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REGULATED RIVER MODELING FOR CLIMATE CHANGE IMPACT ASSESSMENT: THE MISSOURI RIVER[1]

Rollin H. Hotchkiss, Steven F. Jorgensen, Mark C. Stone, and Thomas A. Fontaine[2]

ABSTRACT: The Great Plains of the United States, drained primarily by the Missouri River, are very sensitive to shifts in climate. The six main stem dams on the Missouri River control more than one-half of the nearly 1.5 million square kilometer basin and can store three times the annual inflow from upstream. The dams are operated by the U.S. Army Corps of Engineers using a Master Manual that describes system priorities and benefits. The complex operational rules were incorporated into the Soil and Water Assessment Tool computer model (SWAT). SWAT is a distributed parameter rainfall-runoff model capable of simulating the transpiration suppression effects of CO_2 enrichment. The new reservoir algorithms were calibrated using a 25-year long historic record of basin climate and discharge records. Results demonstrate that it is possible to incorporate the operation of a highly regulated river system into a complex rainfall-runoff model. The algorithms were then tested using extreme climate scenarios indicative of a prolonged drought, a short drought, and a ten percent increase in basin-wide precipitation. It is apparent that the rules for operating the reservoirs will likely require modification if, for example, upper-basin precipitation were to increase only ten percent under changed climate conditions.

(KEY TERMS: meteorology/climatology; modeling/statistics; simulation; surface water hydrology; reservoirs; Missouri River.)

INTRODUCTION

Elevated atmospheric CO_2 will impact the spatial and temporal availability of water on and beneath the earth's surface. Changes in water availability in the Great Plains will be particularly critical because water availability is limited and taxed by both natural ecosystems and managed production. The climatic and economic impacts of climate change will influence the strategies chosen to mitigate adverse effects. For example, the vast Sand Hills region of Nebraska is relatively non-erosive only because of a thin veneer of grasses that depends upon natural rainfall for its maintenance. Managed systems such as agricultural and power production are also dependent upon water for successful production.

The largest drainage area in the Great Plains is the Missouri River basin. The Missouri River basin is at risk in reference to water resources and climate change because (1) annual demand for water is large relative to annual supply, (2) more than 25 percent of total energy production is from hydropower, and (3) the basin ground water supply is susceptible to overdraft (Gleick, 1990). Therefore, it is essential that the consequences of climate change on regional water resources be well understood in terms of physical processes, economic impacts, and adaptation and mitigation strategies. These complex and interrelated issues require an integrated methodology for successful impact assessment. Once developed, the methodology may be applied to other highly regulated river basins in the United States such as the Columbia Basin in the northwest, the Tennessee River in the mid-south, and the Colorado River in the southwest.

Flow in the Missouri River is significantly controlled by the operation of its six main stem reservoirs. The purposes of these reservoirs include flood control, irrigation and consumptive uses, downstream water supply and quality, navigation and power, and wildlife concerns. The purpose of this paper is to

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[2] Respectively, Associate Professor and Director, Albrook Hydraulic Laboratory, Department of Civil and Environmental Engineering, Washington State University, P.O. Box 642910, Pullman, Washington 99164-2910; Civil Engineer, Franson-Noble and Associates, 6 South 100 West, P.O. Box 606, American Fork, Utah 84003; Graduate Research Assistant, Department of Civil and Environmental Engineering, Washington State University, Pullman, Washington 99164-2910; and Assistant Professor, Department of Civil and Environmental Engineering, South Dakota School of Mines and Technology, 501 East St. Joseph St., Rapid City, South Dakota 57701-3995 (E-Mail/Hotchkiss: rhh@wsu.edu).

demonstrate the ability to incorporate complex operation rules for multiple reservoirs into a hydrologic model capable of assessing climate change impacts on water resources of large river basins.

MAIN STEM DAMS

Description

The six reservoirs located on the Missouri River are operated by the Missouri River Regional Office of the Northwestern Division of the Army Corps of Engineers located in Omaha, Nebraska. The watershed and dams are shown in Figure 1 and include Fort Peck Dam and Reservoir, Garrison Dam forming Lake Sakakawea, Oahe Dam and Reservoir, Big Bend Dam which forms Lake Sharpe, Fort Randall Dam impounding Lake Francis Case, and Gavins Point Dam forming Lewis and Clark Lake.

The Missouri River dams provide flood control, hydroelectric power, navigation, recreation, and habitat benefits for endangered species. The dams have prevented an estimated $15.9 billion in flood damage while annually generating 10 billion kWh of hydroelectric power, worth over $1 billion serving 1.3 million residents in six states. The Missouri River provided navigation for 8.165 million tons of cargo in 1996 and 8.172 million tons in 1997 and the reservoirs provided 62 million recreational visitor hours in 1998. In addition, operation of the main stem dams has recently improved habitat for the endangered, least tern, and threatened, piping plover (USACE, 1998).

Operational Strategy

Each defined purpose of the dams requires different release rates, and since these demands are not always compatible, a set of rules has been developed to prioritize releases. Reservoir operations are unique in that the dams are operated more as a system than as individual impoundments. Each dam has an operations manual, but dam releases are based on overall

