)
\]

\[
d \in R_m
\]

This problem has a well known solution (Gunderson and Jacobsen, 1983); the maximum value of total scatter is given by the magnitude of the largest eigenvalue of the scatter matrix, \( S \). Since the matrix \( S \) is symmetric, the eigenspace corresponding to each of its eigenvalues is one-dimensional. The solution to find another line orthogonal to the first line is uniquely determined by an eigenvector of \( S \) corresponding to its second largest eigenvalue, and so forth. The set of direction vectors \( \{d_1, d_2, \ldots, d_m\} \) determined by this procedure forms an orthonormal spanning set of vectors which are a "best" fit to the data \( X \) (in the sense of maximizing the scatter in each of the orthogonal directions) and, together, with the vector determined by equation 2, provide a model for \( X \) in the form of equation 1.

Influence Coefficients

For classification to a family of linear models (\( c>1 \)), the concept of influence coefficients (viewed as weighting coefficients) was introduced. These coefficients provide a measure of the extent to which a given vector \( x_i \) in \( X \) "influences" the formation of a given class model in the simultaneous process of fitting all the data \( X \) to a specified number of class models of the form of equation 1.
Given a particular class \((i=1,2,...,c)\) from the specified number of classes, a weighted scatter matrix, \(S_i\), from the data matrix \(X\) relative to a center (unspecified as yet), \(v_i\), is:

\[
S_i = \sum_{k=1}^{n} (u_k)\delta^2(x_k - v_i)(x_k - v_i)^T
\]

where the influence coefficients, \(u_k\), are required to take on values in the real interval \([0,1]\) and to satisfy the constraint

\[
\sum_{k=1}^{c} u_k = 1
\]

for each \(k=1,...,n\). The value of \(u_k\) for a particular vector \(x_k\) and class \(i=1,2,...,c\) measures the influence of that vector on the model of class \(i\). If \(u_k=0\), the vector has no influence on the class. If \(u_k=1\), the vector influences the \(i\)th class, and only that class. Values in between are interpreted accordingly.

**Equations of FCV Algorithms**

Disjoint principal component models for the \(c\) categories consist of \(c\) centers, \(v_i\), and direction vectors, \(d_j\), for each category \(i=1,2,...,c\) and are defined by the solutions to the minimax problem (Gunderson et al., 1988) as:

\[
\text{minimize} \left( \text{maximum} \{d_j^T s \mid d_j \in R_m, s \in R_m \} \right)
\]

over all possible \(v, s \in R_m, d_j \in R_m\) and \(u_k\) which satisfy the above constraints. They define the following necessary conditions for solving the FCV algorithm for the solution of the minimax problem:

1. For the \(c \times n\) matrix of influence coefficients \(u_k,\)

\[
u_k = 1/\sum_{j=1}^{n} [d_j v_j] / [d_j v_j]^2
\]

for each \(i=1,2,...,c\) and \(k=1,2,...,n\); and

2. For the set of \(c\) class centers \(v_i,\)

\[
v_i/\sum_{k=1}^{n} (u_k)^2 x_k / \sum_{k=1}^{n} (u_k)^2
\]

for each \(i=1,2,...,c,\)

A Picard iteration procedure can be used for finding approximate solutions to the above simultaneous equations. Eigenvalues and eigenvectors of the \(c\) weighted scatter matrices can then be computed.

**WATERSHED PARTITIONING**

An unsupervised fuzzy clustering algorithm is used to identify the dominant categories of ground cover characteristics and surfacial features of a watershed based on 30 m resolution TM data. This identification of categories is based on the assumption that the spectral signature measured by the TM multispectral scanner represents ground cover characteristics in the watershed. The studies and field observations made by Lindsey (1991) and Leu (1988) in this region have validated this assumption. The results of unsupervised classification with the support of other data layers are used in a GIS environment to partition watershed into HRUs using an interactive graphic approach.

**Definition and Criteria**

The hydrologic response unit (HRU) is assumed to be homogeneous with respect to its hydrologic response (Leavesley et al., 1983). The watershed characteristics such as elevation, aspect, slope, vegetation, and soils are considered as important attributes to partition watershed into HRUs, assuming that these are homogeneous over the specified range of variation. It is well known that some of these characteristics vary widely even at smaller spatial extent. However, in view of the commensurate accuracy to be obtained by selecting smaller areal units or grids and large computational problems, the concept of few HRUs with practically reasonable homogeneity within an HRU seems satisfactory for medium to large watersheds.

Ground cover is the critical component affecting the spatial and temporal changes in soil moisture, evapotranspiration, snowmelt, and water yield. The state of equations of the hydrologic models in general and particularly the modification of the PRMS model used in this study indicate priority of
vegetation, elevation, and soils parameters. The occurrence and type of vegetation also reflect about the soils, aspect, and slope. Leavesley and Stannard (1990) suggested that vegetation can be combined with topographic data, such as slope and aspect, to infer physical properties of soil and estimate available water-holding capacity. The studies made by Lindsey (1991) in the Tony Grove area, Utah, also suggest that a relationship exists between vegetative cover type and soil type.

These results further reinforce the idea of assigning higher priority to ground cover in delineating HRUs. As stated above, the classification of ground cover can be performed reasonably well using an unsupervised fuzzy clustering algorithm. Elevation is the next important attribute to be considered, especially in the mountainous watersheds where important climatic input varies with elevation.

Procedure

Applications of the fuzzy clustering procedure for partitioning a watershed into HRUs using remotely sensed data is presented in the following steps and also shown by a flowchart in figure 2.

1. Register the DEM and TM data of watershed to Universal Transverse Mercator (UTM) coordinates.

2. Delineate the watershed and subdivide watershed into subwatersheds based on some minimum defined size, say a minimum of about 3 to 5 percent of the total watershed area. At the same time, the stream order of subwatersheds can also be taken into account.

3. Divide the watershed into elevation, slope, and aspect classes. Use the range of variation and purpose of study to help in deciding the class intervals.

4. Input TM data of all seven bands to an unsupervised fuzzy clustering algorithm such as FCV to classify ground cover into the desired number of spectral classes and assign informational categories to these classes based on field information.

5. Overlay the subwatershed boundaries on the classified watershed ground cover/surfacial features and see how these boundaries match with different classes. Subwatershed boundaries would be further subdivided or merged, based on the cover class, to form tentative HRUs.
6. Overlay these tentative HRUs on the raster containing elevation classes so as to break the tentative HRUs with large elevation differences into smaller HRUs using an interactive graphic procedure to further modify the HRUs.

7. Validate or reinforce this unsupervised partitioning by overlaying HRUs on available field data/information such as some vegetation and soils data.

This interactive-graphic procedure involving the application of FCV clustering algorithm in conjunction with topographic data is an objective and efficient way of partitioning a watershed into HRUs. Under this procedure limited field data are required for "ground truth" checks, but extensive field collection programs are not needed for most parameters.
Chapter IV

MODELING THE EFFECTS OF CLIMATE CHANGE ON THE HYDROLOGIC RESPONSE OF THE CAUSEY WATERSHED

DESCRIPTION OF STUDY WATERSHED

The Causey Dam watershed selected for this study is located in the Weber River Basin in northern Utah (figure 3). Causey Dam, situated at the lower end of the drainage, is about 18 km (11 miles) east of Huntsville, Utah, on the South Fork of the Ogden River in the Weber River Basin. The watershed was instrumented for continuous monitoring of meteorologic and stream records. Figure 4 is an outline of the Causey watershed showing the major drainage channel and instrumentation locations.

The Causey watershed has an area of 208.64 sq km (80.55 sq miles). Its general topography is marked by the rugged Wasatch Mountains. Elevation is one of the most important physiographic factors affecting the hydrology of the watershed, because it affects the precipitation and temperature distributions. Within the Causey watershed elevation ranges from 1605 m (5266 feet) to 2780 m (9121 feet) with a median elevation of 2340 m (7677 feet). The soils are generally coarse grained, pervious, gravelly, stony, and well drained except for some shaley soils near the ridge tops. Textural classes lie between loam and clay loam with moderate to average soil moisture-holding capacity.

The dominant vegetation in the watershed consists of big sagebrush (Artemisia tridentata), aspen forest (Populus tremuloides), and coniferous forest consisting of pinyon-juniper, mountain fir, and mixed conifers. Intermingled with the sagebrush and found as understory in the forested areas are some grasses and broadleaf plants such as mountain shrubs, wheat grass, bunch grass, and Gamble oak.

The average annual precipitation (for the calendar year) at Huntsville is 55.4 cm (21.80 inches) with 75 percent of that received from October through May, largely in the form of snow. Summer precipitation from June to September is usually from high intensity storms of short duration that result from convectional activities. The mean annual air temperature at the Huntsville station is 7.05 °C (44.7 °F) with the lowest and highest mean monthly temperatures in January and July, respectively.

