United States Department of the Interior

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IN REPLY REFER TO:
GP-4600
WTR-4.11

JUL 1 1 2014

Mr. Brian Dunnigan
Director
Nebraska Department of Natural Resources
301 Centennial Mall South
P.O. Box 94676
Lincoln, NE 68509-4676

Subject: Republican River Conservation Committee's Final Report, Republican River Basin Study on the Impacts of Non-Federal Reservoirs and Land Terracing on Basin Water Supplies (Study)

Dear Mr. Dunnigan:

On behalf of the Republican River Conservation Committee, I have enclosed a final report on the Republican River Basin Study on the Impacts of Non-Federal Reservoirs and Land Terracing on Basin Water Supplies. This final report replaces the draft report on the Study presented at the Republican River Compact Administration annual meeting in October 2012. Please discard the draft study report of October 2012. The Report was prepared in accordance with the July 27, 2004, Memorandum of Understanding, which implemented the Study.

I have already provided each of your Conservation Committer representatives with an electronic copy of the report in Adobe Acrobat (pdf) file format. If you have questions please contact your committee representative or call me at 406-247-7736.

Sincerely,

R. Scott Guenthner

R. Scott Guenthner
Republican River Conservation Committee

FOR

Enclosure

Identical Letter Sent To:

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Republican River Basin

Impacts of Non-Federal Reservoirs and Land Terracing on Basin Water Supplies

Final Report

from the

Republican River Compact Settlement Conservation Committee
for The Republican River Compact Administration

June 2014

Executive Summary

Kansas filed suit in the U.S. Supreme Court in May 1998 complaining that the State of Nebraska had violated the Republican River Compact. The three original parties to the Compact, Kansas, Nebraska, and Colorado, became parties to the case and the United States entered the case as *amicus curiae*. The parties agreed to a settlement and the United States Supreme Court approved the Final Settlement Stipulation by decree on May 19, 2003.

The Stipulation required the States to form a committee to develop a study plan to determine the quantitative effects of Non-Federal Reservoirs and land terracing practices on water supplies in the Republican River Basin above Hardy, Nebraska. The Conservation Committee transmitted the study plan to members of the Republican River Compact Administration (RRCA) in April 2004. The RRCA approved the study plan during the meeting on July 27, 2004. The Conservation Committee provided an annual status report on progress of the study to the RRCA annually.

The purpose of this report is to document the study methods and procedures and report the findings of the study to determine the quantitative effects of Non-Federal Reservoirs and land terracing practices on water supplies in the Republican River Basin above Hardy, Nebraska.

The study area consists of the portion of the Republican River Basin above the measuring gage near Hardy, Nebraska (Figure 1). The study area consists of an area of 22,401 square miles (14,336,640 acres) with a drainage area of 14,901 square miles (9,536,640 acres) that contribute runoff to the Hardy gage. Non-Federal Reservoirs are reservoirs other than federal reservoirs that have a storage capacity of 15 acre-feet or greater at the principal spillway elevation. There are 716 of these reservoirs within the study area. The states identified six Non-Federal Reservoirs in Colorado, 148 in Kansas, and 562 in Nebraska. Terraces provide protection for approximately 2.13 million acres of land in the Republican River Basin, which is equivalent to 15 percent of the total area of the study area and about 22 percent of the contributing area in the study area. Colorado has about 290,000 acres of terraced land, Kansas has about 923,000 acres, and Nebraska has about 919,000 acres.

Water balance models for this study simulate the impact of terraces and Non-Federal Reservoirs on surface water supplies. The study consists of four primary components:

- Field investigations to better understand the water balance of the Non-Federal Reservoirs and land terraces,
- Development of databases for model input,
- Evaluation and modification of existing simulation models, and
- Application of the water balance and GIS models to summarize the impact from basins with Non-Federal Reservoirs and land terraces.

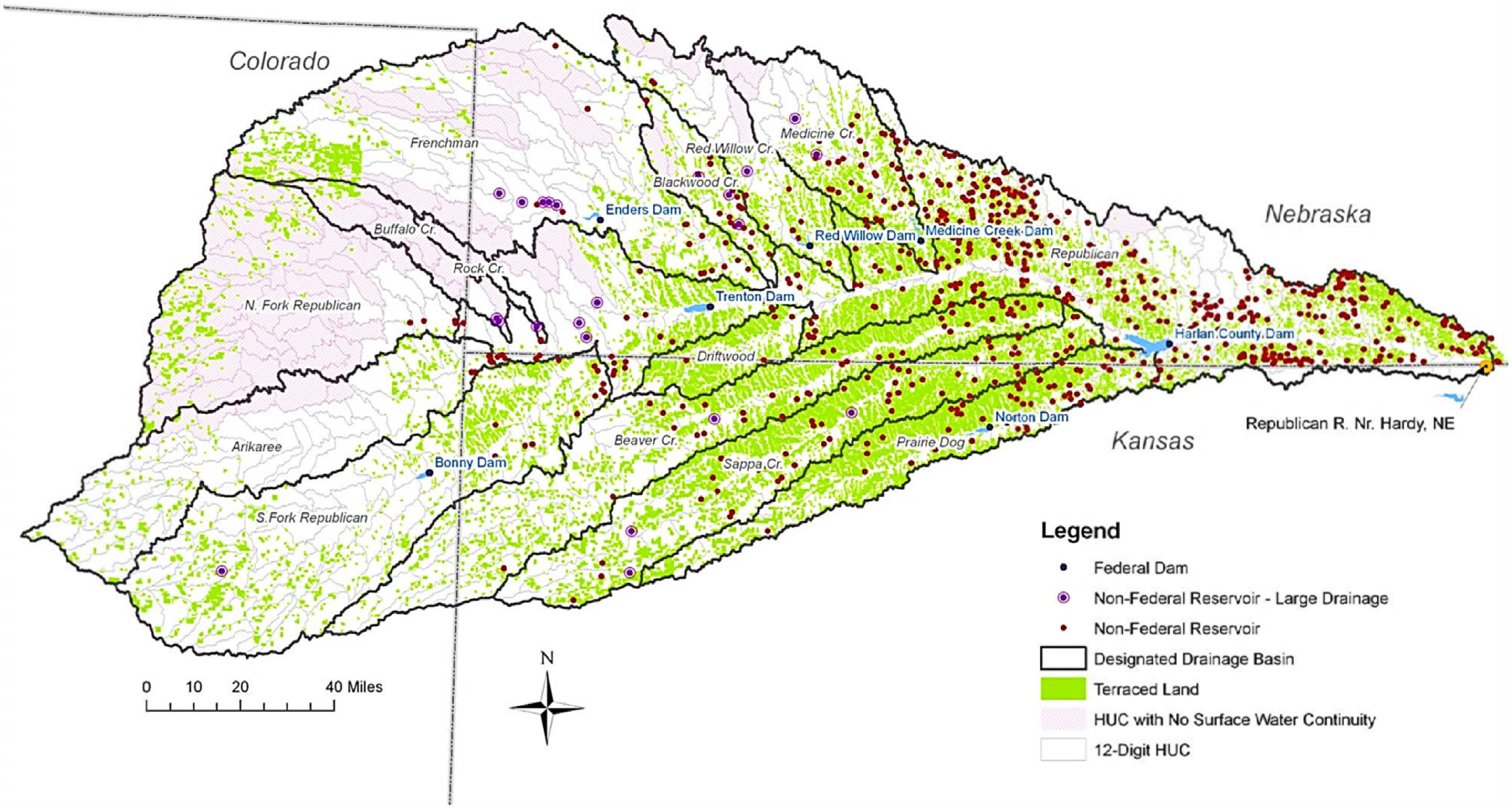


Figure 1. Map of the Study Area Showing the Location of the Terraced Land, Non-Federal Reservoirs, Federal Reservoirs, Designated Drainage Basins, and Hydrologic Units Used for Water Balance Modeling.

Field Investigations

Monitoring of reservoirs and terraced fields provided an on-the-ground assessment of impacts on streamflow. The experimental sites included one reservoir and five terraced fields where detailed data collection provided an improved understanding of the water balance. We also monitored the water level in 31 additional reservoirs over several years.

Non-Federal Reservoirs

The total surface area of all Non-Federal Reservoirs in the study area is approximately 7,400 acres if all reservoirs are full. The average area for a sampling of reservoirs in Nebraska was 3.3 acres for normal water supply conditions compared to about 10.3 acres if the reservoirs were full. Applying this ratio to all Non-Federal Reservoirs in the Basin yields a water surface area of about 2,500 acres for typical storage conditions. Thus, the total surface area for typical water storage conditions is only about 0.026 percent of the contributing drainage area for the basin and 0.017 percent of the total basin area. Thus, evaporation from Non-Federal Reservoirs is not a large component of the water balance for the whole basin, especially considering precipitation that falls on the reservoirs partially offsets the annual evaporation from a water body. Evaporation is important to understanding the water balance of a reservoir, but not as important for the entire basin. There is a significant portion of the basin (up to 15 percent) behind Non-Federal Reservoirs, which has a major impact on the runoff from the portion of the watershed above these reservoirs. Therefore, the retention of runoff is more significant for the watershed than evaporation from the reservoirs.

Thorough examination of the performance of three monitored reservoirs enhanced our understanding of the water balance of these small reservoirs, and provided data to develop simulations and verify model estimates for reservoirs. We developed a relationship between the depth of water in the reservoir and the daily seepage rate from a large inflow event on April 2005 for the DPL-Hogan Reservoir in Phillips County, Kansas. The relationship provided a method to calculate the gross seepage loss in the reservoir seepage model. The reservoir seepage model included three modules: an inflow module, a gross seepage module, and a net seepage module. The inflow module is part of the Potential Yield Revised (POTYLDR) model, the water balance model used in this study. The gross seepage module solves the daily water balance and requires daily data inputs of inflow from the watershed and daily precipitation and evaporation data. Representation of reservoir storage area as fifteen level sections enabled estimation of gross seepage as a function of water depth in the reservoir. Seepage rate calculations depended on the depth of inundation of each level bench. The measured reservoir stage-storage volume and stage-surface area relationships for the DPL-Hogan Reservoir compared very well to the relationships used in the gross seepage module. Monitoring at the DCN-Zimb Reservoir in Cheyenne County, Kansas and DRA-Holste Reservoir in Rawlins County, Kansas produced data to assess the seepage model. Assessment involved comparing simulation results with measured water-depths. The gross seepage module adequately represented reservoirs when properly parameterized. Gross seepage is the dominant outflow of water from reservoirs (equal to about 70 percent of total inflow for the Hogan and Holste Reservoirs and about 80 percent for the Zimb reservoir). Evaporation from the reservoirs averaged between about seven and fifteen percent of the total inflow. Overflow constituted the remainder of the water balance ranging from five to twenty-three percent.

The net seepage module simulates net seepage on a daily basis. Net seepage is the water that percolates below the bottom of the root zone of plants that grow in and along the reservoir. This water can become groundwater recharge from the reservoir. Choodegowda (2009) developed the model and presented more details on the specifics of the model and the data requirements. Choodegowda determined that net seepage accounted for up to 95 percent of the gross seepage.

We applied the reservoir seepage model to simulate a 37-year period using historical weather data for the DPL-Hogan Reservoir. The ratio of net seepage to gross seepage at different levels was similar to the results for the four years of observed data. For the 37-year period, 93 percent of the gross seepage percolated below the lower zone of the soil profile and likely contributed to groundwater recharge. The average annual net seepage amount was 2.34 acre-feet for the 37-year period. The cumulative value of the water balance components for the 37-year period for the DPL-Hogan Reservoir show that gross seepage is about 72 percent of the total inflow to the reservoir due to runoff from the watershed. About 28 percent of the inflow to the reservoir spilled through the spillway as overflow. The cumulative precipitation that fell on the reservoir is about the same as the amount of evaporation from the reservoir over the 37-year period. Similar results occurred when modeling the Zimb and Holste Reservoirs.

