THE YAKIMA RIVER BASIN WATERSHED AND RIVER SYSTEM MANAGEMENT PROGRAM

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INTRODUCTION

The Watershed and River System Management Program (WARSMP) is a cooperative program between Department of the Interior agencies. The WARSMP is sponsored by the Water Resources Division of the U. S. Geological Survey (USGS) and the Science and Technology Research Program of the U.S. Bureau of Reclamation (USBR). The purpose of WARSMP is to develop, test, and implement a framework for the management of water resources in the Reclamation Act States (see Frevert and Lins, this volume). The framework is a fully-integrated data-centered decision-support system (DSS) of physical process models--Modular Modeling System (MMS; Leavesley and others, 1996), resource-management models--RiverWare (Fulp and others 1995), forecast models, data-management interfaces (DMIs) and graphical user interfaces (GUIs). The MMS and RiverWare are linked through a data management system--Hydrologic Database (HDB; Fulp and others, 1995, Leavesley and others, 1997), as are a point and click GIS tool-box (Leavesley and others, 1997), queries and displays, and real-time data and processing.

Beginning in fiscal year 1997, the collaborative work of the program focused on the Yakima River Basin. The Yakima River Basin is representative of water-use and water-resource management in the West, and management of its waters is one of the most difficult tasks the USBR undertakes in the western United States. Program elements are being accomplished jointly by the USGS and USBR.

STUDY AREA AND BACKGROUND

The Yakima River Basin is situated in eastern Washington (fig. 1), has a drainage area of about 6,200 square miles, and produces a mean annual regulated-runoff of 3,600 cubic feet per second. The basin's headwaters are on the east slope of the Cascade Range where annual precipitation is more than 90 inches, and the basin terminates where the river discharges to the Columbia River in the lower, arid part of the basin, which receives about 6 inches of precipitation annually. Most of the precipitation falls during the winter season as snow. The mean annual precipitation in the basin is about 27 inches (approximately 12,000 cubic feet per second) of which more than 80 percent falls in the upper part of the basin that encompasses about 3,660 square miles. Altitudes in the basin range from nearly 8,000 feet in the headwaters to about 400 feet near the mouth of the Yakima River. Although the highest altitudes in the basin are between 7,729 and 7,899 feet, most of the headwater regions lie between 4,000 and 6,000 feet. In the upper parts of the basin, the river has a medium to high slope as it passes through forested lands and deeply incised canyons. In the lower parts of the basin, the river follows a meandering course through hilly and flat agricultural lands to its mouth after traveling nearly 300 miles. Major tributaries to the Yakima River include the Cle Elum, Kachess, Teanaway, Bumping, American, Tieton, and Naches Rivers; there are also numerous small tributaries.

The average annual demand in the basin is about 2,500,000 acre-feet. This amounts to about 3,450 cubic feet per second or about 65 percent of the mean annual unregulated flow in the basin and nearly all of the mean annual regulated flow. Most of the demand is for irrigation of about 500,000 acres, mainly in low-lying semi-arid to arid parts of the basin. The demand is partly met by five major storage reservoirs in the headwaters that are capable of storing 1,065,400 acre-feet or about 28 percent of the mean annual natural flow of the river.

The basin has more than 80 canals, 5 diversion dams, 15 major return flows, and numerous smaller return flows. The major canals divert up to an annual rate of about 400 cubic feet per second, but the majority of the canals divert at an annual rate of 5 to 10 cubic feet per second. Nearly 45 percent of the water diverted for irrigation is eventually returned, at varying time-lags, as both surface and ground-water, to the river system. During the low-flow period, the return-flows account for about 70 to 80 percent of the water in the lower river stem.

WATER ISSUES

Water issues of many western basins are common to the Yakima River Basin. Included are Indian treaty rights, historical water rights, over-appropriation of water, reservoir and irrigation development, increasing population with a concomitant increasing municipal-industrial water use, increasing demand for wildlife and anadromous and resident fish, water quality of the surface and ground waters, and the interaction of ground water and surface water because all new demands are being met by ground-water. In addition, three other issues are of importance. First, with more than 1 million recreational trips per year to the basin, recreational use of water is becoming increasingly important, both with respect to basin-wide economics and competition for limited resources.