DATA/RASTERS PREPARATION

Thematic Mapper (TM) satellite data, Digital Elevation Model (DEM) data, and soils and vegetation data were used in the analyses. The Map and Image Processing System (MIPS, 1992), a commercial geographic information system (GIS) package, was used for data processing and generating data overlays. The steps used in preparing and analyzing TM and DEM data are summarized as follows:

1. The Landsat TM image of June 26, 1990, corresponding to EROS world reference system coordinates path 38 and row 31, was extracted to cover Causey and the adjoining area. The scene of June 26 was chosen as it is close to the peak vegetative period.

2. Control points were identified both on the TM scene and the U.S. Geological Survey (USGS) maps (1:24000) of Causey Dam, Horse Ridge, Monte Cristo Peak, Dairy Ridge, Bybee Knoll, and Lost Creek Dam, Utah quad sheets (eastings and northings). Eleven control points were selected at easily identifiable locations such as road intersections and lake or stream intersections.

3. The portions of quad sheets containing identified control points were scanned and digitized using a scanner to obtain exact coordinates (Eastings & Northings) of the control points on the map. The eleven control points selected above gave a very low root mean square error (1.22m).

4. The DEM data (7.5 minute quad Causey Dam) were extracted and georeferenced. The above DEM raster of the Causey area was then used to delineate the Causey watershed and subwatersheds.

PARTITIONING THE WATERSHED INTO HYDROLOGIC RESPONSE UNITS

Characteristics such as elevation, aspect, slope, vegetation, and soils were used in partitioning the watershed into hydrologic response units (HRU). An unsupervised fuzzy clustering algorithm was used to classify ground cover characteristics from TM data to aid in defining HRUs. This
Figure 1.—Location of Causey watershed in Weber River Basin.

Figure 4.—The Causey watershed.
procedure was applied in conjunction with topographic data layers such as elevation, aspect, and
subwatershed divides. The procedure is described in chapter III of this report and also in Sikka,
1993, and Sikka et al. (in review). The Causey watershed was partitioned into 19 HRUs. The PC
version of the model is limited to a maximum of 25 HRUs.

In this research, the Fuzzy c-Means clustering option available on MIPS and the Fuzzy c-Varieties
program, FCV, developed at USU (Gunderson and Jacobsen. 1983) were used. Although easier
to use, the Fuzzy c-Means in the MIPS is much slower than the FCV program. In order to run the
FCV program on the VAX. the ASCII raster files obtained from MIPS were converted into the
format needed for the FCV program. The FCV output was then converted back into ASCII raster
files for MIPS. The large TM scenes and data files of the Causey watershed were resampled to
compress the data file within 10,000 data points. The FCV program was run on a compressed
data file and the data set classified. Using the centers obtained by classifying the training data set,
the uncompressed (entire image) data file was then classified using the FCV program. Once the
larger TM scene was classified by FCV, it was converted back to an ASCII file and imported into
MIPS for displaying spectrally homogeneous classes.

The following specific steps were involved in partitioning the Causey watershed into HRUs:

1. Classification with the FCV algorithm was done on the VAX by inputting all seven TM
   band values as explained above. The image was classified into six spectral classes.
   Having six classes was based on the assumption that land cover classes such as bare,
   conifers, deciduous, shrubs/grasses, and mixtures are needed as broad vegetation types
   in the watershed hydrologic model.

2. These spectral classes were easily grouped into three broad informational classes: aspen
   forest, conifers forest, and shrubs/grasses. Since the spatial extent of the study area is
too large to consider finer details like species variations, this scheme should be fairly
reasonable.

3. A vector image containing subwatershed boundaries was overlaid on the unsupervised
   fuzzy classified image and edited for merging or expanding the boundaries to form
   tentative HRUs based on the classified ground cover classes. The tentative HRUs were
   saved in a vector file for further refinement.

4. The vector image containing tentative HRUs was overlaid on the raster of elevation
   classes. Each elevation represents a class interval of 300 m (1000 ft) with the lowest
   in 1500-1800 m (5000-6000 ft) and the highest in the range of 2700-3000 m (9000-
   10,000 ft). The vector editing procedure was again followed to break the tentative
   HRUs with large elevation differences into smaller HRUs with relatively small elevation
   differences. It was assumed that an HRU generally will not have an elevation
difference of greater than about 300 m (1000 ft). In the Tony Grove watershed of Utah,
   Lindsey (1991) also reported the importance of elevation zoning and used an elevation
   class interval of about 240 m (800 ft). In a large watershed like the Causey, an
elevation difference of about 300 m appears to be fine. The HRUs thus formed were
   saved in a vector file after cleaning the vector for topology errors. Figure 5 shows
  19 HRUs of the Causey watershed which were used as units in the distributed
  hydrologic model to estimate model parameters and input variables for the hydrologic
  model.

5. These HRUs were then overlaid on the rasters containing vegetation classes and soil
   water capacity derived from Natural Resource Conservation Service (NRCS) reports so
   as to verify the appropriateness of the partitioned HRUs and to ascertain if any
   modifications were needed. If there is little or no such information/data available, this
   step can be skipped. However, some sample field data are needed to ascertain what
   each ground cover class represents on the ground.

6. The HRU vector prepared at step (4) was converted into a raster file for preparing
   masks of each HRU to cut out rasters of different data layers for estimating model
   parameters of each HRU to run hydrologic simulations.

ESTIMATION OF MODEL PARAMETERS

Topographic attributes. Important topographic attributes such as slope, aspect, elevation,
and area of each HRU were obtained from DEM data.

Meteorologic parameters. The monthly maximum (TLX) and minimum (TLN) temperature
lapse rates estimated from temperature data of Huntsville and Woodruff, were used to adjust air
temperatures for elevation in each HRU. To account for the differences in slope-aspect between
Water Yield in Semiarid Environment
Under Projected Climate Change

Figure 5.— Hydrologic response units (HRUs) of the Causey watershed.

the base station and each HRU, an average difference in air temperature between a horizontal surface and the slope-aspect of an HRU for maximum (TXAJ) and minimum (TNAJ) air temperatures between -1 °C to 1 °C depending on the aspect and slope was used (Leavesley (1991, personal communication). For precipitation correction, snow correction factors (DSCOR) varied from 1.2 to 1.35 for different HRUs while rain correction factors (DRCOR) varied from 1.1 to 1.2, based on the seasonal precipitation distribution maps of Utah. A base temperature (BST) of 1.2 °C was used to decide the form of precipitation.

Soils parameters. Data available from the NRCS of the U.S. Department of Agriculture (USDA) were used to determine the soil texture, soil depth, and maximum available soil water holding capacity of the upper (REMX) and lower (BZMX) soil layers. The critical level of soil moisture in the upper layer (WK), above which actual (ES) and potential soil evaporation (ESP) are equal, and the lower critical level (WL), below which soil evaporation is assumed to be zero, were selected from the relevant literature (Wight and Hanks, 1981; Saxton et al., 1974; Ritchie, 1972). The maximum daily infiltration capacity (SRX) for a soil moisture content at soil water holding capacity (SMAX) was initially assumed to be 5 cm/day. This value was later refined by model optimization procedures.

Vegetation parameters. Vegetation types in each HRU were obtained from the vegetation map available from the Geography Department of Utah State University (USU). The vegetation was broadly categorized into aspen forest, conifers forest, and shrubs/grasses. Leaf area index (LAI) values were estimated from the TM data using vegetation specific LAI-NDVI (normalized difference vegetation index) relationships (Asrar et al., 1984; Nemani and Running, 1989; Sikka, 1992). The species dependent light extinction coefficient (EXT) generally varies between 0.35 and 0.87, with an average value of about 0.5 for both conifers and deciduous forests (Eagleson, 1982; Aber and Melillo, 1991). Values of EXT for given vegetation types in different HRUs were found in the literature. Maximum stomatal conductance (CCMX) values for the predominant vegetation types in the various HRUs also were taken from the literature (Jones, 1983; Lee, 1980; Caldwell et al., 1981; Aber and Melillo, 1991; Massman and Kaufmann, 1991; Running and Coughlan, 1988).

Values for the soil moisture parameter (SC) for reduction of CCMX below a particular level of available soil moisture were derived from relationships which suggest that stomatal closure begins when approximately one-half to two-thirds of the extractable water in the soil is utilized (Arris and Eagleson, 1989; Dolman, 1988; Turner, 1991). The coefficient for correcting the effects of vapor
pressure deficit (VPD) on CCMX was assumed to be between 0.42 and 0.03 Mbar, based on the literature (Dolman, 1988; Running and Coughlan, 1988; Massman and Kaufmann, 1991). The LAI factor (FAC) used to estimate the peak LAI from the initial LAI value used at the beginning of the season for each vegetation type was estimated from the results of seasonal LAI variations and the relative growth curves as reported in this area for various vegetation types (Spanner et al., 1990; Jaynes, 1978; Hanson, 1976; Wight and Hanks, 1981). For deciduous trees such as aspen, values of FAC were found to fall in the range from 3 to 5, while for sagebrush and grasses values between 4 and 5 were used. The beginning (ITST) and end (ITEND) of the active transpiration period were determined using weekly degree-days.

