Hydrologic Simulation Modeling for Streamflow Forecasting and Evaluation of Land and Water Management Practices in the Sprague River, Upper Klamath Basin, Oregon, USA

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Abstract

The Upper Klamath Basin, Oregon, USA, is an area of major issues and severe conflicts in water management and use, which also has high political visibility. A key need in promoting sustainable agriculture in this area is hydrologic tools and models that can be used for producing streamflow forecasts, predicting the effects of land management and irrigation practices, and obtaining a better understanding of the basin's hydrology. Semi- and fully distributed hydrologic simulation models are being investigated for these purposes in the Sprague River catchment, a major tributary in the basin. These models require considerable spatial data input preparation, both for watershed characteristics and the meteorological forcing data. Model validation is accomplished by comparing simulated with observed snowpack at meteorological stations, comparing simulated snow fields with satellite snow covered area images, and comparing simulated with observed hydrographs at the catchment outlet. The application of these models is challenging due to the complex hydrology and high degree of spatial and temporal climatic variability in the basin, so there are interesting scientific issues to be addressed while at the same time producing tools of practical value.

Introduction

One important element affecting sustainability in agricultural areas is how the water resources are managed. Efficient and effective water management is based on a solid understanding of the hydrology of the area and the ability to predict the availability of water. Mathematical models are the vehicle into which this hydrologic understanding is embedded and from which hydrologic predictions can be made.

In western North America, much of which is arid or semi-arid, agriculture is predominantly based on irrigation. Surface water is the main source for irrigation, and much of this water derives from snowmelt. Predictions of the spring and summer snowmelt streamflow, then, are key to managing the water and to crop choice and planting decisions. In addition, management of on-farm water, particularly regarding the irrigation methods used, and the management of reservoirs affect the efficiency of water use. Other hydrologic and ecosystem issues can also be important considerations, such as the effect of vegetation and land management within the catchment area and riparian zones on water yield, and the instream flows made available for the support of fish populations. On a broader timescale, an understanding of and ability to assess the hydrologic effects of climate teleconnections, climate variability, and climate warming are essential in not only year-to-year water management but also the development of long-range planning and management policies.

The Upper Klamath Basin of southern Oregon in the United States is an irrigated agricultural area in which all of these issues are of concern and in which conflict over water is particularly severe. It is highly visible area politically and has received much publicity. It is therefore an area worthy of special focus from a hydrologic point of view. The U.S. agency responsible for managing the irrigation water resources of the basin, the Bureau of Reclamation, is keenly interested in improving the ability to understand and predict the water yield. This is the primary motivation for the investigation into the application of hydrologic simulation models in the Upper Klamath Basin described in this paper.

Upper Klamath Basin and Sprague River Description

The basin of interest is the drainage area to Upper Klamath Lake (Figure 1). This is the water source for the irrigated areas to the south and is regulated by the Bureau of Reclamation. The two main tributaries are the Williamson River, which drains the northern part of the basin and enters the lake south of the town of Chiloquin; and the Sprague River, which drains the northeastern part of the basin and flows into the Williamson River near the town of Chiloquin. Together, these two rivers represent 79 percent of the Upper Klamath Lake drainage area (7,770 out of a total of 9,869 kilometers^2 [km]) and 59 percent of the average annual streamflow (989.2 out of a total of 1,685.9 million meters^3 [m], base period 1971-2000).