The second issue is how judicial law affects water management in the basin. For example, the 1945 Consent Decree established procedures or 'rules' for the operation of the Yakima Project by the USBR and for the allocation of water to junior or 'proratable' rights; senior or 'non-proratable' rights are not reduced in years of water shortages unless the shortages are such that the senior rights can not be met. Judicial law will continue to affect water management because of the current, basin-wide adjudication of water rights and the Congressionally mandated Yakima River Basin Water Enhancement Project (YRBWEP). Currently, the second phase of the YRBWEP includes an analysis for determining biologically-based flows for fisheries, mainly anadromous salmon and steelhead, the latter of which is proposed for listing under the Endangered Species Act.

The last issue is the intrabasin variability in topography and climate that results in spatial and temporal variations in the quantity and quality of streamflow. The humid, headwater parts of the basin produce the streamflow and the semi-arid to arid, lowland parts of the basin produce the need for much of the water use. Thus, there are long distances between reservoirs and demands with travel times from reservoirs to lower-basin demands and flow target points being on the order of 12 to 48 hours. This issue is further compounded by short-term variations in both inflows and demands.

Most of the above issues can be addressed by improving: a) the management of water for the beneficial use of the resource by agriculture, recreation, wildlife, and water supply; b) flows for enhancing the quality of the resource; and c) the efficiency of the system-wide operations. To provide a means for making these improvements is the essential part of this project. Long-term goals to address these means were identified during the planning stages of the project.

LONG-TERMS GOALS AND SCIENTIFIC ISSUES

The following long-terms goals of the project have been identified: 1) development of alternative runoff-volume forecasts; 2) development of runoff and streamflow forecasting for short-term operations and decision making; 3) enhancement of the operation simulation capability including long-term basin-wide planning models; 4) new capability to estimate quality parameters from operational actions--some quantity demands are affected by quality standards; 5) new capability to estimate water-budget components such as evapotranspiration to assist in irrigation management for quantity and quality for assessment of Total Maximum Daily Loads and Best Management Practices; 6) development of the system-wide relational HDB that is linked to MMS and RiverWare, contains historical and real-time data, GIS data layers, and operational rules, and is easily queried, updated, and linked to a graphical-statistical interfaces; and 7) overall improvement and development of analytical tools. By meeting some or all of these goals the 3 major improvements should be able to be accomplished.

There also are various scientific issues that need to be addressed. These issues include better methods for estimating forest-evapotranspiration, and snow accumulation and ablation. A pressing issue is the integration of ground-water and surface-water models within the decision support system because of the over-appropriation of water within the basin and the need for new supplies. Modeling physical processes in ungaged watersheds is important for providing estimates of inflows to the river system; these inflows provide the initial water for irrigation during the reservoir refill season. Incorporation and analysis of habitat and biologically-based flow requirements is another scientific issue. The need to understand the affects of water-conservation measures on water quality and quantity in both space and time will be addressed by scaling up the results from the field-plot studies of best management practices to a basin-wide scale through the use of modeling. New methods for seasonal forecasting of runoff at different lead-times are also being explored.

TASKS, METHODS, AND PROGESS

The following sections briefly describe the major tasks to be completed. The tasks fall into 5 general categories: 1) data and the HDB; 2) GIS and the GIS Weasel; 3) physical process modeling in the MMS; 4) river and reservoir management modeling in the RiverWare system; and 5) forecasting of streamflow. The tasks are described by identifying the goals, methods, and progress as of fiscal year 1997. Note that some of the planned work (goals) described may be limited by the overall scope of the program in the future.