Terraces

Terrace systems capture runoff from the upland contributing area and temporarily store water in the terrace channel. Terrace systems with closed ends retain water behind the terrace berm in the channel until the water infiltrates or evaporates. Other types of terraces are open on the ends to allow water to slowly flow from the terrace. Runoff from the contributing area may exceed the storage capacity of the channel for large storms and some water may overtop the terrace end or ridge. A significant portion of the water that overtops terraces, or that flows from the ends of open-ended terraces, will likely end up in streams; however, some of the water also seeps into dry channels between the field and the stream. Water retained in the terrace channel becomes crop evapotranspiration or percolates below the root zone of crops grown in the channel. Deep percolation ultimately reaches the local groundwater where it may (1) return to the stream as baseflow, (2) be pumped for irrigation, or (3) be stored in the groundwater system. The goal for this portion of the study was to determine the amount of water that runs into terrace channels and partition the retained water into either deep percolation or evapotranspiration.

Estimates of total impact of terraces across the basin are dependent on the amount of land terraced, the condition of terraces, and the distribution of terrace types across the basin. The location and amount of terraced land in the Republican River Basin was determined by digitizing terraced fields using the 2006 National Agriculture Imagery Program digital orthophotographs from the USDA-NRCS.

The physical characteristics of terraces also play a significant role in determining the amount of water collected in terraces and ultimate fate of retained water. We conducted a study to determine the storage conditions and types of terraces across the Basin. A survey of 167 terraced fields across the Basin indicated about eighty percent of the fields are broad-based terraces and twenty percent are flat-channel terraces (*i.e.,* conservation bench terraces). We surveyed 128 fields with broad-base terraces and measured the storage characteristics of 277 representative terraces. The survey also included 32 fields with flat-channel terraces, which included volume calculations for 64 representative terraces. In general, flat-channel terraces occur in fields with more gentle slopes than for broad-base terraces. Approximately 11 percent of the broad-base terraces had zero storage even though the terraces had closed ends. The median runoff storage capacity for all of the broad-base terraces was 0.28 inches. Approximately 1.6 percent of the flat-channel terraces had zero storage. The median storage of the flat-channel terraces was 1.01 inches. As would be expected, the median storage of flat-channel terraces was higher than for broad-base terraces.

Research at five field sites generated empirical data on the impact of terraces. The sites included two conservation bench (*i.e.,* flat-channel) terrace systems located near Culbertson, Nebraska and Colby, Kansas; two broad-based (level) terrace systems with closed ends near Curtis, Nebraska and Norton, Kansas; and one broad-based (level) terrace system with open end(s) near Stamford, Nebraska. Field sensors and loggers continuously measured field conditions beginning in the spring of 2006 for three growing seasons. Field measurements allowed us to calibrate and validate simulation models for partitioning runoff from the contributing area into seepage, ET, or overland flow.

Utilization of a GeoProbe direct push sampler produced soil cores throughout the top 25 feet of the soil profile for the five research sites for terraced fields. Sampling included two locations in the contributing area and two in the terrace channel at all field sites. The goals of sampling the profiles were to (1) obtain a water content profile to a depth of 25 feet, and (2) collect undisturbed samples for lab determination of hydraulic conductivity. We conducted the deep profiling in the spring of 2006 and 2009. Probing provides a depiction of the soil water profile throughout the 25-foot profile. Results show that regions below the terrace channels are consistently wetter than beneath the contributing areas. These data provide strong evidence that the channels for conservation terraces contribute to groundwater recharge in the area.

The POTYLDR model uses the NRCS Curve Number method to estimate runoff from contributing areas and infiltration of runoff. Seepage and infiltration depend on the field saturated hydraulic conductivity of the soil. Several field and simulation studies utilized data from the five field sites to improve the estimates of these quantities for modeling. A study determined the temporal variability of runoff curve numbers for each of the four phases of the ecofallow cropping rotation common in the Basin. The calculated curve numbers of 85 and 84 for the fallow after row crop and fallow after wheat phases of the rotation, respectively. These values compare well with the NRCS (2004) tabulated value for fallow of 83. However, the curve number of 85 calculated for the row crop phase was higher than the tabulated value of 75. In addition, the tabulated curve number for wheat of 72 was much lower than the calculated value of 92. This is most likely due to using all runoff events in the analysis instead of removing smaller precipitation events. There were significant differences between curve numbers obtained for the phases. The curve number for the wheat phase of the rotation was significantly higher than the curve numbers for the two fallow periods.

The Water Erosion Prediction Project (WEPP) model has the ability to simulate changes of infiltration rates and predict the variability of hydraulic conductivity within an ecofallow cropping rotation. The WEPP model predicted hydraulic conductivity to range from 1.6 inches/hour following tillage to less than 0.2 inch/hour when the soil was frozen. The hydraulic conductivity was approximately 0.79 inches/hour when no tillage occurred. Curve numbers developed from the simulated hydraulic conductivity ranged from 60 following tillage to 90 with frozen soil. The curve numbers were approximately 75 during the growing season when no recent tillage had occurred.

We used the Root Zone Water Quality Model (RZWQM) to simulate the hydrology of the field sites. Instrumentation at the Colby south terrace and the Norton lower terrace produced data to calibrate the RZWQM. Input parameters derived from measurements at the field sites, and from GeoProbe soil core characteristics, permitted 30-year simulations for these sites. Results of the 30-year simulations produced estimates of long-term ET, deep percolation, and runoff. Long-term simulations relied on soil properties, initial conditions, and management practices determined while calibrating to the sites. Over the course of the simulations, the Colby broad-base terrace retained about 90 percent of the runoff from the contributing slope, while the Colby conservation bench terrace retained 100 percent of the contribution runoff. At Norton, broad-base terrace retained 91 percent and conservation terrace retained 95 percent of the runoff from the respective contributing areas. More ET and deep percolation consistently occurred in the terrace channels than on the contributing slope. The portion of retained water used as ET ranged from about 20 to 45 percent and the remainder became deep percolation. Deep percolation was very episodic and occurred primarily because of specific precipitation events. For example, at Colby, 19.3 inches of rain fell over a 14-day period resulting in 25.4 percent of the deep percolation under the conservation bench terrace during the 30-year simulation. At Norton, 16.5 inches of rain fell over an 8-day period and produced 12.9 percent of the deep percolation under the broad-base terrace during the 30-year simulation.

The distribution of evapotranspiration across the growing cycles of the ecofallow cropping rotation is relatively uniform. Evaporation during the two fallow periods is about the same as ET when wheat grows or during row crop growth. At Colby, the ET of each of the four phases of the rotation ranged from 20 to 28 percent of the total ET, and at Norton, the ET of each of the four phases of the rotation ranged from 21 to 29 percent of the total ET. Higher daily ET occurred during the row crop and wheat growing periods, but the fallow periods lasted longer resulting in similar cumulative ET.

Transmission Loss

Transmission losses in the waterway network downstream of terraced land and small reservoirs decrease the impact of land use and water impoundment. After runoff water leaves reservoirs or terraced fields, some of the streamflow is lost to the unsaturated materials in the stream channel by infiltration into the banks and the floodplain for out-of-bank flow. Jordon (1977) estimated losses of about 2 percent of the flow volume per mile of stream length for relatively large flow events at paired stations. Evaluation of several runoff events that occurred in the western part of the Basin during a dry portion of the study period indicated that the average transmission loss exceeded 7 percent per mile of travel.

The following example illustrates the effect of transmission loss. If the transmission loss rate was 2 percent per mile and the water flowed 10 miles, then 80 percent of the water would still be in the stream 10 miles downstream. For the same loss rate but a travel distance of 30 miles, then only about 55 percent of the flow from the original runoff volume would remain as streamflow 30 miles downstream. We applied an average transmission loss of about 2 percent per mile in the study to account for the impact at the land terrace or reservoir location to downstream locations. Modeling simulations used transmission losses of 2.5 percent per mile for about the western half of the Basin and 1.5 percent per mile for the area below Harlan County Reservoir. Stream transmission loss was an important factor in estimating the impact of both land terraces and Non-Federal Reservoirs since the median travel distance from the centroid of the HUC-12s in the Basin to the outlet of 19 sub-basins was 46 miles and ranged from less than 2 miles to more than 270 miles.

Databases

We developed databases for simulating the hydrologic impact of Non-Federal Reservoirs and land terraces. Data needed for this study included the location of Non-Federal Reservoirs and land terraces, weather, soils, crops, irrigated land amount and location, and the catchment area of the Non-Federal Reservoirs, among other data. Geodatabases have been developed including the location of terraced lands, the delineation of watershed and subwatershed (HUC-12 level) boundaries, and the location of waterways and water bodies using the National Hydrographic Dataset (NHD).

The states of Colorado, Kansas and Nebraska provided the location and descriptive information of the Non-Federal Reservoirs in the Basin. We incorporated that data into a GIS database. The location and amount of terraced land was digitized from aerial photographs obtained from the National Agricultural Imagery Program (NAIP) for 2006.

Two types of weather data contributed to an additional database. Data from the automated weather data network (AWDN) operated by the High Plains Regional Climate Center and data from the Colorado Agricultural Meteorology network were the basis for computing reference crop evapotranspiration using the hourly Penman-Monteith method. The Hargreaves method also provides estimates of reference crop ET using only the daily maximum and minimum air temperature. We calibrated the Hargreaves method to results from the Penman-Monteith method for the AWDN data across the Basin. Data from the Cooperative program operated by NOAA and the National Weather Service (NWS) from the High Plains Regional Climate Center provide data to apply the Hargreaves method to develop estimates of reference crop ET for the sites. The NWS data provided a continuous record of data after 1950 for the stations. These data are necessary for the POTYLD model.

Soil characteristics information derived from the NRCS SSURGO dataset provided data as well. The SSURGO includes the digital soil survey prepared for each county and the associated spatial and tabular data for the soil series in a county. The POTYLDR model only considers certain general soil types. Processing of the SSURGO spatial data produced a map and GIS coverage of the soil types used in the POTYLDR model. The results show that the majority of the Basin is a deep silt loam soil that corresponds to Soil Type 5 in the POTYLDR model.

The USDA Crop Data Layer supplied information for a crops database. We processed the Crop Data Layer information to develop a dataset with fewer, more generalized, crop groups used by the POTYLDR model.

Two sources of data provide information for determining the amount and location of irrigated land in the basin. Accounting documents from the settlement of the Republican River Compact Administration include data for estimating the amount and location of irrigated land for the 2007 accounting summary. The second data source for Nebraska was the survey conducted by COHYST in 2007.

Data from the National Hydrography Dataset (NHD) Plus database were used to determine the drainage basins for the Non-Federal Reservoirs in the basin. The NHD Plus database is similar to the general NHD database but is at a much finer resolution.

Simulation of Impacts

Simulation of the water-budget for estimating the impact of terraces and the Non-Federal Reservoirs involved three tasks: (1) pre-processing, (2) simulation with the POTYLDR model, and (3) post-processing.

A pre-processor defined separate geographical areas (HUC-12) and extracted characteristics of interest for each area from GIS coverages. The information extracted included:

- The HUC-12 identifier.
- Amount of terraced land.
- Stream length to the outlet of the sub-basin from the centroid of the HUC-12.
- Total drainage area of reservoirs, percent of three soil types under terraced lands.
- Percent of seven land uses in terraced areas,
- Percent of five terrace types.

- Weighted fraction and identification number for the three nearest meteorological stations.
- Estimated transmission loss factor.
- The subbasin in which the HUC-12 is located.

The POTYLDR model provided estimates of basic inputs for the water balance to simulate water budgets for 20 hydrologic response units (HRUs) necessary to evaluate impacts of seven land uses and "typical" reservoirs. Simulations included assessment of the operation of Non-Federal Reservoirs in subbasin areas represented by each of the 32 meteorological stations. This required six simulations at each location, one for each of the three soil types to simulate the effects of no land terraces in the drainage area of the Non-Federal Reservoirs and another set, for comparative purposes, of three soil types with land terraces in the drainage area of the Non-Federal Reservoir at each of the meteorological stations. It required 192 runs of the POTYLDR model for a complete simulation of the entire Basin. Results from the water-balance modeling simulations are in units of acre-feet/square mile, which facilitated calculating subbasin impacts for each HUC-12 and each scenario. POTYLDR provided values of long-term average annual evapotranspiration, runoff, and groundwater recharge from each land use with and without terraces, and long-term average annual amounts of inflow, overflow, net evaporation, and groundwater recharge for the Non-Federal Reservoir with and without terraces in the contributing drainage area for the respective reservoir. A post-processing program aggregated simulation results from the four scenarios for the designated drainage basins in the Republican Basin.