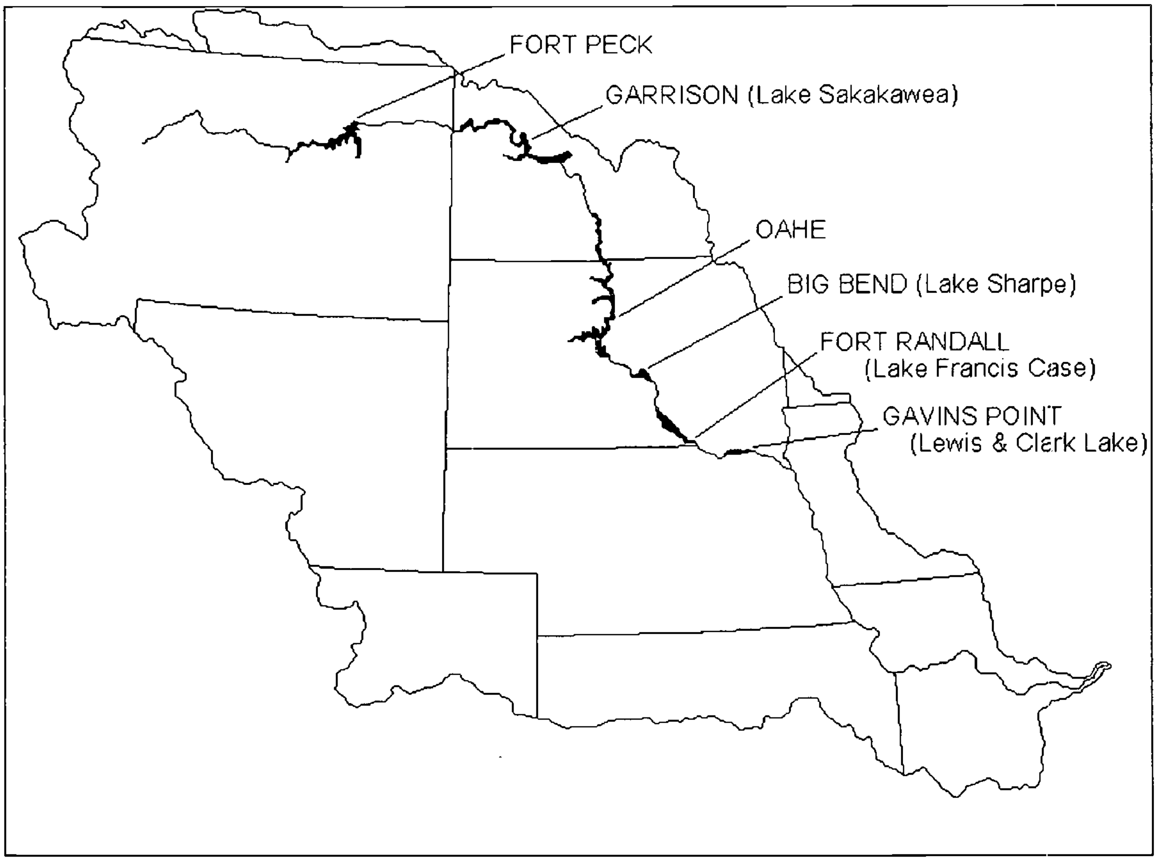


Figure 1. Map of Missouri River Basin With Main Stem Reservoirs.

system rules that take precedence over individual project guidelines. The amount of water released from each dam is a function of the time of year, current storage in the system and in each reservoir, and forecast tributary inflows.

Water storage usually peaks in July and then declines until late winter when snowmelt begins to fill the reservoirs. The system refills during the high runoff period in the spring and early summer. System storage is reduced during late summer, fall and winter to meet prioritized objectives and to provide storage for the following season's high inflows.

Reservoir system storage in the reservoirs is divided into operational zones to help meet prioritized objectives – which are not always compatible. For example, releasing water from a project is compatible with the functions of flood control, navigation, and power supply, but not with storing water for recreation and irrigation. The operational zones were defined such that the maximum possible service could be provided to each of the functions given the physical and authorizing limitations of the projects.

The upper storage zone in each reservoir, reserved for exclusive flood control, is used only for retaining extreme flood flows. System operation seeks to hold reservoir levels in the lower annual flood control zone. Most storage is designated for the carryover and multiple use zone, designed to provide for system functions during a prolonged drought period. Minimum reservoir storage is called the permanent zone. Storage by zones for each reservoir and other data are summarized in Table 1.

Operational Rules

A document called the Master Manual (USACE, 1979) prioritizes operation of the multi-objective system. Although currently under discussion, system priorities are in order, flood control, irrigation and other upstream beneficial consumptive uses, downstream water supply and water requirements, and finally, releases from Gavins Point to allow equitable service to navigation and power. Additionally, without serious interference to the previous functions, the reservoirs are operated to maximize benefits for fish and wildlife.

The flood control priority dictates the overall release and filling rates in the system. Navigation benefits are provided by releasing necessary flows for a normal eight-month season from April to November from Gavins Point Dam. Rules that fix the release rate and the end of the navigation season are dependent upon system storage. Power generation is achieved through the operations for flood control and navigation. Releases for endangered species and wildlife have been emphasized recently, but currently there are no specific rules for addressing these issues.

Conflicts over operation of the main stem reservoirs has led the U.S. Army Corps of Engineers to revise the Missouri River Master Manual, scheduled for release in October 1999. Revisions may shift the operational priorities from flood control and navigation to flood control, wildlife, and recreation. The Corp has released the Preliminary Revised Draft Environmental Impact Statement (PRDEIS) (USACE, 1999a), which investigates eight alternatives for the Master Manual revision. Alternatives FW10 and FW15 are so

TABLE 1. Main Stem Reservoir Information (USACE, 1979).

Project	**Fort Peck**	**Garrison**	**Oahe**	**Big Bend**	**Fort Randall**	**Gavins Point**	
Reservoir	**Fort Peck**	**Sakakawea**	**Oahe**	**Sharpe**	**Francis Case**	**Lewis and Clark**	**Total**
Construction Started	1933	1946	1948	1959	1946	1952	
Closure Date	1937	1953	1958	1963	1952	1955	
Drainage Area (km^2)	148,920	320,900	160,810	15,130	36,650	41,440	723,850
Dam Height (meters)	76	64	75	29	50	23	
Dam Length (meters)	6,410	3,445	2,835	3,223	3,262	2,652	
Storage (thousand hectare meters)							
Exclusive Flood Control	12	18	14	1.2	12	1.2	58
Annual Flood Control	33	52	39	1.2	16	1.2	142
Carryover	133	162	166		20		481
Permanent	52	62	67	21	18	3	223
Gross (total)	231	293	296	23	67	5	906

called "fish and wildlife alternatives" and would modify operations to mimic pre-dam flows on the Missouri River through a high spring rise and low summer flows. The PRDEIS showed that this operation would benefit fish and wildlife and floodplain farmers while supporting a full navigation season.

