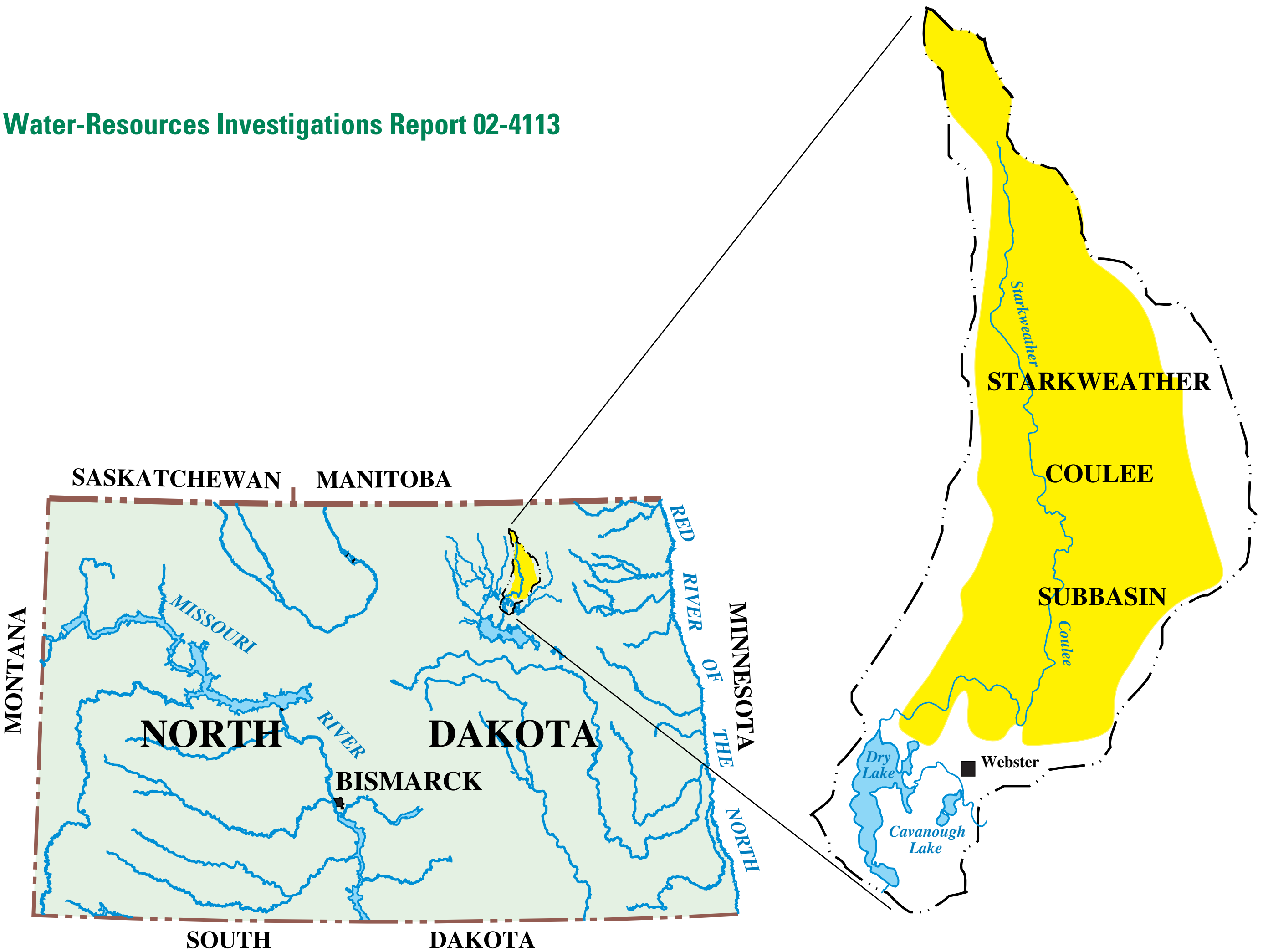
In cooperation with the North Dakota State Water Commission

Simulation of Streamflow and Wetland Storage, Starkweather Coulee Subbasin, North Dakota, Water Years 1981-98

Water-Resources Investigations Report 02-4113



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By Kevin C. Vining

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Bismarck, North Dakota
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U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
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Simulation of Streamflow and Wetland Storage, Starkweather Coulee Subbasin, North Dakota, Water Years 1981-98

By Kevin C. Vining

Abstract

A study was conducted to simulate streamflow and wetland storage within a part of the Starkweather Coulee subbasin. Information on streamflow and wetland storage in Starkweather Coulee subbasin may help with the management of water issues in the Devils Lake Basin. Information from a digital elevation model and geographic-information-system analyses of the study area was used to develop the Devils Lake Basin wetlands model. Digital elevation model data and other climatic and topographic data were used as inputs to the model. Within the study area, the average wetland depth was about 2.21 feet, the total maximum wetland area was about 30,890 acres at the overflow elevation, and the total maximum wetland volume was about 68,270 acre-feet.

Model runs were made for water years 1981-98 to calibrate the model to observed streamflows that were obtained from the Starkweather Coulee gaging station. Observed annual peak streamflows were greater than simulated annual peak streamflows for all water years except 1983. The differences probably were caused mostly by the lack of a subroutine in the model to account for frozen soil. The largest amount of simulated daily wetlands area occurred in April 1997 when about 40,500 acres of the study area was covered with water. Also during April 1997, the simulated daily water volume in the open and closed wetlands combined attained a maximum of about 116,000 acre-feet. By increasing the spillage thresholds from 0.2 to 1.0, simulated streamflow was reduced by 8.77 inches (from about 17.88 to 9.11 inches; 49 percent) for the 18-year period. During water years 1994-98, simulated annual streamflows for open-wetland spillage thresholds of 1.0 remained less than for thresholds of 0.2 even though the open wetlands probably were near maximum volume. The greatly increased size of the closed wetlands during water years 1994-98 probably allowed for increased water storage and decreased simulated streamflow from the study area.

INTRODUCTION

Since the summer of 1993, the region around the Devils Lake Basin in northeastern North Dakota (fig. 1) has had intermittent flooding conditions. Copious amounts of rainfall have inundated roads, croplands, and properties. Because of the low-relief topography and the lack of a prominent outlet from Devils Lake, precipitation and runoff remain within the basin, and water levels in Devils Lake increased from about 1,422 feet above sea level[1] in October 1992 to more than 1,447 feet above sea level in August 1999. Millions of dollars have been spent to protect property from the rising flood waters and to maintain the transportation network around Devils Lake. Many local, State, and Federal agencies are concerned about the current flooding problem and have a long-term interest in devising means for managing water levels in the Devils Lake Basin. Some alternatives suggested to help stabilize Devils Lake water levels are to create drains to channel water from Devils Lake to adjacent-basin rivers and lakes and to re-establish and expand wetlands areas upstream from Devils Lake.

The extent to which water can be retained in the Devils Lake Basin was revealed when greater-than-average precipitation in the 1990's filled many of the wetlands in the basin. However, to evaluate the wetland storage available in the basin and to evaluate wetland storage changes on streamflow, accurate knowledge of surface topography was required. Therefore, a study was initiated by the U.S. Geological Survey (USGS) in cooperation with the North Dakota State Water

[1]In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

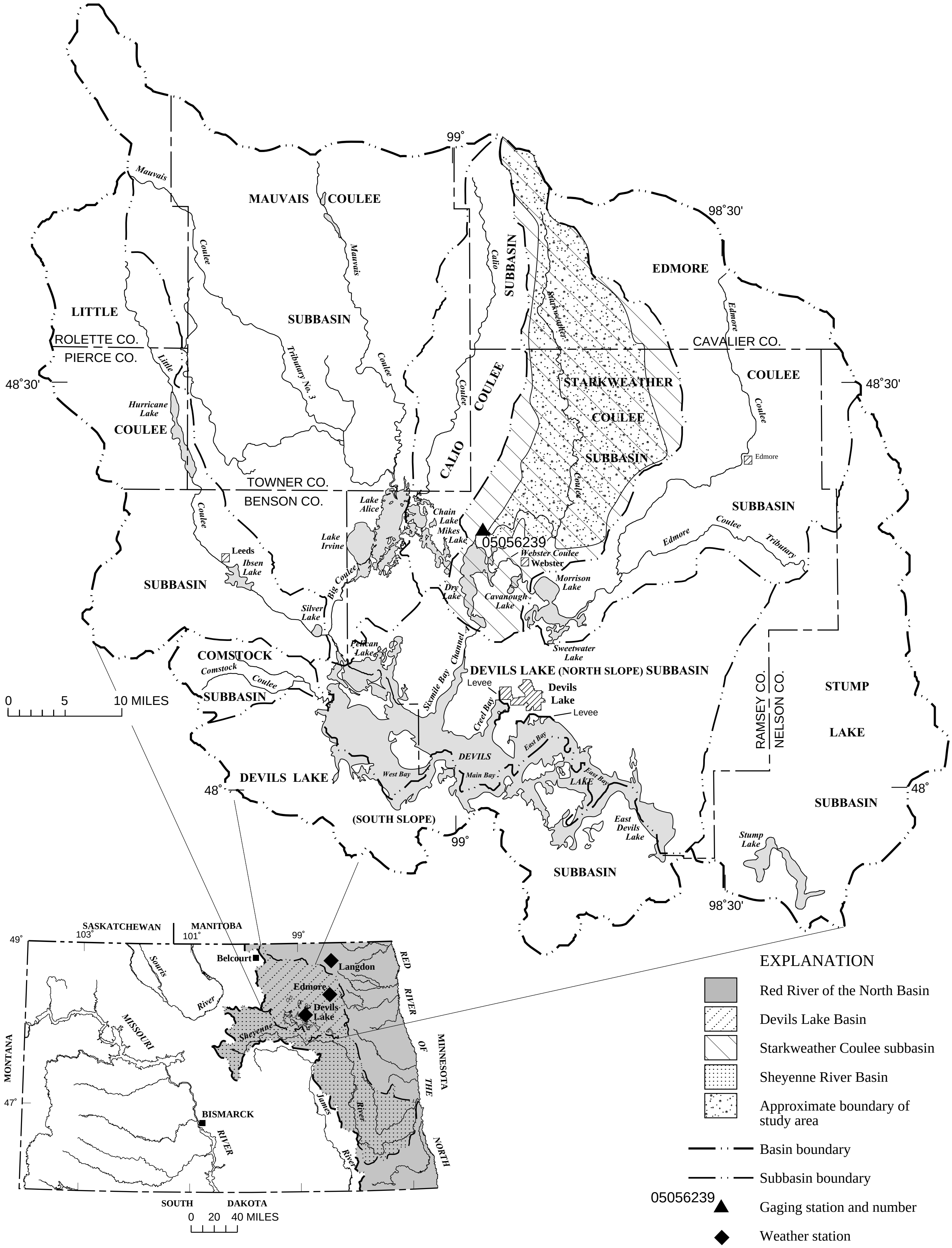

Figure 1. Major subbasins within the Devils Lake Basin and locations of study area, gaging station, and weather stations. (Modified from Devils Lake Basin Advisory Committee, 1976.)

Commission to simulate streamflow and wetland storage within a part of the Starkweather Coulee subbasin of the Devils Lake Basin. This subbasin was selected for the study because of the availability of streamflow data from a gaging station located on Starkweather Coulee. The study utilized digital elevation data, geographic-information-system (GIS) tools, and the Devils Lake Basin wetlands model, which is a modified version of the USGS Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983) (see appendix), to define flow networks, to estimate wetland storage, and to simulate streamflow and storage within the low-relief landscape of the study area. Information from the study may be useful to water managers, researchers, and others associated with the water issues that have arisen because of the rising water levels of Devils Lake. This report describes the results of the study.

In a demonstration of the capability to accurately define surface topography within the Devils Lake Basin, a high-resolution digital elevation model (DEM) of a portion of the Calio Coulee subbasin, a subbasin of the Devils Lake Basin, was provided by the Earth Resources Observation Systems (EROS) facility of the USGS. The high-resolution DEM was created by using contour and other information from standard, USGS 1:24,000-scale topographic maps. Generally, wetland information derived from the high-resolution DEM was consistent with the U.S. Fish and Wildlife Service's National Wetlands Inventory and the results of a study conducted by the U.S. Fish and Wildlife Service and the North Dakota State Water Commission to measure the total storage capacity of wetlands within many quarter-section test sites (Ludden and others, 1983). The demonstration indicated that high-resolution DEM information is sufficient to derive surface hydrologic parameters, such as basin areas and boundaries, surface-flow networks, and the areas and volumes of wetlands, that could be used in hydrologic models of a basin.

Many hydrologic models exist that could be used to investigate watershed hydrology, hydraulics, channel routing, and water quality, but not all hydrologic models have incorporated a snowmelt routine that is needed for some watershed hydrology studies. Parekh (1977) used a version of the Stanford Watershed Model to continuously model the hydrologic conditions within the Mauvais Coulee subbasin, the Edmore Coulee subbasin, and the Devils Lake Basin. However, extensive calibration of the model algorithms was needed to produce adequate results, and difficulties in modeling resulted from inadequate simulation of snow accumulation and snowmelt and from a lack of information related to surface-water storage features other than soil moisture indices. Because during any year in North Dakota, snowmelt typically generates the largest amount of runoff during rapid snowmelt and overland flow across a frozen landscape, the Devils Lake Basin wetlands model, which contains a snowmelt routine, was used to develop the streamflow data for the Devils Lake Basin. The Devils Lake Basin wetlands model and the PRMS are modular systems for constructing distributed-parameter models that use physics-based mathematical relations to represent the hydrology of an area. The systems utilize partitioning of a watershed into hydrologic response units (HRUs) on the basis of characteristics such as slope, aspect, elevation, soil type, and vegetation type so that each unit has a homogeneous response to physical, meteorologic, and hydrologic inputs. All components of the Devils Lake Basin wetlands model and the PRMS currently are contained within the Modular Modeling System (MMS) (Leavesley and others, 1996). The MMS uses a graphical interface that allows the user to select the appropriate algorithms necessary to create the model needed for the desired application.