Hydrologic parameters. Values of the interception storage coefficient for rain (XINCFS) and snow (XINCFS) were based on results of previous studies at the USU School Forest and elsewhere as reported in Lindsey, (1991); Running and Coughlan (1988); Zinke (1967); and Waring and Schlesinger (1988). Observed streamflow data were used to obtain initial estimates of interflow and base flow recession constants and initial groundwater storage. The range of values used by Leavy et al. (1991) in the upper Weber basin for groundwater seepage rates and maximum and minimum runoff contributing areas were used initially and then optimized.

MODEL CALIBRATION

The water year 1989 was taken as base year for applying the model to the Causey watershed. Recorded daily flow data for model calibration were available for only this year. Daily inputs of precipitation, maximum and minimum air temperatures, and solar radiation were used for model simulation. Modeled streamflow was first matched with observed data on the basis of annual runoff volume. The calibration procedure then concentrated on the time series of the runoff. Once the parameters for annual simulated volumes were adjusted, the monthly flow totals were matched. A satisfactory matching of monthly flow totals provided a good start for matching daily flows. Obviously, for this study the optimized parameter values have limitations because of the availability of suitable data for only a single year.

RESULTS AND DISCUSSION

Ground data were used to check the results of the unsupervised fuzzy clustering procedure used for classifying ground cover and partitioning the watershed into HRUs. The ground cover classification of Causey watershed obtained from seven bands of TM data using unsupervised fuzzy clustering compares reasonably well with the map showing broad vegetation types of the Causey. The results were also verified with aerial photographs and information from a few sample spots. The procedure appears to be a quick and satisfactory way of ground cover classification for a watershed when sufficient ground data are either not available or are difficult to obtain. The potential for human error or bias is also minimized in this method of ground cover classification.

Results are encouraging for the procedures developed for partitioning a watershed into HRUs by applying unsupervised fuzzy clustering to TM data, in conjunction with topographic data using an interactive-graphic approach in a GIS environment. Figure 6, showing the overlays of HRUs on the soil water holding capacity (SMAX) and vegetation rasters, generally demonstrate a reasonably good homogeneity within an HRU in terms of important attributes influencing hydrologic response.

The spatial distribution of input variables and model parameters for the Causey watershed obtained from the identified HRUs has provided acceptable results of model calibration and hydrologic simulations of the Causey watershed. The simulated daily hydrograph matched well with the observed hydrograph. The model gave a fairly good fit with both daily and monthly coefficients of determinations (r) which were 0.88 and 0.97, respectively. The model results are discussed in detail by Sikka (1993) and Sikka et al. (in review).

Based on the definition of HRU, the important watershed attributes are assumed to be homogeneous within an HRU. However, in some large HRUs two predominant vegetation types existed, and in such cases weighted area average parameter values of the two vegetation types were used. This limitation was there because of the constraint limiting the number of HRUs within 25 in the PC version of the model. Overall, the results suggest that this procedure does a satisfactory job of partitioning a watershed into HRUs and offers a fast, less data-demanding but rationally-objective approach in providing a distributed parameter capability for watershed hydrologic simulations. Such an approach may be extended to subdivide large areas into similar response units for the purpose of providing effective parameterization and feedback from climatic models to hydrologic models, and vice versa. The fuzzy clustering algorithm (Fuzzy c-Varieties [FCV]) is capable of classifying watershed ground cover. The procedure developed for partitioning a watershed into HRUs through the utilization of DEM data and the application of an unsupervised fuzzy pattern recognition algorithm to Landsat TM.
data provided good results. If the definition of assuming uniform characteristics within an HRU is kept in mind, the procedure is quick, easy to apply, and relatively less demanding of data than the traditional ground-based approach.

**Model Calibration**

Comparisons between the simulated and observed daily hydrographs and mass curves are shown in figures 7 and 8. The daily simulated flows closely match the observed flows both in terms of the magnitude and timing of flows. A comparison of both recorded and simulated total runoff quantities by month also indicates a good match. The coefficients of determination ($r^2$) for daily and monthly flows are 0.88 and 0.97, respectively. In an attempt to further verify the calibration results, the simulated depth of snow water equivalent (PWEQV) also was compared with the observed PWEQV at the Horse Ridge site (figure 5). Although this site might not be representative of the entire watershed, in the absence of additional data, it was reasoned that the observations could strengthen the verification results. The overall agreement in figure 9 is reasonably close. The dates for the beginning of snowpack accumulation (11 November 1988) and snowpack depletion (around 8 May 1989) are very close to simulated dates. However, for the peak snow water equivalent the plots show a significant difference.

The simulated actual evapotranspiration (AET) for the Causey watershed for the 1989 water year was 261 mm (10.3 inch), with a maximum average daily AET of 3.5 mm (0.14 inch) during the month of June. Based on the literature values of average ET for aspen, spruce/fir, and sagegrass in the area (Sikka, 1993), the simulated ET seems reasonable for a moisture stressed watershed with a low value of LAI. The pattern of daily variations and timing of simulated available soil moisture in the profile also suggests satisfactory simulation of the soil moisture in the absence of measured soil moisture data.

**Sensitivity Analyses of Hydrology to Climate Change Scenarios**

Because general circulation models (GCM) are currently unable to provide realistic meteorological input variables at the basin scale, assumed scenarios are used for this study. Extreme climate and vegetation change scenarios are based on conditions which reflect a doubling of the atmospheric CO$_2$ content. The temperature change and precipitation change scenarios are based on climate change hydrology studies (Nemec and Schaake, 1982; Flachsha et al., 1987; Gleick, 1986; McCabe and Ayers, 1989; Schaake, 1990). The changes assumed for the LAI and stomatal conductance as
Figure 7.—Comparison of observed and simulated streamflow hydrographs of the Causey watershed for water year 1989.

Figure 8.—Mass curve of observed and simulated flows of the Causey watershed for water year 1989.
Water Yield in Semiarid Environment
Under Projected Climate Change

Sensitivity analyses were conducted by modelling the various scenarios given in table 2. Based on these scenarios, the daily temperature and precipitation data of the base year (water year 1989) were adjusted. Unlike other studies, the temperature changes were not applied uniformly throughout, but instead were based on a disaggregation approach. Different weights were assigned to adjust the minimum and maximum temperatures for each month. The weights were obtained from historical data by Wang (1992), based on a disaggregation model which was applied in the Salt Lake valley.

Annual Changes

Sensitivity to single factor scenarios. The effects of climate and vegetation change scenarios on annual evapotranspiration (AET) and runoff are presented in table 3, lines 1 to 7 and 14 and 15. On a comparative basis, the results indicate that changes in LAI (L) and stomatal conductance (CC) produce more pronounced effects on AET than on runoff in this watershed. Increases in AET were found at 11, 18, and 24 percent for temperature increases of 4°, 6°, and 8 °F, while a temperature decrease of 6 °F decreased AET by 8.6 percent. At higher temperatures, the soil evaporation component of AET becomes more significant because of the increased rain/snow ratio and the faster snowmelt, thus making surface soils wet for evaporation, especially for parts of the watershed with low LAI. Transpiration losses are relatively more sensitive to canopy conductance (CC) than to LAI. This result suggests that a significant increase in LAI would be needed to offset the effect of increased stomatal resistance due to increased CO₂ in the atmosphere.

Annual runoff decreased by 4, 9, 13, and 18.6 percent for temperature increases of 4°, 6°, 8°, and 10 °F, respectively, assuming no change in precipitation. The magnitude of changes in annual water yield ranged from a decrease of 18 percent, for a precipitation decrease of 10 percent (P-10), to an increase of 15 percent, for a precipitation increase of 10 percent (P+10). The results of this study suggest that climate change will have significant but less severe impacts on annual water yield in this watershed than those results reported by others for the Colorado River basin (Nash and Gleick, 1991; Schaeke, 1990; Flaschka et al., 1987). A greater sensitivity of the annual runoff to precipitation changes, rather than to temperature changes, agrees with the results of recent studies in the Colorado River basin (Nash and Gleick, 1991; Schaeke, 1990).