Water Balance Modeling

The POTYLDR Model served as the basic operational framework to simulate the impacts from hydrologic response units for this study. POTYLDR is a unit area, physically based water balance model that simulates the water balance for a watershed for a wide range of land uses and cropping patterns. It also simulates the water balance for a small reservoir as a part of its operation. Aggregation of results from up to 24 separate land uses produces estimates of the streamflow and groundwater recharge from a small watershed. This model simulates the water balance on a daily basis and allows estimates of the water yield on monthly or annual basis for a given watershed area. Runoff curve numbers partition daily precipitation into runoff and infiltration. We improved the accuracy of the model for this study with revision of routines that estimate potential evapotranspiration, runoff, interception, and the contribution of snow, along with a more precise simulation of terrace performance. The original POTYLDR Model used the revised curve number (RCN) method from the NRCS for the entire field using the upslope contributing area and the terrace channel area. The new approach uses a three-subprogram system to model the operation of terraces. POTYLD simulated the upslope area to produce runoff into the terrace channel. A subprogram, TERRACEPOND, represents the storage area above the bottom of the terrace as a series of level benches at different heights to account for overflow from and infiltration into each level of the terrace channel. A third subprogram, TERRACECHANNEL, simulates the water budget for each level bench to determine the amount of evapotranspiration and deep percolation from each bench. It totals the results from each bench for the terrace channel to apportion the runoff into the channel into overflow, additional evapotranspiration and deep percolation or groundwater recharge. This approach provides more complete water balance calculation for the terraced area above the lowest terrace in a field. The field survey of terraces in the Basin found that only 65 percent of the total land in a terraced field is above the lowest terrace. Runoff from parts of the field that are situated below the lowest terrace was assumed to be unaffected by terraces in the field.

Simulation of reservoir performance involved assigning characteristics for a “typical” reservoir for the 32 meteorological stations. The POTYLDR model generated results in units of acre-feet per square mile of drainage area. Multiplication of the unit responses by the amount of land associated with a given practice produced results for the total drainage area of Non-Federal Reservoirs in each HUC-12.

The model used weather data from 1948 through 2008 for 32 weather stations distributed across the study area to simulate runoff and the water balance of Non-Federal Reservoirs and land terraces. These data provided a continuous period of 59 years to quantify results for each cropping rotation.

The impact of conservation practices on streamflow depended on assessment of three situations: (1) land terracing without Non-Federal Reservoirs, (2) Non-Federal Reservoirs without land terracing in the contributing area, and (3) Non-Federal Reservoirs with land terracing in the contributing area. Results without terraces or reservoirs provided a benchmark to evaluate conservation practices.

Land Terracing without Non-Federal Reservoirs

Simulation of the impact of terraces required information about the characteristics of terraces across the Basin. The field survey of 167 terraced fields provided estimates of the storage capacity of terraces. Results show that the median runoff storage capacity for broad-based, level terraces with closed ends is about 0.48 inches of runoff and the median storage capacity for flat-channel terraces is about 0.99 inches of runoff. About 80 percent of the surveyed fields were the broad-base type. The field investigations indicated that approximately 35 percent of the terraced field was below the ridge of the bottom terrace in the field. These data, and additional information, govern calculation of the water balance for hydrologic response units.

Simulated water balances for two types of terraces at two locations illustrate the performance of terraces and reservoirs. Results for these locations show a reduction in runoff at the edge of terraced fields of over 90 percent for flat-channel terraces and over 80 percent for broad-base terraces. In these locations, about 40 percent of the retained runoff becomes evapotranspiration and 60 percent percolates below the bottom of root zones in the terrace channel. A greater portion of the retained water becomes evapotranspiration in drier regions in the western regions of the Basin. A larger portion of the retained water percolates below root zones in wetter areas on the eastern side of the Basin and for irrigated fields.

The runoff reduction is at the edge of the terraced field and not at the mouth of a designated drainage basin. A stream transmission loss needs to be applied to the runoff reduction to estimate the impact of the terraces on the water supply at the bottom of designated drainage basins and for the full Republican River Basin above Hardy, Nebraska.

Conservation terraces have greater effect than reservoirs in reducing runoff during periods when runoff is average or less because the magnitude of runoff events is small. They also have the greatest quantitative effect when runoff is above average. For example, simulation of a wheat-corn-fallow rotation on an unterraced field near Oberlin, Kansas, yielded an average annual runoff of 53.3 acre-feet per square mile for the 59-year period. Simulated runoff for a field with broad-base terraces with closed ends and a storage capacity of 0.57 inches was 10.7 acre-feet per square mile at this location. This represents an 80 percent reduction in runoff at the field edge. About nine out of 10 years yielded some runoff from the unterraced field while the terraced field produced runoff less than four out of 10 years at Oberlin, Kansas.

Non-Federal Reservoirs without Land Terracing

The States' inventory of Non-Federal Reservoirs does not contain all data required to assess the impact of reservoirs on streamflow. Information on drainage area, volume, and depth are not available for some reservoirs in the inventory. We developed characteristics of typical reservoirs for each State based on reservoirs in the inventory that included a complete set of descriptive information. Incorporation of the characteristics of typical reservoirs into the POTYLDR model facilitated simulation of the impact of reservoirs on streamflow. Characteristics for a typical reservoir varied for locations across the basin. Reservoir storage typically decreases as one moves east to west across the Republican River Basin.

The water balance model simulated operation of typical reservoirs for a 59-year period. Reservoirs in the eastern portion of the basin overflow about half of the years, while reservoirs in the center of the basin overflow about one in five years, and reservoirs in the west overflow only about 5 percent of the years. Reservoirs in the eastern portion of the basin have the largest average annual reduction in runoff on a volume basis where runoff declined by about 70 percent. Reservoirs in the western portion of the basin store nearly all of the runoff into the reservoir. Because runoff is generally much less in the western portion of the basin, the volume of the runoff reduction is much smaller than in the east. The POTYLDR model simulates the water balance at point locations. After processing with POTYLDR, a stream transmission loss was applied to the computed runoff reduction to estimate the impact of the Non-Federal Reservoirs on the surface water supply at the bottom of designated drainage basins and the Republican River Basin above Hardy, Nebraska.

Non-Federal Reservoirs with Land Terracing

Land terraces are located within the contributing drainage area of some reservoirs. Terraces reduce the average annual inflow to such reservoirs. For example, estimated annual inflow to a typical reservoir at Oberlin, Kansas is 40.6 acre-feet per square mile when no terraces are in the contributing area. The annual inflow decreases to 34.8 acre-feet per square mile when terraces are in the upstream drainage area. For the entire Basin, the reduced inflow resulting from upstream terraces averaged about 3.9 acre-feet per square mile less than would flow through the reservoir if no terraces were in catchment areas.

Summary of Findings

Land terracing and Non-Federal Reservoirs are having a substantial effect on the water resources of the Republican River Basin above Hardy, Nebraska. When land terraces and Non-Federal Reservoirs operated in the basin the average annual net evapotranspiration increased by an average of about 35,900 acre-feet and groundwater recharge increased about 89,400 acre-feet annually. When terraces and reservoirs were present the average annual surface runoff at the outlet of the sub-basins decreased by about 60,500 acre-feet and transmission loss decreased 64,800 acre-feet compared to conditions with no land terraces or Non-Federal Reservoirs. Data in Table 34 of the report summarizes the effects of land terracing and Non-Federal Reservoirs for designated drainage Basins.

Non-Federal Reservoirs alone reduced runoff by an average of about 33 acre-feet/year per square mile of effective drainage area for an average total of about 58,000 acre-feet/year at the reservoirs. Evaporative processes account for about 20 percent (12,000 acre-feet /year) of the retained runoff and the remainder of the retained water or 46,000 acre-feet seeps from the reservoir and becomes groundwater recharge.

Land terracing reduces runoff from the areas above terraces by an average of about 32 acre-feet/year per square mile for an average total of about 71,000 acre-feet/year in the fields. Additional evapotranspiration processes accounts for 33 percent (24,000 acre-feet /year) of the runoff water retained in the terrace channels while the remaining 67% (47,000 acre-feet/year) of the runoff goes to recharge beneath the terrace channels.

The additional recharge under the reservoirs and terraced fields may eventually contribute to increased surface streamflow or groundwater use in the Basin. The decrease in transmission losses within the stream system results in less recharge along the streams and less evapotranspiration along the steams. The locations for recharge with terraces and reservoirs are further upstream than where the recharge would have occurred without the terraces and reservoirs. Only the additional water lost by evaporation from the reservoirs and additional ET from the terrace channels is a direct loss from the hydrologic cycle in the Basin. The additional recharge may still be available, depending on many other factors and the time of concern. Upstream recharge may offset a portion of the decreased downstream recharge that occurs along the stream system due to reduced flow in the streams.

Uncertainty of Assumptions in Estimating Impacts

Transmission losses are larger in the western portions of the basin and lowest in the eastern portion of the basin. Periods with wetter conditions likely have lower losses than during dry periods, but there is not enough known about transmission loss to make a better assumption on how and when to apply different loss factors. The range of uncertainty for this factor is ±25 percent, which can affect estimates of streamflow and decreased losses along the stream system.

The portion of streamflow that is no longer going to transmission losses decreases the estimates of the effects on groundwater recharge in the Basin because much of the water that previously was lost no longer infiltrates through the stream channel and into the alluvial groundwater system. The uncertainty factor is ±25 percent

This study only evaluated the impacts of Non-Federal Reservoirs and land terraces on water supplies in the Republican River Basin above Hardy, Nebraska. The study did not evaluate other impacts such as tillage practices, on-farm irrigation practices, or other water conservation practices, or reservoirs that do not meet the criteria for Non-Federal Reservoirs. These practices may influence water supplies but they are not part of this evaluation. Other small reservoirs in the Basin may affect streamflow or groundwater recharge by about 15 percent, *i.e.* the uncertainty factor is ±15 percent.

Table of Contents

Appendices

D

List of Figures

List of Tables

List of Variables

List of Acronyms

AMC-	Antecedent Moisture Condition, I = dry, II = average, and III = wetter
ArcGIS	ESRI GIS software for working with maps and geographic information
ARC-II	Antecedent runoff curve number for AMC-II, average conditions
ATV	All-terrain vehicle
AWDN	Automated weather data network
AWHCCode	Available water-holding capacity code
BB	Broad-based terrace
BSE	Bare soil evaporation
CALMIT	Center for Advanced Land Management Information Technologies
CBT	Conservation bench terrace
CLIGEN	Climate and weather generator simulator program
CLU	Common land unit
CNSLD	Computer program that produces the PRS file
COHYST	Platte River Cooperative Hydrology Study
CS	Contributing slope above a terrace
DCN	Dam in Cheyenne County, KS
DEM	Digital elevation model
DNR	Department of Natural Resources
DOQQ	Digital Ortho Quarter Quads produced by the USGS
DPL	Dam in Phillips County, KS
DRA	Dam in Rawlins County, KS
ESRI	Economic and Social Research Institute
ET	Evapotranspiration
ETo	Evapotranspiration for short or grass reference crops
EToHG	Reference ET for a grass crop using the Hargreaves method
EToPM	Reference ET for grass crop using the ASCE Penman-Monteith method.
FAO	Food and Agriculture Organization of the United Nations
FC	Flat-channel terrace
FORTRAN	Programming language for numeric and scientific computing
FSA	Farm Services Agency, USDA
GIS	Global positioning system

HPRCC	High Plains Regional Climate Center
HRU	Hydrologic response unit
HUC-12	Hydrologic Unit Code at the 12-digit size for a watershed
HUCDAT	HUC database set for all HUC-12 watersheds in the Basin
I	Inflow of runoff to Non-Federal Reservoir
MSL	Mean sea level
NAIP	National Agricultural Imagery Program
NASS	National Agricultural Statistical Survey, USDA
NetET	Surface evaporation plus additional ET from a Non-Federal Reservoir
NHD	National Hydrographic Dataset
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service, USDA
NWS	National Weather Service
POST	Program that processes PSR and HUCDAT values into simulation results
POTYLDR	Potential Yield Revised computer simulation model
PSR	File that contains POTYLDR simulation results
PVC	Polyvinyl chloride
RCN	Runoff curve number
RRCA	Republican River Compact Administration
RZWQM	Root Zone Water Quality Model
SCS	Soil Conservation Service, USDA
SSURGO	Soil Survey Geographic database, NRCS
SURFER	A contouring and 3-D mapping computer software program
TERRACECHANNEL	Terrace channel, a computer simulation program
TERRACEPOND	Terrace pond, a computer simulation program
USDA	United States Department of Agriculture
USGS	United States Geological Survey
V	Volume of storage in Non-Federal Reservoir
WEPP	Water Erosion Prediction Project
WIMAS	Water Information Management and Analysis System

Unit Conversion Factors

The Report Includes English and Metric Units. These Factors Help in Converting Between Units.