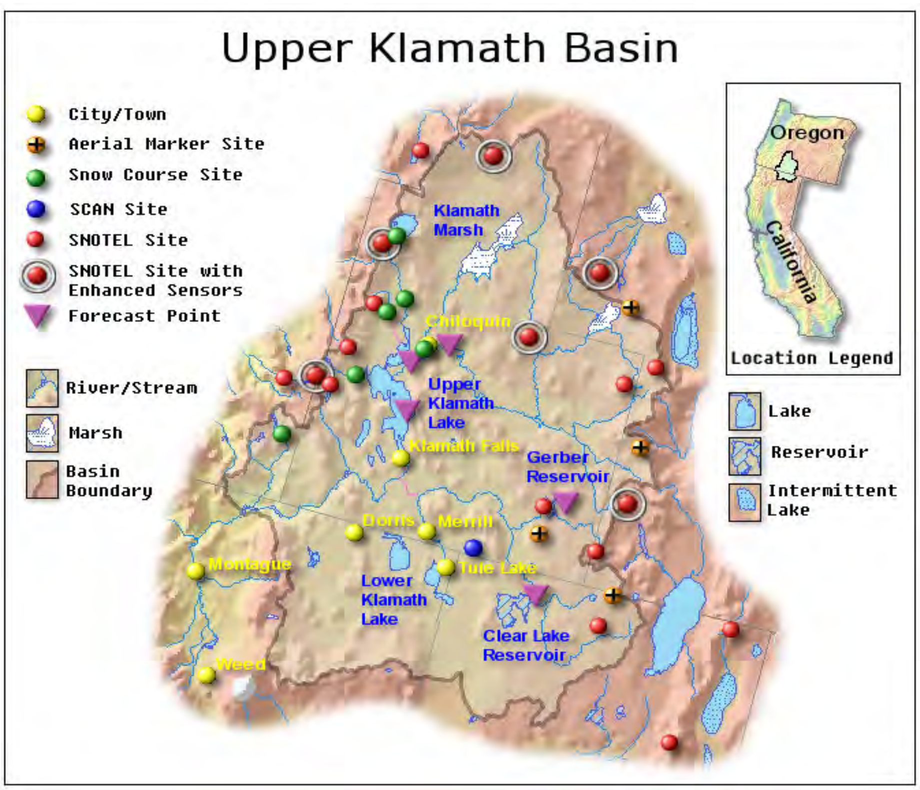

Figure 1. Upper Klamath Basin showing Natural Resources Conservation Service data sites.
Source: http://www.wcc.nrcs.usda.gov/special/klamath.pl

The focus of the hydrologic modeling is the Sprague River, with a drainage area of 4053 km^2 and an average annual streamflow of 567.1 million m^3. Much of the catchment is dry plateau, and mountains form the northern and eastern drainage divide. Elevations range from 1,284 to 2,525 m, with an average elevation of 1,600 m.

Hydrologic Modeling

Goals

There are several goals to be accomplished by the application of hydrologic simulation models in the Sprague River and eventually the entire Upper Klamath Basins:

- In general, obtain a better understanding of the hydrology and water balance of the basin and develop the ability to represent this system in models.
- Apply and develop models with a strong physical basis and a high spatial and temporal resolution so that the hydrologic effects of vegetation and land use changes as well as climate variability and warming can be quantitatively evaluated.
- Evaluate the ability to simulate and forecast snowpack and streamflow using (1) a commonly used semi-spatially distributed conceptual model (Precipitation Runoff Modeling System [PRMS]; Leavesley, et al. 1983); and (2) newer, more physically explicit, fully spatially distributed (i.e., grid-based) models (Distributed Hydrology-Soil-Vegetation Model [DHSVM] and ISNOBAL; Wigmosta, et al. 1994 and Marks, et al. 1999, respectively).

The goals having to do with assessing vegetation and land use changes (specifically, removal of juniper trees that have encroached onto rangelands, restoring riparian areas and wetlands, and switching from flood to sprinkler irrigation) are part of a project under the Conservation Effects Assessment Project (CEAP), which is a major effort by the U.S. Department of Agriculture to assess quantitatively the hydrologic and water quality effects of conservation practices on agricultural land (see links at http://www.nrcs.usda.gov/technical/nri/ceap/index.html). Part of this program consists of intensive modeling and monitoring studies in selected catchments around the country. One of these catchments is the Sprague River.

All of these goals are of interest to the Bureau of Reclamation that has sponsored two major studies currently being led by the author’s two agencies. They are anxious to obtain as much understanding and predictive capability as possible to assist them in managing the water.

Spatially Distributed Modeling

Spatially distributed hydrologic modeling has become more commonplace in the past decade or so. One possibility is what could be called a semi-distributed approach, such as what is done in PRMS, where the basic spatial unit is a Hydrologic Response Unit (HRU); each of which is defined as an area of the catchment that is approximately homogeneous according to some combination of one or more characteristics, such as topography, vegetation, soils, etc. Other models are fully distributed, that is, the basic spatial unit in the model is a grid cell, each of which contains its own unique set of characteristics.

In either case, the idea is to assign model parameters as much as possible from basic spatial layers of elevation, vegetation, and soils and values derived from them. This then helps minimize the number of parameters that must be estimated by calibration. Figure 2 shows the basic spatial data layers and the model parameter layers that can be derived from them.

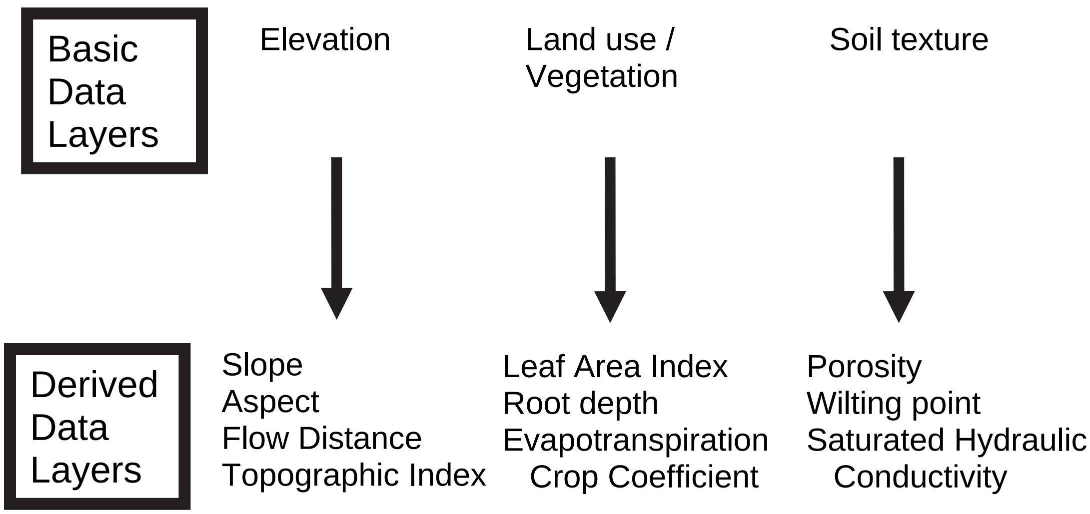

Figure 2. Basic spatial data layers and the model parameter data layers commonly derived from them.