The most important system quantity is the release rate from Gavins Point Dam, the control point for navigation, flood control, and other downstream uses. The other five reservoirs can be operated in different ways to achieve a relatively constant release rate from Gavins Point. Releases are a function of calendar date, system storage, tributary inflows downstream, and the possible occurrence of winter ice jams.

Reservoir Modeling

The U.S. Army Corps of Engineers has developed two specific models for routing flows through the main stem dams. Prior to 1997 the USACE Reservoir Control Center used the Long Range Study Model (LRS) to simulate the operating criteria for each of the main stem projects using historical monthly data. Development of a Daily Routing Model (DRM) was completed in 1997 and uses historical daily data. Neither model begins with rainfall-runoff simulations (USACE, 1999b).

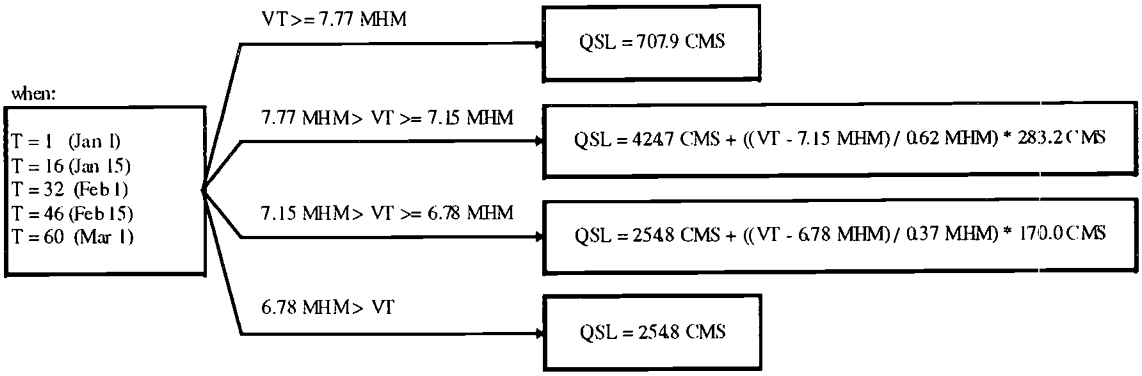
Existing rainfall-runoff computer codes do not, of course, contain algorithms to simulate the operation of the main stem dams on the Missouri River. A new algorithm was developed for such a purpose. The final version of the subroutine and the 12 detailed flowcharts that show all the procedures can be found in Jorgensen (1996). A sample flowchart for determining the release rate from Gavins Point dam is shown in Figure 2.

The objective of the subroutine is to find the appropriate release rate from each reservoir. The release from Gavins Point is obtained first, followed by the other reservoirs in order working upstream. Fort Randall and Big Bend were combined since Big Bend is relatively small.

The initial estimate for Gavins Point flow release is determined using equations based upon Master Manual charts that relate the calendar date to desired system storage and service level (service level is defined as the desired flow in the Missouri River downstream from the reservoirs). The Corps releases the service level discharge from Gavins Point with adjustments made for downstream inflows (particularly when high) and projected tributary recessions for future flows.

For the remaining reservoirs, initial releases are determined by multiplying the release equation for Gavins Point by the ratio of historical outflow from each reservoir to the historical outflow from Gavins Point, as shown in Table 2.

Initial releases are adjusted based upon the storage in the next downstream reservoir. Fort Randall and Oahe releases are modified by comparing the reservoir volume to input target volumes. Release is adjusted for Garrison and Fort Peck to maintain relative balance amongst the upper three reservoirs by comparing the relative storage in Oahe, Garrison, and Fort Peck.



Notes: MHM = million hectare-meters
CMS = cubic meters per second
VT = total system storage, million hectare-meters
QSL = release from Gavins Point Dam (service level), cms

Figure 2. Flowchart for Determining Gavins Point Dam Release Rate.

TABLE 2. Percentage of Gavins Point Release Used for Other Projects.

Reservoir	Historic Average Flow (cms)	Percent of Gavins Point Release	Percent of Gavins Point Release Used in Model
Gavins Point	787		
Fort Randall	714	90.7	90
Oahe	691	87.8	85
Garrison	629	79.9	75
Fort Peck	280	35.6	35

Limits are built into the model to simulate extreme conditions. Releases are not allowed to exceed the maximum summer and winter release rates specified for each dam. Releasing a percentage of the maximum summer flow as the volume approaches the top of the exclusive flood control zone prevents spillway overtopping. Releases less than the minimum are not allowed unless the volume reaches critically low values. No release is allowed if storage is less than the permanent pool volume.

Limitations of Reservoir Algorithms

The computer algorithm developed for simulation captures all significant aspects of the reservoir operations scheme as reflected in the Master Manual and in daily operating decisions. There are, however, three simplifications in the model. First, adjustments for downstream flow are not made which would account for high or low flows from downstream tributaries. Second, Fort Randall and Big Bend were combined and simulated as one reservoir. Third, no flow modifications to accommodate endangered species are made since there are currently no written rules for this purpose.