Figure 9.—Observed and simulated depth of snow water equivalent of the Causey watershed for water year 1989.
Table 2.—Assumed climate change scenarios for the Causey watershed

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Temperature change (°F)</th>
<th>Precipitation change (%)</th>
<th>Leaf-area index (%)</th>
<th>Stomatal conductance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T4</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T6</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T8</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P5</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P10</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P15</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P-5</td>
<td>0</td>
<td>-5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P-10</td>
<td>0</td>
<td>-10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P-15</td>
<td>0</td>
<td>-15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P+10</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P-10 T4</td>
<td>6</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P-10 T6</td>
<td>4</td>
<td>-10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CC-20 L15 T4</td>
<td>4</td>
<td>0</td>
<td>15</td>
<td>-20</td>
</tr>
<tr>
<td>CC-20 L15 P10 T4</td>
<td>4</td>
<td>10</td>
<td>15</td>
<td>-20</td>
</tr>
<tr>
<td>CC-20 L15 P:10 T4</td>
<td>4</td>
<td>-10</td>
<td>15</td>
<td>-20</td>
</tr>
<tr>
<td>CC-30 L25 T6</td>
<td>6</td>
<td>0</td>
<td>25</td>
<td>-30</td>
</tr>
</tbody>
</table>

T2 = an average annual temperature increase of 2 °F.
P5 = an average annual precipitation increase of 5 percent.
CC-20 = an average annual decrease in stomatal conductance of 20 percent.
L15 = average annual change in leaf area index (LAI) of 15 percent.

Table 3.—Effect of climate change on runoff and actual evapotranspiration for the Causey watershed

<table>
<thead>
<tr>
<th>Climate change scenario</th>
<th>Change in annual runoff (%)</th>
<th>Change in spring runoff (%)</th>
<th>Change in summer runoff (%)</th>
<th>Change in annual AET (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T+4</td>
<td>-3.82</td>
<td>-19.1</td>
<td>-17</td>
<td>11.0</td>
</tr>
<tr>
<td>T+6</td>
<td>-8.97</td>
<td>-34.3</td>
<td>-28.5</td>
<td>18.1</td>
</tr>
<tr>
<td>T+8</td>
<td>-12.5</td>
<td>-44.4</td>
<td>-37.8</td>
<td>24.0</td>
</tr>
<tr>
<td>P+5</td>
<td>+7.6</td>
<td>+8.9</td>
<td>+9.3</td>
<td>2.1</td>
</tr>
<tr>
<td>P-5</td>
<td>-9.5</td>
<td>-9.8</td>
<td>-10.3</td>
<td>-0.8</td>
</tr>
<tr>
<td>P+10</td>
<td>+15.5</td>
<td>+16.6</td>
<td>+17.5</td>
<td>3.8</td>
</tr>
<tr>
<td>P-10</td>
<td>-18.3</td>
<td>-19.8</td>
<td>-20.8</td>
<td>-3.0</td>
</tr>
<tr>
<td>T+4P+10</td>
<td>-12.7</td>
<td>-2.9</td>
<td>-1.9</td>
<td>13.4</td>
</tr>
<tr>
<td>T+4P-10</td>
<td>-21.3</td>
<td>-35.7</td>
<td>-33.3</td>
<td>7.87</td>
</tr>
<tr>
<td>T+6P+10</td>
<td>+8.8</td>
<td>-19.4</td>
<td>-15.1</td>
<td>19.4</td>
</tr>
<tr>
<td>T+6P-10</td>
<td>-27.3</td>
<td>-49.4</td>
<td>-43.8</td>
<td>14.4</td>
</tr>
<tr>
<td>T+8P+10</td>
<td>+5.6</td>
<td>-31.8</td>
<td>-25.4</td>
<td>24.1</td>
</tr>
<tr>
<td>T+8P-10</td>
<td>-30</td>
<td>-61.2</td>
<td>-52.3</td>
<td>20.2</td>
</tr>
<tr>
<td>CC-20</td>
<td>+1.3</td>
<td>---</td>
<td>---</td>
<td>-5.5</td>
</tr>
<tr>
<td>CC-30</td>
<td>+1.7</td>
<td>---</td>
<td>---</td>
<td>-8.6</td>
</tr>
<tr>
<td>T+4L+15</td>
<td>-3.95</td>
<td>-20.0</td>
<td>-18.8</td>
<td>13.4</td>
</tr>
<tr>
<td>T+4L+15 CC-20</td>
<td>-2.5</td>
<td>-18.0</td>
<td>-15.8</td>
<td>8.7</td>
</tr>
<tr>
<td>T+6L+15 CC-20</td>
<td>-7.3</td>
<td>-33.2</td>
<td>-27.3</td>
<td>15.9</td>
</tr>
<tr>
<td>T+8L+15 CC-20</td>
<td>-10.9</td>
<td>-43.5</td>
<td>-36.6</td>
<td>21.8</td>
</tr>
<tr>
<td>T+8P+10 L+15 CC-20</td>
<td>-29.3</td>
<td>-56.8</td>
<td>-50.5</td>
<td>18.2</td>
</tr>
<tr>
<td>T+8P+5L+15 CC-20</td>
<td>-1.5</td>
<td>-35.7</td>
<td>-29.0</td>
<td>20.4</td>
</tr>
<tr>
<td>T+8P+10L+15 CC-20</td>
<td>+7.25</td>
<td>-31.0</td>
<td>-24.3</td>
<td>23.4</td>
</tr>
</tbody>
</table>

AET = actual evapotranspiration.
T = air temperature in °F.
P = precipitation change in percent.
CC = canopy conductance change in percent.
L = change in leaf area index (LAI) in percent.
Water Yield in Semiarid Environment Under Projected Climate Change

**Sensitivity to multiple factor scenarios.** Increases of 12.7, 8.8, and 5.6 percent in annual water yield were found as a result of a 10 percent increase in precipitation when combined with 4°, 6°, and 8 °F increases in temperature, respectively (table 3). Decreases in water yield of 21.3, 27.3, and 30 percent were obtained for a 10 percent decrease in precipitation when combined with 4, 6, and 8 percent increases in temperature, respectively. Relatively lower percentage changes in water yield for increased precipitation scenarios are attributed to increased ET losses under wet conditions. This result suggests a greater effect on runoff for warming than for cooling, which may be attributed to the aridity of the basin.

The results from combined scenarios indicated that a temperature increase of 4 °F, coupled with a 20 percent decrease in stomatal conductance and a 15 percent increase in LAI from doubled CO₂, decreased water yield by 2.6 percent. In snowfed watersheds, such as Causey, a major portion of the annual runoff is contributed from snowmelt during the spring (April-June). However, ET rates are highest in the late spring and summer. Thus, changes in ET appear to have a relatively small effect on total annual water yield from the Causey watershed. Therefore, based on these results, for this watershed, increases in runoff from stomatal closure in the event of CO₂ doubling (Aston, 1984; Idso and Brazel, 1984) appear unlikely when stomatal changes are combined with assumed increases in temperature and LAI. These predictions also agree with those of Martin et al. (1989).

**Monthly/Seasonal Changes**

The effect of assumed scenarios on the timing of peak monthly runoff and variations in monthly flows is illustrated in figures 10 and 11, respectively. Temperature increases of 2°, 4°, and 6 °F alone and in combination with other scenarios shifted the peak runoff from May to April, while a temperature increase of 8 °F temperature shifted the peak runoff from May to March. The magnitude of the peak is reduced in all the cases except those with increased precipitation.

Seasonal changes in spring (April-June) and summer (July-September) are presented in figure 12 and table 3. Spring and summer flows decreased by 2 to 3 percent for a T+4°F P+10 scenario and by about 52 to 61 percent for a T+8°F P+10 scenario. As might be expected, impacts from climate changes are generally more severe for spring than for summer flows. An increase of about 17 percent in spring and summer runoff results from a precipitation increase of 10 percent with no other changes. A temperature increase of 4 °F, when coupled with a precipitation increase of 15 percent, augments spring and summer runoff by about 7 percent.

![Figure 10](image-url) — Simulated monthly flows of Causey watershed illustrating the effects of climate change on timings of peak flow.

---

40
Figure 11.—Simulated monthly flows of the Causey watershed illustrating changes in monthly flow volumes.

Figure 12.—Changes in annual and seasonal flows of the Causey watershed under different climate change scenarios.
A significant increase in winter runoff (especially in March) was found in all the cases except the scenarios where precipitation was decreased. This result occurs because of an increased rain-to-snow ratio and early snowmelt in winter because of warming. Although average spring streamflows are reduced, increased temperature and precipitation scenarios (for example, T+4 P+10) would produce a flooding potential during the early spring if sufficient reservoir storage is not available.

Variations in the available soil moisture for a range of scenarios indicated that warming increases winter soil moisture and reduces summer soil moisture, with a shift in the peak soil moisture level from April to March resulting from early snowmelt due to warming.

The results of this study must be interpreted with caution until the model can be rigorously validated with additional data. However, it is felt that the approximate calibration presented here is sufficient to demonstrate the applicability of the model for simulating the effects on assumed climate changes and CO₂-induced vegetation changes on hydrology. The model needs to be extended to include an explicit linkage with the CO₂ diffusion gradient for simulating vegetation dynamics.

The assumed scenarios used in this analysis provide an insight into the hydrologic sensitivity of the basin. However, it is recognized that the scenarios might not be internally consistent. Linking a realistic meteorological and/or climate model with the hydrologic model would overcome this deficiency.