To convert Column 1 to Column 2, multiply by	Column 1	Column 2	To convert Column 1 to Column 2, multiply by
Length			
0.621	kilometer, km (1000 m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.281	meter, m	foot, ft	0.305
0.394	centimeter, cm	inch, in	2.54
0.0394	millimeter, mm (1/1000 m)	inch, in	25.4
Area			
2.47	hectare, ha	acre	0.405
0.386	square kilometer	square mile	2.59
43560	acres	square feet	2.30E-05
640	square miles	acre	0.00156
144	square foot	square inches	0.00694
0.0929	square foot	square meter	10.76496
6.455	square inch	square cm	0.15492
Volume			
0.00972	cubic meter, m3	acre-inch	102.9
0.000810	cubic meter, m3	acre-foot	1234
35.3	cubic meter, m3	cubic foot, ft^3	0.0283
0.946	liter, L (10−3 m3)	quart (liquid), qt	1.057
0.264	liter, L (10−3 m3)	gallon	3.785
1.244	bushel	cubic feet, ft^3	0.804
Mass			
0.002205	grams, g	pound, lb	454
2.205	kilograms, kg	pound, lb	0.454
2000	ton (US)	pound, lb	0.00050
1.102	megagrams = 1 metric ton	ton (U.S.)	0.9072
Yield and Rate			
0.892	kilograms per hectare, kg/ha	pound per acre, lb/acre	1.12
0.0149	kilograms per hectare, kg/ha	bushel per acre @ 60 lb/bu	67.2
0.0159	kilograms per hectare, kg/ha	bushel per acre @ 56 lb/bu	62.7
0.0186	kilograms per hectare, kg/ha	bushel per acre @ 48 lb/bu	53.8
14.9	megagrams per hectare, Mg/ha	bushel per acre @ 60 lb/bu	0.0672
15.9	megagrams per hectare, Mg/ha	bushel per acre @ 56 lb/bu	0.0627
18.6	megagrams per hectare, Mg/ha	bushel per acre @ 48 lb/bu	0.0538
2.24	meters per second, m/s	miles per hour	0.447

Density			
1.00	megagrams per cubic meter, Mg/m3	grams per cubic centimeter, g/cm^3	1.00
1000	kilograms per cubic meter, kg/m^3	grams per cubic centimeter, g/cm3	0.0010
62.43	grams per cubic centimeter, g/cm3	pounds per cubic foot, lb/ft^3	0.016
Pressure			
1021	bars	water head (@60°F), cm	0.000980
10.21	bars	water head (@60°F), m	0.0980
10.21	centibars	water head (@60°F), cm	0.0980
2.31	pound per square inch, lb/in^2	water head (@60°F), ft	0.433
10.21	kilopascal, kPa	water head (@60°F), cm	0.098
0.1021	kilopascal, kPa	water head (@60°F), m	9.797
0.145	kilopascal, kPa	pound per square inch, lb/in^2	6.895
0.001	kilopascal, kPa	bars	1000
10.0	kilopascal, kPa	centibars	0.100
Temperature			
(1.8 × T °C) + 32	Celsius, °C	Fahrenheit, °F	1.8 × (T °F − 32)
Energy, Work, Quantity of Heat			
1.00	joules per second, J/s	Watts	1.00
11.6	megajoules per square meter per day, $MJ/m^2/day$	Watts/square meter, W/m^2	0.0864
1.00	langlely	$calories/cm^2$	1
0.0418	langley	megajoule per square meter, MJ/m^2	23.90
0.746	horsepower	kilowatts, kW	1.341
Plane Angle			
57.3	radian, rad	degrees (angle), °	0.0175
Water Measurement			
264	cubic meter, m^3	U.S. gallon	0.00379
0.00972	cubic meter, m^3	acre-inch	102.9
0.00081	cubic meter, m^3	acre-foot	1234.4
0.00980	cubic meter per hour, m^3/hr	cubic foot per second, ft^3/s	102.0
4.399	cubic meter per hour, $m^{3/hr}$	U.S. gallon per minute, gpm	0.227
0.972	hectare centimeter, ha-cm	acre-inch	1.028

Introduction

In May 1998, Kansas filed suit in the U.S. Supreme Court complaining that the State of Nebraska had violated the Republican River Compact. The Court accepted the lawsuit and assigned Vincent L. McKusick as Special Master. The three original parties to the Compact (Kansas, Nebraska and Colorado) became parties to the case and the United States entered the case as *amicus curiae.* In December 2001, the Special Master granted a stay to allow the parties time to attempt to negotiate a settlement. In December 2002, the states completed a Final Settlement Stipulation and the Special Master approved the stipulation in February 2003. The United States Supreme Court, by decree dated May 19, 2003, approved the Final Settlement Stipulation.

The Stipulation required the States, in cooperation with the United States, to form a Conservation Committee. Further the stipulation required the Conservation Committee to develop a proposed study plan to determine the quantitative effects of Non-Federal Reservoirs and land terracing practices on water supplies in the Republican River Basin above Hardy, Nebraska, including whether such effects can be determined for each of the Designated Drainage Basins (refer to Section VI of the Final Settlement Stipulation). Each state and the United States appointed individuals to represent them on the Conservation Committee. The Conservation Committee members participated in a series of meeting and conference calls to develop a study plan to quantify the effects of Non-Federal Reservoirs and land terracing practices on water supplies in the Republican River Basin above Hardy, Nebraska. The Conservation Committee transmitted the study plan to the Republican River Compact Administration (RRCA) in April 2004. The RRCA approved the study plan during the meeting on July 27, 2004. A Memorandum of Understanding specified the responsibilities of each party for funding and completing the study.

The study area consists of the portion of the Republican River Basin above the measuring gage near Hardy Nebraska (Figure 1). The study area consists of an area of 22,401 square miles (14,336,640 acres) with a drainage area of 14,901 square miles or 9,536,640 acres that contribute runoff to the Hardy gage (http://waterdata.usgs.gov/nwis/). The study area consists of all of 15 drainage basins and part of a 16th basin as described by the twelve-digit hydrologic unit codes (*i.e.*, all of HUC units 1025001 through 10250015 and part of 10250016).

The states identified 716 Non-Federal Reservoirs as defined in the Final Settlement Stipulation. The Final Settlement Stipulation defines Non-Federal Reservoirs as reservoirs other than federal reservoirs that have a storage capacity of 15 acre-feet or greater at the principal spillway elevation. The states identified six Non-Federal Reservoirs in Colorado, 148 in Kansas, and 562 in Nebraska. The Federal Reservoirs in the Final Settlement Stipulation include: Bonny Reservoir, Swanson Lake, Enders Reservoir, Hugh Butler Lake, Harry Strunk Lake, Keith Sebelius Lake, Harlan County Lake, and Lovewell Reservoir which lies below the streamflow gage near Hardy, NE. Each state completed an inventory of the Non-Federal Reservoirs in their portion of the basin. Inventories includes data related to reservoir location, size, date constructed, dam height and other reservoir characteristics. The inventories prepared by each state resulted in 709 reservoirs that still function (Appendix A).

The amount and location of terraced land in the basin (Figure 1) was determined by digitizing terraced land from aerial photographs. Approximately 2.13 million acres of terraced land existed in the Basin in 2006, which is equivalent to 15% of the total area of the study area and about 22% of the contributing area in the study area. Colorado has less terraced land (about 290,000 acres) than Kansas

(923,000 acres) and Nebraska (919,000 acres). We also determined the conditions and types of terraces installed across the basin.

Procedure

The study relies primarily on water balance models to simulate the impact of terraces and Non-Federal Reservoirs on surface water supply. The study consists of four primary components:

- Field investigations to better understand the water balance of the Non-Federal Reservoirs and land terraces to build and verify models, and to corroborate conclusions,
- Development of databases for model input,
- Evaluation and modification of existing simulation models, and
- Application of the water balance and GIS models to summarize impact from basins with Non-Federal Reservoirs and land terraces.

The Republican River Basin Study Plan for assessing the Impacts of Non-Federal Reservoirs and Land Terracing on Basin Water Supplies dated April 28, 2004 provided a thorough description of the study. The project was a joint effort between Colorado, Kansas, Nebraska, the University of Nebraska-Lincoln, Kansas State University and the Bureau of Reclamation, with contributions from the USDA Natural Resources Conservation Service (NRCS).

Field Investigations

Monitoring of reservoirs and terraced fields provided an on-the-ground assessment of impacts on streamflow. The experimental sites included one reservoir and five terraced fields where detailed data collection provided an improved understanding of the water balance. We also monitored the water level in 31 additional reservoirs over several years.

Reservoirs Research

Characteristics of Reservoirs

The states identified 716 reservoirs Non-Federal Reservoirs; however, further inspection of storage volumes for reservoirs showed that only 709 reservoirs still have capacity to store runoff. The location and characteristics of the reservoirs are in the associated database for the project. The majority of the Non-Federal Reservoirs are in the eastern half of the watershed (Figure 2), *i.e.*, east of the 101th meridian. The contributing drainage area identified for twenty-two of the reservoirs surpasses the area of the 12-digit hydrologic unit surrounding the reservoir. In some cases, the identified contributing drainage area for a reservoir exceeds the size of the entire hydrologic unit where the reservoir exists. This generally occurs when the Non-Federal Reservoir is on the mainstem of a stream or a major tributary. The listed storage volume for these reservoirs is not large enough to store or control the water supply for such a large drainage area. The 22 reservoirs listed as Large Reservoirs in Figure 2 exceed the size of the HUC-12 hydrologic unit. The Large Reservoirs are in the western half of the watershed. The water balance model treated Large Reservoirs differently than reservoirs with smaller catchment areas.

Many of the reservoirs in the Basin are small and supplement the water supply for livestock (Figure 3). Kansas reported the surface area for 141 reservoirs when the water was at the height of the spillway. The surface area for the majority of these reservoirs is smaller than 10 acres when they are full (Figure 4). Nebraska reported the normal surface area when 220 reservoirs are full. The reservoirs in Nebraska have a slightly smaller surface area distribution than the reservoirs in Kansas (Figure 4). The combined total water surface area at the spillway height for the 141 reservoirs in Kansas is approximately 1,520 acres. The total normal surface area for the 220 reservoirs in Nebraska is 2,256 acres. The area for Nebraska and Kansas is 3,776 acres for 361 reservoirs. Using the average area per reservoir gives a total surface area of approximately 7,400 acres if all reservoirs are full. Nebraska digitized the water surface area of 527 reservoirs when the water level was near normal conditions. The average area for those reservoirs was 3.3 acres compared to 10.3 acres for full reservoirs. Applying this ratio to all reservoirs produces a water surface area for Non-Federal Reservoirs of about 2,500 acres for normal conditions. Thus, the typical water surface area is only about 0.026% of the contributing drainage area for the basin and 0.017% of the total basin. Evaporation from reservoirs depends on the water surface area and the evaporative demand of the atmosphere. The total surface area for the reservoirs is quite small compared to the watershed. Thus, evaporation from Non-Federal Reservoirs is not a large component of the water balance for the whole basin, especially when precipitation that falls on the reservoirs is approximately the same as the annual evaporation from a water body. Evaporation is important to understand the water balance of a reservoir, but not as important for the whole basin. A significant portion of the basin (about 15%) is upstream of reservoirs, which has a major impact on the runoff from the treated portion of the watershed. Thus, the retention of runoff and its subsequent loss by seepage out of the reservoirs is more significant for the watershed than evaporation from the reservoirs.