MODELING MISSOURI RIVER BASIN CLIMATE IMPACTS

Climate Change Studies

The MINK project assessed the economic consequences of climate change in Missouri, Iowa, Nebraska, and Kansas and is the widest known global climate change research project for the Missouri River basin. This project used the "dust bowl" of the 1930s as an analog for global climate change. Representative farms were used to analyze economic impacts of the climate change scenario. The model simulated hydrology, erosion, sedimentation, nutrients, plant growth, tillage, soil temperature, and crop management. Study results predicted that society will adapt to climate change with few system wide negative effects (Crosson and Rosenberg, 1993).

Hurd *et al.* (1996) examined several watersheds including the Missouri River basin. Information about the physical effects of climate change was used with a model of resource allocation based on economic theory. A climate change scenario was characterized by incrementally changing average annual precipitation and temperature across the region, and a hydrologic model predicted changes in runoff. The modified runoff was used as input to an economic model that allocated water to various consumptive and nonconsumptive uses over space and time in the Missouri River basin.

Hydrologic Models

Conceptual lumped-parameter models are the most widely used type of hydrologic model for large watersheds such as the Missouri River (Leavesley, 1994). These use approximations of physical laws to simulate hydrologic cycle processes. The hydrologic model used to evaluate climate change impacts on water resources should simulate processes involving soil moisture, evapotranspiration, snow and snowmelt, overland flow, shallow subsurface stormflow, groundwater, and channel routing. It must also include components that respond to changes in CO_2 and related input variables such as rainfall and temperature. It must accommodate the extreme heterogeneity of hydrologic and atmospheric conditions, and must very efficiently extract required input data over large spatial scales and for long time periods. The model should not require detailed calibration for each sub basin but must be capable of continuous simulation for long periods of daily streamflow (e.g., 50 years), and have existed long enough for independent validation and applications. After considering several existing models, the Soil and Water Assessment Tool (SWAT) was selected as the best available model for this research.

SWAT

Recently, SWAT has been developed and applied to large watersheds throughout the United States (Srinivasan *et al.,* 1994). Although not specifically developed for climate change impact assessment, it has been so used because the model is capable of simulating the transpiration suppression effects of CO_2 enrichment (Arnold *et al.,* 1995).

SWAT is a continuous watershed scale model that simulates major hydrologic cycle components using a daily time step. The hydrologic model is based on a water balance equation around soil water content as follows (Arnold et al., 1998):

$$SW_t = SW_{t-1} + P_t - Q_t - ET_t - SP_t - QR_t$$

where SW_t is the soil water content for the current day, SW_{t-1} is the soil water content for the previous day, P is precipitation, Q is surface runoff, ET is evapotranspiration, SP is percolation or seepage, and QR is return flow from groundwater to the surface. Major hydrologic processes modeling methods are summarized in Table 3.

The runoff component is modeled using the SCS Curve Number approach (USDA-SCS, 1972). The Runoff Curve Number (RCN) is a retention parameter that varies according to soil type, land use, cover, and water content. The RCN in SWAT is updated on a daily basis according to soil water content. Previous research has shown that the increased model complexity of methods such as the Green-Ampt equation over the relatively simple curve number approach does not necessarily translate to better accuracy (Wilcox *et al.,* 1990; Beven, 1989; Loague and Freeze, 1985).

SWAT also simulates biomass production, plant growth, and the fertilization and transpiration suppression effects of CO_2 enrichment. Details of all processes may be found in Arnold *et al.* (1998).

SWAT is a watershed-structured program, meaning that the area modeled is divided into subareas depending on watershed boundaries. For the Missouri River basin model, the watershed scale corresponds to 8-digit subbasins, ranging in size from 2000 to 5000 km^2 (U.S. Geological Survey, 1987). There are 310 such 8-digit watersheds in the Missouri River basin.

The model of the Missouri River used in climate change analysis was adapted from the nationwide Hydrologic Unit Modeling of the United States (HUMUS) project. For the HUMUS project, each 8-digit subbasin was divided into as many as 15 smaller basins depending upon watershed boundaries, land use, and soil composition, producing more than 3,000 distinct subbasins for modeling purposes. A simplified model was created by maintaining the dominant characteristics for each 8-digit subbasin without further subdivision. The purpose was to produce an easily calibrated dataset that would require less computational time for testing reservoir algorithms.

SWAT efficiently accommodates the large datasets used in this project. Through software linked to GRASS, a Geographic Information System, watershed boundaries and other necessary input variables are obtained for the SWAT program from digital databases (Arnold *et al.,* 1995).

The input variables for the models were extracted from the digital databases summarized in Table 4. GRASS accessed the digital datasets and interface routines formatted the necessary input parameters for each subbasin in the SWAT model.

Climate input included measured daily precipitation, daily temperature and monthly average wind speed data from weather stations in the basin from

TABLE 3. Modeling of Hydrologic Processes in SWAT (Arnold *et al.,* 1998).

Process	Algorithm
Precipitation	Observations or First-Order Markov Chain Model
Surface Runoff	SCS Curve Number Method
Channel Routing	Variable Storage Coefficient
Reservoir Routing	Stage-Storage or Reservoir Operating Procedures
Percolation	Storage Routing Combined With Crack-Flow Model
Snowmelt	Mean Air Temperature and Soil Layer Temperature
Lateral Subsurface Flow	Kinematic Storage Model
Ground Water Flow	Baseflow Period, Ground Water Storage and Re-evaporation
Transmission Losses	Lane's Method
Evapotranspiration	Penman-Monteith, Hargreaves, or Priestley-Taylor Methods
Sediment Yield	Modified Universal Soil Loss Equation (MUSLE)

TABLE 4. Databases Accessed by GRASS and Used in SWAT.