The PRMS has been applied to many watersheds and river basins to estimate runoff into reservoirs (Nakama, 1993; Jeton, 2000), to simulate the effects of land use on runoff and streamflow (Risley, 1993), and to provide estimates of tributary inflows to use in streamflow-routing models (Laenen and Risley, 1995). Emerson (1988) used the PRMS to investigate the snowmelt-dominated hydrologic systems of two small watersheds, Hay Creek watershed in Montana and West Branch Antelope Creek watershed in North Dakota. Although model calibration for snowmelt runoff was reasonably accurate, the greatest model errors occurred because of the difficulty in defining the quantity and distribution of snow cover. The PRMS also has been applied to ungaged basins to estimate streamflows (Norris, 1986; Jeton, 1999). These investigations generally indicate that results from the modeling efforts were accurate. The investigations also suggest that the PRMS could be modified sufficiently to incorporate the influence of various topographic features on the hydrology and streamflows of small watersheds in the Devils Lake Basin.

The author acknowledges the assistance and contributions made by George Leavesley, Roland Viger, and Glenn Kelly of the USGS. Leavesley incorporated a wetland hydrology subroutine into the PRMS, Viger provided initial PRMS parameterization with GIS Weasel, and Kelly provided DEM analyses of the Starkweather Coulee subbasin.

STUDY AREA

The Starkweather Coulee subbasin is a major subbasin within the Devils Lake Basin (fig. 1). The Starkweather Coulee subbasin covers an area of about 310 square miles, of which about 210 square miles reportedly contributes to streamflow (Harkness and others, 1998). However, abnormally wet conditions since the summer of 1993 may have increased the amount of area that contributes to streamflow. A USGS gaging station is located on Starkweather Coulee about 3.8 miles northwest of Webster. The study area is located upstream from the Starkweather Coulee gaging station and covers an area of about 262 square miles (fig. 1). The study area topography generally is level to slightly rolling in the south, somewhat more rolling in the center, and generally level in the north. The soils are predominately loams to silty clays (Bigler and Liudahl, 1986; Simmons and Moos, 1990). Thousands of wetlands exist on the surface. Some of the original wetlands were drained years ago and currently are being farmed. Most of the land in the study area is owned privately and is used for agriculture. Some land areas are used for pasture or are enrolled in the U.S. Department of Agriculture's Conservation Reserve Program.

Generally, the climate of the area consists of short, warm summers and long, cold winters. Average monthly temperatures range from -15.6 degrees Celsius in January to 20.6 degrees Celsius in July (Owenby and Ezell, 1992). Average annual precipitation is about 17.3 inches, of which about 75 percent occurs during April through September (Owenby and Ezell, 1992). During 1991-97, however, average annual precipitation within the study area increased to about 21.7 inches. The increase contributed to the intermittent flooding conditions and the rising water levels of Devils Lake. Average seasonal snowfall is about 37 inches (Jensen, 1972), which contributes about 3.5 inches of water to the precipitation on the study area. Windy conditions often redistribute the snow into large drifts, leaving some land areas bare.

CLIMATE DATA ACQUISITION

Climate data requirements for the PRMS are daily total precipitation and daily maximum and minimum temperatures. For water years[2] 1981-98, climate data were obtained from stations located at Devils Lake, near Edmore, and at the Langdon Agricultural Experiment Station near Langdon (see index map in fig. 1). For the summers of 1981-98, additional daily precipitation data were obtained from the precipitation reporting network of the North Dakota Atmospheric Resource Board (ARB). Data from nine ARB stations were used in this study. The ARB stations are located within the boundary of Starkweather Coulee subbasin. For water years 1990-98, daily radiation data were obtained from the North Dakota Agricultural Weather Network station at Langdon. Missing values of radiation were derived from empirical equations contained in the PRMS. Snow water equivalent information was obtained from the National Weather Service's National Operational Hydrologic Remote Sensing Center in Chanhassen, Minn. Data on the physiography, vegetation, soils, and hydrologic characteristics of the study area were derived from field visits, topographic maps, digital data sets, and the Cavalier and Ramsey Counties soil survey publications (Bigler and Liudahl, 1986; Simmons and Moos, 1990). For water years 1981-98, daily streamflow data for Starkweather Coulee during ice-free months (generally April through October) were obtained from records at the Starkweather Coulee gaging station.

Daily precipitation at the ARB stations was recorded only during April through September, and several stations were not in continuous operation during water years 1981-98. Therefore, the stations were split into a north group with five stations and a south group with four stations, and the recorded daily precipitation data were averaged for each group to form two time series of data. Supplemental winter precipitation data for each group also were averaged from data records at Langdon and Edmore (north group) and at Devils Lake and Edmore (south group). The north half of the study area used the precipitation data from the north group and the south half of the study area used the precipitation data from the south group. Monthly precipitation for the study area, calculated as the average of the north and south groups, is shown in figure 2. Daily maximum and minimum temperature data for the study area were obtained by averaging the daily values from Devils Lake, Edmore, and Langdon.

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[2]In U.S. Geological Survey reports, water year is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends; thus, the water year ending September 30, 1998, is called "water year 1998."

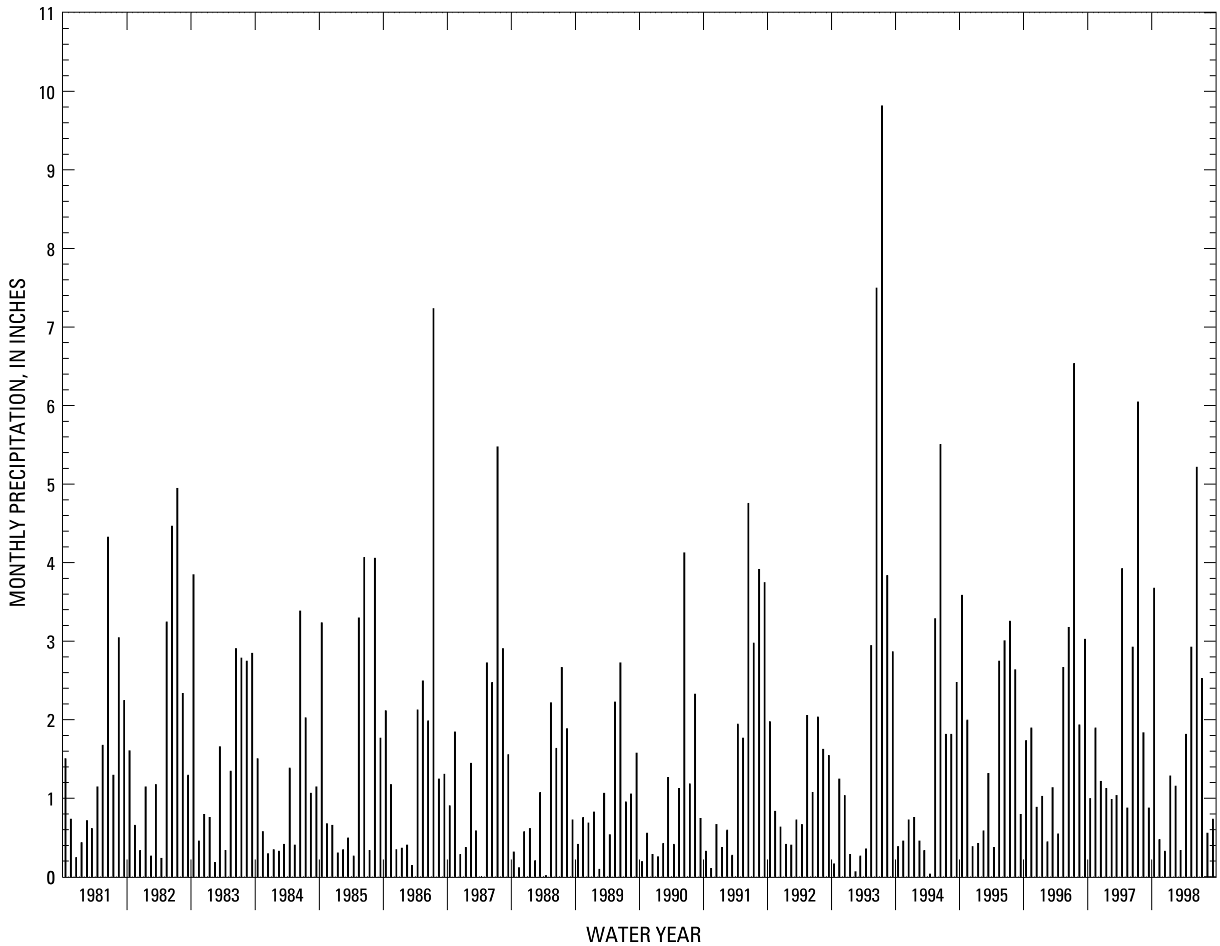


Figure 2. Monthly precipitation for the study area, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

DIGITAL ELEVATION MODEL AND ESTIMATION OF WETLANDS AREA AND VOLUME

High-resolution DEMs provided the topographic information needed for application of the PRMS hydrologic model. USGS personnel created 20 initial DEMs using 20 USGS 7.5-minute topographic maps with contour intervals of 5 feet. Elevation data from the topographic maps were sampled horizontally every 33 feet (10 meters) and interpolation schemes were used to create a digital representation of the map. During construction of the final DEM for the study area, edge-matching was used on the initial DEMs to guarantee that elevation contour lines were continuous between adjacent maps. Some of the initial DEMs that were created for the western side of the study area had elevations reported to 0.1-foot increments, which were considered sufficient for this study. Midway through the study, the USGS initiated a nationwide change in all DEM formats. The change resulted in elevations being reported to only 1.0-foot increments for the initial DEMs for the eastern side of the study area. Thus, the final DEM contained a combination of formats with elevations reported to 1.0 foot. GIS Weasel (Viger and others, 1998) was used to determine the final DEM streamflow network within the study area. A shaded-relief version of the assembled final DEM was used for field verification of hydrologic and topographic features within the study area, and a few minor modifications were made.

The final DEM for the study area had hydrologic and topographic features similar to those observed during field reconnaissance. The streamflow network determined by GIS Weasel (fig. 3) closely resembles the actual hydrography of the basin. However, two potential problems evident from field reconnaissance and from the DEM-generated streamflow network are possible flow outlets on the southeast and south-central boundaries of the study area (fig. 3). USGS personnel have observed flow from the south-central outlet of the study area into Webster Coulee during very high flows, indicating some flow bypasses the Starkweather Coulee gaging station. No measurements or estimates have been made of the cross-

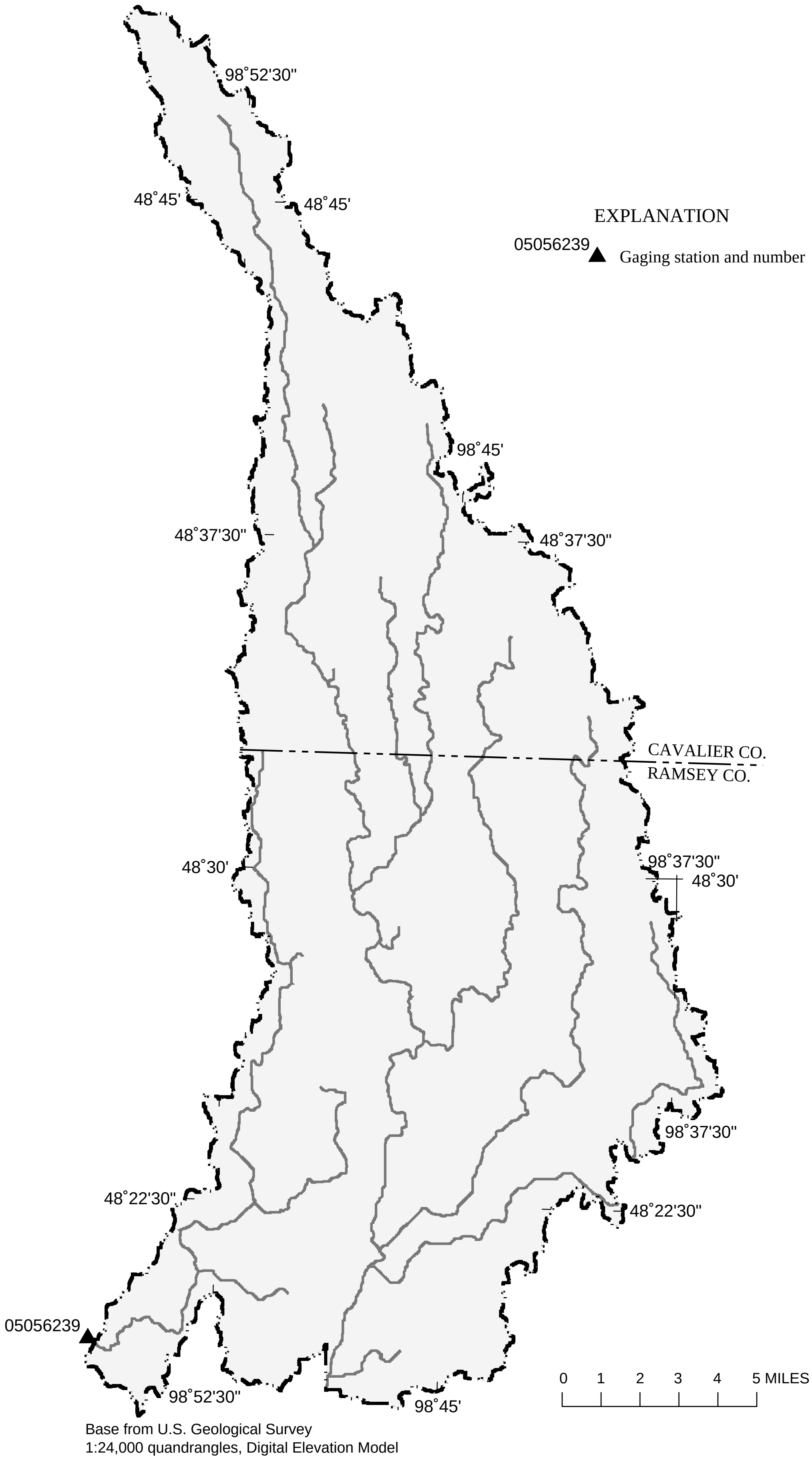


Figure 3. Streamflow network of the study area as determined by GIS Weasel, and location of gaging station, Starkweather Coulee subbasin, North Dakota.

basin flows, but the potential exists for overestimating some observed flows because the Devils Lake Basin wetlands model assumes that all simulated flows from within the study area move past the Starkweather Coulee gaging station. Incorporation of additional flow outlets is not feasible because the model does not support more than one flow outlet for each modeled basin. Also, even if subbasins for the other flow outlets are modeled, no data are available to verify model performance.