CONCLUSIONS

Application of the model to the Causey watershed provided a basis for determining the effects of assumed climate and CO₂-induced vegetation changes on hydrologic response. The results of this study suggest significant but less severe impacts of climate change on water yield than previous studies in the Western United States have indicated. A decrease in annual runoff of 15 to 20 percent could be possible for cases of warming associated with decreased precipitation. In most cases, projected changes in monthly flows suggest a shifting of runoff peaks from May to March or April. Atmospheric warming combined with precipitation increases could increase the flood hazard from spring runoff. The changes in evapotranspiration produced by warming largely occur during late spring and summer and thus have little effect on annual runoff, which is dominated by snowmelt runoff in the Western United States.
CHAPTER V

MODELING OF WEBER RIVER BASIN
FOR DETERMINING THE HYDROLOGIC
IMPLICATIONS OF CLIMATE CHANGE

THE STUDY AREA

The Weber River Basin is located in northern Utah east of the Great Salt Lake. The major
tributaries to the Weber River are Chalk Creek, Lost Creek, East Canyon Creek, Southfork of the
Ogden River, and Smith and Morehouse Creek (figure 13). The Ogden River is the largest of the
tributaries. The Southfork of the Ogden River is fed mainly by the subwatershed above Causey
Reservoir. The Ogden joins the Weber River near Ogden, just before the river enters the Great
Salt Lake. Within the Weber River drainage area, the elevation varies from 4200 feet above mean
sea level at the surface of the Great Salt Lake to 11,200 feet at the top of the Uintah mountains.
The mean elevation of the drainage basin is 6700 feet; 50 percent of the area lies between
5900 feet and 7450 feet. Only 16 percent of the total area is at elevations which are less than
5000 feet. However, it is in this area that most of the cultural pursuits take place (Haws, Jeppson,
and Huber 1970). Elevation, along with aspect and slope, affects the vegetation in the area. The
dominant vegetation in the watershed consists of big sagebrush (Artemisia tridentata), aspen
(Populus tremuloides) forest, and coniferous forest consisting of pinyon-juniper, mountain fir, and
mixed conifers intermingled with some grasses and broadleaf plants in the understory. A
schematic diagram of the Climate Vegetation Hydrologic Model (CVHM) which was applied to
the Weber River Basin is shown in figure 1.

Streamflow records are available for a period of 38 years (1951 to 1989) for each of the six Weber
Basin subdrainages shown by figure 13 (Haws, Jeppson, and Huber 1970). Some stream gauging
stations, such as that on Chalk Creek at Coalville, record near natural flows, but most of the
gauging stations are located below dams which create storage reservoirs. Missing records were
estimated from the dam operation records and downstream recording stations. Runoff records
from ungauged areas were estimated by comparative area techniques using a nearby or
representative gauged watershed. Streamflow and reservoir data are available from the Weber
Basin Conservancy District, located in Ogden; the Bureau of Reclamation (Reclamation) office in
Denver; and Earth Information CD-ROM (Compact Disc-Read Only Memory). Solar radiation
data were taken from the station located in Kaysville. Precipitation and temperature data were
taken from CLIMDATA CD-ROM available for the Western United States. Lapse rates for

Water Yield in Semiarid Environment
Under Projected Climate Change

temperature were computed from temperature data taken from stations at different elevations.
Appropriate lapse rates for precipitation were taken from precipitation maps developed by the Utah
Climate Center at Utah State University.

HYDROLOGIC RESPONSE UNIT DELINEATION

Topographic maps (7.5 minute quad maps) for the six gauged watersheds were obtained from the
United States Geologic Service (USGS) in Salt Lake City. Maps were combined, as needed, to
make up a composite for each watershed, and the watershed boundaries were then delineated on
each composite map. "Seeds" were located manually on the composite map at intersections of
secondary streams, and subwatersheds were delineated above these seed points. The subwatershed
areas were then restructured on the basis of elevation differences within the subwatersheds to form
tentative hydrologic response units (HRUs). For the six watersheds, satellite thematic mapper (TM)
data and vegetation maps in ERDAS Geographic Information System (GIS) formats were procured
from the U.S. Fish and Wildlife Service (1992), the Utah Cooperative Fish and Wildlife Research
Unit located on the Utah State University campus. The data were consolidated in a commercial
GIS package, Map and Image Processing System (MIPS) of Microlmages, Inc. (1992), and rasters
were prepared. Vegetation maps gave the vegetation type at each pixel. All the vegetation types
were broken down into three prominent vegetation types—aspen, sagebrush, and conifers. From
band 3 and 4 of the TM data, the normalized difference vegetation index (NDVI) was computed as follows:

\[
NDVI = (\text{Band 4} - \text{Band 3}) / (\text{Band 4} + \text{Band 3})
\]

The stream networks were manually located on the vegetation maps. NDVI for each pixel was
read using the "INSPECT" mode in MIPS with the appropriate vegetation map as a reference.
NDVI values were read from the text screen with the pixel location on the vegetation map
coresponding to the tentative HRUs. The HRUs were then finalized by considering both elevation
and vegetation cover. The HRUs that were thus identified for Chalk Creek, Lost Creek, East
Canyon Creek, Causey subwatershed, Smith and Morehouse Creek, and Wheeler Creek watersheds
are shown by figures 14 through 18. It is noted that the Causey subwatershed is only a portion of the
Southfork of the Ogden River drainage. Because the Causey subwatershed represents the
primary water-yielding area in this drainage and because the model had already been applied to the
Water Yield in Semi-arid Environment
Under Projected Climate Change

Figure 13.—Study area: Weber River Basin.

Water Yield in Semi-arid Environment
Under Projected Climate Change

Figure 14.—Hydrologic response units (HRUs): Chalk Creek watershed.

Figure 15.—Hydrologic response units (HRUs): Lost Creek watershed.
Water Yield in Semiarid Environment
Under Projected Climate Change

subwatershed by Sikka (1993), the Causey subwatershed was used to represent the changes in runoff from the Southfork of the Ogden River. The remainder of the Southfork drainage is included as an ungauged area.

PARAMETER ESTIMATION

Watershed parameters. The mean elevation, slope, and aspect of each HRU were then computed from the composite. For determining the area of each individual HRU, the watersheds and HRUs were plotted on tracing paper, each HRU was cut individually, and rasters were prepared for each. The area of each HRU was found by using INSPECT RASTER in MIPS. From the NDVI values, LAI estimates were made using relationships developed for the region by Sikka (1993).

Hydrologic parameters. Based on results of previous studies at the USU School Forest, and elsewhere reported in Lindsey (1991), Running and Coughlan (1988), Zinke (1967), and Waring and Schlesinger (1985), interception storage coefficients for rain (XINCFR) and snow (XINCFS) were derived.

The observed streamflow data were used to obtain initial estimates of base flow recession constant (RCB) and initial groundwater storage (GW). The range of values used by Leavesley (1991, personal communication) in the upper Weber basin for interflow routing coefficient (RCF), seepage rate from subsurface reservoir to groundwater reservoir (RSEP), and maximum and minimum runoff contributing areas (SCX and SCN) were optimized by matching observed and simulated flows.

MODEL CALIBRATION

The purpose of model calibration is to select a set of model parameter values within a reasonable range such that simulated flows achieve the best possible match with observed flows. Data for water year 1989 were taken for the purpose of model calibration, since annual precipitation for that year was close to the mean precipitation for the drainage basin as estimated from the years in which all data were available. Precipitation, maximum and minimum temperatures, solar radiation, and observed flow were input to the model for calibration.

Figure 16.—Hydrologic response units (HRUs): East Canyon Creek watershed.

Figure 17.—Hydrologic response Units (HRUs): Smith and Morehouse Creek watershed.

Figure 18.—Hydrologic response units (HRUs): Wheeler Creek watershed.
As mentioned in chapter II, the model contains a self calibration or self optimization capability based on either the absolute difference between the simulated and observed values or the sum of squares of the differences between the two flows. In this study, the sum of squares of the difference between the two flows was used for optimization. A groundwater recession constant and subsurface (or interflow) recession constant were input for optimization, since they were found to be sensitive in the calibration process. Allowable ranges for each of the parameters were selected from the literature or other studies conducted in the surrounding area. Even after completion of the self optimizing process, some manual interventions were necessary to bring about the required results.

As mentioned, the most sensitive parameters were the groundwater and subsurface (interflow) recession constants, RCB and RCF, respectively. Increases in RCB shift the timing of the outflows and also increase the total volume of the outflow, whereas increases in RCF increase the rate at which interflow occurs. In the calibration process, matching was done, first, for the yearly total volume of flow, followed by that for monthly flows.

Daily flow calibration required adjustment of both the timing and peak flow rates. More importance was given to matching the yearly flow volumes than to matching peak flows because the yearly runoff volume is a more critical variable in water yield studies. The calibration results for each of the six watersheds are discussed in detail later in this chapter.