PRMS and DHSVM are both comprehensive hydrologic models containing all of the process components shown in Figure 3, although PRMS has simpler and more conceptual process algorithms than DHSVM. ISNOBAL (Figure 4) is a very detailed energy balance model of snowpack, but it does not contain the land surface components. It has been used successfully in several catchments (Marks, et al., 1999; Garen and Marks, 2005), so it is of interest to test in the Sprague River Basin and see how snowpack simulation compares to that of other two models.

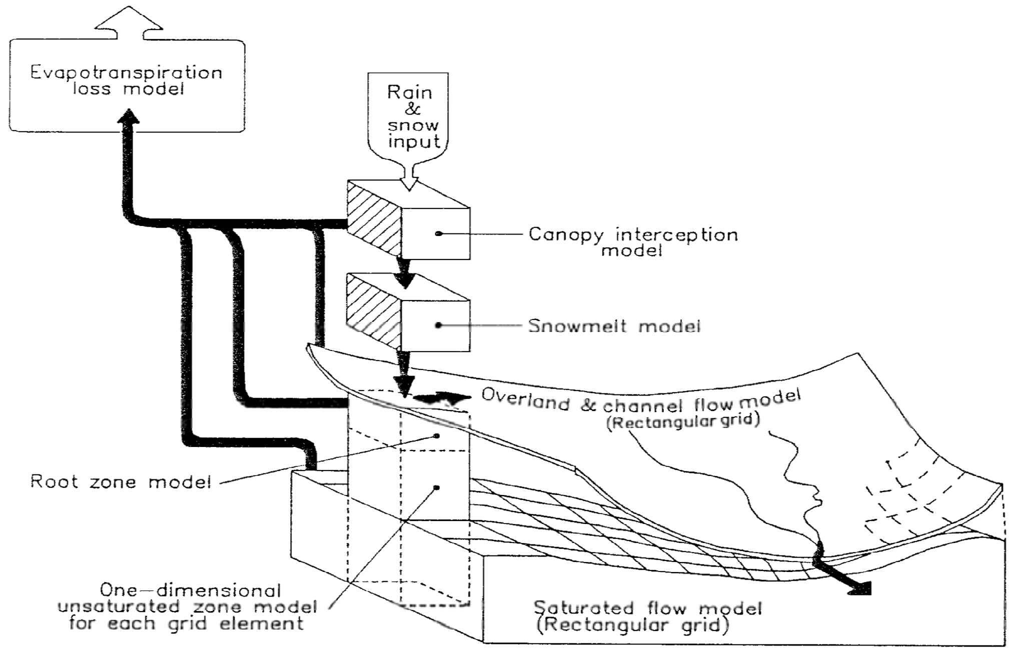

Figure 3. Schematic depiction of hydrologic processes represented in spatially distributed hydrologic modeling, many of the parameters of which are derived from basic and derived spatial data layers.

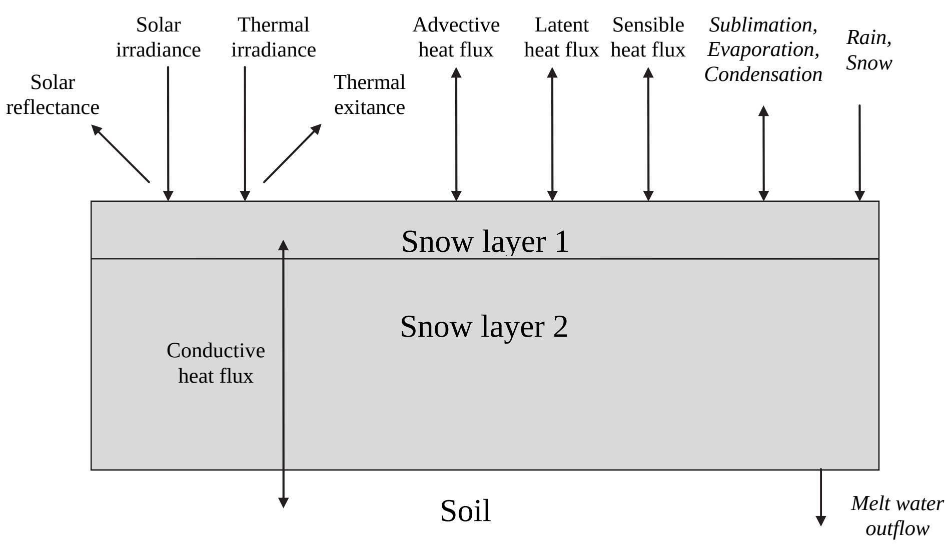

Figure 4. Diagram of ISNOBAL model components (energy fluxes in normal type, water fluxes in italics). Source: Garen and Marks (2005).