Database or Data Source	Used For
USGS Digital Elevation Models (DEMs)	Topography, Basin Delineation
USGS Land Use/Land Cover	Land Cover
USGS Maps	Hydrography
STRATSGO, STRATSGO I	Soils Data
Census of Agriculture, Department of Commerce Cty. Map	Crop Type
Tillage Residue Database	Cropping Practice
Shallow Aquifer Baseflow Period Map	Aquifer Data

1962 to 1989. Representative precipitation values were found for each subbasin by the Thiessen polygon method (Wanielista, 1990).

Existing Reservoir Algorithms

Reservoirs are modeled within the original SWAT program in two ways: as an on-line impoundment, or as a basin-accumulated ponding area. The on-line impoundment method simulates reservoirs on the main stem of a basin. Four options are available. The first option simply releases the amount of inflow minus evaporation and seepage losses from the reservoir. The second uses observed outflow records to complete the water balance equation for the reservoir. The third is used for larger reservoirs and sets the target storage at the emergency spillway elevation for the non-flood season and at the principal spillway for the flood season. When either elevation is exceeded storage is returned to the target elevation in a number of user-input days. The forth option is a simulated inflow-outflow regression model.

The second method for modeling reservoirs with SWAT combines all basin storage into one equivalent pond. Outflow occurs when storage exceeds the combined permanent pool level. This routine is designed for smaller stormwater-type impoundments. Implementation of the aforementioned algorithms provided a method more suitable for modeling the complex operation of the Missouri River reservoirs.

RESULTS OF RESERVOIR MODELING

Calibration of Simplified Missouri River Dataset

The SWAT dataset required preliminary calibration before the reservoir algorithms could be tested. Average historic long-term releases for each reservoir were used to adjust RCNs to match computed versus observed runoff volumes into Ft. Peck reservoir (USDA, 1972). There are two shortcomings in SWAT for modeling regions with a large snowmelt component. Current snowmelt algorithms (Table 3) are quite simple and underestimate snowmelt from mountainous regions in the northern part of the river basin and thus underpredict inflow (Fontaine *et al.*, 1996). Additionally, historically observed climatalogical data does not account for increases in precipitation with elevation. Thus, mountain snowpack depth is underestimated and inflows to the upper reservoirs will likely be low. Future model work will account for elevation-driven lapse rates and will also contain improved algorithms for snowmelt modeling.

At this stage in the long-term project, RCNs were adjusted without regard to the physical properties they represent. Thus, some subbasins may have inappropriate curve numbers when compared to recommended values. RCN modifications and the original minimum and maximum RCNs for each major river basin are shown in Table 5. The RCN over the entire basin was increased by one. As, expected the mountainous region above Ft. Peck reservoir required the largest RCN increase. A moderate increase was necessary for the Yellowstone River basin. The RCN was reduced for the high-plains dominated Cheyenne River basin.

Calibration of Reservoir Subroutine

The reservoir operations algorithm was calibrated by adjusting the release rate from Gavins Point and maximum releases from the dams. The service level flow was adjusted to best match observed release rates and total system storage.

Maximum reservoir releases were adjusted to maintain system storage below the top of the exclusive flood control zone. Maximum and minimum releases suggested by the Corps and those used in the model are shown in Table 6. The maximum summer releases for all reservoirs are only slightly higher

TABLE 5. Modifications of Runoff Curve Numbers in Calibration of Dataset.

River Basin Modified	Number of 8-Digit Subbasins Modified	RCN Increment	Original Minimum RCN	Original Maximum RCN
Missouri River Basin	All 310 Subbasins	1	36	89
Missouri Into Fort Peck	24 Subbasins	8	36	89
Yellowstone River Basin	41 Subbasins	3	60	89
Cheyenne River Basin	22 Subbasins	-3	60	89

TABLE 6. Maximum and Minimum Reservoir Releases.

	Average Summer Maximum Release (cms)		Average Winter Maximum Release (cms)		Average Minimum Release (cms)	
Project	Historic	SWAT	Historic	SWAT	Historic	Swat
Gavins Point	1841	2265	425	425	283	283
Fort Randall	1700	2265	708	708	28	28
Oahe	1700	2265	708	708	28	28
Garrison	1841	2265	708	708	283	283
Fort Peck	1133	1700	566	566	113	113

than the Corps values to compensate for some predicted daily inflows that were unrealistically high.

Calibration results are shown in Figure 3 for the period of 1965 to 1989. Main stem reservoirs simulated storage with the new reservoir algorithm follows observed trends very well. Errors are not systematic, showing no bias toward over or underestimation. The simulation mimics the historic storage dropping into the carryover zone, significant because it shows that the model routines are flexible enough to allow the system to drop out of the normal operating range.

The original SWAT code without the new reservoir algorithm was run for comparison to the calibrated reservoir model. The simulated storage without the new reservoir algorithm is also shown in Figure 3. The system volume is much higher when the new reservoir algorithms are not used. This is a product of the target-outflow scheme that uses the base and top of the exclusive flood control zone as targets. The original code was designed such that the reservoirs operate within a relatively narrow storage range, and thus is incapable of predicting system drawdown during a dry period. This shortcoming is illustrated when the system dropped below the annual flood control level in 1981 but a corresponding decrease was not simulated with the original code.

Statistical analysis of the results is shown in Figure 4. Regression analysis of predicted versus measured monthly storage shows that the data fit the line of perfect agreement quite well. The mean square error was 0.45 million hectare-meters, or six percent of the average system storage. The hypothesis that the mean of the residual errors was equal to zero, assuming residuals were normally distributed, was accepted at the 95 percent confidence interval.

Three other comparisons were made for the calibration run. The first, shown in Table 7, compares simulated and historic average yearly storage for each reservoir. Fort Randall was not included because it was combined with Big Bend in the model. Overall, the simulated reservoir volumes compare very well with historic data.

The second test compares simulated and historic average releases from each reservoir. The results, in Table 8, indicate that even without the advantages of weather forecasting and predicting downstream inflows, releases agree with historic averages. The model underestimates runoff from the upper basin. However, this was made up in the lower reservoirs where inflows produced a higher Gavins Point release than the long-term average. Overall results are acceptable for analyzing climate change impacts.