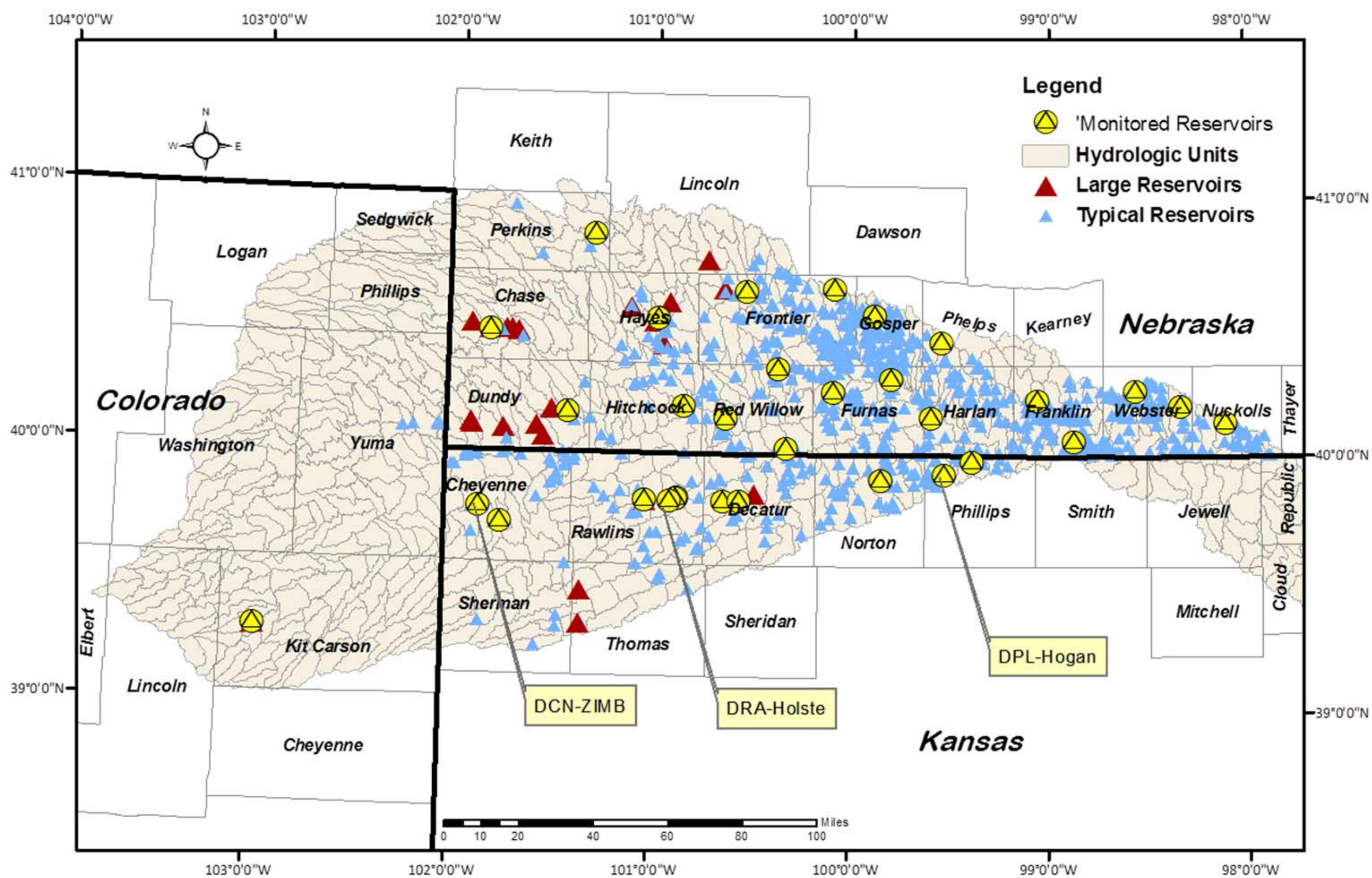


Figure 2. Map of Non-Federal Reservoirs and Hydrologic Units in the Republican River Basin.

Figure 3. Example of a Small Reservoir Used to Partially Supply Water for Livestock.

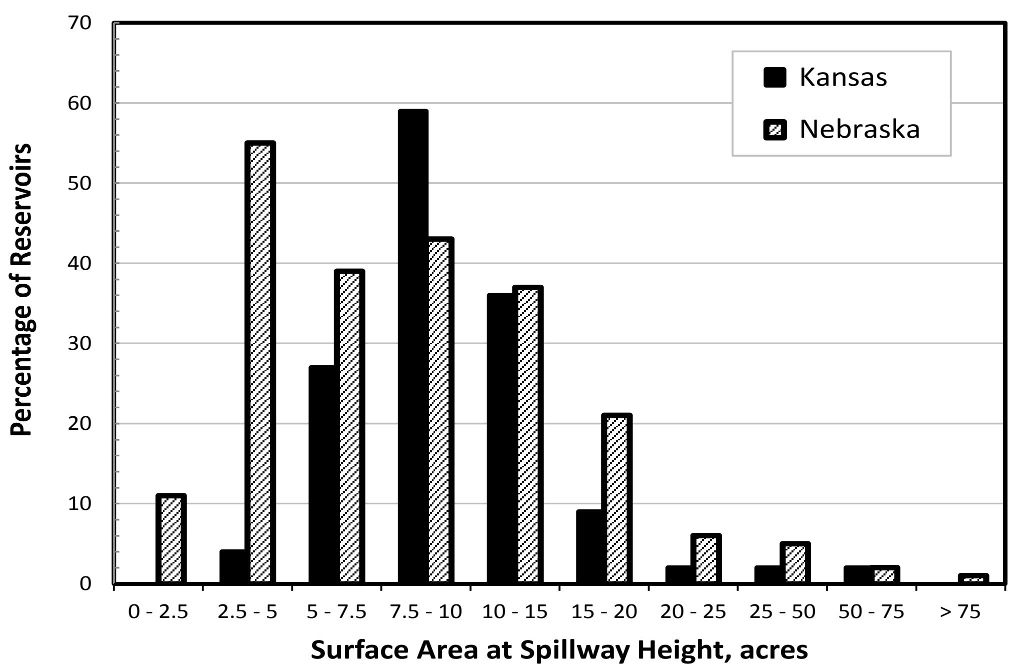


Figure 4. Histogram of Storage Volume in Non-Federal Reservoirs in Kansas and Nebraska.

Many processes affect the water balance of reservoirs (Figure 5). Additions to the reservoir come from water that runs off lands above the reservoir. Precipitation that falls directly on the reservoir also adds to storage. Losses from the reservoir include evaporation for the exposed surface and seepage through the sides and bottom of the reservoir. Water overflows the spillway when the water level rises above the spillway height. Water that seeps through the sides and bottoms of the reservoir contributes to evapotranspiration from grasses, trees, and shrubs that grow along the edge of the reservoir. Thus, the gross seepage from the reservoir is larger than the amount of water that percolates toward the groundwater. We refer to net storage as the gross seepage minus the evapotranspiration of plants lining the reservoir. Seepage and evaporation losses depend on the depth of water in the reservoir as the wetted area of the sides of the reservoir increases with the depth of water. Simultaneously, the hydraulic head driving seepage increases with the depth of water. The water balance model used a series of level benches to represent the effect of water depth on water lost from the reservoir (Figure 5). Representing reservoirs required as many as 15 levels depending on the size of the reservoir. Later sections of the report describe simulation processes.

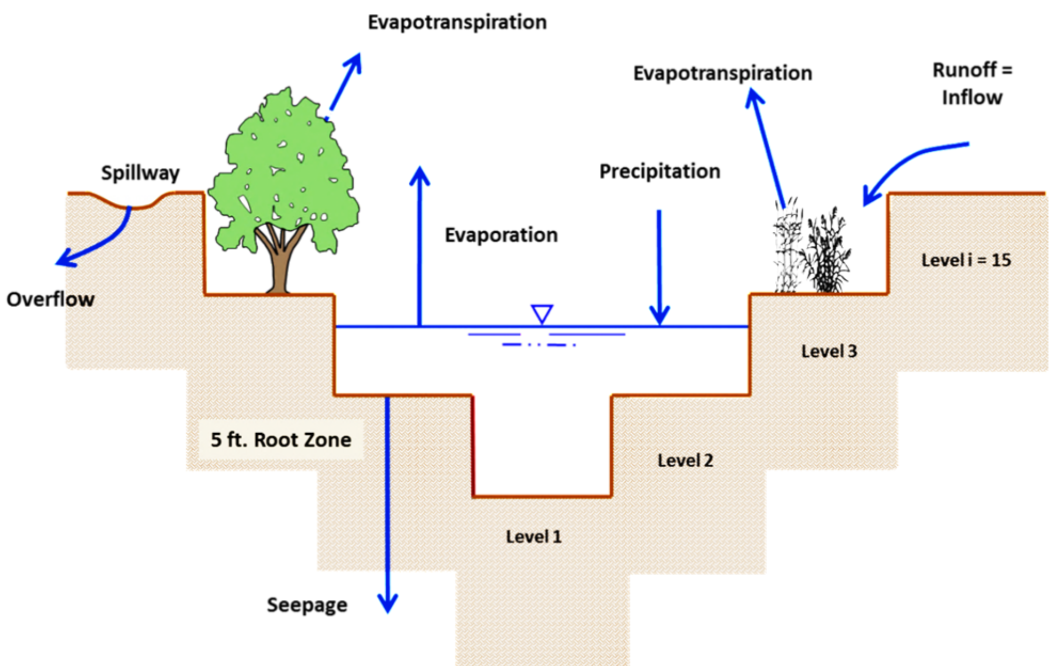


Figure 5. Reservoir Representation of Level Sections to Estimate Losses for Different Depths.

Monitored Reservoirs

One component of the study involved measurements of water stored in a sampling of reservoirs across the basin (1 in Colorado, 11 in Kansas, and 20 in Nebraska). Continuous monitoring of thirty-two reservoirs (Figure 2) produced a record of reservoir water levels. The Conservation Committee met with personnel from the Bureau of Reclamation and each State in McCook, Nebraska on September 13, 2004 to begin installation of equipment and data collection at the reservoir sites. State and Reclamation staff continued installation of monitoring equipment through the fall of 2004 and early spring of 2005. The list of monitored reservoirs is included in Appendix A. State personnel made periodic site visits to retrieve water level data, determine reservoir surface area at corresponding water levels, and document overall conditions at the reservoir sites. Weather conditions resulted in very little runoff to most of the reservoirs between the fall of 2004 and the fall of 2006. Fifteen of the 32 reservoirs were dry during at least two of the three or four site visits prior to the fall of 2006. Runoff occurred at some monitored reservoirs during the fall of 2006 and spring of 2007. Site visits during March and April of 2007 found that 20 of the 32 reservoirs stored water. Site visits to the Kansas reservoirs in mid-June showed that all eleven reservoirs had stored water, many of them during runoff on or about April 24. These records show that the Non-Federal Reservoirs do not continuously store water and are frequently essentially dry. Reservoirs in the western portion of the basin experience more dry periods than reservoirs in the east.

An example of water level fluctuations for a reservoir in Nebraska is in Figure 6. This reservoir is located in the eastern third of the basin and just west of Holdrege, Nebraska, and in a location that is one of the best in the basin for maintaining water in a reservoir. Precipitation from October 2004 through April 2006 totaled about 28.7 inches (76 percent of average precipitation). Precipitation increased over the next year. The precipitation from October 2004 through April 2007 totaled about 56.6 inches, nearly 8 inches in April 2007, and 89 percent of long-term average precipitation. The maximum storage in this reservoir during the observation period was about 14 acre-feet on August 17, 2006. The reservoir typically receives runoff in the spring and early summer. The stored water is nearly loss during the late summer and fall. Water levels are frequently quite low during the fall and winter months.