Data and the HDB: The data being assembled fall into several categories: 1) daily streamflow, diversions, return flows, and reservoir stages, 2) climatological (daily precipitation, air-temperature, and snowpack, mean-monthly spatial distribution of precipitation, and snow-course data), 3) GIS layers, 4) real-time (HYDROMET, National Weather Service, NEXRAD, SNOTEL, and the agricultural community's AGRIMET), 5) daily and monthly estimates of unregulated streamflow at selected sites, 6) river channel characteristics, 7) historical water-quality, 8) historical fisheries (such as adult return counts for selected species), 9) habitat (such as benthic communities and woody debris), and 10) ground-water (shallow water-levels and pumpage). The first part of the project has focused on identifying, assembling, and assuring the quality (including potential error ranges) of some of these data.

A goal is to establish a consistent and long-term data-base to reside in the HDB, and be available for management of the system. Thus, not only will the complete historical data be assembled, but one consistent period of record, 1956-96, was identified for analysis and storage. For that period, most pertinent data series are being compiled with the missing values estimated and the records extended when necessary. For example, 37 weather sites have been identified and their records filled in for missing data and extended in time when needed. In addition, methods will be established to update the information in a timely manner. For example, the precipitation and air-temperature at National Weather Service (NWS) observer sites (part of the Hydroclimatology Network) will be updated regularly by an established method. Methods to both capture and update the USBR's HYRDOMET data in the HDB have already been developed as part of WARSMP.

The method planned for implementation of the HDB is two-fold. The complete HDB will reside in the USBR's Yakima Project Office, and a subset of the HDB will reside in the USGS's Washington office. The USGS HDB will be used to assure that MMS input and output is correctly being transferred to and from the HDB. In addition, parts of the HDB will be updated in the USGS office. These parts will mimic both the real-time capability of the HDB and the use of that data to drive the physical models in MMS. Thus, real-time linkages to HYDROMET, SNOTEL, NEXRAD, and other systems will not need to be implemented in the USGS office during this stage of the study, allowing for additional time to be focused on the scientific issues.

Last, as part of the data-assimilation stage, selected data were identified that needed to be collected. For example, one data item that is lacking is incoming solar radiation. This data item would provide valuable information for driving watershed and other physical-biological models. Thus, if new data collection is initiated, the data would be linked to the real-time network and to the HDB.

GIS and the GIS Weasel: The GIS and its associated data layers are an important component of the project, and allow for routine assessment of the landscape and water resources on a timely basis. The long-term goal is to provide a consistent GIS data-base of important spatial data for the Yakima River Basin for potential users. As part of the process, basin-wide data layers are continually being acquired and developed for the basin in a consistent manner. The tool being used to analyze much of the data is the GIS Weasel (Leavesley and others, 1997). The GIS Weasel is a point and click basin-analysis tool being developed by the USGS as part of the WARSMP project, and is an integral part of the data-centered approach.

__Physical Process Modeling Using the MMS__: This task includes several items. The first was to subdivide or delineate the Yakima River Basin into subbasins. Each of these subbasins generally represents a stream drainage or a part of a drainage. In turn, each subbasin then was characterized or further divided for application of a watershed model. This characterization and allied information will be incorporated in the MMS and within a watershed model. Last, the model will be constructed and used.

__Subbasins__: The subbasins that will be modeled using MMS or delineated and characterized for future work were defined using the GIS Weasel. Data layers used to delineate basins included gaging station locations, important river management locations, and landscape characteristics. The most important factor was that the subbasins correspond to the system-wide sites identified by the USBR for operational considerations and for use by RiverWare. A total of 59 subbasins were delineated (fig. 2), 4 of which represent the low-lying agricultural subbasins. The subbasins will be the basic modeling units for the study and for future operational use.

The delineation of the subbasins was completed at a scale compatible with the GIS data layers, data storage and handling ability, and preservation of the overall landscape characteristics of the basin. Delineations by the GIS Weasel were compared to several subbasins delineated by hand-drawn boundaries on different scale maps. The subbasins included a smaller, high-altitude basin that corresponds to a reservoir outflow point, and a larger basin with both high and low altitudes. Comparison of landscape characteristics, such as slope and location of stream networks was also done at several scales. Based on these comparisons, a 60 meter grid was selected to store and analyze the data layers in GIS, and to perform the subbasin delineation.