The third comparison showed reservoir release rate differences. With no limits in the original code, discharge ranged from zero to values greatly exceeding Corps limits. Figure 5 is a comparison of the number of days in the 25-year period when discharge was simulated to be within the Corps limits of release rates for each reservoir. The new reservoir algorithm predicted discharge almost always within the limits, while the original code performed quite poorly. Overall, the new routines are a significant addition to the

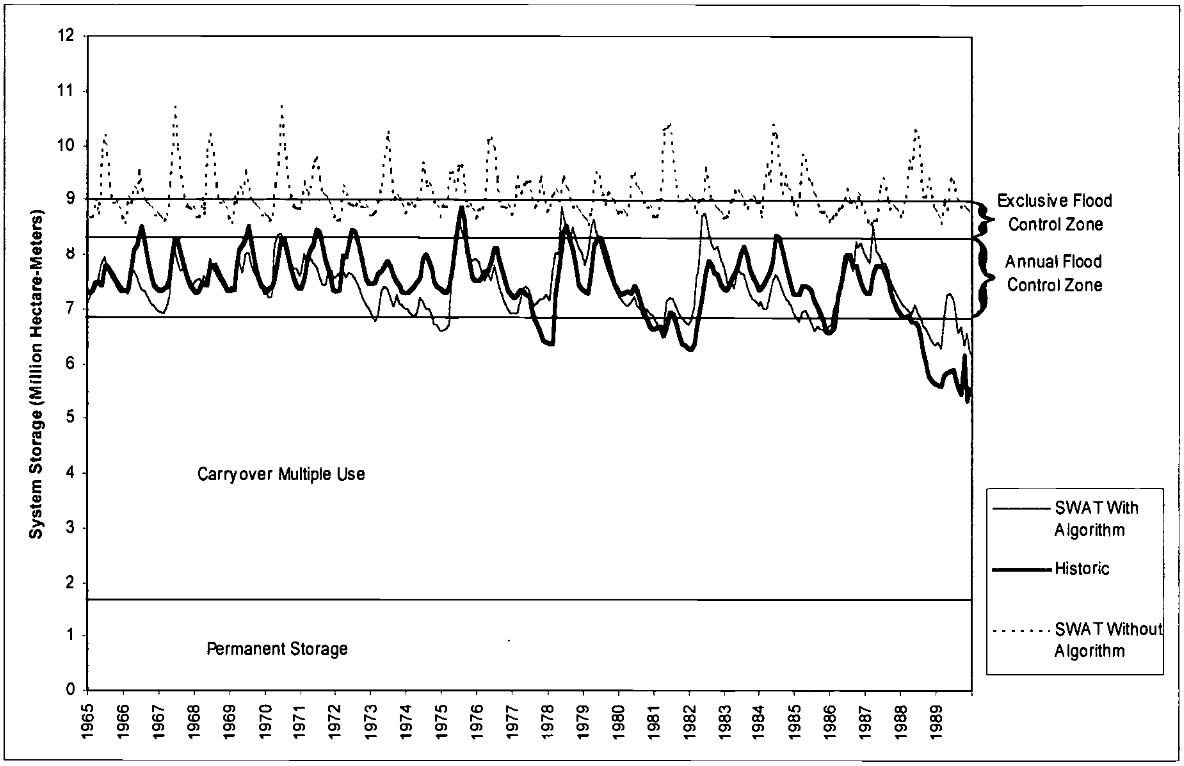


Figure 3. Historical, Original SWAT, and Modified SWAT System Storage Comparison.

model because predicted releases are within flow limits, storage follow the historical data more closely, and the model now has a crucial amount of flexibility.

Extreme Climate Simulation Tests

Once the model was shown to reproduce historic system storage, four simulations were run to test extreme operation assumptions. It is important to note that these simulations were not intended to represent climate change, but were intended to further test the new model algorithms.

The first simulation uniformly increased precipitation for the 25-year period by 10 percent over the entire basin. The results were as expected, with both flows and system storage increasing. The system continued to fill beyond the maximum storage as the release rates are not set high enough to handle this type of inflow. For future work, the Master Manual maximum releases will need to be modified to mitigate increases in precipitation. Results of the extreme climate tests are shown in Figure 6.

The second test assumed zero precipitation for the entire basin for the 25-year period. The system slowly drained for approximately five years until the code set all reservoir releases to zero, after which the seepage and evaporation routines continued reservoir depletion. This simulation was successful since the rules slowed and stopped releases as the total storage reached the minimum pool levels.

The third simulation used historical precipitation for the period, but initially set the storage in the reservoirs to zero. The system filled after several years as expected.

The fourth simulation tested a short and intense drought scenario by setting the 1967 and 1968 precipitation values to zero for the basin. Results demonstrate that the system responded logically by decreasing storage during the years of zero precipitation and then recovering over the next several normal years. The rate of storage recovery depended upon the amount of precipitation over the basin following the drought and the release rules that apply when the system is below the normal operating range.