Preparation of Spatial Meteorological Forcings

Hydrologic models require meteorological input forcing data. Older, simpler models were built to operate with just precipitation and temperature data as input, but this was in the era when these were the only station data available. Now, more data sites and variables are available, so these can be used to force spatially distributed models that have better physical process descriptions. The basic meteorological variables needed to force a physically based energy balance hydrologic model include:

- Precipitation
- Air temperature
- Solar radiation
- Thermal radiation
- Relative humidity
- Wind speed

These are needed at a daily to hourly time step. To obtain these spatial fields, interpolation of station data is necessary. Various procedures must be used, depending on the characteristics of each variable and the number of stations available (Garen and Marks, 2005). Below, the first three variables on the list above are discussed for illustration purposes.

Precipitation

Detrended kriging has been used successfully to compute spatial fields of daily precipitation in a number of studies (Garen, et al., 1994; Garen and Marks, 2005). This method is also being used in the Sprague Basin to prepare the precipitation forcings for PRMS, DHSVM, and ISNOBAL. The procedure begins with computing an elevation trend for each day, as illustrated in Figure 5.

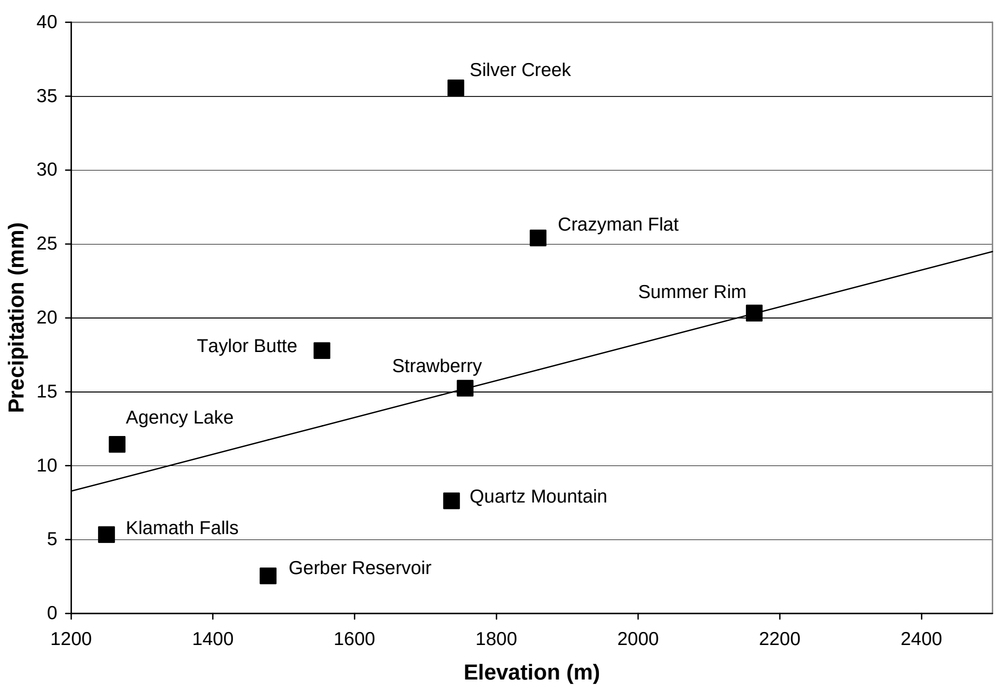

Figure 5. Precipitation in Sprague River catchment for January 1, 2004, showing elevation trend.

The trend is subtracted from each station's data to obtain residuals. These residuals are then used in an ordinary kriging algorithm to obtain an interpolated residual field. Finally, based on the digital elevation model, the elevation trend is added back to each grid cell's kriged residual to obtain the precipitation estimate. The kriging algorithm places high weight on Silver Creek for the grid cells in this vicinity due to their proximity to this station, therefore the estimated residuals for these cells are also positive, making their final precipitation estimates also lie above the elevation trend line and producing this especially wet area in the precipitation field.

For PRMS, this field is spatially aggregated to correspond with the HRUs. For DHSVM and ISNOBAL, this spatial resolution is appropriate (i.e., grid cells), but the field must be temporally disaggregated to 3-hourly amounts, as these models are run at this computational time step (in contrast with PRMS, which is run at a daily time step in this work). Temporal disaggregation is accomplished with a simple fractioning scheme (Garen and Marks, 2005), which is used instead of interpolating the 3-hourly data directly due to excessive noise in the 3-hourly precipitation observations.