GIS tools were used to compute the surface areas and volumes to the spill elevations of the wetlands in the study area (fig. 4). The distribution of simulated wetlands corresponds generally to the National Wetlands Inventory locations of wetlands in the study area (fig. 5). The potential wetland storage in all basins to the spill elevations of the basins was calculated, and the depths and areas of individual wetlands were determined for every 10-meter grid cell from the difference between the filled DEM elevation and the final DEM elevation. The average depth and total maximum wetland area computed in this manner within each HRU then was determined. Within the study area, the average wetland depth was about 2.21 feet, the total maximum wetland area was about 30,890 acres at the overflow elevation, and the total maximum wetland volume was about 68,270 acre-feet. The total maximum wetland volume represents the condition of all wetlands being totally full, but this condition may not be attainable from precipitation or runoff because of insufficient catchment areas for all wetlands.

HYDROLOGIC MODEL

Information from the final DEM and the GIS analyses was used to develop the Devils Lake Basin wetlands model of the study area. Data sets from the GIS analyses, climatology, and geomorphology were incorporated into the model to simulate precipitation accumulation, snowmelt, evapotranspiration, soil infiltration, seepage to ground water, surface runoff, and streamflow (see appendix). Because snow catch by precipitation gages can underestimate the actual amount of snowfall on a basin from 20 percent to as much as 90 percent (Yang and others, 1995), the amount of precipitation from snowfall was multiplied by an adjustment factor of 1.5 to account for the undercatch. Also, because the Devils Lake Basin wetlands model does not have a continuous streamflow-routing mechanism for daily time-step calculations, all streamflow that is generated by the model during the daily time step is designed to leave the modeled study area by the next time step. Observations on Starkweather Coulee have indicated that the time lag for surface-water routing may be 3 to 5 days. The model does not have a routine for handling frozen soil conditions that occur during spring snowmelt events but does have a parameter to limit soil infiltration during periods when snow exists on the surface.

The study area was divided into 50 HRUs on the basis of elevation, slope, aspect, flow planes, soil types, and vegetation, using GIS Weasel (fig. 6). Each HRU produced a water balance and an energy balance that then were quantified to represent the combined effect for the study area (see appendix).

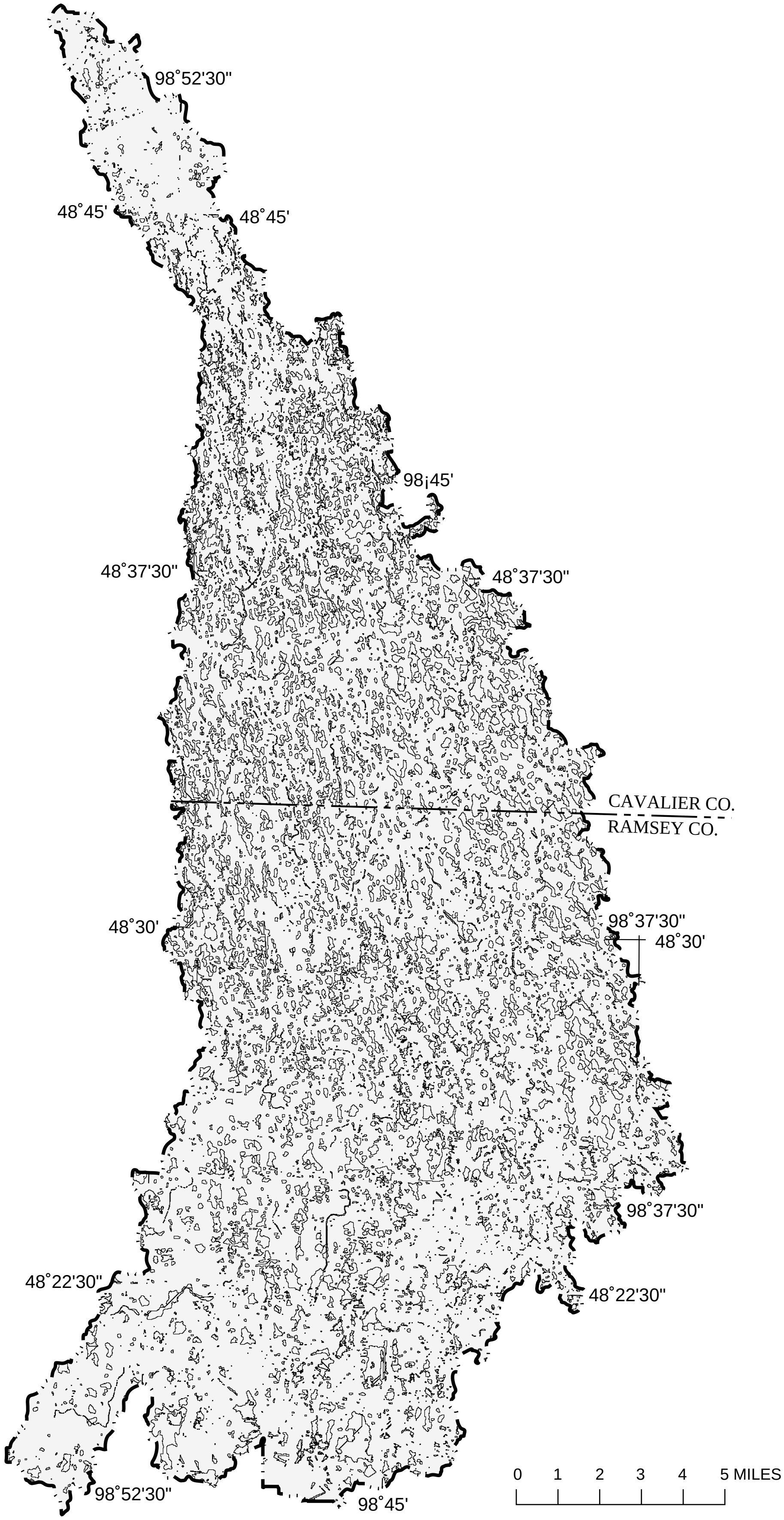
Individual wetland areas and volumes within the study area were determined from the DEM and GIS analyses. However, because of model constraints and the complexities of including thousands of individual basins, only one wetland per HRU was simulated. Therefore, 50 wetlands were modeled within the study area, and each wetland represented the combined area and volume of all DEM wetlands within the respective HRU. This large-scale simplification may lead to inaccuracies about the interactions of multiple wetland catchment areas and spill elevations with hydrologic processes but was deemed satisfactory for introducing the concept of wetlands into the PRMS. Each HRU wetland had an average depth and maximum area as determined by the DEM. The maximum wetland volume for each HRU was calculated as the average wetland depth multiplied by the maximum wetland area. The area-to-volume equation for each wetland was defined as

$$A_{max} = e^{c(\ln V_{max})}$$

where

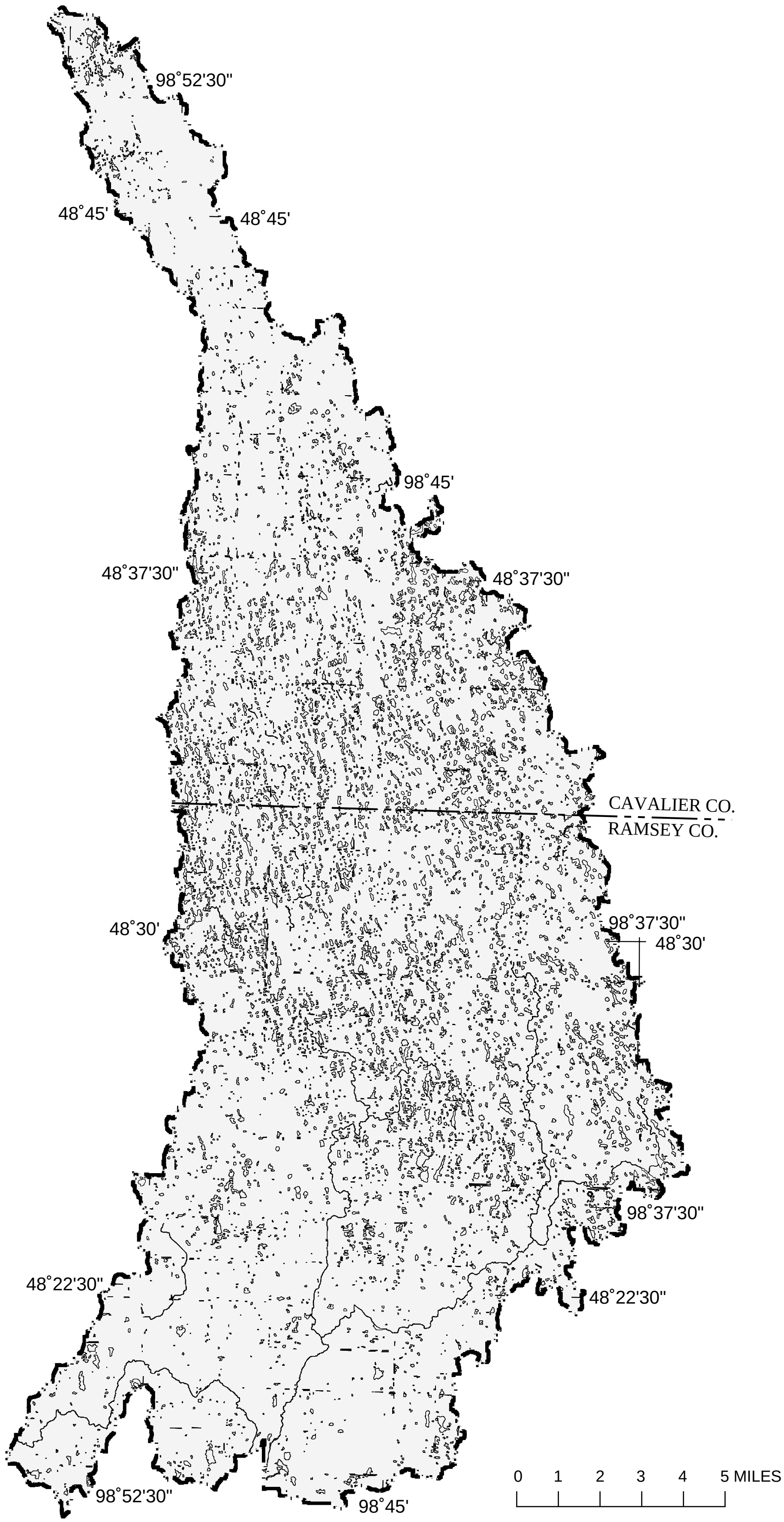
A_{max} is the decimal fraction of the maximum wetland area,
c is the area-to-volume coefficient, and
V_{max} is the decimal fraction of the maximum wetland volume.

The area-to-volume coefficient was estimated to equal 0.5 on the basis of surveying information obtained by the USGS in 1996 at several wetlands near Berthold, N. Dak. (unpublished data on file at the USGS office, Bismarck, N. Dak.).



Base from U.S. Geological Survey
1:24,000 quandrangles, Digital Elevation Model

Figure 4. Simulated wetlands from the digital elevation model of the study area, Starkweather Coulee subbasin, North Dakota.