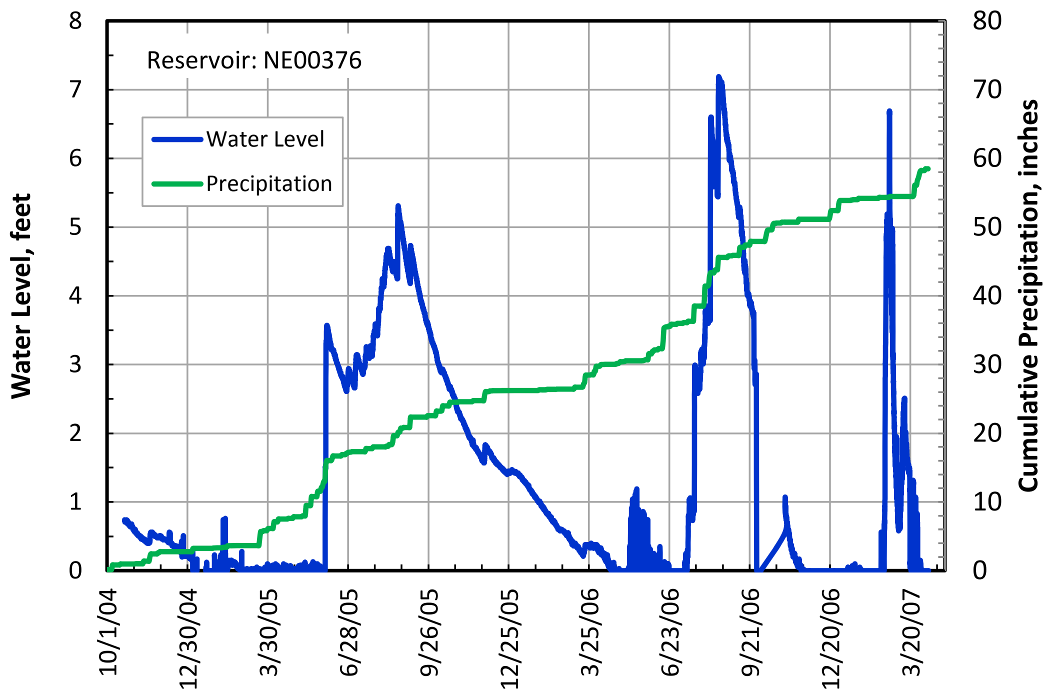


Figure 6. Water Levels and Accumulated Precipitation for a Reservoir Near Holdrege Nebraska.

Estimation of Seepage Losses

We selected three of the monitored reservoirs to develop and verify methods to model seepage from reservoirs. Selected reservoirs are highlighted in Figure 2. The sensors for these reservoirs were reliable and provided a nearly complete record of water levels for the period of analysis. The characteristics of the watersheds surrounding the reservoirs were also well known. The reservoirs represent a range of precipitation and land-use characteristics across the Basin. It was difficult to find reservoirs that contained water over long portions of the sampling period and generated a continuous record of the water levels.

Partitioning water lost from the reservoir to either evaporation or seepage focused on data collected at the monitored reservoirs. Examination of water levels from ten sites in Kansas showed that reservoirs contained little water from when measurements began, September 2004, until April 2007.

The DPL-Hogan reservoir, near Long Island, KS, stored enough water during two periods to estimate seepage and overflow from the reservoir. Overflow occurred during a 3-hour period on April 5, 2005. The runoff on this date was about 6.67 acre-feet or about 1.0 inch from the 81-acre watershed. The water balance for this reservoir for April 5 through August 22, 2005 is in Table 1.

Table 1. Preliminary Water Balance for the DPL-Hogan Reservoir from 4/5/2005 to 8/22/2005.

Water Balance Parameter	Water Volume, acre-feet
Runoff	7.39
Rainfall on Reservoir	0.35
Overflow	2.33
Estimated Evaporation	0.52
Estimated Seepage	4.81
Change in Storage	0.08

The water-depth record in a reservoir depends on the stage-storage volume, stage-surface area and stage-discharge relationships for the reservoir. The depth also varies based on the soil characteristics at the site, precipitation on and evaporation from the free-water surface of the reservoir, and water used from the reservoir. A daily water balance helps develop daily seepage estimates. The change in storage volume (ΔV) was determined using the change in water depth in the reservoir and the stage-storage volume relationship for each reservoir.

Seepage (S) is the summation of daily values using the following function:

$$S = P + I - E - O - U \pm \Delta V \qquad (1)$$

where,

- S = Daily seepage volume from the sides and bottom of the reservoir,
- P = Precipitation from the nearest reporting station times free-water surface area,
- I = Inflow (sum of runoff and drainage),
- E = Weighted reference crop evapotranspiration (ETo) for the nearest weather station(s) times free-water surface area,
- O = Estimated overflow from recorded water depth and spillway characteristics,
- U = Water use from the reservoir, and
- ΔV = Daily change of water storage in the reservoir.

We used the water depth at 12:00 a.m. to represent the daily water depth in the reservoir. Water only flows into reservoirs occasionally and the inflow rate is uncertain since precipitation only occurs about one day in five. Seepage and evaporation occur continually as long as there is water in the reservoir. The only consumptive use of water from the reservoir was for livestock consumption. We show below that livestock water consumption is negligible and unnecessary for the analysis.

We defined seepage as the change in the daily volume of storage minus the evaporation when no inflow or precipitation occurred. Evaporation was assumed to equal the reference crop evapotranspiration for short reference crops (ETo) refer to Allen et al (1998). When daily inflow produced an increase in water depth greater than precipitation minus evaporation and seepage, the volume of inflow was set to the seepage volume for the preceding day. A special adjustment accounted for the additional evaporation due to expansion of the water surface area when large inflows caused water levels to rise significantly. We estimated seepage on days with large inflows through inspection of reservoir records for a series of adjoining days. Overflow occurred very infrequently. Overflow volumes were determined by examining the hourly water-depth record and the stage-discharge relationship for the reservoir. These methods with Equation 1 predicted the volume balance of the selected reservoirs.

Detailed Evaluation of Non-Federal Reservoir DPL- Hogan Reservoir

The DPL-Hogan Reservoir located in Phillips County, Kansas (Figure 2) has a contributing watershed area of 81 acres. The surface area at the minimum water depth is 0.074 acres while the surface area is 1.01 acres at the spillway height of 9.3 feet. Pastured rangeland is the dominant land use in the watershed. The storage volume in the reservoir at the 20-ft. wide earthen spillway elevation is 4.36 acre-feet, which is equivalent to 0.68 inches over the watershed. A weighted average annual ETo between Colby, KS and Scandia, KS was used for the site. The average annual reference crop evapotranspiration is about 51.2 inches. Average annual ETo agreed well with the average annual evaporation from small reservoirs of about 53inches in this area as provided by the USDA NRCS (Viessman et al., 1977, p. 45). Soil in the watershed is primarily Uly or Penden silt loam, both of which have been assigned to group B of the NRCS hydrologic soil groups system. Slopes range from 7 to 20% in many locations in the contributing area of the watershed (NRCS, 2008). The soils have a moderate permeability of 0.6 to 1.9 inches/hr. Precipitation data was from the nearest weather station near Long Island, KS. The long-term mean annual precipitation at Long Island is about 24.4 inches. The water depths in the Figure 7 illustrate the nature of the water supply for reservoirs during the study period from 2004 to 2007.

The reservoir was one of two water sources for about 30 cattle in the approximately 200-acre pasture that surrounds the reservoir. Cattle were in the area only during the grazing season, which was about 150 days long. Water consumption by cattle averages about 8 gallons/day (Guyer, 1977). If all 30 cattle drank from the reservoir, total water use for a day would be about 240 gallons/day. At a reservoir depth of 3 feet, the surface area is about 20,000 ft^2. Cattle consumption would equal less than 0.04 inches from the reservoir when the water is 3 feet deep in the reservoir. This difference is less than the resolution of the water-depth sensor record for a given day. If the entire livestock use had been from the reservoir for the 150-day season then the cumulative water use would have been approximately 0.11 acre-feet. Based on this analysis we omitted livestock water consumption from consideration of reservoir water balances for this project.

We computed the reservoir seepage equation (Equation 1) on a daily basis using a spreadsheet. Hourly water-depth sensor data provided the water depth at midnight to facilitate the daily balance. The water depth versus water-storage volume and surface-area relationships provided data to develop stage-storage volume and stage-surface area relationships (Figure 8).

Data in Table 2 summarize the water balance for the DPL-Hogan Reservoir for a period after a large inflow event on April 5, 2005. It rained 3.75-inches on that day which produced an estimated 7.53 acre-feet of runoff. Runoff filled the reservoir and produced an estimated overflow of 2.73 acre-feet. Note that some of overflow occurred on April 5 while the remainder occurred on

April 6. Dividing the volume of seepage by the surface area for the day yielded the daily depth of seepage.

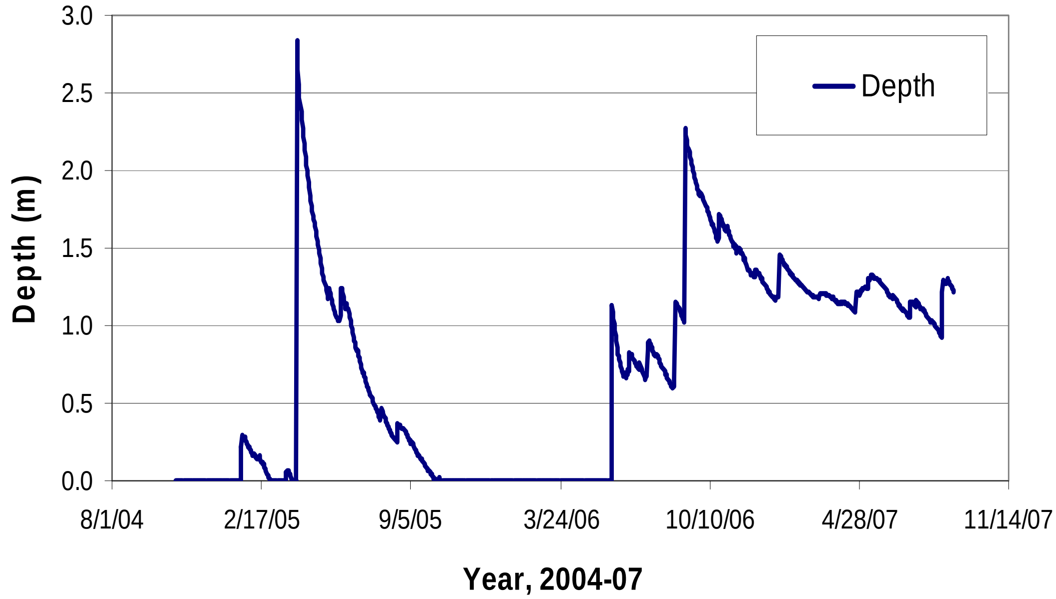


Figure 7. Temporal Change in Depth of Water in the DPL-Hogan Reservoir from 2004 through 2007.

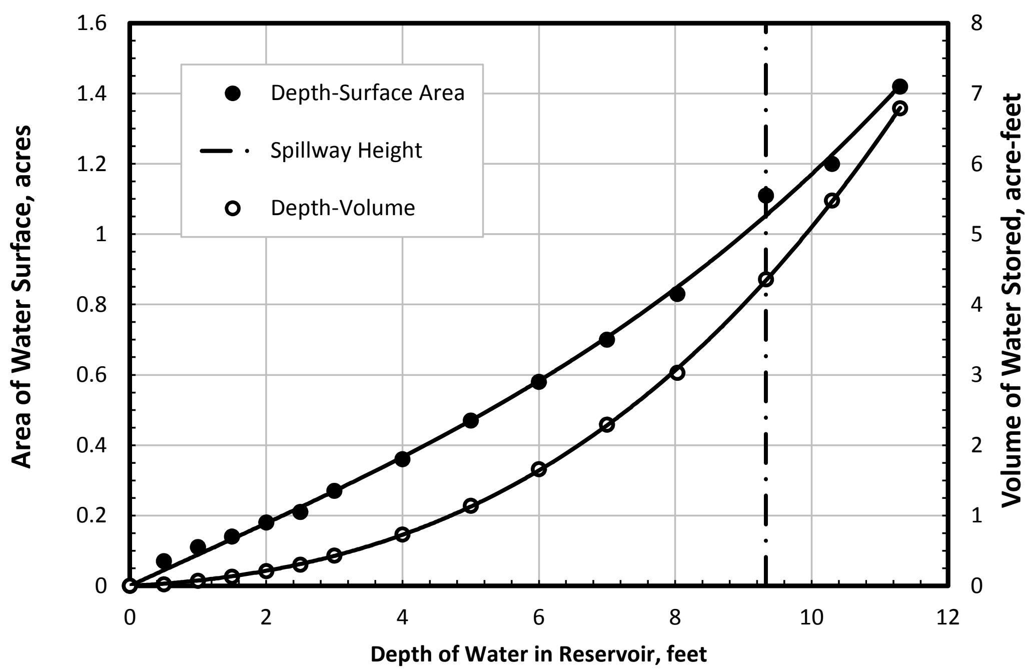


Figure 8. Stage-Storage Volume and Stage-Surface Area Relationships for the DPL-Hogan Reservoir.