Air Temperature

The same detrended kriging procedure used for interpolating precipitation can also be used for air temperature. It can be used with daily data (maximum, minimum, average), as with precipitation, but, unlike precipitation, 3-hourly data can also be interpolated directly because temperature data are much more stable and contain much less noise than precipitation.

Figure 6 shows the 3-hourly average temperature station data and elevation trend for the period 1,200-1,500 on January 1, 2004, (the same day for precipitation shown in Figure 5).

Solar Radiation

Preparing solar radiation inputs for a hydrologic model requires a multi-step process combining the analysis of observations and the use of models. These steps are shown in the flowchart in Figure 7. This represents the processing steps used to prepare spatial net radiation forcings for ISNOBAL as developed by Garen and Marks (2005). The solar radiation and snow albedo models mentioned in Figure 7 are contained in the Image Processing Workbench (IPW) software package (http://cirque.nwrc.ars.usda.gov/~ipw). Note that this process is run at a 20-minute time step, but these fields are temporally averaged to obtain 3-hourly fields for model input. Solar radiation observations are used to compute the cloud cover correction factor in the third box of the flowchart by comparing observed values to modeled theoretical clear sky values. There are four stations in the Sprague River Basin that have solar radiation data beginning approximately in 2002. Of course, there are times of instrument outages and other data quality problems, which have to be dealt with when processing these data.

Model Verification

Several methods must be used to verify a hydrologic model, as no single test is adequate. Some examples of how spatial hydrologic models can be verified are shown below. Since simulations have not yet been done in the Sprague River Basin, examples will be given for the Boise River Basin in Idaho in the United States from Garen and Marks (2005).

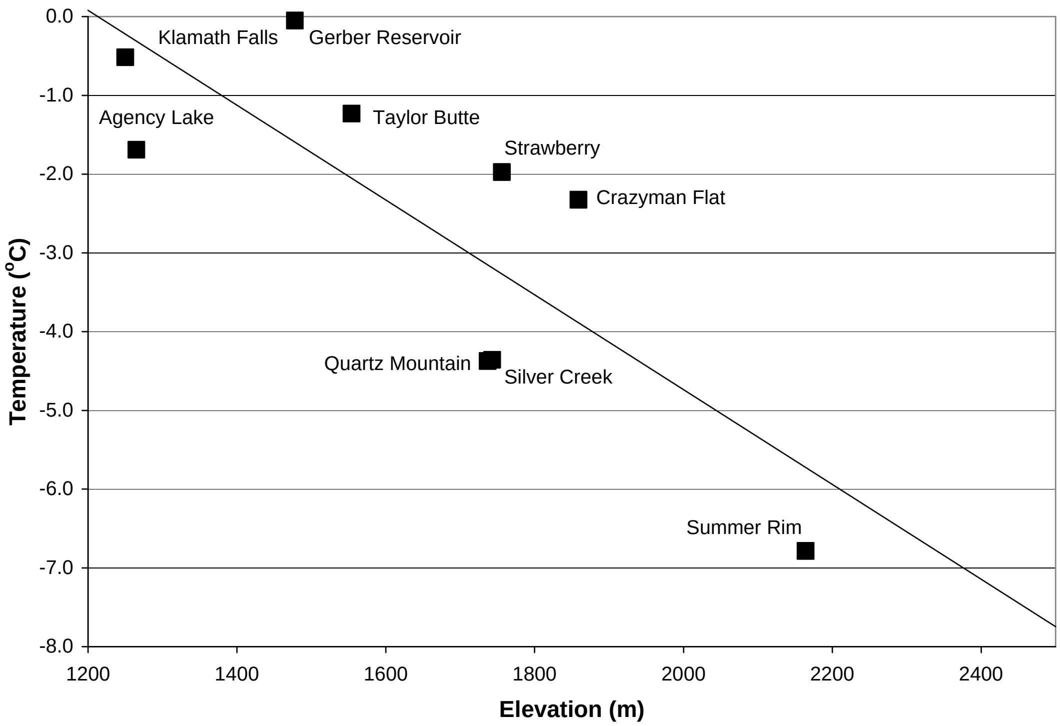

Figure 6. Air temperature in Sprague River catchment for January 1, 2004, 1,200-1,500, showing elevation trend.