APPLICATION OF CLIMATE CHANGE SCENARIOS TO THE WEBER RIVER BASIN

Parameter estimation and model calibration were performed for each of the six gauged watersheds. Specific scenarios were then imposed on the calibrated model to study the effects of climate change on the basin as a whole. The procedure used in the model application is reviewed here. Monthly flows from the 14 water yielding areas within the Weber River Basin were available from historical records for 38 years (1951-1989). The Weber River Simulation Model was calibrated by the state division to represent the demands in 18 service areas (figure 19). Six of the 14 water-yielding areas contain the gauged watersheds considered in the application of Climate Vegetation Hydrologic Model (CVHM). Each of the remaining eight areas was assigned a nearby gauged watershed. It is assumed that each of the ungaged areas has hydrologic response characteristics
which are similar to those of its assigned gauged watershed. Therefore, the percent changes in flow in each of the gauged watersheds under imposed climate change scenarios are assumed to apply to its assigned ungauged area. The historical monthly flow records of 38 years, which were provided by the Utah State Division of Water Resources, are modified according to the applicable percent change.

CLIMATE CHANGE IMPACT

Climate Change Scenarios

Due to limitations of basin scale predictions from general circulation models, assumed scenarios based on GCM predictions were used for this study. The temperature change (2 °F to 8 °F) and precipitation change (-10 to +10 %) scenarios were based on climate change hydrology studies (Nemec and Schaeke, 1982; Flaschik et al., 1987; Gleick, 1987; McCabe and Ayers, 1989; Schaeke, 1990; United States Environmental Protection Agency, 1989). The LAI (-15 to +25 %) and stomatal conductance (CC) (-10 to -20 %) scenarios of change as a result of elevated CO₂ were based largely on the studies of Rosenberg et al. (1990) and Argen et al. (1991). The temperature (T), precipitation (P), LAI (L), and stomatal conductance (CC) changes for each scenario are given in table 2, chapter IV.

The limitations of such scenarios should be kept in mind because all scenarios might not be internally consistent in the real world. However, in the absence of basin-scale general circulation model (GCM) outputs, these assumed scenarios were used to test the model and make some suggestive evaluation of the effects of climate change on the hydrologic response of the Weber River Basin.

Sensitivity Studies

Sensitivity analyses of actual evapotranspiration, soil moisture, and water yield to climate and changes in vegetation were conducted by applying the assumed scenarios singly and in combinations. Based on these scenarios, the daily temperature and precipitation data of the base year (water year 1989) were adjusted. Changes in maximum and minimum air temperatures were not obtained by uniformly adding these incremental changes to daily values as is commonly done. Different weights were assigned to adjust the minimum and maximum temperatures in each month; these weights were obtained from historical data by Wang (1992) based on a disaggregation model.

RESULTS AND DISCUSSION

This section deals with the Climate Vegetation Hydrologic Model (CVHM) calibration results for the six gauged watersheds shown by figure 13. Also discussed are the results of sensitivity studies for the same six watersheds involving various assumed climate change scenarios. Corresponding results for the Weber River Basin as a whole are expressed in terms of the effects of the assumed scenarios on water yields from the six gauged watersheds.

Results of the CVHM Calibration for the Six Gauged Watersheds

The model simulation results for the most important four of the six watersheds (Chalk Creek, Lost Creek, East Canyon, and Causey subwatershed) for the base year 1989 can be seen from the daily hydrographs in figures 20, 21, and 22 and also in figure 7 (chapter IV). The Causey subwatershed was used to represent changes on the Southfork of the Ogden River watershed. The hydrographs of the simulated and observed flows indicate the calibration results in terms of both timing and magnitude. These figures show a reasonable match between the observed and simulated flows over the year, particularly with respect to total runoff volumes. It is noted, however, that in some cases the peak flows are not well reproduced.

In the second and third months (November and December), the simulated flows tend to be less than the observed flows. This observation can be explained on the basis of temperature inversions in some parts of the watersheds which are not reflected in general temperature lapse rates. Temperature lapse rates are computed between upper and lower elevation temperature stations from specific recorded data, and they often do not well represent the actual conditions at a specific point of time. In all cases, the peak flows for the watershed result from snowmelt during the spring months. However, as indicated by the observed hydrographs, the lower level watersheds (Chalk Creek and East Canyon Creek) reflect more flow fluctuations than the higher level watersheds. It is speculated that the flow fluctuations from the lower watersheds result because air temperatures at these elevations tend to fluctuate across the freezing point, particularly the differences between night and day temperatures, during the early spring months.
Weber River basin 1989
Model calibration on Chalk Creek

Figure 20.—Model calibration for the Chalk Creek watershed.

Weber River basin 1989
Model calibration on Lost Creek

Figure 21.—Model calibration for the Lost Creek watershed.
Figure 22.—Model calibration for the East Canyon Creek watershed.

Figure 23.—The effects of climate change temperature scenarios on spills to the Great Salt Lake.
Figure 24.—The effects of climate change precipitation scenarios on spills to the Great Salt Lake.

Figure 25.—The effects of climate change dual parameter scenarios on spills to the Great Salt Lake.
As indicated earlier, the model was previously calibrated using data from the 1989 water year on the Causey subwatershed (Sikka, 1993). It is noted that the discharge measurements by Reclamation were made at three to four day intervals so that daily peaks are not always reflected by the data.

Results of Climate Change on Individual Watersheds

In the absence of realistic GCM outputs regarding climate change scenarios, 18 assumed climate change scenarios were run on the six gauged watersheds (table 4). Climate change scenarios referred to most often in the literature consist of temperature increases ranging from 2°F to 8°F, precipitation changes ranging from -10 to +10 percent, LAI changes ranging from +15 to +25 percent, and a -20 percent change in stomatal conductance. The stomatal conductance change is suggested by Rosenberg et al. (1990) and also by Sikka (1993). The model computes all remaining needed changes in the input data and parameter values during execution.

The specified temperature changes were not applied uniformly throughout the year. Different values for maximum and minimum temperatures were assigned to each month based on a disaggregation model used by Wang (1992) for the nearby Salt Lake valley. A defined temperature change for a particular month was assumed to apply to all days during the month. Table 5 shows the average responses of the six gauged watersheds in the basin to each climate change scenario

Single parameter change scenarios. These scenarios represent a change in a single parameter, such as surface air temperature. An increase in temperature decreases the annual water yield. It also shifts the timing of the snowmelt to earlier in the spring, increases the evapotranspiration loss from the watershed and, therefore, increases winter stream flows and reduces spring and summer flows.

There seems to be general agreement in the direction of temperature change resulting from increases in atmospheric greenhouse gases. However, the literature indicates no such agreement regarding projected changes in precipitation, possibly because precipitation changes in and regions are a fairly local phenomenon. Therefore, though it is generally believed that there will be an increase in precipitation over the United States with global warming, changes in both directions