Table 2. Daily Water Balance for the DPL-Hogan Reservoir Following a Large Inflow Event on April 5, 2005.

Date	Water Depth, feet	Surface Area, acres	Storage Volume	Precipitation	Inflow	Evaporation	Overflow	Seepage Volume	Seepage Depth, inches
			acre-feet						
4/6/2005	9.28	1.06	4.10	0.00	6.66	0.00	2.17	0.39	8.66
4/7/2005	8.72	0.91	3.59	0.00	0.00	0.01	0.00	0.51	6.10
4/8/2005	8.40	0.86	3.33	0.00	0.00	0.01	0.00	0.24	3.18
4/9/2005	8.10	0.84	3.11	0.00	0.00	0.01	0.00	0.22	3.10
4/10/2005	7.94	0.82	2.96	0.00	0.00	0.01	0.00	0.14	2.00
4/11/2005	7.81	0.79	2.86	0.04	0.00	0.00	0.00	0.14	2.05
4/12/2005	7.64	0.77	2.71	0.00	0.00	0.00	0.00	0.14	2.22
4/13/2005	7.45	0.74	2.59	0.00	0.00	0.00	0.00	0.12	1.96
4/14/2005	7.31	0.72	2.48	0.00	0.00	0.00	0.00	0.10	1.66

As a caution, these results include uncertainty and are estimates of the water balance for the reservoir. Sources of uncertainty result from spatial variation in precipitation that was from the weather station located about 3.5 miles from the reservoir site. The ETo values were weighted by the distance from the reservoir to weather stations at Scandia and Colby. Judgments were necessary to estimate the inflow volume from the water level records for the reservoir. Regardless of the uncertainty, the water balance from the reservoir is reliable for estimating seepage from the Non-Federal Reservoirs.

This event, and the subsequent period with very little inflow, provided an opportunity to observe seepage rates for the full range of depths for the reservoir. Water depth and seepage volume after the large inflow event for the DPL-Hogan Reservoir in Figure 9 illustrate how water seeps from the reservoir. Inflow from the watershed accounted for about 8.43 acre-feet of water supply while precipitation directly on the reservoir contributed about 0.35 acre-feet during the period from April 6 to August 22, 2005. Thus, the total water supply was approximately 8.78 acre-feet.

Overflow amounted to 35% of the total supply during the period. Evaporation loss was about 0.52 acre-feet, which only accounts for about 6% of the total supply. Precipitation directly on the reservoir equaled about 67% of the evaporation from the water surface. Gross seepage was about 4.94 acre-feet, which represents about 58% of the total supply to the reservoir. The water stored in the reservoir increased during the period by about 1% of the total water supply during the period.

A relationship between the depth of water in the reservoir and the daily seepage rate was developed for this period (Figure 10). The seepage rate increases as the water depth in the reservoir increases. The increase is nearly linear with depth of water in the reservoir for the lower half of the reservoir. These areas flood much more frequently than the upper areas of the reservoir, and therefore have lower and more constant seepage rates. Lower rates result due to a combination of accumulation of fine material in the bottom of the reservoir and some surface sealing caused by biological growth. The seepage rate increases substantially when the reservoir is nearly full. Higher seepage rates occur due to larger rates of infiltration into the sides of the reservoir that flood infrequently and due to additional hydraulic head in the reservoir.

The relationship in Figure 10 provides estimates of gross seepage losses; however, estimates of the net seepage that moves below the rooting depths of plants in and along the reservoir are necessary. The next section details components of the overall seepage model.

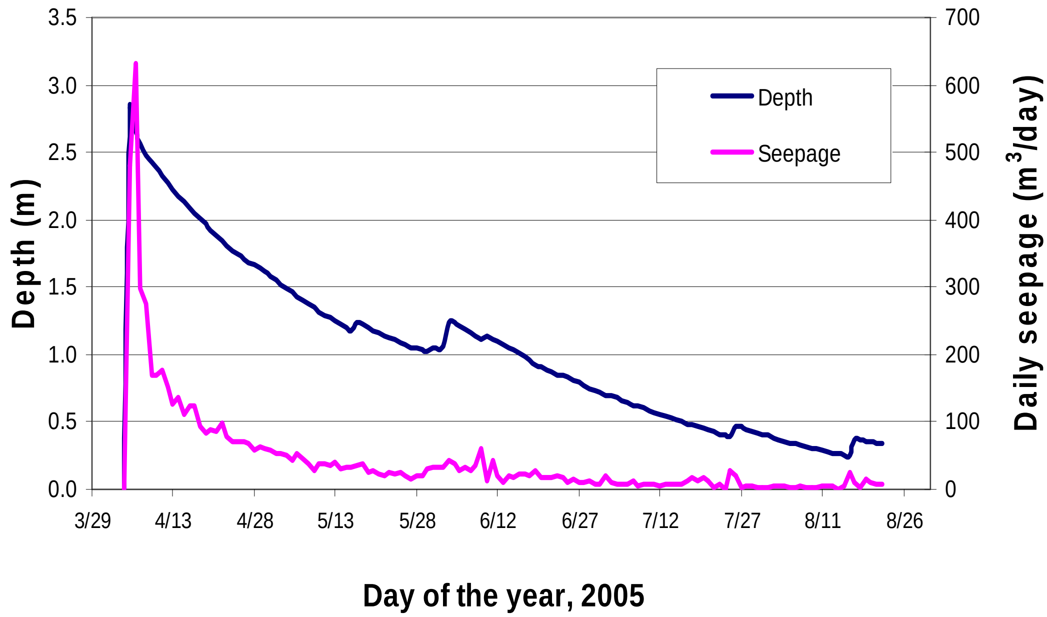


Figure 9. Pattern of Water Depth and Seepage Rates Following a Large Precipitation Event on April 5, 2005.

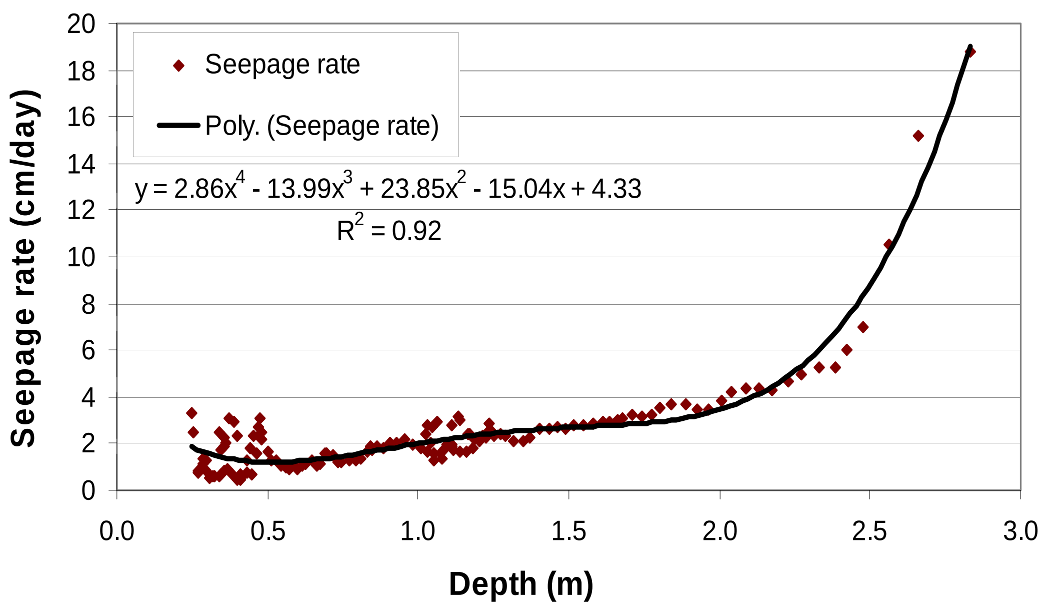


Figure 10. Calculated Daily Seepage Rate Versus Water Depth in DPL-Hogan for the 2005 Inflow Event.

Reservoir Seepage Model

The reservoir seepage model comprises three modules: an inflow module, a gross seepage module and a net seepage module. The inflow module is part of the POTYLDR model where runoff from Hydrologic Response Units (HRU) generated the input for the gross seepage module along with precipitation on the water surface. The gross seepage module solves the daily water balance and requires daily data inputs of inflow from the watershed, and daily precipitation and evaporation data. The stage-surface area and stage-storage volume relationships for the reservoir are input in an incremental fashion. Fifteen level sections or benches represent the topography of the reservoir storage area for estimating gross seepage as a function of water depth in the reservoir (Figure 5). The user must define the height of each bench above the bottom of the reservoir and the surface area for each bench. The measured reservoir stage-storage volume and stage-surface area relationships for the DPL-Hogan reservoir compared well to the relationships used in the gross seepage module (Figure 11).

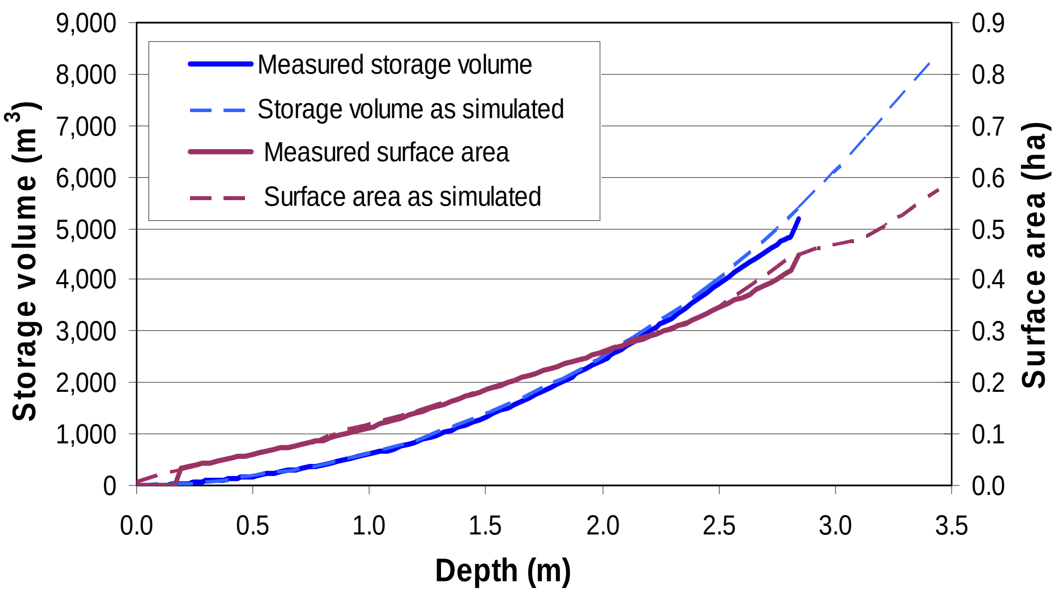


Figure 11. Stage-Storage Volume and Stage-Surface Area Relationships for the DPL-Hogan Reservoir.

We described seepage and infiltration as vertical movement resulting in one-dimensional soil-water flow. A power function describes the daily seepage rate for each bench as:

$$\begin{aligned} S_L &= S_O\, h_L^{\alpha} && \text{for } h_L > 1 \text{ foot} \\ &= S_O && \text{for } h_L \le 1 \text{ foot} \end{aligned} \qquad (2)$$

where,

S_L = daily gross seepage rate for a bench
S_O = basic seepage rate when the water is one foot above the bench elevation
h_L = height of water above the bench elevation
α = empirically derived seepage exponent.

Seepage rate calculations depend on the depth of inundation of each bench. The model reads daily inputs at the beginning of the day and updates the depth in the reservoir by adding inflow and precipitation to the depth at the end of the previous day. The new water depth and any overflow determine which benches inundate that day. We assume that benches not inundated at the beginning of the day contribute runoff at the same volume per unit area as the upstream watershed. The model then computes the seepage and evaporation for all inundated benches. Finally, the model computes the depth of water in the reservoir at the end of the day. The process then repeats for the next day.