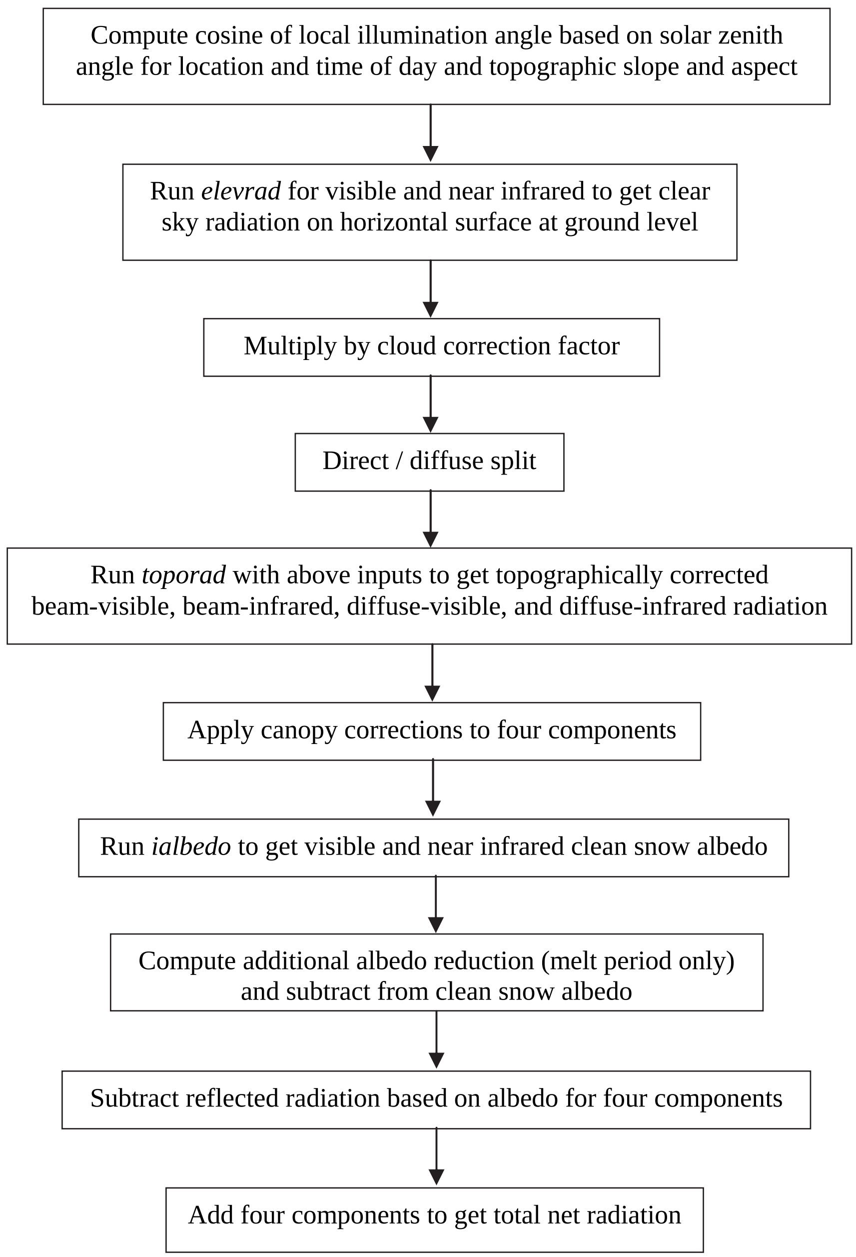

Figure 7. Flowchart of net radiation calculations for each 20-minute time step when the sun is up for each grid cell within the catchment (IPW utility names in italics). Source: Garen and Marks (2005).

Snow Model Verification at Meteorological Stations

Snow water equivalent and snow depth observations at meteorological stations can be used to provide first-level model verification. Examples of this from the Boise River Basin, as given by Garen and Marks (2005), are shown in Figures 8 and 9. While these results are quite satisfactory, it must be remembered that there is a mismatch of spatial scale in this comparison. The basic spatial unit of the model is a grid cell (a 250-m square in this case), whereas these values are being compared to point measurements. One must expect some discrepancies, particularly if physical characteristics at the meteorological station are not representative of the grid cell as a whole. Nevertheless, these comparisons are useful in assessing model simulations.