CONCLUSION

The complex operating rules of the Missouri River main stem reservoirs were successfully implemented in a climate change model. A simplified dataset for the basin was calibrated for use in testing the

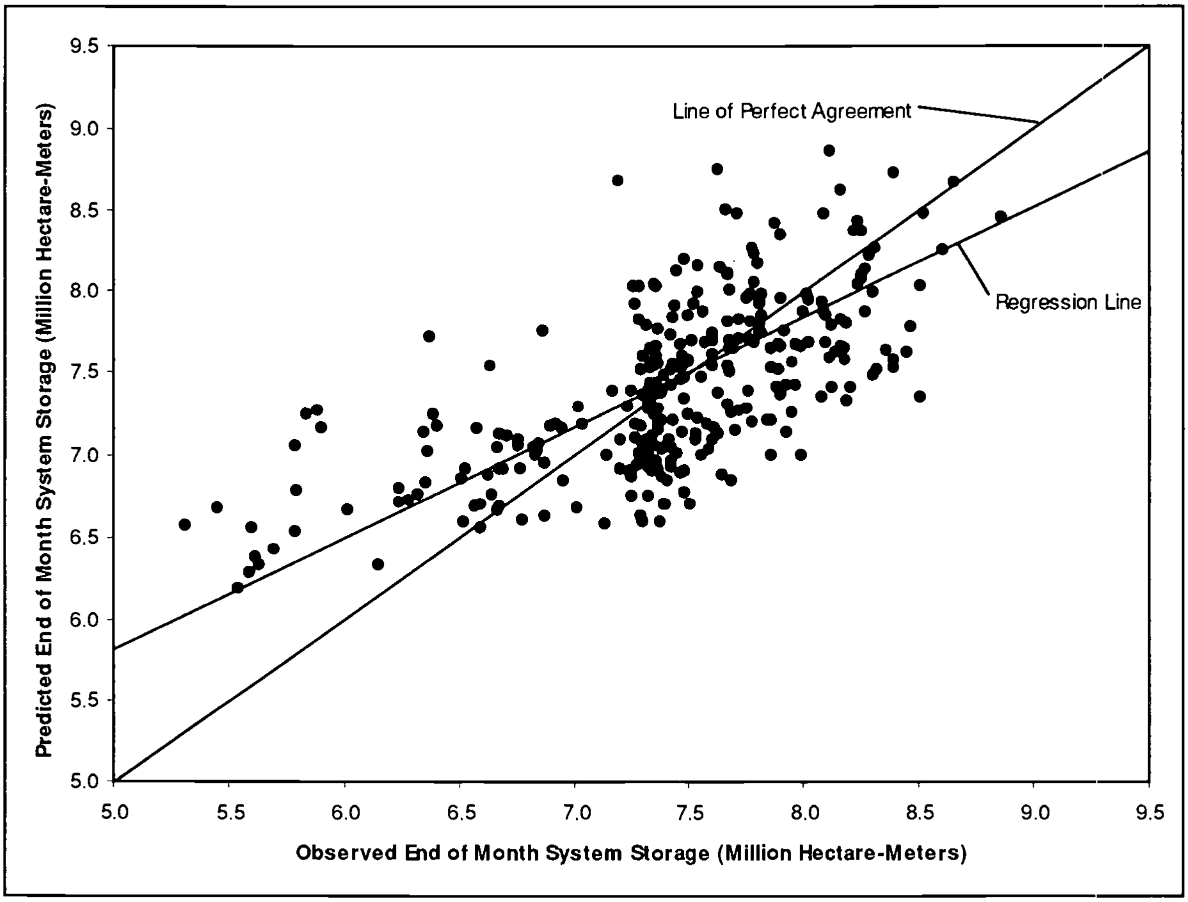


Figure 4. Statistical Analysis of Historical and Simulated System Storage.

TABLE 7. Comparison of 1968-1989 Historic and Simulated Volumes.

Reservoir	Historic Average Volume (million hectare meters)	Simulated Average Volume (million hectare meters)	Difference (million hectare meters)	Percent Difference
Gavins Point	0.052	0.048	-0.004	-7.7
Oahe	2.32	2.27	-0.05	-2.2
Garrison	2.38	2.46	0.08	3.4
Fort Peck	1.99	2.1	0.11	5.5

TABLE 8. Comparison of 1968-1989 Average Reservoir Releases.

Reservoir	Historical Release (cms)	SWAT Release (cms)	Difference (cms)	Percent Difference
Gavins Point	833	843	10	1.2
Fort Randall	764	707	-57	-7.5
Oahe	741	739	-2	-0.3
Garrison	668	569	-99	-14.8
Fort Peck	300	258	-42	-14.0