Base from U.S. Geological Survey
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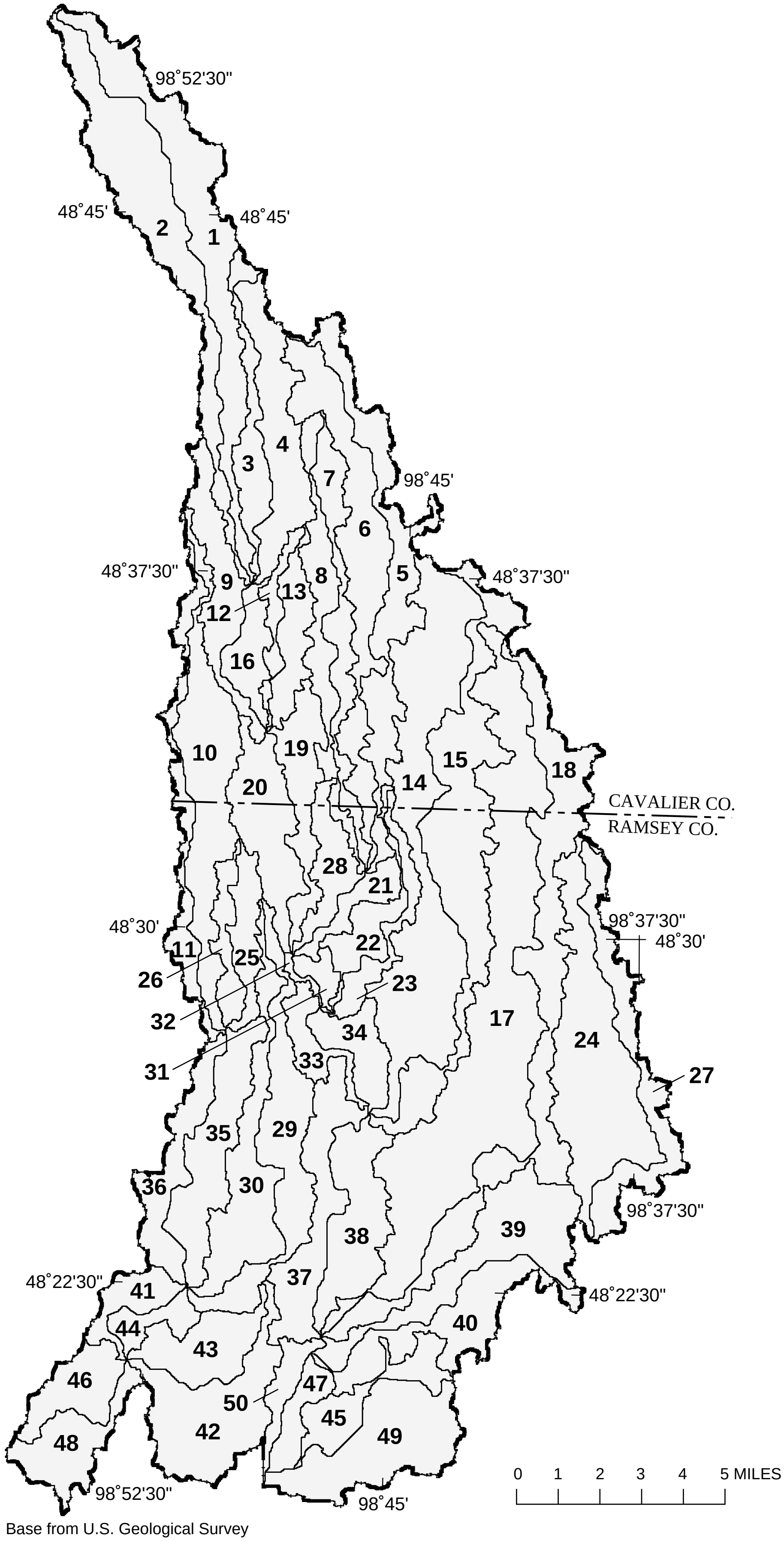
Figure 5. Locations of wetlands in the study area, Starkweather Coulee subbasin, North Dakota. (Based on data from U.S. Fish and Wildlife Service National Wetlands Inventory.)



Base from U.S. Geological Survey
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Figure 6. Simulated hydrologic response units of the study area using GIS Weasel, Starkweather Coulee subbasin, North Dakota. (Numbers indicate the individual hydrologic response units.)

Each HRU wetland was partitioned into two parts, an open wetland and a closed wetland. A parameter was used to determine the part of the HRU wetland that was defined as open, and the remainder of the HRU wetland then was defined as closed. The open wetland was defined as having an outlet with a spillage threshold that was equal to a fraction of the total volume of the open wetland without an outlet. If an open wetland had a spillage threshold of 0.5, water would flow from the wetland when the volume of the open wetland reached 50 percent of its total volume without an outlet. Precipitation volumes falling on an open wetland and evaporation volumes lost from an open wetland were dependent on calculated open-water area. Surface runoff generated for each HRU was routed into the open wetland using a user-defined fraction of runoff into the wetland. The remaining runoff entered the streamflow network. Spillage volumes from the open wetland were directly proportional to the difference between the wetland volume and the wetland water volume at the spillage threshold. Spillage volumes were routed into the streamflow network. Wetland ground-water-recharge rates were set to vary directly with wetland water depth. The closed wetland was defined as not having an outlet. Therefore, the closed wetland did not spill, but did gain and lose water in the same manner as the open wetland. All closed wetlands were allowed to increase their volume beyond their maximum to simulate the expansion of wetlands areas within the study area.

The hydrologic model was set to run on a daily time step and to simulate conditions for water years 1981-98. The initial volume of water stored in the study area at the beginning of the run was about 33,240 acre-feet. This total was calculated from the assumed initial conditions for the wetlands and the soil portions of the study area. The wetland water volume was assumed to equal 10 percent (6,827 acre-feet) of the total maximum wetland volume (68,270 acre-feet) and was assumed to occupy 9,760 acres of the total maximum wetland area of 30,890 acres based on the area-to-volume equation applied to each of the 50 wetlands and summed. Soil water content was assumed to be 2 inches (0.167 foot) over the remaining study area (167,900 minus 9,760 equals 158,140 acres) for a total soil water volume of about 26,410 acre-feet. The model partitioned the precipitation and snowmelt into the wetland, into the soil, or into stream channels. Runoff from impervious areas of the study area can occur, but no such areas were defined in the model. Once the soil moisture conditions were satisfied, additional inputs of water were routed to ground water or as surface runoff into the wetland or into stream channels. Modeled surface runoff into the wetland represents 90 percent of total surface runoff generated. The remaining 10 percent flowed directly to stream channels. The amount of evapotranspiration from the soil and wetlands was modeled using the Jensen-Haise formulation (Jensen and Haise, 1963).

Model Parameterization

Parameter values were chosen to closely approximate actual conditions in the study area. Most values associated with surface features and atmospheric conditions were determined from information derived from GIS tools, climate data, field observations, and soil survey publications. Parameter values associated with physics-based processes, such as snowmelt, infiltration, and radiation transfer, were obtained from the default parameter lists of previous versions of the PRMS. Selected parameter values assigned to each HRU are listed in table 1.

Several assumptions about wetlands and wetland processes were made prior to parameterization. The percentage of wetlands in the study area that spilled to channels (open wetlands) was estimated from DEM products to be 50 percent. The assumption was based on the knowledge that many, but probably not all, wetlands in the study area have had some degree of drainage. Another assumption was that the open wetlands would begin to spill when 20 percent of the storage volume was reached. The storage volumes of the wetlands were determined from the difference between the filled DEM elevations and the final DEM elevations. Initial storage in the wetlands was assumed to be 10 percent of the maximum possible storage. Wetland seepage rates were set to 0.002 of the current wetland water depth (Winter and Rosenberry, 1995), which would equal 0.1 inch per day for wetlands with water depths of 50 inches.

Model Calibration

Model runs were made for water years 1981-98 to calibrate the model to observed streamflows that were obtained from the Starkweather Coulee gaging station. Model calibration was achieved by adjusting the values for maximum available soil water in the soil profil6e within the root zone until the simulated streamflow from the study area for the 18-year period nearly equaled the observed streamflow for the 18-year period. The values of maximum available soil water in the soil profile that were used for calibration remained within the ranges of values for the soils involved as reported in the county soil surveys (Bigler and Liudahl, 1986; Simmons and Moos, 1990). Other parameter values could have been

Table 1. Hydrologic response unit parameters used in the hydrologic model, Starkweather Coulee subbasin, North Dakota, water years 1981-98

[HRU, hydrologic response unit]

HRU	Area (acres)	Elevation (feet above sea level)	Slope (foot per foot)	Summer canopy fraction	Winter canopy fraction	Fraction of HRU area that is wetland	Mean wetlands water depth (inches)	Wetlands seepage rate (inches per day)	Fraction of open wetlands	Open-wetland fractional volume at spillage	Fraction of runoff that enters wetland	Daily maximum surface water that enters ground water (inches)	Maximum available soil water in soil profile (inches)	Maximum available soil water in upper zone (inches)
1	6,182	1,610	0.002	0.9	0.5	0.081	16.7	0.002	0.5	0.2	0.9	0.12	10.45	7.91
2	6,286	1,610	0.002	0.9	0.5	0.085	16.4	0.002	0.5	0.2	0.9	0.12	10.68	7.91
3	2,020	1,600	0.002	0.9	0.5	0.145	23.9	0.002	0.5	0.2	0.9	0.12	10.45	7.91
4	3,684	1,600	0.002	0.9	0.5	0.175	23.5	0.002	0.5	0.2	0.9	0.12	10.45	7.91
5	4,936	1,580	0.002	0.9	0.5	0.212	23.9	0.002	0.5	0.2	0.9	0.12	10.37	7.85
6	5,507	1,575	0.002	0.9	0.5	0.234	25.3	0.002	0.5	0.2	0.9	0.12	10.39	7.87
7	2,591	1,575	0.002	0.9	0.5	0.219	25.3	0.002	0.5	0.2	0.9	0.12	10.33	7.83
8	2,690	1,570	0.002	0.9	0.5	0.222	24.8	0.002	0.5	0.2	0.9	0.12	10.33	7.83
9	2,627	1,570	0.002	0.9	0.5	0.210	28.5	0.002	0.5	0.2	0.9	0.12	10.36	7.84
10	5,298	1,530	0.002	0.9	0.5	0.258	32.4	0.002	0.5	0.2	0.9	0.12	10.24	7.76
11	2,249	1,520	0.002	0.9	0.5	0.247	32.6	0.002	0.5	0.2	0.9	0.12	10.24	7.75
12	1,751	1,570	0.002	0.9	0.5	0.250	29.4	0.002	0.5	0.2	0.9	0.12	10.30	7.80
13	806	1,565	0.002	0.9	0.5	0.197	25.4	0.002	0.5	0.2	0.9	0.12	10.33	7.82
14	9,888	1,535	0.002	0.9	0.5	0.225	29.9	0.002	0.5	0.2	0.9	0.12	10.24	7.76
15	7,725	1,535	0.002	0.9	0.5	0.216	26.7	0.002	0.5	0.2	0.9	0.12	10.23	7.75
16	1,422	1,570	0.002	0.9	0.5	0.209	28.3	0.002	0.5	0.2	0.9	0.12	10.26	7.77
17	14,558	1,535	0.002	0.9	0.5	0.207	30.0	0.002	0.5	0.2	0.9	0.12	10.18	7.71
18	8,010	1,540	0.002	0.9	0.5	0.194	29.8	0.002	0.5	0.2	0.9	0.12	10.19	7.71
19	2,428	1,550	0.002	0.9	0.5	0.226	27.6	0.002	0.5	0.2	0.9	0.12	10.23	7.75
20	3,289	1,540	0.002	0.9	0.5	0.188	28.5	0.002	0.5	0.2	0.9	0.12	10.23	7.75
21	1,656	1,550	0.002	0.9	0.5	0.208	27.3	0.002	0.5	0.2	0.9	0.12	10.23	7.75
22	1,493	1,550	0.002	0.9	0.5	0.219	30.1	0.002	0.5	0.2	0.9	0.12	10.23	7.75
23	1,319	1,560	0.002	0.9	0.5	0.188	27.1	0.002	0.5	0.2	0.9	0.12	10.23	7.75
24	7,059	1,515	0.002	0.9	0.5	0.213	30.9	0.002	0.5	0.2	0.9	0.12	10.27	7.78
25	1,465	1,510	0.002	0.9	0.5	0.236	29.4	0.002	0.5	0.2	0.9	0.12	10.23	7.75

Table 1. Hydrologic response unit parameters used in the hydrologic model, Starkweather Coulee subbasin, North Dakota, water years 1981-98—Continued

[HRU, hydrologic response unit]

HRU	Area (acres)	Elevation (feet above sea level)	Slope (foot per foot)	Summer canopy fraction	Winter canopy fraction	Fraction of HRU area that is wetland	Mean wetlands water depth (inches)	Wetlands seepage rate (inches per day)	Fraction of open wetlands	Open-wetland fractional volume at spillage	Fraction of runoff that enters wetland	Daily maximum surface water that enters ground water (inches)	Maximum available soil water in soil profile (inches)	Maximum available soil water in upper zone (inches)
26	1,167	1,510	0.002	0.9	0.5	0.202	25.2	0.002	0.5	0.2	0.9	0.12	10.23	7.75
27	3,454	1,520	0.002	0.9	0.5	0.176	28.6	0.002	0.5	0.2	0.9	0.12	10.27	7.78
28	1,030	1,545	0.002	0.9	0.5	0.177	28.9	0.002	0.5	0.2	0.9	0.12	10.23	7.75
29	4,398	1,495	0.002	0.9	0.5	0.160	24.8	0.002	0.5	0.2	0.9	0.12	9.88	7.48
30	4,021	1,480	0.002	0.9	0.5	0.198	24.6	0.002	0.5	0.2	0.9	0.12	10.20	7.73
31	529	1,520	0.002	0.9	0.5	0.264	39.8	0.002	0.5	0.2	0.9	0.12	10.23	7.75
32	161	1,510	0.002	0.9	0.5	0.033	17.2	0.002	0.5	0.2	0.9	0.12	10.23	7.75
33	1,179	1,510	0.002	0.9	0.5	0.188	26.0	0.002	0.5	0.2	0.9	0.12	10.23	7.75
34	1,658	1,515	0.002	0.9	0.5	0.197	27.2	0.002	0.5	0.2	0.9	0.12	10.23	7.75
35	3,634	1,500	0.002	0.9	0.5	0.137	20.6	0.002	0.5	0.2	0.9	0.12	10.17	7.70
36	2,514	1,490	0.002	0.9	0.5	0.133	17.8	0.002	0.5	0.2	0.9	0.12	9.91	7.50
37	3,506	1,500	0.002	0.9	0.5	0.209	26.5	0.002	0.5	0.2	0.9	0.12	9.90	7.50
38	3,508	1,500	0.002	0.9	0.5	0.209	26.2	0.002	0.5	0.2	0.9	0.12	10.02	7.59
39	4,534	1,505	0.002	0.9	0.5	0.143	29.2	0.002	0.5	0.2	0.9	0.12	10.27	7.78
40	3,500	1,505	0.002	0.9	0.5	0.136	23.9	0.002	0.5	0.2	0.9	0.12	10.43	7.90
41	1,278	1,470	0.002	0.9	0.5	0.115	18.1	0.002	0.5	0.2	0.9	0.12	9.92	7.51
42	4,561	1,470	0.002	0.9	0.5	0.169	16.6	0.002	0.5	0.2	0.9	0.12	9.80	7.42
43	2,457	1,475	0.002	0.9	0.5	0.083	18.7	0.002	0.5	0.2	0.9	0.12	9.76	7.39
44	956	1,465	0.002	0.9	0.5	0.146	32.0	0.002	0.5	0.2	0.9	0.12	9.85	7.46
45	1,984	1,480	0.002	0.9	0.5	0.211	19.1	0.002	0.5	0.2	0.9	0.12	10.24	7.75
46	2,005	1,465	0.002	0.9	0.5	0.102	16.4	0.002	0.5	0.2	0.9	0.12	9.93	7.52
47	1,108	1,475	0.002	0.9	0.5	0.125	15.5	0.002	0.5	0.2	0.9	0.12	10.12	7.67
48	2,318	1,470	0.002	0.9	0.5	0.067	19.9	0.002	0.5	0.2	0.9	0.12	10.23	7.75
49	4,592	1,480	0.002	0.9	0.5	0.155	21.3	0.002	0.5	0.2	0.9	0.12	10.18	7.71
50	951	1,475	0.002	0.9	0.5	0.122	17.6	0.002	0.5	0.2	0.9	0.12	10.48	7.93

adjusted to achieve calibration, but the model appeared to be less sensitive to the other parameters. By adjusting only the values for maximum available soil water in the soil profile, additional assumptions about changes in other parameter values were not required and physically-realistic values were maintained.