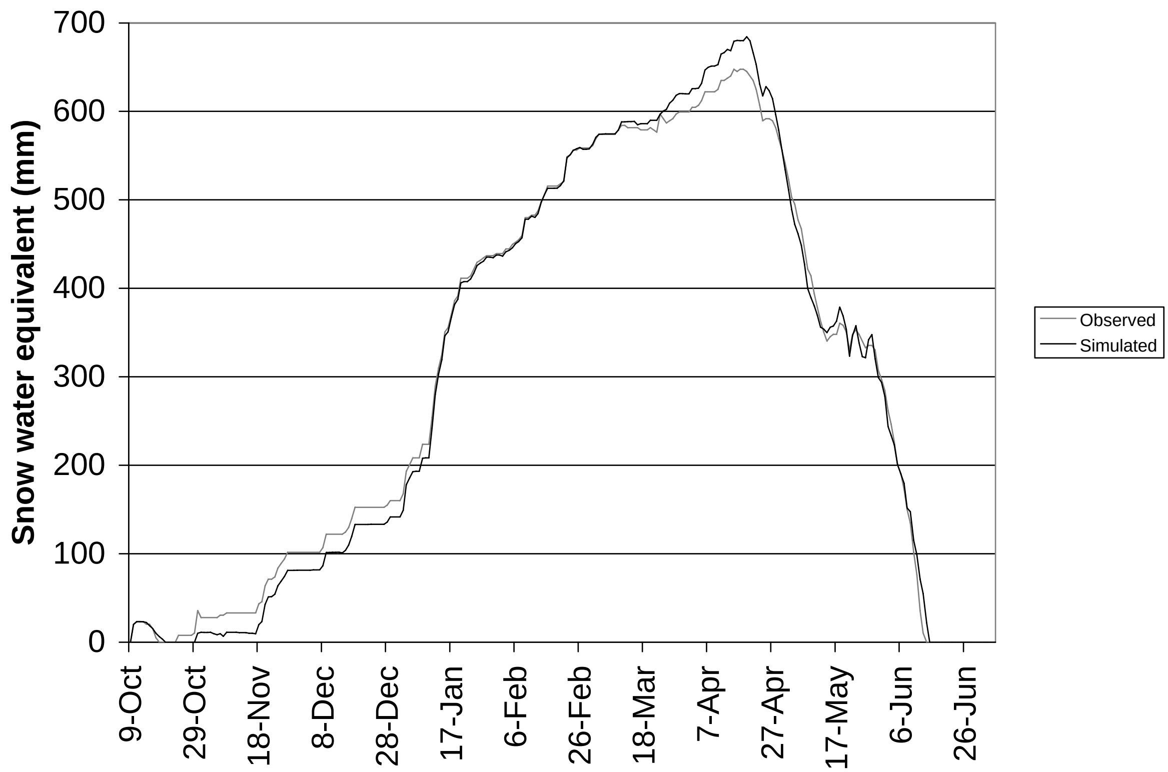

Figure 8. Observed, simulated (with ISNOBAL) snow water equivalent for water year 1998 at Jackson Peak SNOTEL site (elevation 2,155 m), Boise River Basin, Idaho. Source: Garen and Marks, 2005.

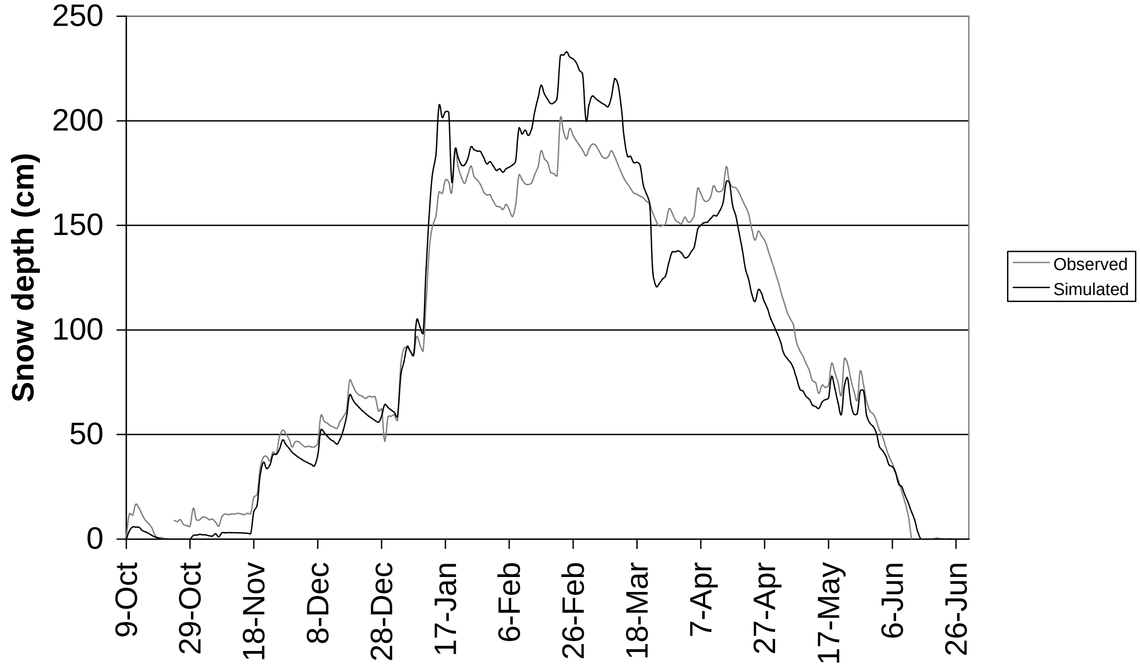

Figure 9. Observed, simulated (with ISNOBAL) snow depth for water year 1998 at Jackson Peak SNOTEL site (elevation 2,155 m), Boise River Basin, Idaho. Source: Garen and Marks, 2005.

Areal Verification of Snow Model

Remotely sensed snow cover images can be used to verify the areal extent of simulated snowpack. The limitations of this verification method are that clouds can obscure the image, and the satellite cannot "see" snow beneath a forest canopy. Some of these problems are being addressed with continued research in remote sensing as well as with new spatial products that are composites of remotely sensed images and model simulations (e.g., products available at http://www.nohrsc.noaa.gov).

Verification of Hydrologic Model

The standard way to verify a hydrologic model is to compare observed and simulated streamflow at the catchment outlet. This verifies the overall, integrated catchment behavior and is the most important quantity with respect to managing surface water resources. It does not, however, verify spatial distributions of hydrologic quantities, such as streamflow from tributaries, soil moisture, runoff source areas, etc. Nevertheless, the integrated basin response is one test that must be met in verifying a hydrologic model.