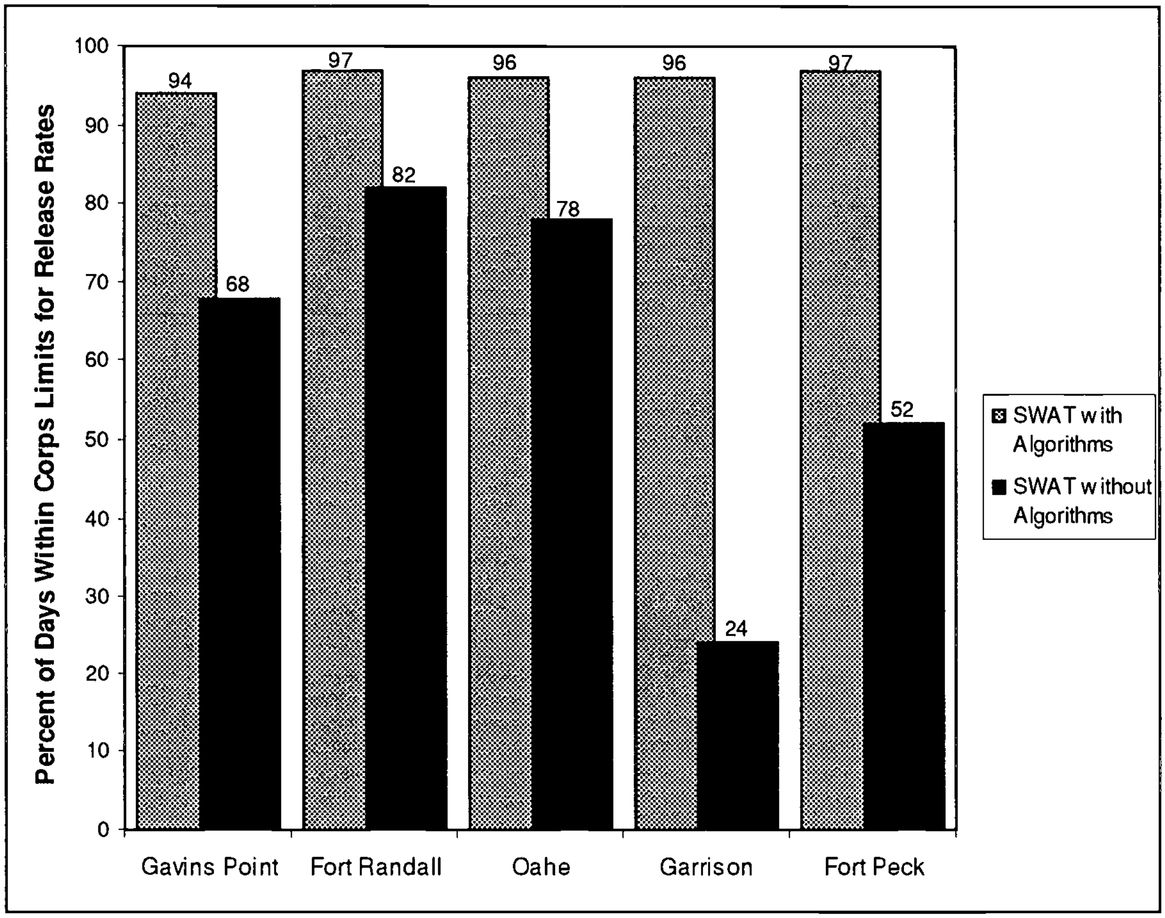


Figure 5. Comparison of Percentage of Days Within Corps Release Rate Limits.

reservoir operations. The reservoir subroutine reproduced system storage and reservoir release rates very well using historical data. Further, simulations with extreme bounds proved that the routines perform well for many ranges of input. The reservoir subroutine is a valuable addition to the climate change model and serves as an example of coupling climate change models with operating rules for highly managed rivers.

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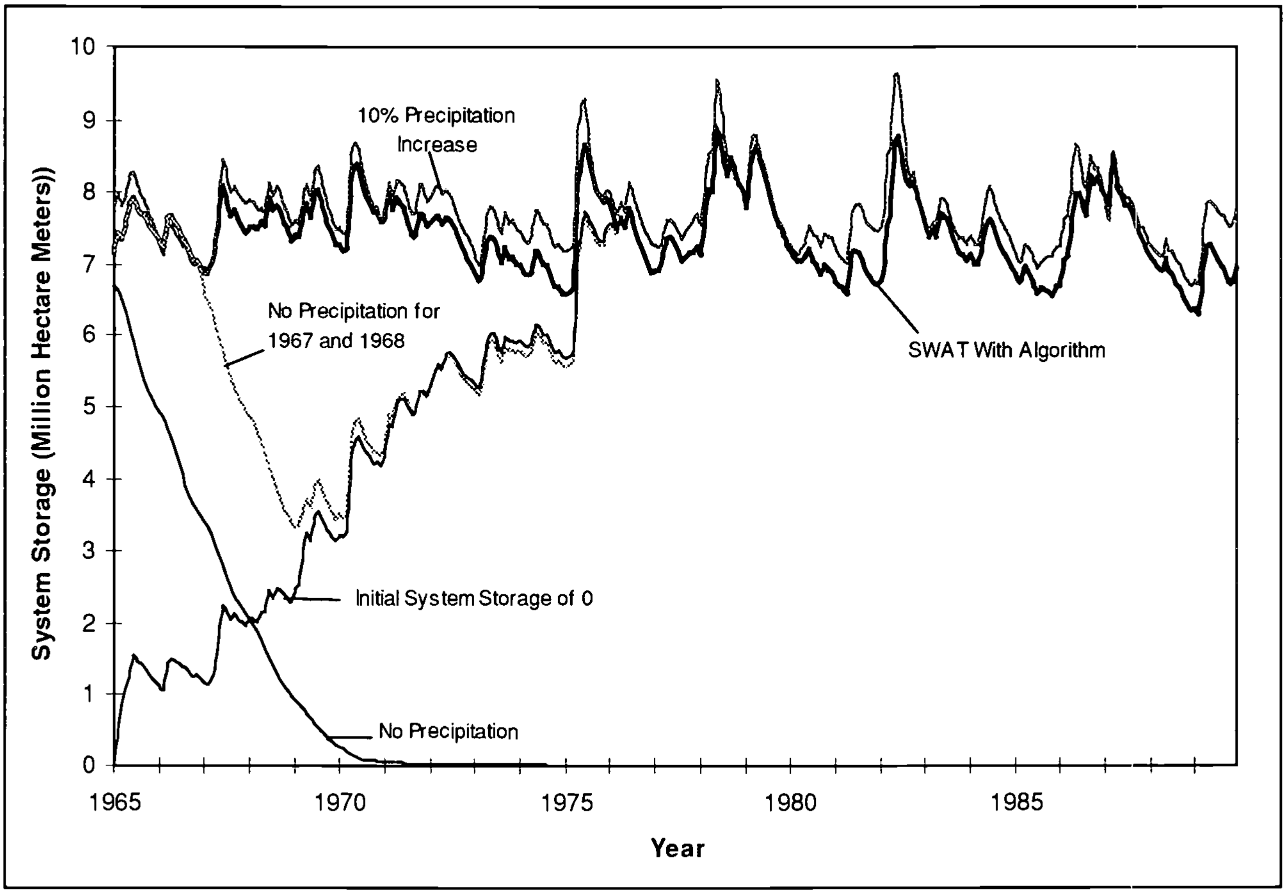

Figure 6. Simulations of Extreme Climate Scenarios.

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