Table 4—Response of the six gauged watersheds to various climate change scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Causey</th>
<th>Lost</th>
<th>Smith</th>
<th>East</th>
<th>Chalk</th>
<th>Wheeler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>60.54</td>
<td>21.62</td>
<td>8.06</td>
<td>33.45</td>
<td>43.93</td>
<td>5.79</td>
</tr>
<tr>
<td>T 2</td>
<td>60.03</td>
<td>19.17</td>
<td>7.89</td>
<td>32.26</td>
<td>41.09</td>
<td>5.41</td>
</tr>
<tr>
<td>T 4</td>
<td>58.25</td>
<td>16.65</td>
<td>7.32</td>
<td>30.61</td>
<td>38.82</td>
<td>4.83</td>
</tr>
<tr>
<td>T 6</td>
<td>55.45</td>
<td>15.14</td>
<td>7.35</td>
<td>28.43</td>
<td>32.84</td>
<td>4.47</td>
</tr>
<tr>
<td>T 8</td>
<td>53.44</td>
<td>13.6</td>
<td>6.93</td>
<td>24.38</td>
<td>27.68</td>
<td>3.87</td>
</tr>
<tr>
<td>P 5</td>
<td>65.14</td>
<td>23.41</td>
<td>8.64</td>
<td>36.95</td>
<td>49.9</td>
<td>6.48</td>
</tr>
<tr>
<td>P 10</td>
<td>69.19</td>
<td>25.65</td>
<td>10.34</td>
<td>39.59</td>
<td>56.02</td>
<td>7.23</td>
</tr>
<tr>
<td>P 15</td>
<td>75.44</td>
<td>27.93</td>
<td>10.7</td>
<td>42.68</td>
<td>63.56</td>
<td>7.93</td>
</tr>
<tr>
<td>P -5</td>
<td>54.78</td>
<td>19.58</td>
<td>6.93</td>
<td>31.12</td>
<td>37.46</td>
<td>5.14</td>
</tr>
<tr>
<td>P -10</td>
<td>49.49</td>
<td>17.71</td>
<td>6.48</td>
<td>28.28</td>
<td>32.48</td>
<td>4.51</td>
</tr>
<tr>
<td>P -15</td>
<td>44.89</td>
<td>15.47</td>
<td>5.91</td>
<td>25.71</td>
<td>28.31</td>
<td>3.81</td>
</tr>
<tr>
<td>P10 T4</td>
<td>68.45</td>
<td>20.34</td>
<td>8.43</td>
<td>35.85</td>
<td>46.95</td>
<td>6.21</td>
</tr>
<tr>
<td>P10 T6</td>
<td>66.19</td>
<td>17.69</td>
<td>8.32</td>
<td>33.85</td>
<td>42.41</td>
<td>5.78</td>
</tr>
<tr>
<td>P10 T4</td>
<td>47.73</td>
<td>14.22</td>
<td>6.11</td>
<td>25.74</td>
<td>29.35</td>
<td>3.44</td>
</tr>
<tr>
<td>P10 T6</td>
<td>44.31</td>
<td>12.91</td>
<td>5.71</td>
<td>23.44</td>
<td>25.32</td>
<td>3.2</td>
</tr>
<tr>
<td>CC 20 L15 T4</td>
<td>59.02</td>
<td>17.06</td>
<td>7.47</td>
<td>31.54</td>
<td>40.09</td>
<td>4.91</td>
</tr>
<tr>
<td>CC 20 L15 P10 T4</td>
<td>69.27</td>
<td>21.06</td>
<td>8.84</td>
<td>36.9</td>
<td>49.94</td>
<td>6.31</td>
</tr>
<tr>
<td>CC 20 L15 P-10 T4</td>
<td>48.36</td>
<td>14.4</td>
<td>6.44</td>
<td>26.71</td>
<td>30.62</td>
<td>3.54</td>
</tr>
<tr>
<td>CC 30 L25 T6</td>
<td>56.7</td>
<td>15.74</td>
<td>7.59</td>
<td>29.67</td>
<td>35.63</td>
<td>4.6</td>
</tr>
</tbody>
</table>

T = air temperature in °F
P = precipitation change in percent
CC = canopy conductance change in percent
L = change in leaf area index (LAI) in percent
Table 5.—Average response of the watersheds to each of the climate change scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>% change in flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 2</td>
<td>-5.66</td>
</tr>
<tr>
<td>T 4</td>
<td>-11.71</td>
</tr>
<tr>
<td>T 6</td>
<td>-20.33</td>
</tr>
<tr>
<td>T 8</td>
<td>-29.28</td>
</tr>
<tr>
<td>P 5</td>
<td>10.42</td>
</tr>
<tr>
<td>P 10</td>
<td>20.64</td>
</tr>
<tr>
<td>P 15</td>
<td>33.10</td>
</tr>
<tr>
<td>P -5</td>
<td>-10.71</td>
</tr>
<tr>
<td>P -10</td>
<td>-20.26</td>
</tr>
<tr>
<td>P -15</td>
<td>-29.13</td>
</tr>
<tr>
<td>P10 T4</td>
<td>5.49</td>
</tr>
<tr>
<td>P10 T6</td>
<td>-2.86</td>
</tr>
<tr>
<td>P -10 T4</td>
<td>-28.54</td>
</tr>
<tr>
<td>P -10 T6</td>
<td>-35.75</td>
</tr>
<tr>
<td>CC-20 L15 T4</td>
<td>-9.42</td>
</tr>
<tr>
<td>CC-20 L15 P10 T4</td>
<td>9.52</td>
</tr>
<tr>
<td>CC-20 L15 P -10 T4</td>
<td>-26.51</td>
</tr>
<tr>
<td>CC-30 L25 T6</td>
<td>-19.92</td>
</tr>
</tbody>
</table>

T 2 = average annual temperature increase of 2 °F.

P 5 = average annual precipitation increase of 5 percent.

P10 T4 = average annual precipitation increase of 10 percent and temperature increase of 4 °F.

CC-20 L15 T4 = average annual maximum stomatal conductance decrease of 20 percent, a leaf area index increase of 15 percent, and a temperature increase of 4 °F.

were taken into consideration in this study. As expected, increases in precipitation result in significant increases in stream flows over the year. Similarly, decreases in precipitation markedly decrease the flows.

Multiple change scenarios. These scenarios are based on changes in two or more of the input parameters. Because real global climate changes involve more than one parameter, these scenarios may be considered to be more realistic than those which involve only a single parameter. Temperature increases coupled with precipitation decreases cause a further decrease in flow, whereas temperature increases, with increases in precipitation result in increases in flows. These results suggest that flows are more sensitive to changes in precipitation than to change in temperature, which supports a conclusion drawn by Sikka (1993).

Leaf area index (LAI) was one of the parameters which was incorporated into this aspect of the study. Rosenberg et al. (1990) suggest that increases in atmospheric CO₂ will lead to increases in LAI. For this reason, in the scenarios posed for this study, only positive increases in LAI were assumed. Increases in LAI cause a decrease in stomatal conductance. The model studies also suggest that increases in LAI, along with corresponding decreases in stomatal conductance and combined with increases in precipitation and temperature, increase the flow. When the same LAI increases are coupled with decreases in precipitation and increases in temperature, flows decrease.

Table 5 summarizes the average response of the six gauged watersheds to different climate change scenarios.

Impacts of the Climate Change Scenarios on Weber River Outflows

The recorded flows for each of the six calibrated watersheds for the period 1951 to 1989 (38 years) were adjusted in accordance with the flow responses of the six watersheds to the various climatic scenarios for the 1989 water year as shown by table 4. The flows, changed by the various percentages calculated from table 4, were then routed through the basin to estimate the effect of the scenarios on the water yields of the basin as a whole. The Weber River Simulation Model of the Utah Division of Water Resources was used for this purpose, since this model accounts for most of the major water demands and storages along the main stem of the Weber River. Water yield from the basin can be viewed from two perspectives: (1) demand shortages and (2) outlet volume to the Great Salt Lake. Demand shortages throughout service areas in the basin are listed in the output as average shortages in supplies over 38 years to various land areas within the service areas designated in figure 19. These shortages are expressed in terms of average present day demands. It may be noted that average present day demands will change as a
result of population density and user requirements. User requirements are, of course, partly influenced by climate, so that climate changes will induce changes in demands. However, an examination of changes in demands from the service areas within the basin is beyond the scope of this study. Thus, the average present day demand is used as a base in this study for examining the effects of assumed climate change scenarios on the water yields from the Weber River Basin.

All the scenarios listed in tables 2, 4, and 5 were run through the Weber River Simulation Model. Observed demand shortages for different service areas of the basin for each scenario are given in tables 6 through 9. The base run, with no climate change scenario imposed, gives small shortages throughout the basin during the 38 year study period. Service area 2 (Oakley to Wanship) and service area 12 (Ogden Valley) showed some shortages (0.2 and 1.2 percent, respectively).

As expected, the climate change scenarios caused the greatest impacts in those service areas of the basin which are not regulated by significant reservoir storage. For example, service area 1 (Weber-Provo Diversion Canal), service area 2 (Oakley to Wanship), and service area 12 (Ogden Valley) are served by only small reservoirs (the Smith and Morehouse reservoir for service areas 1 and 2 and the Causey reservoir for service area 12). On the other hand, service areas 15 through 20 are little affected by any of the scenarios because of the significant volume of water which can be stored in the Willard Bay reservoir.

The effects of the various climate change scenarios on outflows from Weber River Basin to the Great Salt Lake are shown in figures 23, 24, and 25 and in table 10. It is interesting to note that reservoir storage within the basin has a significant impact on these outflows. For example, a temperature increase of 4 °F caused no significant shortages within the service areas (except service area 2, where a shortage of about 16 percent is predicted as shown in table 6), but it produced a reduction in inflow to the Great Salt Lake of 40 percent (figure 23).
Table 6 — The effects of climate change temperature scenarios on water shortages to demand areas within Weber River Basin