Figure 10 is an example of observed and simulated streamflow for the Boise River basin for 1998, as given by Garen and Marks (2005). This verification was done primarily as a way to determine if the snowmelt input to the catchment was reasonable. Since the simulated flow followed the rises and recessions of the observed hydrograph quite closely, this gave confirmation to the snowmelt simulation as well as the hydrologic model in general.

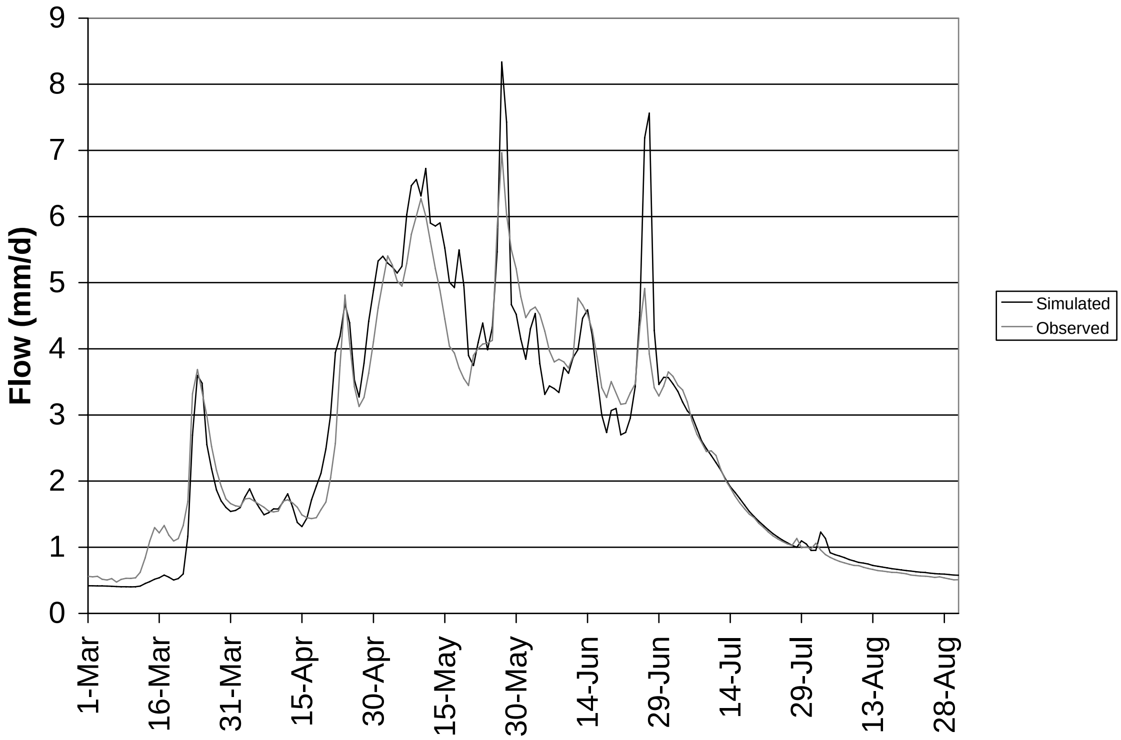

Figure 10. Observed, simulated streamflow for Boise River near Twin Springs, Idaho, 1998. Source: Garen and Marks, 2005.

Ensemble Streamflow Prediction

An initial set-up and calibration of PRMS has been done for the Sprague Basin (Risley and Hay, 2006). Since this model is well-established and is embedded within a supporting software environment, the facilities exist to use the model right away in an operational forecasting mode, once the database and data quality infrastructure that supplies the necessary input data is in place (which is a major effort in itself).

The primary method for using simulation models for streamflow forecasting is the so-called Ensemble Streamflow Prediction (ESP) method. This involves running the model with observed meteorological forcings up to the current day then running multiple scenarios into the future, each scenario using the meteorological forcings from a different year in the historical record. These multiple scenarios can then be used individually as input to a water resources system operation model, or they can be analyzed statistically to obtain distributions of relevant hydrologic quantities, such as seasonal volumes, peak flows, dates to recession below criterion flows, etc.

Conclusion

Because of the competing water uses, conflicts, and high political visibility of the Upper Klamath Basin, there is much interest in how hydrologic modeling and streamflow forecasting can play a significant role in helping to understand, predict, and manage the water resources. Complex geology and hydrology coupled with high spatial and temporal variability of climate, however, make for a challenging environment in which to apply models.

By applying hydrologic simulation models in the Upper Klamath Basin, it is hoped that this will provide new tools for improving streamflow forecasts over what is possible with the current generation of statistical models as well as help with other land and water management questions. They also may be of help in setting policies regarding fish flow requirements and in assessing the effects of climate warming. These modeling efforts are therefore significant both for the scientific issues involved as well as for the practical relevance of the results.

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