Modeling Response Units: Fifty-six of the subbasins (all the non-agricultural subbasins and the smallest agricultural subbasin) have been further divided (characterized) into modeling response units (MRUs) using the GIS Weasel. A MRU is considered to be a unit of landscape that has relatively consistent physical and climatological characteristics such that the hydrologic response to climate forcing is somewhat unique or homogenous. The initial MRU characterization is implicitly based on aspect because it was made by dividing a subbasin into 2-flow planes. That is, the GIS Weasel was used to define the flow planes (contributing areas) to the left and right banks of the stream network. These initial MRUs were then subdivided using altitude and mean annual precipitation. A final characterization was completed using soil characteristics. Land-cover and slope have generally been accounted for because of their strong relation to mean annual precipitation in most of the non-agricultural areas. All MRU delineation was done consistently so that MRUs in each subbasin could be interrelated. This is important for the physical modeling of ungaged watersheds so that model parameters can be transferred from calibrated models of gaged watersheds.

About 1,000 MRUs have been delineated for the 56 subbasins. However, watershed modeling does not lend itself to the 3 large low-lying agricultural subbasins, with minimal to no runoff. Thus, these major agricultural basins were only characterized by one MRU. In these areas the integration or linkage of ground-water, surface water, and land-surface-process models needs to be developed for addressing some of the major problems in the basin.

MMS Application and Module Selection: The initial physical modeling is focusing on part of upper Yakima River Basin (855 square miles) and most of the Naches River Basin (940 square miles). These 2 areas are above most diversions, account for about 90 percent of the runoff in the basin, and contain all of the reservoirs. They will be modeled with two separate models. The long-term goal is to extend the watershed models to all but the four low-lying agricultural subbasins.

The physical processes to be modeled are represented by modules in MMS. For this study, most of the modules are contained in the USGS Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983). Additionally, several processes that are known to be important may need more appropriate algorithms. For example, two of the subbasins contain enough glacier area in the headwaters to affect summer streamflow, but MMS does not contain a module to account for glacier hydrology.

Model Construction and Use: Prior to parameter estimation, the periods of record for calibration and verification of the subbasin models will be selected from the 1956-96 period of record. Sensitivity of the model parameters will then be determined and analyzed for potential future work. The sensitivity of a particular parameter may indicate the need for additional data-collection activities or module development in MMS. An error analysis will be completed in conjunction with the sensitivity analysis. The error analysis will focus on how errors propagate through the modeling system and how they may affect operational considerations using RiverWare.

The daily-model output will be linked to HDB for later input to RiverWare. The model output will be available at several levels. For daily operation, the model will calculate estimates of the next days' runoff for the major river-management points. These values will be input to RiverWare for helping to guide operations. Daily values of streamflow will also be calculated using 5-day forecasts of climate. These 5-day streamflow values should allow for improved operations on a weekly basis. Next, extended streamflow predictions will be made at selected times prior to and during the runoff season for input to RiverWare.

River and Reservoir Management Modeling Using the RiverWare System: RiverWare is currently being developed for simulation on a daily time-scale for both short-term and mid-term operations. The development is currently focusing on the same areas as the two watershed models, and will include similar river points, reservoir outflow locations, and ungaged watershed outflow locations. As part of relating between HDB and RiverWare, data management interfaces will be written into the system. Associated information for operational purposes in the RiverWare models includes such aspects as reservoir characteristics, diversions and associated return flow requirements, instream flows, flood rule-curves, stream routing, and basin water-rights information. This information will provide for improved daily short-term operations.

The need for mid-term operations will be met in several ways throughout each irrigation season. The extended and long-lead forecasts will be used by RiverWare to develop potential operational-strategies that will be available to USBR analysts for decision making. As a step in development of the long-term policy and planning model, a RiverWare model will be developed at a monthly time-step. The monthly model will complement the daily mid-term model. It is planned that the mid-term monthly model will use the same forecasts as the daily model but aggregated to monthly or weekly time-steps.