Annual water balances were determined for the final calibration run as the differences between the annual water gains (precipitation) and the annual water losses (evapotranspiration plus change in storage plus streamflow). Generally, the cumulative water balances for most years of the calibration run were less than 0.03 inch, which indicated that almost all water during those years was accountable (table 2). Four water years (1981, 1983, 1991, and 1998) had cumulative water balances greater than 0.03 inch, which indicated a greater amount of water gain than water loss. However, the following water years (1982, 1984, and 1992) had cumulative water balances that were again near zero, which indicated a near-zero water balance for the 2-year period. The result indicates that some model discrepancy was acting to simulate excess water one water year but then remove the excess the next water year for a 2-year balance. The reason for this discrepancy is unknown.

Table 2. Annual water balance components and cumulative water balance from calibration of the hydrologic model, Starkweather Coulee subbasin, North Dakota, water years 1981-98

Water year	Precipitation (inches)	Evapotranspiration (inches)	Storage change (inches)	Simulated streamflow (inches)	Annual water balance[1] (inches)	Cumulative water balance (inches)
1981	19.025	17.027	1.635	0.228	0.135	0.135
1982	22.608	22.053	0.167	0.522	-0.134	0.001
1983	22.085	20.339	0.394	1.086	0.266	0.267
1984	13.395	15.650	-2.232	0.241	-0.264	0.003
1985	20.960	18.757	1.917	0.287	-0.001	0.002
1986	22.334	22.318	-0.597	0.607	0.006	0.008
1987	22.314	21.673	0.347	0.294	0	0.008
1988	12.606	14.518	-2.046	0.135	-0.001	0.007
1989	13.999	13.804	0.133	0.062	0	0.007
1990	13.842	13.488	0.297	0.061	-0.004	0.003
1991	22.687	19.154	2.979	0.322	0.232	0.235
1992	16.185	16.938	-1.105	0.577	-0.225	0.010
1993	30.312	23.920	4.184	2.208	0	0.010
1994	18.664	20.843	-3.074	0.896	-0.001	0.009
1995	23.954	22.502	-0.333	1.787	-0.002	0.007
1996	27.293	23.490	1.879	1.921	0.003	0.010
1997	27.989	23.189	-0.191	4.976	0.015	0.025
1998	23.830	24.473	-2.531	1.673	0.215	0.240

[1]Annual water balance = precipitation - evapotranspiration - change in storage - simulated streamflow.

Simulated and observed daily streamflows for water years 1981-98 are shown in figure 7. The two hydrographs have many similarities, especially in the timing of spring runoff from snowmelt. However, observed annual peak streamflows were greater than simulated annual peak streamflows for all water years except 1983. The differences probably were caused mostly by the lack of a subroutine in the model to account for frozen soil. Generally, recessionary limbs extended more on the simulated hydrographs than on the observed hydrographs. The model also tended to simulate more streamflow during summer and autumn rainfall. Simulated streamflows were much higher than observed streamflows in the spring of 1997. The difference between the streamflows during that time may have occurred because some of the water flowed out of the study area and into Webster Coulee (referred to as breakout flows); thus, the flow bypassed the Starkweather Coulee gaging station. Breakout flows were observed during the spring of 1997. However, it also is possible that the difference between streamflows in 1997 resulted from problems with calibration of the model to high flows. Although the simulated and observed streamflows for the 18-year period were similar, simulated annual streamflow for the individual years varied considerably from observed annual streamflow during many of the water years (table 3). Perhaps the actual hydrologic processes in the study area could not be accounted for adequately by the equations and parameters that simulated soil water infiltration and storage, snowmelt, and wetlands hydrology.

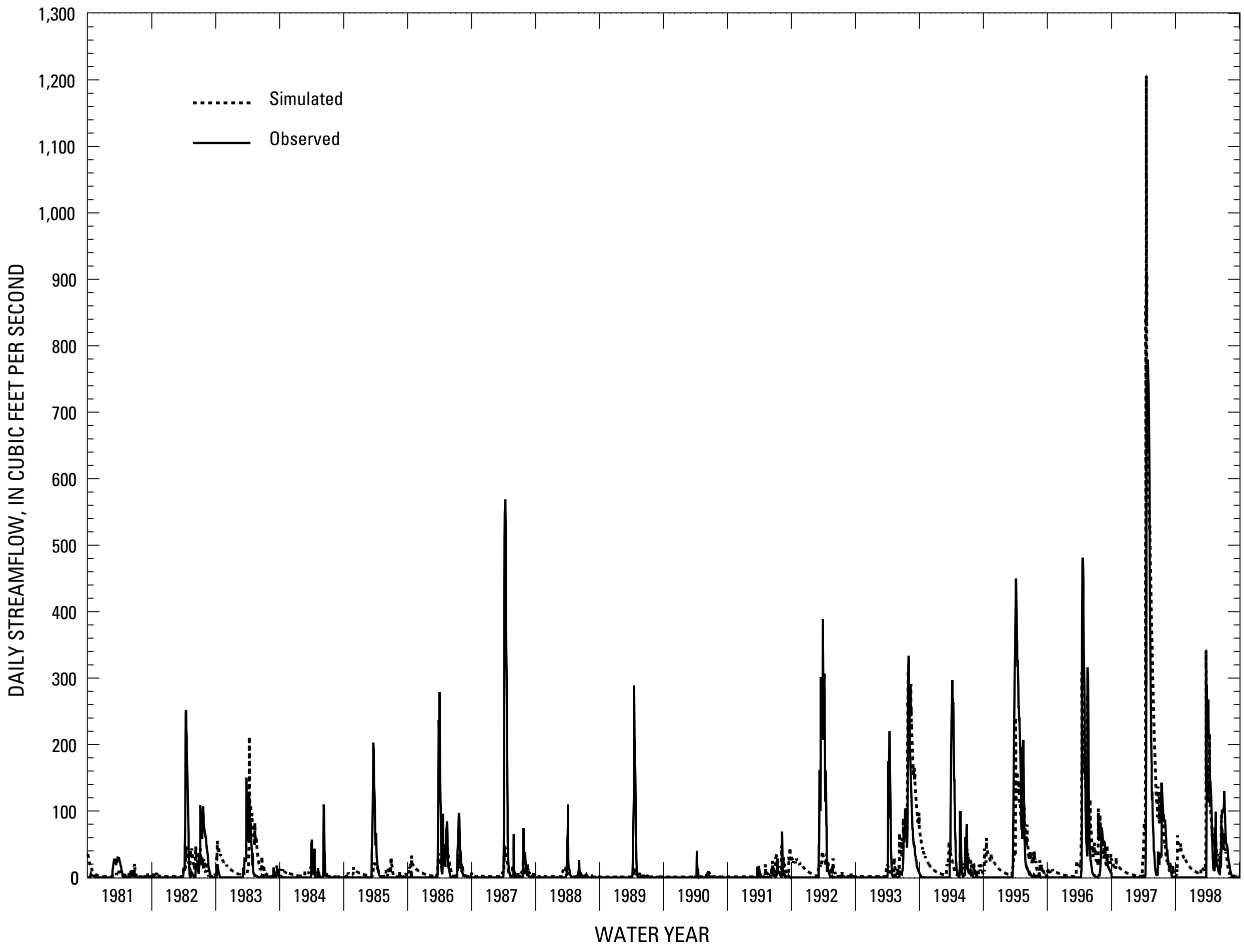

Figure 7. Precipitation-Runoff Modeling System simulated and observed daily streamflows, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

Simulated daily wetlands areas for water years 1981-98 are shown in figure 8. The simulated daily wetlands area is the sum of open and closed wetlands areas. The model permitted the closed wetlands to expand beyond their DEM-determined areas to simulate the inundation of surface area that has occurred since the recent wet period began in water year 1993. Simulated daily wetlands areas increased during large runoff events but decreased during drier periods, mostly summertime, because of increased evapotranspiration. The largest amount of simulated daily wetlands area occurred in April 1997 when about 40,500 acres (24 percent) of the study area was covered with water. Also during April 1997, the simulated daily water volume in the open and closed wetlands combined attained a maximum of about 116,000 acre-feet (fig. 9). The open wetlands contained about 44,000 acre-feet of water, and the closed wetlands contained about 72,000 acre-feet of water. During most of the calibration run, the simulated daily wetlands area was less than about 31,000 acres, which was about equal to the amount of wetlands area originally determined from the final DEM of the study area.

Comparisons of simulated annual water volumes in the wetlands to simulated annual water volumes in the study area for water years 1981-99 are shown in figure 10. Total water storage includes water stored in wetlands, channels, soils, and ground-water reservoirs. During water years 1981-92, the percentage of study area water stored in wetlands ranged from about 17 to 31 percent. During water years 1993-98, the percentage of study area water stored in wetlands had risen to between 37 and 66 percent. During water year 1998, annual evapotranspiration exceeded annual precipitation for the first time since water year 1994 (table 2), which resulted in a considerable reduction in the soil moisture portion of the total water storage within the study area.

Table 3. Observed and simulated annual streamflows and simulated streamflow as a percentage of observed streamflow, Starkweather Coulee subbasin, North Dakota, water years 1981-98

Year	Observed streamflow (inches)	Simulated streamflow (inches)	Percent error[1]
1981	0.214	0.228	6
1982	1.043	0.522	-50
1983	0.503	1.086	116
1984	0.194	0.241	24
1985	0.435	0.287	-34
1986	0.879	0.607	-31
1987	1.267	0.294	-77
1988	0.120	0.135	12
1989	0.411	0.062	-85
1990	0.026	0.061	135
1991	0.126	0.322	156
1992	1.316	0.577	-56
1993	1.619	2.208	36
1994	1.063	0.896	-16
1995	2.186	1.787	-18
1996	1.798	1.921	7
1997	3.187	4.976	56
1998	1.513	1.673	11
Total	17.901	17.884	0

[1]Percent error = (simulated streamflow - observed streamflow) x 100/observed streamflow.

SIMULATION OF STREAMFLOW AND WETLAND STORAGE

After calibration, the simulated streamflow response to increased open-wetlands spillage thresholds was evaluated. The implied physical effect of increasing spillage thresholds is a filling of the spillways from open wetlands to permit the wetlands to hold more water. The larger the spillage threshold, the larger the open-wetlands water volume must be before spillage can occur. Closed wetlands were not affected by the change in spillage thresholds because closed wetlands are defined as not spilling. In addition to the calibration spillage threshold of 0.2, spillage thresholds of 0.3, 0.4, 0.6, 0.8, and 1.0 times the wetlands volumes were used in the simulations. A spillage threshold of 1.0 makes an open wetland respond similarly to a closed wetland until the spillage volume of the open wetland is reached. By increasing the spillage thresholds from 0.2 to 1.0, simulated streamflow was reduced by about 8.77 inches (from about 17.88 to 9.11 inches; 49 percent) for the 18-year period, and simulated annual streamflow was reduced by more than 80 percent for water years 1982, 1986, and 1992 (table 4). During the drier water years of 1988-90, simulated streamflows for spillage thresholds of 1.0 were reduced by no more than about 50 percent from simulated streamflows for spillage thresholds of 0.2 because smaller amounts of streamflow were generated and wetlands were not filled. However, by increasing the spillage thresholds from 0.2 to 1.0, simulated annual streamflow for water year 1997 was reduced by only 20 percent (table 4). Water year 1997 was a large-runoff year and wetlands were filled.

The increase in open-wetlands spillage thresholds from 0.2 to 1.0 resulted in an increase in simulated daily wetlands area throughout most of the simulation period (fig. 11). Early in the simulation period, water years 1983-88, the wetlands area simulated for a spillage threshold of 1.0 remained greater than for a spillage threshold of 0.2. Beginning in water year 1988, a 4-year dry period resulted in simulated wetlands areas that were about the same for both thresholds. However, beginning in water year 1993, the beginning of the recent wet period, simulated wetlands areas were as much as 25 percent more for spillage thresholds of 1.0 than for spillage thresholds of 0.2. The largest simulated daily wetlands area occurred in 1997; the wetlands area increased from about 40,500 acres at a spillage threshold of 0.2 to about 45,000 acres at a spillage threshold of 1.0.