<table>
<thead>
<tr>
<th>Demand Area</th>
<th>Base Volume (AF)</th>
<th>Base Percentage</th>
<th>T2 Volume (AF)</th>
<th>T2 Percentage</th>
<th>T4 Volume (AF)</th>
<th>T4 Percentage</th>
<th>T6 Volume (AF)</th>
<th>T6 Percentage</th>
<th>T8 Volume (AF)</th>
<th>T8 Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1</td>
<td>6.0</td>
<td>0.0</td>
<td>245.0</td>
<td>0.3</td>
<td>1511.0</td>
<td>2.2</td>
<td>1898.0</td>
<td>2.7</td>
<td>5963.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Area 2</td>
<td>96.0</td>
<td>0.2</td>
<td>1273.0</td>
<td>3.2</td>
<td>6224.0</td>
<td>15.7</td>
<td>7905.0</td>
<td>20.0</td>
<td>11589.0</td>
<td>29.4</td>
</tr>
<tr>
<td>Area 3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 8</td>
<td>0.0</td>
<td>0.0</td>
<td>88.0</td>
<td>0.8</td>
<td>160.0</td>
<td>1.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 11</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 12</td>
<td>333.0</td>
<td>1.2</td>
<td>424.0</td>
<td>1.5</td>
<td>739.0</td>
<td>2.7</td>
<td>1316.0</td>
<td>5.0</td>
<td>1935.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Area 13</td>
<td>0.0</td>
<td>0.0</td>
<td>22.0</td>
<td>0.2</td>
<td>86.0</td>
<td>0.4</td>
<td>166.0</td>
<td>0.7</td>
<td>180.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Area 14</td>
<td>0.0</td>
<td>0.0</td>
<td>180.0</td>
<td>0.5</td>
<td>499.0</td>
<td>1.2</td>
<td>443.0</td>
<td>1.1</td>
<td>572.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Area 15</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 16</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 17</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 18</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 19</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 20</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

1 Refer to figure 4.
2 AF = acre-feet.
Table 7 — The effects of climate change precipitation scenarios on water shortages to demand areas within Weber River Basin

<table>
<thead>
<tr>
<th>Demand areas</th>
<th>Base</th>
<th>P15</th>
<th>P10</th>
<th>P5</th>
<th>P-5</th>
<th>P-10</th>
<th>P-15</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume (AF)</td>
<td>Percentage</td>
<td>Volume (AF)</td>
<td>Percentage</td>
<td>Volume (AF)</td>
<td>Percentage</td>
<td>Volume (AF)</td>
</tr>
<tr>
<td>Area 1</td>
<td>6.0</td>
<td>0.0</td>
<td>3.0</td>
<td>0.0</td>
<td>2.0</td>
<td>0.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Area 2</td>
<td>96.0</td>
<td>0.2</td>
<td>96.0</td>
<td>0.0</td>
<td>96.0</td>
<td>0.0</td>
<td>96.0</td>
</tr>
<tr>
<td>Area 3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 11</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 12</td>
<td>333.0</td>
<td>1.2</td>
<td>49.0</td>
<td>0.2</td>
<td>131.0</td>
<td>0.5</td>
<td>232.0</td>
</tr>
<tr>
<td>Area 13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 14</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 15</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 16</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 17</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 18</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 19</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 20</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

1 Refer to figure 4.
Table 8.—The effects of climate change dual scenarios on water shortages to demand areas within Weber River Basin.

<table>
<thead>
<tr>
<th>Demand area 1</th>
<th>Base</th>
<th>P10T6</th>
<th>P10T4</th>
<th>P-10T4</th>
<th>P-10T6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume (AF)</td>
<td>Percentage</td>
<td>Volume (AF)</td>
<td>Percentage</td>
<td>Volume (AF)</td>
</tr>
<tr>
<td>Area 1</td>
<td>6.0</td>
<td>0.0</td>
<td>141.0</td>
<td>0.1</td>
<td>75.0</td>
</tr>
<tr>
<td>Area 2</td>
<td>96.0</td>
<td>0.2</td>
<td>940.0</td>
<td>2.3</td>
<td>546.0</td>
</tr>
<tr>
<td>Area 3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 11</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 12</td>
<td>333.0</td>
<td>1.2</td>
<td>684.0</td>
<td>2.5</td>
<td>360.0</td>
</tr>
<tr>
<td>Area 13</td>
<td>0.0</td>
<td>0.0</td>
<td>22.0</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 14</td>
<td>0.0</td>
<td>0.0</td>
<td>43.0</td>
<td>0.1</td>
<td>22.0</td>
</tr>
<tr>
<td>Area 15</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 16</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 17</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 18</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 19</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 20</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

1 Refer to figure 4.
### Table 9 — The effects of climate change multiple parameter scenarios on water shortages to demand areas within Weber River Basin

<table>
<thead>
<tr>
<th>Demand area</th>
<th>Base</th>
<th>C-20</th>
<th>C-20L15T6</th>
<th>C-3</th>
<th>L15T4</th>
<th>L15T6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume (AF)</td>
<td>Percentage</td>
<td>Volume (AF)</td>
<td>Percentage</td>
<td>Volume (AF)</td>
<td>Percentage</td>
</tr>
<tr>
<td>Area 1</td>
<td>6.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1148.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Area 2</td>
<td>96.0</td>
<td>0.2</td>
<td>28.0</td>
<td>0.1</td>
<td>5700.0</td>
<td>14.3</td>
</tr>
<tr>
<td>Area 3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>659.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Area 4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 11</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 12</td>
<td>333.0</td>
<td>1.2</td>
<td>323.0</td>
<td>1.2</td>
<td>1254.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Area 13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>60.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Area 14</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>301.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Area 15</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 16</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 17</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 18</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 19</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Area 20</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

1 Refer to figure 4
Table 10.—The effects of climate change scenarios on spills to the Great Salt Lake

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average spill to Great Salt Lake (AF/year)</th>
<th>Percent change from base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>351983</td>
<td>0</td>
</tr>
<tr>
<td>C-20</td>
<td>372307</td>
<td>5.8</td>
</tr>
<tr>
<td>C-20 L15 T6</td>
<td>237613</td>
<td>-32.5</td>
</tr>
<tr>
<td>C-30</td>
<td>376774</td>
<td>7</td>
</tr>
<tr>
<td>L15 T4</td>
<td>244568</td>
<td>-30.5</td>
</tr>
<tr>
<td>L15 T6</td>
<td>219939</td>
<td>-37.5</td>
</tr>
<tr>
<td>P-10</td>
<td>223150</td>
<td>-36.6</td>
</tr>
<tr>
<td>P-10 T4</td>
<td>136582</td>
<td>-61.2</td>
</tr>
<tr>
<td>P-10 T6</td>
<td>117326</td>
<td>-66.7</td>
</tr>
<tr>
<td>P-15</td>
<td>163610</td>
<td>-53.5</td>
</tr>
<tr>
<td>P-5</td>
<td>286640</td>
<td>-18.6</td>
</tr>
<tr>
<td>P10</td>
<td>519422</td>
<td>47.6</td>
</tr>
<tr>
<td>P10 T4</td>
<td>382525</td>
<td>8.7</td>
</tr>
<tr>
<td>P10 T6</td>
<td>348032</td>
<td>-1.1</td>
</tr>
<tr>
<td>P15</td>
<td>610834</td>
<td>73.5</td>
</tr>
<tr>
<td>P5</td>
<td>435305</td>
<td>23.7</td>
</tr>
<tr>
<td>T2</td>
<td>285917</td>
<td>-18.8</td>
</tr>
<tr>
<td>T4</td>
<td>244678</td>
<td>-30.5</td>
</tr>
<tr>
<td>T6</td>
<td>219890</td>
<td>-37.5</td>
</tr>
<tr>
<td>T8</td>
<td>199564</td>
<td>-43.3</td>
</tr>
</tbody>
</table>

T = air temperature in °F.
P = precipitation change in percent.
CC = canopy conductance change in percent.
L = change in leaf area index (LAI) in percent.
AF = acre-feet
Chapter VI

CONCLUSIONS

The purpose of this study was to develop and demonstrate the practical application of a distributed parameter watershed model for simulating watershed hydrologic responses under existing conditions and those assumed for CO₂-induced climatic and plant physiologic changes, such as LAI and stomatal conductance. The distributed parameter hydrologic model presented in chapter II incorporates a biophysical approach that simulates actual ET, soil moisture, and water yield in natural vegetated watersheds. The results of model application using limited data from the Causey watershed suggest that the model provides a good framework for an integrated approach to modeling the effects of assumed climate and CO₂-induced vegetation changes on hydrology. However, the model needs to be extended to include a linkage with the CO₂ diffusion gradient for explicit simulation of vegetation changes. Application of the model to the Weber River Basin provided a basis for determining the impacts of climate change on the hydrologic response of large river basins. Changes in plant transpiration rates and in vegetative cover under a CO₂-altered climate and the effects of these changes on water yield are investigated by the model in a “what if” mode.

The results suggest significant but less severe impacts of climate change on water yield than previous studies in the western United States have indicated. A decrease in annual runoff of 15 to 20 percent could be possible for cases of warming associated with decreased precipitation. In most cases, projected changes in monthly flows are relatively greater than corresponding changes in annual flows with monthly peak runoff shifting from May to March or April. An increase in winter and early spring runoff may lead to increased flooding in the early half of spring as a result of warming combined with precipitation increases of more than 10 percent.

Interpretation of the results must be tempered by the fact that limited data of one water year was used for model calibration, and the sensitivity analyses results are based on the assumed scenarios, all of which may not be internally consistent. However, the results do indicate how the monthly, seasonal, and annual water supplies in the Weber River Basin could be altered as a result of climate change.
BIBLIOGRAPHY