For long-term policy and planning, a monthly RiverWare model will use the historical data in HDB to calculate various scenarios. These will be readily available for decision making by analysts. The ability to have feedback between RiverWare and HDB should allow for a full range of long-term scenarios to be integrated into a planning process. Additionally, the need is recognized for a long-term planning model to have a resolution of a daily time-step, with reporting aggregated to weekly or monthly time-steps as is needed for mid-term operations. Daily estimated unregulated reservoir inflows and basin reach gains are currently being developed for this purpose.

The major new development in RiverWare to be completed under the aegis of the Yakima River Basin WARSMP is the writing of software code to account for prior appropriation doctrine. This development will not only allow for increased operational flexibility in the basin but also will enhance the transferability and usability of the RiverWare System to other basins throughout the United States.

Forecasting of Streamflow: There are four categories of forecasts that will be attempted during this study, these are 1) long-lead, 2) short-lead, 3) near real-time, and 4) extended forecasts. Long-lead forecasts are forecasts of monthly flows or seasonal (April-August) inflows made about 12 to 4 months prior to April 1. Two methods are being analyzed for long-lead forecasts. In the first, non-linear spline regressions are being developed by Lall (U. Lall, Utah State university, oral commun., 1997). This method uses both the historical monthly discharge time-series and atmospheric and sea-surface temperature data to forecast monthly time-series of streamflow. Initial results using this method are promising. In the second method, multiple-linear regression equations that use monthly climate-related indices to calculate the seasonal inflows are being developed by the USGS. It is planned to have both methods available to complement each other.

Short-lead forecasts are those for the seasonal inflows that are made March 1 and April 1 using April 1 snowpack, and antecedent weather and reservoir inflow information. The current short-lead forecast equation used by the USBR will be examined for possible improvement by including such factors as monthly climate-related indices. In addition, the

NWS April 1 forecast equation will also be examined. Together, the long- and short-lead forecasts should provide a reasonable analysis tool for system operations for the irrigation season, and they also will meet several of USBR's defined needs.

Near real-time forecasts use the real-time data that the USBR has linked to the HDB and that the USGS has used to construct the physical-hydrology models. These data are used to operate the models for short-term forecasts on a daily mode. These forecasts are linked to RiverWare through the HDB. This category of forecasts will also incorporate the NWS 5-day forecasts.

Last, the MMS has a modified version of the NWS's Extended Streamflow Prediction Program as a module. This module provides forecasting capabilities using historic or synthesized meteorological data. Thus, alternative time-series of inflows could be developed. These time series would have probabilities associated with them. In addition, based on the results of the long- and short-lead forecasts, the number of years of meteorological data used to drive the module will be constrained to be some subset of the historical record that has a higher probability of occurrence. That is, given both the forecasts and the climate-state during the winter, particular years of the historical record are more likely than other years to be representative of what will occur over the runoff season.

Additionally, under development is the use of NEXRAD information to make quantitative precipitation-forecasts and linkage of them to the HDB. When this technique is fully developed, these forecasts could be used to make improved short-term forecasts of inflows.

SUMMARY

The 6,200 square mile Yakima River Basin in eastern Washington is being studied under the collaborative work of WARSMP. Water-use and water-resource management in the Yakima River Basin is representative of that in the West. In keeping with WARSMP goals, the DSS is being applied to the basin and new tools are being developed to assess additional management and scientific issues. These issues include water rights-prior appropriation law, ground water and surface water interaction, and forecasting of streamflow.

Tools developed previously in WARSMP are being used regularly and have greatly expanded the ability to apply the DSS in a reasonable time-frame. These tools and new tools will be used in the remainder of the study to develop a comprehensive DSS that includes all of the major components: the MMS, HDB, and RiverWare. Increased efficiency in systems operations obtained from the DSS will be to the benefit of water use in the basin, and will allow for improved long-term resource planning.