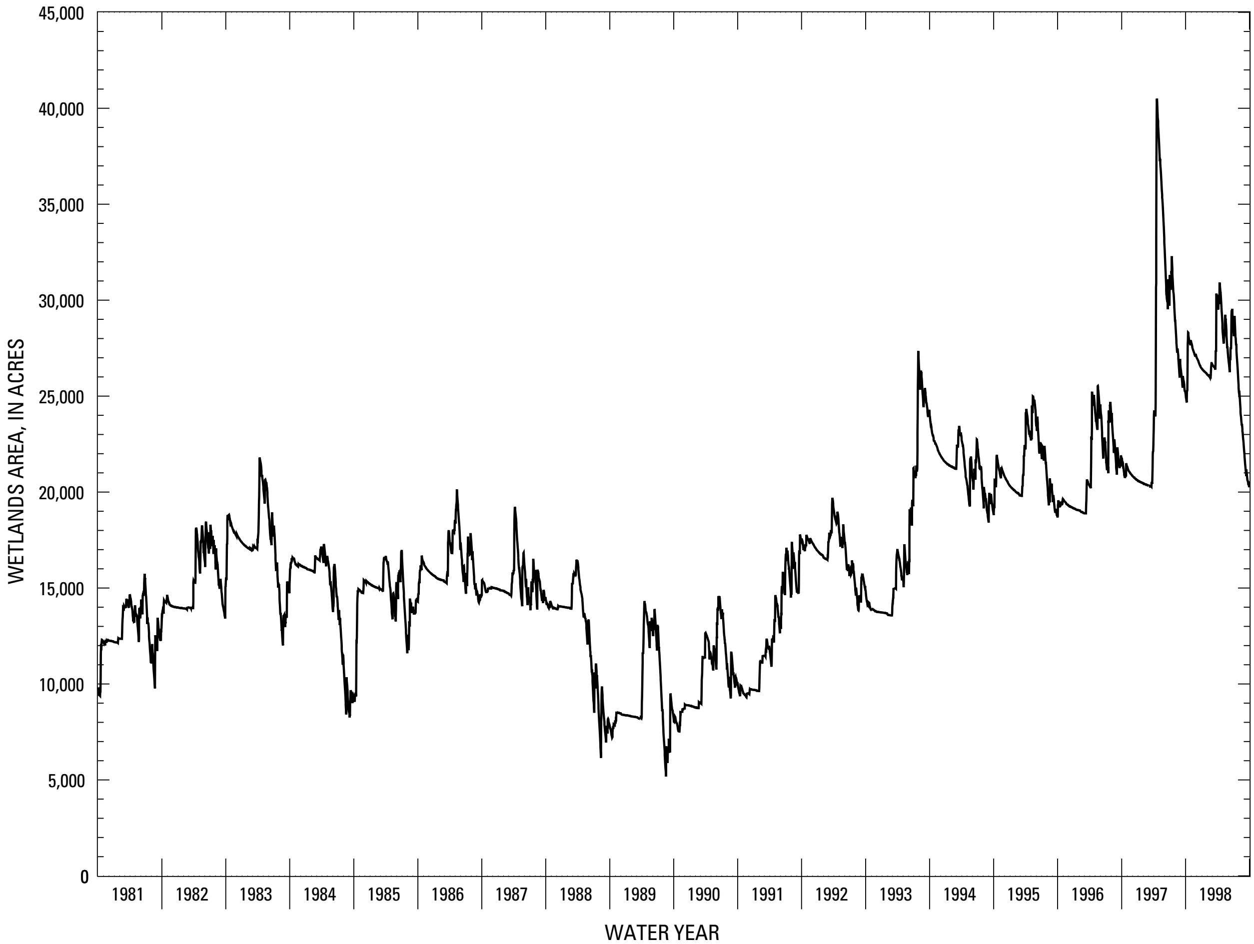

Figure 8. Precipitation-Runoff Modeling System simulated daily wetlands areas, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

The changes in simulated wetlands area for an increase in open-wetlands spillage thresholds from 0.2 to 1.0 are shown in figure 12. From water year 1981 to the beginning of water year 1993, the annual change in total wetlands area was less than 4,000 acres. However, beginning in water year 1993, the increased spillage thresholds resulted in increased simulated amounts of total wetlands area and amounts of water retained. Simulated differences in wetlands areas remained great throughout water years 1994-98, and the change in wetlands area rarely fell below 4,000 acres. Also, the model indicated that total wetlands (open and closed combined) area simulated at open-wetlands spillage thresholds of 1.0 remained greater even in periods of water-level decline during water years 1994-98. The increased size of the open wetlands with thresholds of 1.0 made open wetlands respond more similarly to closed wetlands because the enlarged open wetlands could retain more water for longer periods of time.

Simulated open-wetlands water volumes at spillage thresholds of 0.2 and 1.0 (fig. 13) show a similar pattern to simulated daily wetlands areas at the same thresholds (fig. 11). The simulated maximum open-wetlands water volume for a spillage threshold of 1.0, about 68,000 acre-feet, occurred during water year 1997. The 68,000-acre-feet volume is an increase of 24,000 acre-feet over the simulated maximum volume for a spillage threshold of 0.2, which also occurred during water year 1997. During water years 1994-98, simulated annual streamflows for open-wetlands spillage thresholds of 1.0 remained less than for thresholds of 0.2 even though the open wetlands probably were near maximum volume (table 4). The greatly increased size of the closed wetlands during water years 1994-98 probably allowed for increased water storage and decreased simulated streamflow from the study area.

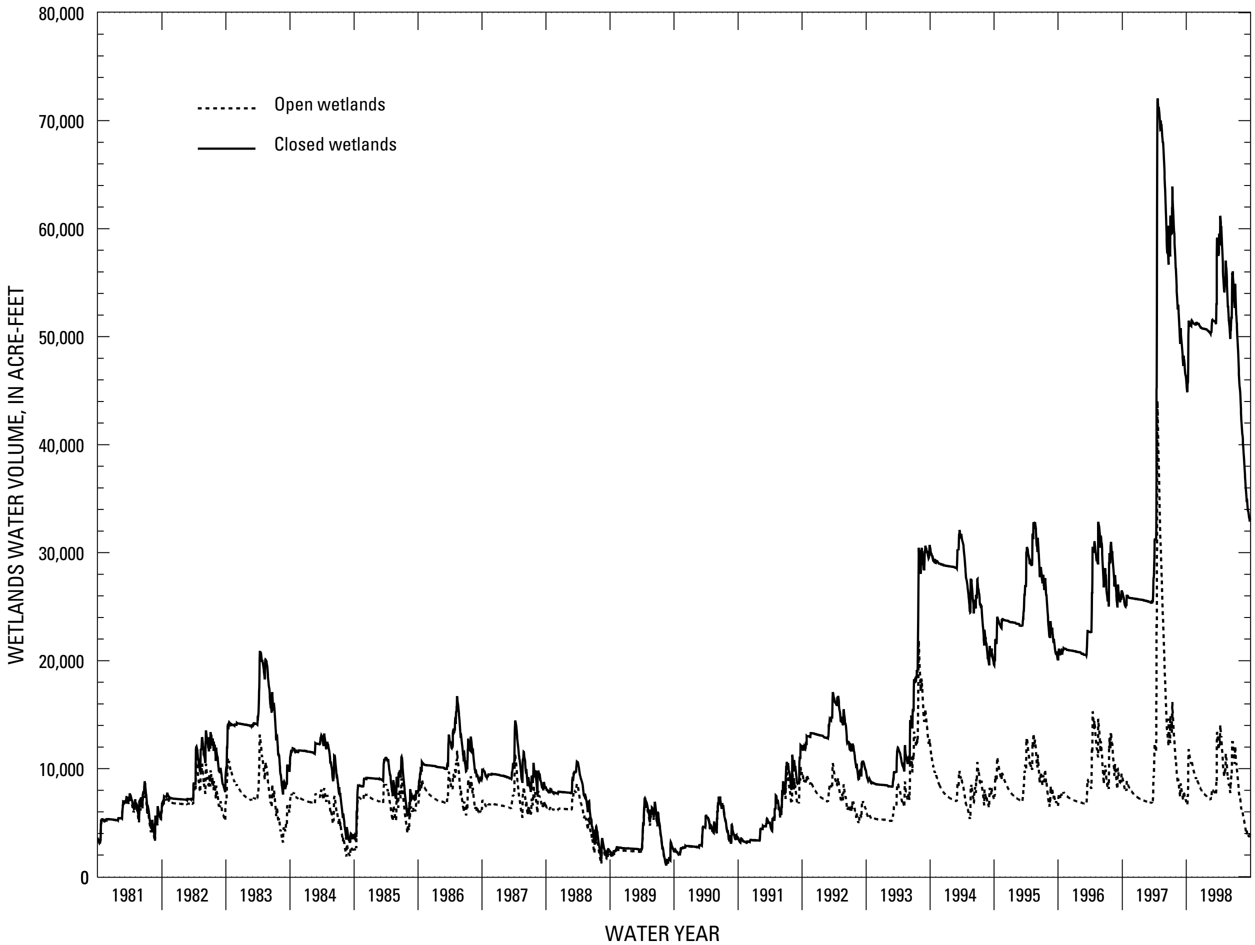

Figure 9. Precipitation-Runoff Modeling System simulated daily water volumes in open and closed wetlands, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

MODEL LIMITATIONS AND CONSIDERATIONS

The Devils Lake Basin wetlands model applied to the study area simulated many features of the streamflow record from the Starkweather Coulee gaging station. Although the model was challenged by the relatively flat terrain of the Devils Lake Basin, the model performed well for this study because of many modifications made to the PRMS. The inclusion in the PRMS of a wetlands hydrology subroutine that allowed for the addition of wetland storage in each HRU permitted the Devils Lake Basin wetlands model to better simulate streamflow conditions in the study area. However, the lack of a frozen-soils subroutine in the model probably inhibited the accurate simulation of snowmelt-runoff amounts. Many of the parameters that concerned wetlands hydrology were reasonable approximations of the physical features even without a quantitative representation of those processes in the model.

The DEM and the Devils Lake Basin wetlands model did not include information about the locations of roads, ditches, or other diversionary structures within the study area. The DEM was used to estimate the amounts of water stored, or potentially stored, in the study area as defined from topographic maps with 5-foot contour intervals. Therefore, it was possible that the depths and areas of all wetlands that existed in the basin were not represented adequately. However, the horizontal sampling increment of 33 feet (10 meters) permitted the identification of small wetlands that may not have been evident on a standard DEM that has a horizontal sampling increment of 100 feet (30 meters).

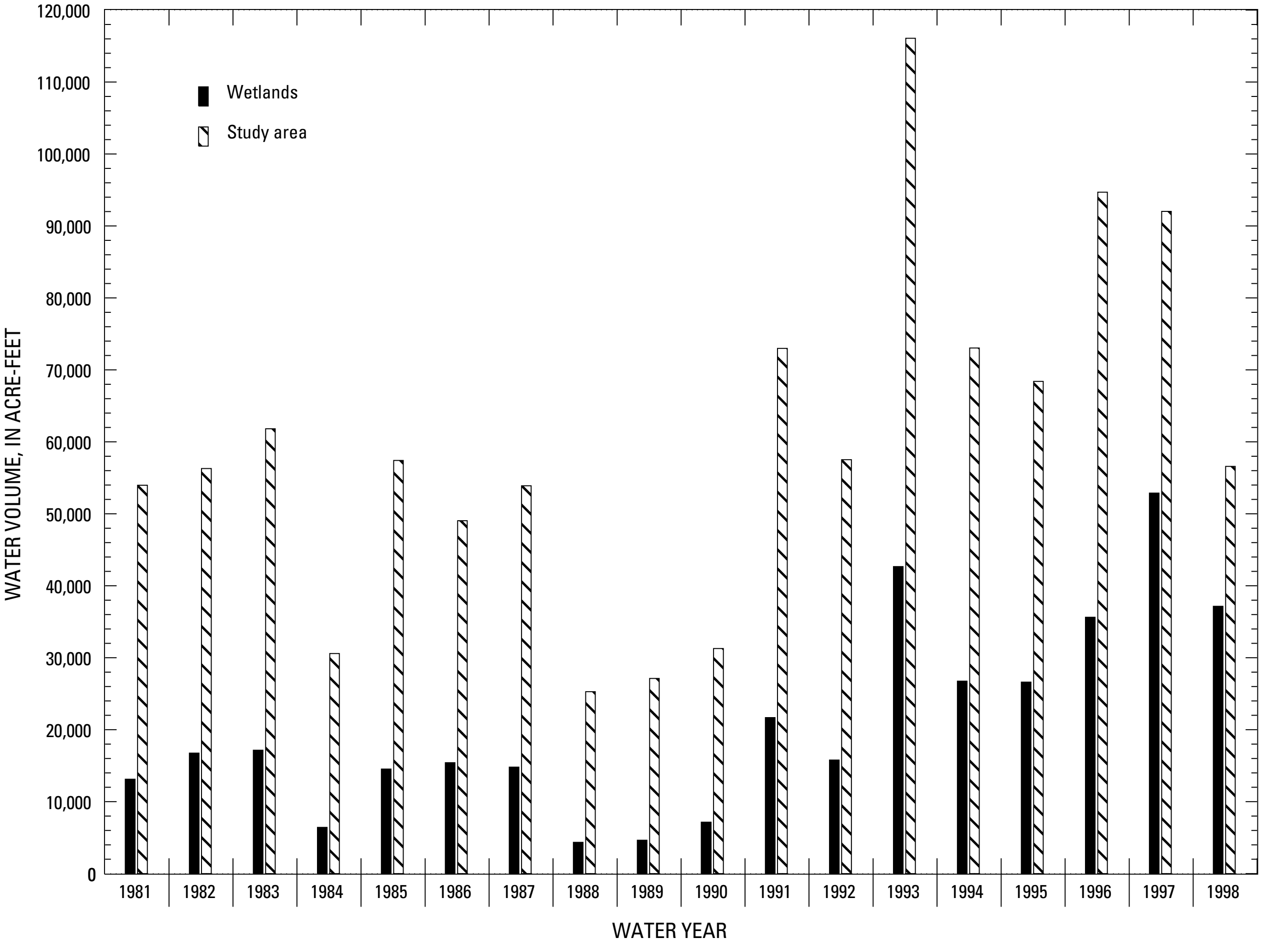

Figure 10. Precipitation-Runoff Modeling System simulated annual water volumes in wetlands and in the study area, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

More work is important to improve the wetlands hydrology subroutine and to include a frozen-soils subroutine. Methods for incorporating more than one wetland in each HRU and for better defining the hydrology of the wetlands could be developed and utilized in the model. A frozen-soils subroutine was developed for an earlier version of the PRMS (Emerson, 1991) and work will continue to incorporate the subroutine into the current modular versions of the PRMS. In addition, other data are being collected at various sites to help define the roles and functions of wetlands in small watersheds.

SUMMARY

A study was initiated in cooperation with the North Dakota State Water Commission to simulate streamflow and wetland storage within a part of the Starkweather Coulee subbasin. The study utilized digital elevation data, geographic-information-system tools, and the U.S. Geological Survey Precipitation-Runoff Modeling System to define flow networks, to estimate wetland storage capacity, and to simulate streamflow and storage within the low-relief landscape of the study area. Information from the study may be useful to water managers, researchers, and others associated with the water issues that have arisen because of the rising water levels of Devils Lake.

U.S. Geological Survey personnel created a final digital elevation model of the study area by using 20 U.S. Geological Survey 7.5-minute topographic maps with contour intervals of 5 feet. Elevation data from the topographic maps were sampled horizontally every 33 feet (10 meters) and interpolation schemes were used to create a digital representation of the map. The final digital elevation model had elevations reported to 1.0 foot and had features similar to those observed during field reconnaissance. The streamflow network determined by GIS Weasel closely resembles the actual hydrography of the basin. Geographic-information-system tools were used to compute the surface areas and volumes to the spill elevations of the wetlands in the study area. Within the study area, the average wetland depth was about 2.21 feet, the total maximum wetland area was about 30,890 acres at the overflow elevation, and the total maximum wetland volume was about 68,270 acre-feet.

Table 4. Simulated annual streamflow and total-period streamflow for various open-wetlands spillage thresholds, Starkweather Coulee subbasin, North Dakota, water years 1981-98

Water year	Simulated streamflow for indicated spillage threshold (inches)					
	0.2	0.3	0.4	0.6	0.8	1.0
1981	0.228	0.170	0.167	0.167	0.167	0.167
1982	0.522	0.248	0.123	0.091	0.091	0.091
1983	1.086	0.904	0.703	0.522	0.439	0.410
1984	0.241	0.149	0.105	0.084	0.084	0.084
1985	0.287	0.106	0.084	0.083	0.083	0.083
1986	0.607	0.350	0.186	0.112	0.107	0.107
1987	0.294	0.157	0.109	0.089	0.088	0.088
1988	0.135	0.082	0.066	0.065	0.065	0.065
1989	0.062	0.049	0.048	0.048	0.048	0.048
1990	0.061	0.052	0.052	0.052	0.052	0.052
1991	0.322	0.119	0.075	0.073	0.073	0.073
1992	0.577	0.429	0.218	0.099	0.096	0.096
1993	2.208	1.988	1.801	1.404	1.164	1.062
1994	0.896	0.725	0.622	0.481	0.413	0.384
1995	1.787	1.610	1.424	1.100	0.831	0.763
1996	1.921	1.712	1.509	1.159	0.885	0.799
1997	4.976	4.828	4.711	4.510	4.295	3.959
1998	1.673	1.527	1.382	1.111	0.902	0.778
Total	17.884	15.207	13.385	11.250	9.884	9.111

Information from the final digital elevation model and the geographic-information-system analyses was used to develop the Devils Lake Basin wetlands model of the study area. Data sets from the geographic-information-system analyses, climatology, and geomorphology were incorporated into the model to simulate precipitation accumulation, snowmelt, evapotranspiration, soil infiltration, seepage to ground water, surface runoff, and streamflow. The study area was divided into 50 hydrologic response units on the basis of elevation, slope, aspect, flow planes, soil types, and vegetation. Individual wetland areas and volumes within the study area were determined from the digital elevation model and the geographic-information-system analyses. However, because of model constraints and the complexities of including thousands of individual basins, only one wetland per hydrologic response unit was simulated. Therefore, 50 wetlands were modeled within the study area, and each wetland represented the combined area and volume of all digital elevation model wetlands within the respective hydrologic response unit. Each wetland was partitioned into two parts, an open wetland and a closed wetland. The open wetland was defined as having an outlet with a spillage threshold that was equal to a fraction of the total volume of the open wetland without an outlet. The closed wetland was defined as not having an outlet. Therefore, the closed wetland did not spill, but did gain and lose water in the same manner as the open wetland. All closed wetlands were allowed to increase their volume beyond their maximum to simulate the expansion of wetlands areas within the study area.

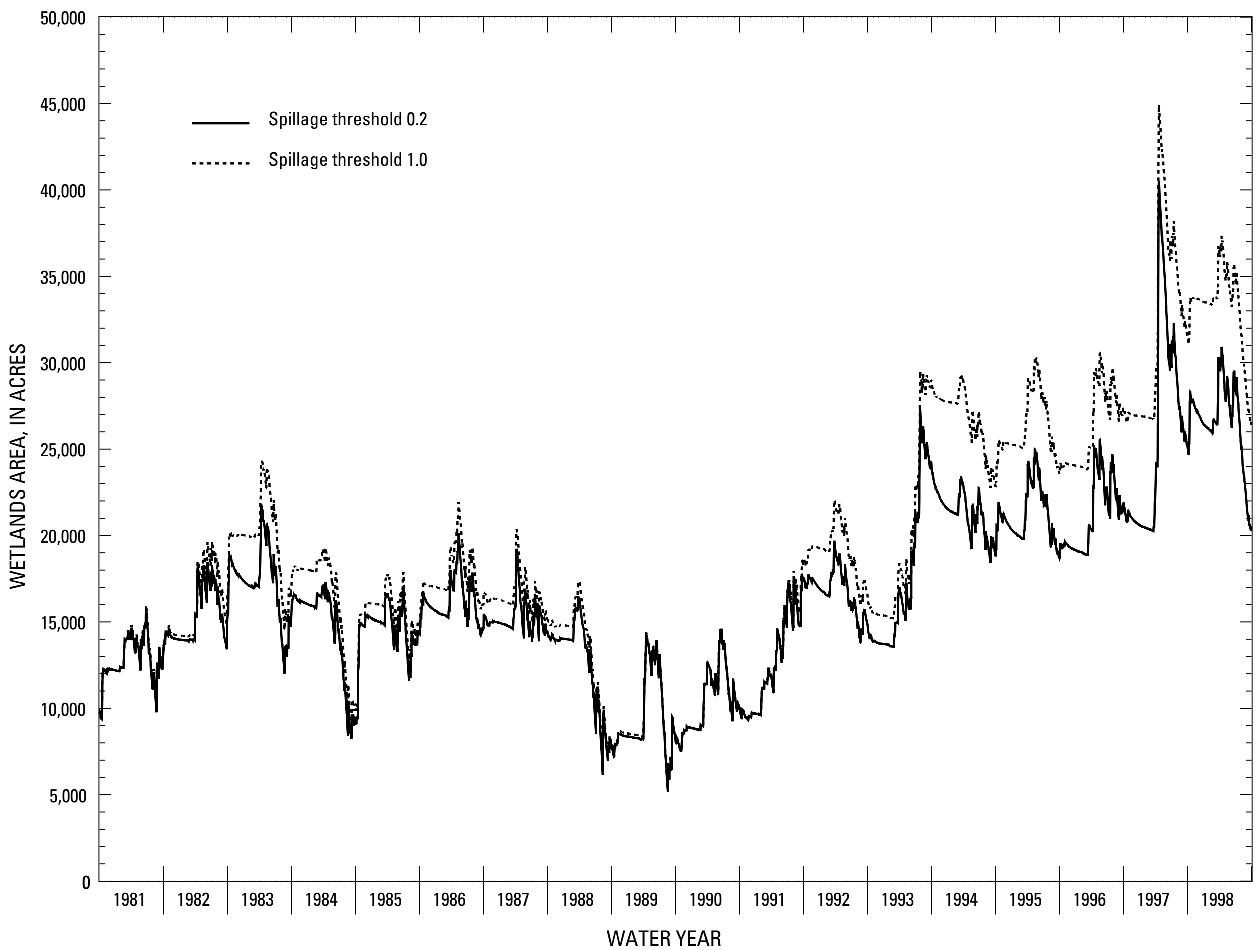

Figure 11. Precipitation-Runoff Modeling System simulated daily wetlands areas for open-wetlands spillage thresholds of 0.2 and 1.0, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

Model runs were made for water years 1981-98 to calibrate the model to observed streamflows that were obtained from the Starkweather Coulee gaging station. Simulated and observed daily streamflows for water years 1981-98 have many similarities, especially in the timing of spring runoff from snowmelt. However, observed annual peak streamflows were greater than simulated annual peak streamflows for all water years except 1983. The differences probably were caused mostly by the lack of a subroutine in the model to account for frozen soil. The largest amount of simulated daily wetlands area occurred in April 1997 when about 40,500 acres of the study area was covered with water. Also during April 1997, the simulated daily water volume in the open and closed wetlands combined attained a maximum of about 116,000 acre-feet. The open wetlands contained about 44,000 acre-feet of water, and the closed wetlands contained about 72,000 acre-feet of water.

After calibration, the simulated streamflow response to increased open-wetlands spillage thresholds was evaluated. The implied physical effect of increasing spillage thresholds is a filling of the spillways from open wetlands to permit the wetlands to hold more water. By increasing the spillage thresholds from 0.2 to 1.0, simulated streamflow was reduced by about 8.77 inches (from about 17.88 to 9.11 inches; 49 percent) for the 18-year period. However, by increasing the spillage thresholds from 0.2 to 1.0, simulated annual streamflow for water year 1997, which was a large-runoff year, was reduced by only 20 percent. During water years 1994-98, simulated annual streamflows for open-wetlands spillage thresholds of 1.0 remained less than for thresholds of 0.2 even though the open wetlands probably were near maximum volume. The greatly increased size of the closed wetlands during water years 1994-98 probably allowed for increased water storage and decreased simulated streamflow from the study area.

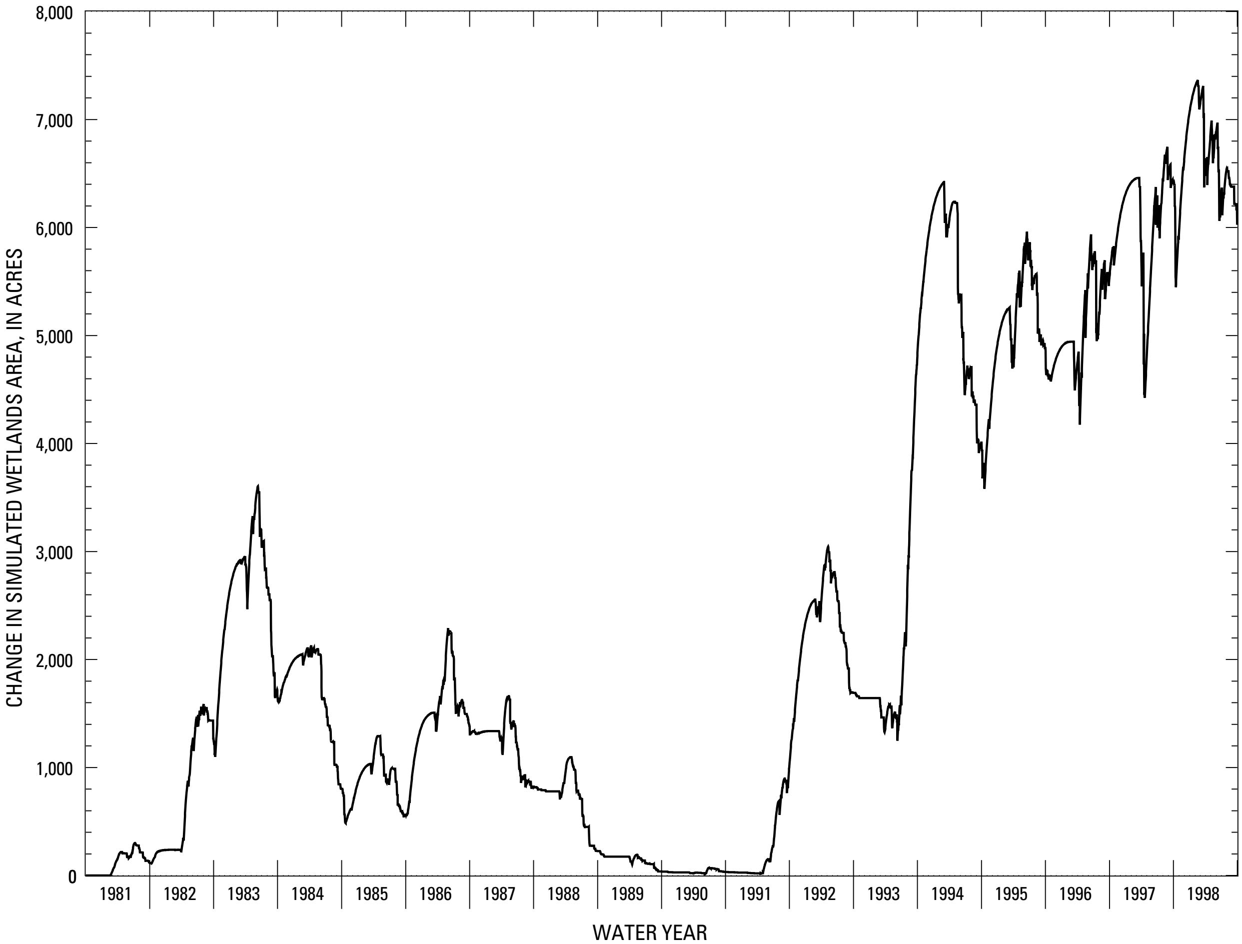

Figure 12. Changes in Precipitation-Runoff Modeling System simulated wetlands area for an increase in open-wetlands spillage thresholds from 0.2 to 1.0, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

The Devils Lake Basin wetlands model of the Starkweather Coulee subbasin simulated many features of the streamflow record from the Starkweather Coulee gaging station. The model performed well for this study because of many modifications made to the Precipitation-Runoff Modeling System. More work is important to improve the wetlands hydrology subroutine and to include a frozen-soils subroutine. Additional data collection at various sites will help define the roles and functions of wetlands in small watersheds.