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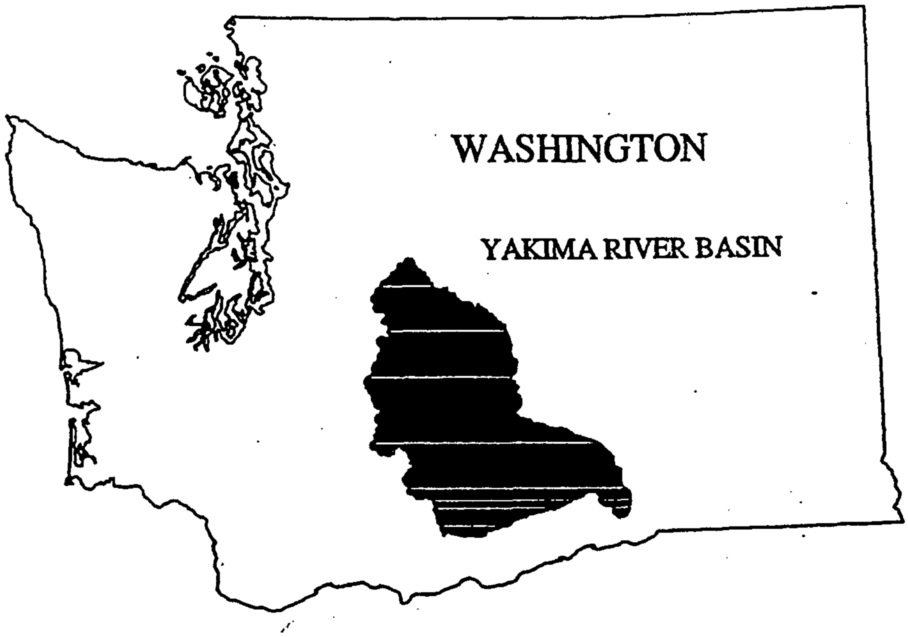

Figure 1. — Location of Study Area

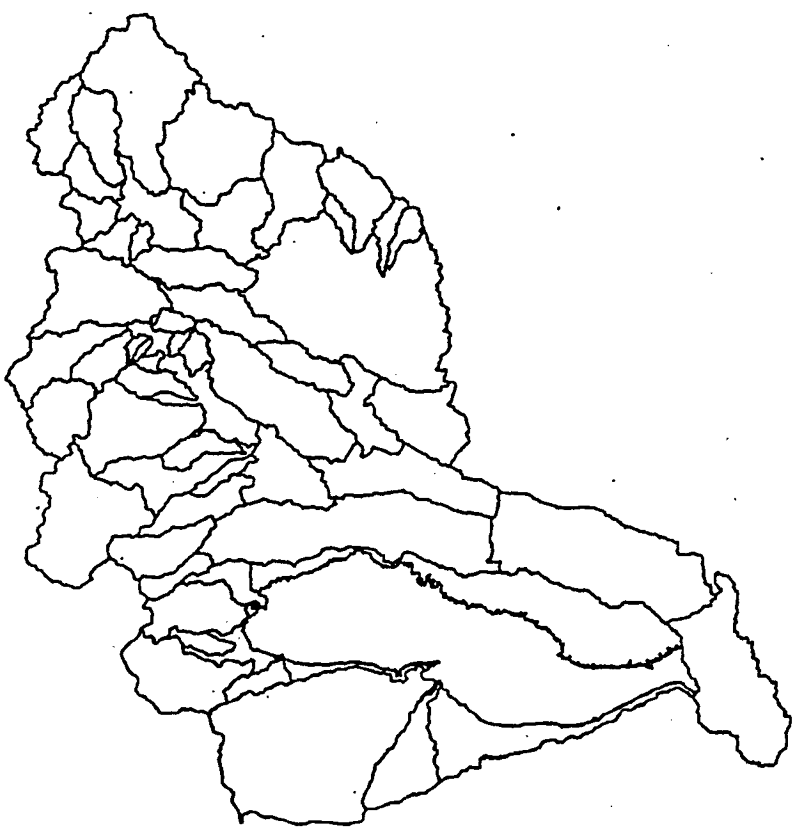

Figure 2. — Location of the 59 delineated subbasins