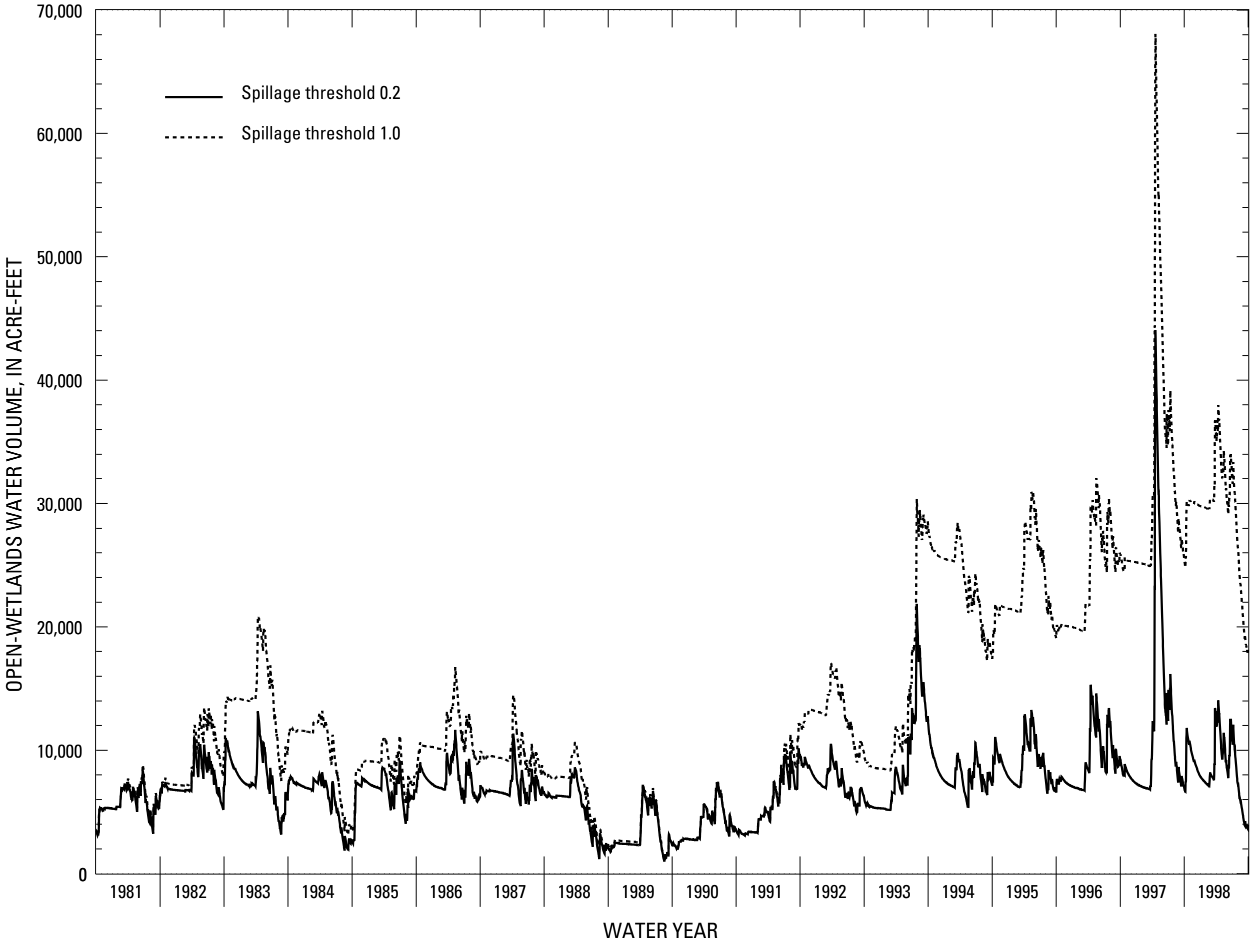

Figure 13. Precipitation-Runoff Modeling System simulated open-wetlands water volumes at spillage thresholds of 0.2 to 1.0, Starkweather Coulee subbasin, North Dakota, water years 1981-98.

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APPENDIX

APPENDIX - The Devils Lake Basin Wetlands Model

By George H. Leavesley

INTRODUCTION

The Devils Lake Basin wetlands model is a modified version of the U.S. Geological Survey's (USGS) Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983; Leavesley and Stannard, 1995). PRMS is a distributed-parameter, physical process watershed model. Distributed-parameter capabilities are provided by partitioning a watershed into units, using characteristics such as slope, aspect, elevation, soil type, vegetation type, and precipitation distribution. Each unit is assumed to be homogeneous with respect to its hydrologic response and to the characteristics listed above. Each unit is termed a hydrologic response unit (HRU). A water balance and an energy balance are computed daily for each HRU. The sum of the responses of all HRUs, weighted on a unit-area basis, produces the daily watershed response.

Snow is a major form of precipitation in the Devils Lake Basin and a major source of streamflow. The snow components of PRMS simulate the accumulation and depletion of a snowpack in each HRU. A snowpack is maintained and modified both as a water reservoir and as a dynamic heat reservoir. A water balance is computed daily and an energy balance is computed twice each day. The energy-balance computations include estimates of net shortwave and longwave radiation, the heat content of precipitation, and approximations of convection and condensation terms.

PRMS uses daily inputs of solar radiation and the variables precipitation (PRCP), maximum air temperature (TMAX), and minimum air temperature (TMIN). Solar radiation is distributed to each HRU as a function of HRU slope and aspect. Where solar radiation data are not available on a daily basis, they are computed using existing algorithms in PRMS. Estimates of daily shortwave radiation received on a horizontal surface are computed using air temperature, precipitation, and potential solar radiation.

PRMS and the Devils Lake Basin wetlands model modifications have been developed and applied using the USGS Modular Modeling System (MMS) (Leavesley and others, 1996; Leavesley and others, 2002). MMS is an integrated system of computer software that provides a common framework in which to focus multidisciplinary research and operational efforts to develop, evaluate, and apply a wide range of modeling capabilities across a broad range of spatial and temporal scales. MMS has a master library that contains compatible modules for simulating a variety of water, energy, and biogeochemical processes. The library may contain several modules for a given process, each representing an alternative conceptualization to simulating that process. The different conceptualizations are functions of a variety of constraints that include the types of data available and the spatial and temporal scales of application. A model for a specified application is created by coupling appropriate modules from the library. If existing modules cannot provide appropriate process algorithms, new modules can be developed and incorporated into the library.

The process modules that compose the original version of PRMS are given in table A1. The documentation for these modules can be found on the Internet at http://wwwbrr.cr.usgs.gov/mms. The process modules that compose the Devils Lake Basin version of PRMS are given in table A2. Only those modules given in table A2 that contain the word "wet" in their name have been modified from the original PRMS version. The complete documentation for these new modules can also be found on the Internet at http://wwwbrr.cr.usgs.gov/mms. A general description of the modifications made to PRMS to create the Devils Lake Basin version of the model are given in the Watershed Characterization and Parameterization section of this appendix.

WATERSHED CHARACTERIZATION AND PARAMETERIZATION

A watershed is delineated, characterized, and parameterized using the USGS GIS Weasel. GIS Weasel is a geographic information system (GIS) interface for applying tools to delineate, characterize, and parameterize topographical, hydrological, and biological basin features for use in a variety of lumped- and distributed-modeling approaches. It is composed of ARC/INFO (Environmental Systems Research Institute, 1992) GIS software, C language programs, and shell scripts. Distributed basin features, such as the HRUs of PRMS, are delineated within a watershed using spatially distributed attributes, such as elevation, slope, aspect, soils, and vegetation. HRUs can be characterized using these attributes.

Table A1. Original PRMS modules

Module
basin_prms.f
obs_prms.f
soltab_prms.f
ddsolrad_prms.f
temp_1sta_prms.f
precip_prms.f
potet_jh_prms.f
intcp_prms.f
snowcomp_prms.f
srunoff_smidx_prms.f
smbal_prms.f
ssflow_prms.f
gwflow_prms.f
strmflow_prms.f
basin_sum_prms.f
hru_sum_prms.f

Table A2. Prairie-pothole PRMS modules

Module
basin_wet.f
obs_prms.f
soltab_prms.f
ddsolrad_prms.f
temp_1sta_prms.f
precip_prms.f
potet_jh_prms.f
intcp_wet.f
snowcomp_prms.f
srunoff_smidx_wet.f
smbal_wet.f
ssflow_wet.f
gwflow_wet.f
strmflow_prms.f
basin_sum_wet.f
hru_sum_prms.f

Parameter estimation methods are implemented using ARC Macro Language (AML) functions applied to available digital data bases. A library of parameter estimation methods is maintained in a similar fashion to the library of process modules in MMS. For a given model, a recipe file of AML functions can be created and executed to estimate a selected set of spatial parameters. This recipe file also can be modified to change the parameter estimation method associated with a selected parameter, thus enabling the evaluation of alternative parameter estimation methods.

Spatially distributed parameters in PRMS are estimated using available digital data bases for the United States including: (1) USGS 3-arc second digital elevation models (DEMs); (2) State Soils Geographic (STATSGO) 1-kilometer gridded soils data (U.S. Department of Agriculture, 1994); and (3) Forest Service 1-kilometer gridded vegetation type and density data (U.S. Department of Agriculture, 1992). Spatially distributed HRU parameters estimated using these data bases include elevation, slope, aspect, topographic index, soil type, available water-holding capacity of the soil, vegetation type, vegetation cover density, solar radiation transmission coefficient, interception-storage capacity, stream topology, and stream reach slope and length.

Parameters that are derived from categorical data, such as vegetation type or soil type, are calculated as the most commonly occurring category for an HRU. Parameters derived from non-categorical data, such as elevation, slope, and aspect, are calculated as the statistical mean or median of the distribution of values for an HRU. Estimation of some model parameters required the use of two or more of the digital data bases, in combination with user estimates of an associated variable. For example, in PRMS, the available water-holding capacity of the soil zone of an HRU is a function of the average rooting depth of the dominant vegetation on that HRU. No digital data base of rooting depth exists. However, default rooting depths for each vegetation group type were estimated to create a rooting-depth data base for use in the computation of available water-holding capacity. The user can modify the defaults as needed to reflect conditions on a specific basin.

MODEL CONCEPTUALIZATION

In the Devils Lake Basin version of PRMS, one additional parameter is computed for each HRU using GIS Weasel. This parameter is an estimate of the storage volume contained in the aggregate of all wetlands contained within an HRU.

This volume is estimated by computing the difference between the raw DEM and a new, modified version of the DEM that has had all the wetlands artificially filled to make a hydrologically contiguous surface. That is, a drop of water placed anywhere on this new surface could flow to the outlet of the basin and would not be captured in a wetland.

The wetland storage for each HRU is divided into wetlands that do not spill and those that are openly connected to stream channels. The flow from an open wetland is computed as a linear function of the volume in storage that is above a threshold storage volume. The linear routing coefficient and the threshold storage values also are model parameters. No flow is routed from a closed wetland.

Precipitation or snowmelt occurring on wetland areas adds to the storage volume of these wetlands. Changes in the surface area of the ponded water in the wetlands change with time as a function of inflow, evaporation, seepage to ground water, and outflow to stream channels. Evaporation from the area covered by water is computed as a user-defined percentage of potential evapotranspiration. Evapotranspiration from the soil areas of an HRU are computed as a function of potential evapotranspiration, soil texture, and the amount of water available in the soil profile. The dynamic changes in areas of open water and soil on an HRU are accounted for at each time step to enable appropriate water-balance computations on each HRU.

Precipitation or snowmelt occurring on non-wetland areas of an HRU are assumed to infiltrate and/or run off into the stream channel adjacent to the HRU. Surface runoff is computed as a function of antecedent soil moisture conditions and precipitation volume. Infiltration is computed as the difference between net precipitation (total precipitation minus precipitation stored on vegetation cover) and surface runoff. Currently, there is no frozen-soil algorithm in the model. During the period of spring snowmelt, the soil is assumed to be frozen and no infiltration from the melt is assumed to occur.

The sum of the surface runoff and wetland outflow of each HRU plus the subsurface and ground-water outflows, all weighted on a contributing area basis, is equal to the streamflow from the basin. Using a daily time step, there is no channel routing computation.

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