Overflow Calculation

The maximum depth or capacity of a reservoir depends on the elevation of the spillway. Overflow occurs when the water depth exceeded the spillway height. The water depth of the 13^{th} bench corresponds with the spillway elevation. Water above the 13^{th} bench either overflows through the spillway or temporarily remains as storage in the reservoir above the spillway elevation. The elevation of the 14^{th} bench corresponds to the top of the reservoir. The potential volume of overflow equals the volume of water in the reservoir above the spillway elevation. Overflow was determined by inspecting the hourly water-depth sensor data. The overflow for the day equaled two-thirds of the potential overflow volume for any day when the volume of water in the reservoir was less than the elevation of the top of the dam. The 2/3 ratio applied for each day that the water level was above the spillway elevation.

Large storms can result in inflow volumes that when added to the existing storage in the reservoir exceeds the capacity of the dam. The overflow for a day when this occurred was equal to the total volume (existing volume plus inflow) minus the volume that could be stored if the water was at the height of the top of the dam (equal to the elevation of the 14^{th} bench). The overflow rate for the following day was equal to 2/3 of the water above the spillway elevation. The daily water balance determined the volume of water in the reservoir.

Calibration of Gross Seepage Module

Records for the DPL-Hogan reservoir from April 5 through October 22, 2005 provided data to calibrate the gross seepage module. Water depths in the reservoir started at the spillway height and dropped to zero during the period. The calibration used daily precipitation, ETo, inflow, and water depth data. Reservoir characteristics for the 14 benches included their height above the bottom of the reservoir, the surface area and estimated seepage rate as a function of hydraulic head. We compared simulated water depths in the reservoir to the measured water depths.

Seepage rates depend on the basic seepage rate (S_O) for a water depth of one foot and the seepage exponent (α). We varied these values to produce an acceptable correlation to measurements for the DPL-Hogan reservoir from April 6 to October 22, 2005. We determined the basic seepage rate (S_O) as a function of the depth of water in the reservoir from data presented in Figure 10. This resulted in basic seepage rate values as shown in Figure 12. The basic seepage rate increases from 0.25 inches/day at a depth of one foot to 6 inches/day for the upper benches of the reservoir.

We calibrated the seepage exponent (α) in equation 2 using measured water levels. We computed the simulated water depths in the reservoir for exponent values of 0.0, 0.25, 0.50, and 1.0. An exponent value of 0.25 produced the best fit with the measured water depth; see the sum of squares between measured and modeled daily depths in Table 3. The water depths in Figure 13 compare the simulated and measured values for each exponent. The simulated water depths were generally within ±0.1 meters of the measured depths for the exponent value of 0.25 (Figure 14). There is an upward trend in errors with increasing water depths; however, at a depth of 2 meters the error is only about

5% of the storage depth. We consider this level of accuracy acceptable given the variation in other inputs.

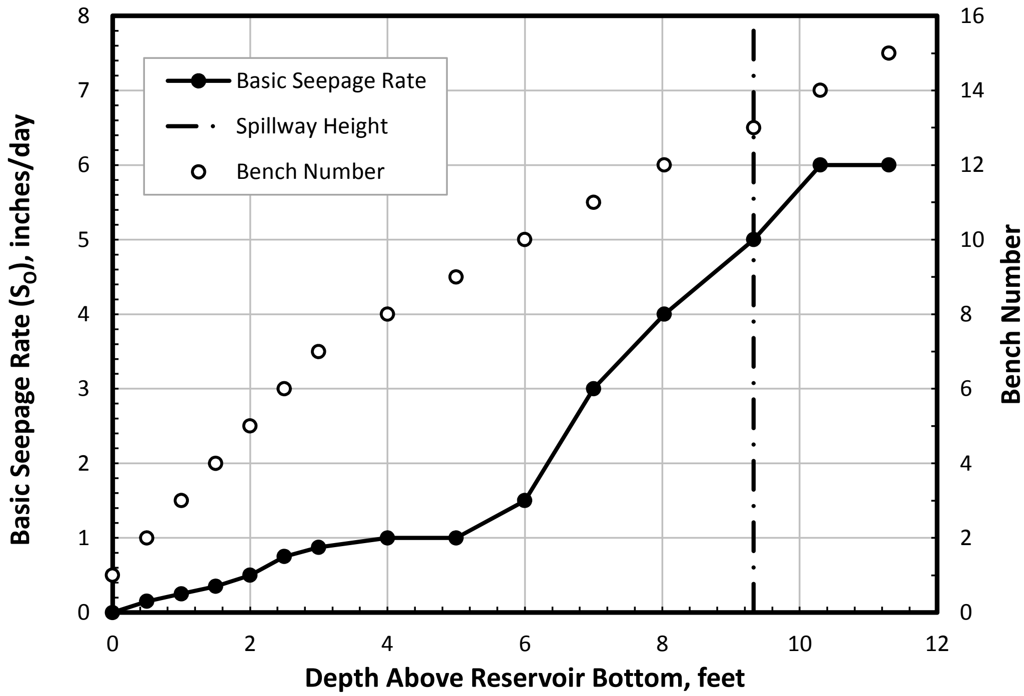


Figure 12. Basic Seepage Rate Coefficients and Bench Numbers for the DPL-Hogan Reservoir.

Table 3. Sum of Squares of Difference Between Measured and Simulated Daily Water Depths When the Seepage Exponent Ranged from 0 to 1.

Seepage exponent			
0.00	0.25	0.50	1.00
Sum of squares			
1.52	0.58	2.25	14.05

Subsequently, we simulated the water balance for the DPL-Hogan reservoir for four years using the basic seepage rate and the seepage exponent determined from calibration. Conditions for the four years are similar to the period used for calibration except no overflow occurred. The measured and simulated daily water depths are similar for the period (Figure 15). Results were very good with an average difference between measured and simulated daily water depths of approximately 0.4 inches. Gross seepage accounted for 94% of the inflow to the reservoir during the four-year period.

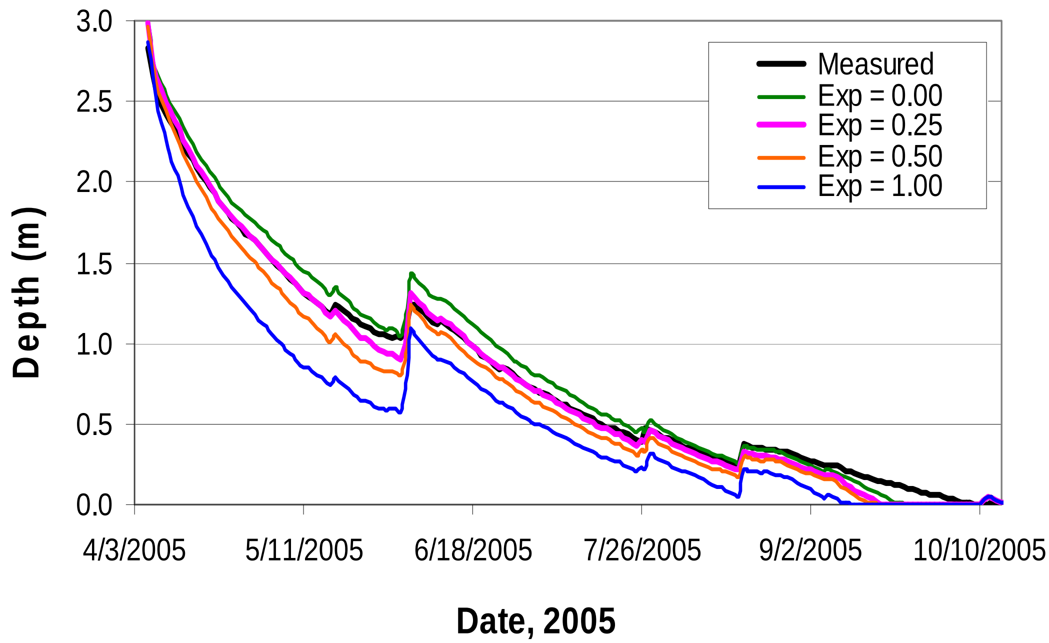


Figure 13. Comparison of Predicted and Measured Water Depth for a Range of Seepage Exponents.

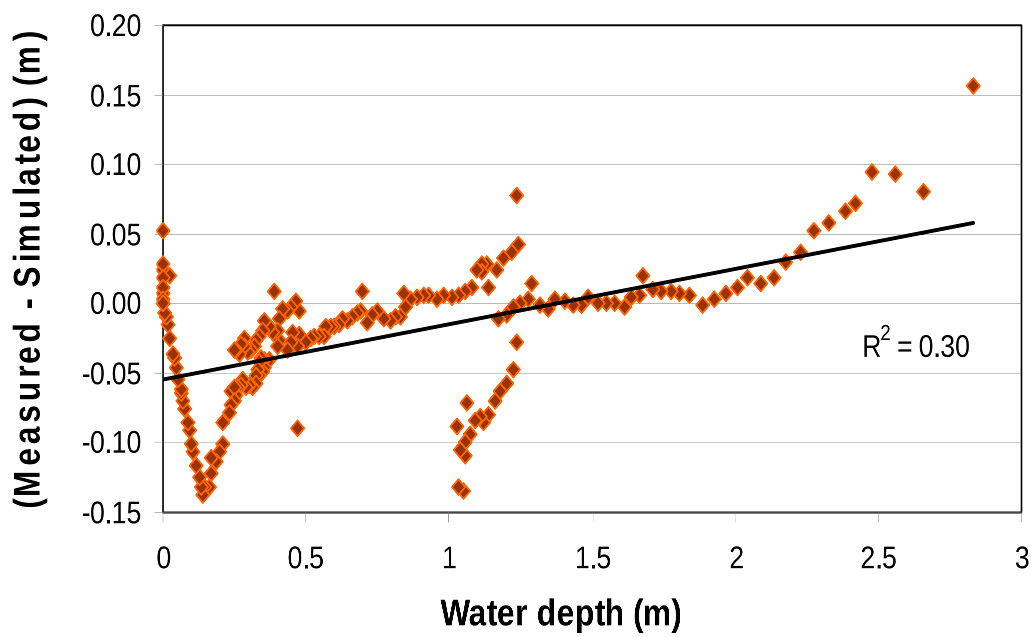


Figure 14. Differences in Measured and Simulated Daily Reservoir Water Depths for a Seepage Exponent of 0.25.

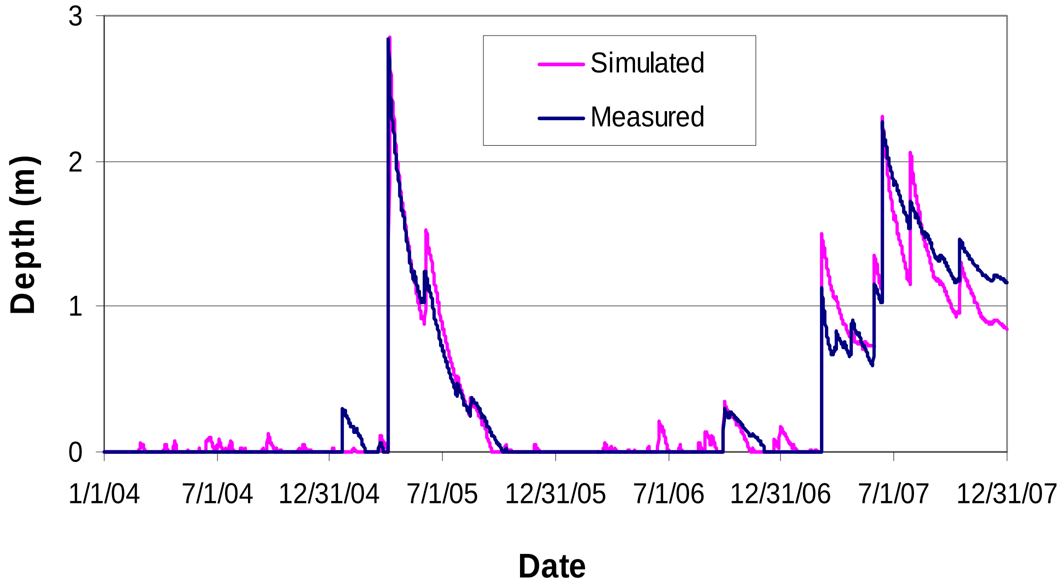


Figure 15. Simulated and Observed Water Depths for the DPL-Hogan Reservoir for the Calibrated Seepage Model.

Assessment of Gross Seepage Module

Water level measurements at the DCN-Zimb and DRA-Holste Reservoirs provided data to assess the seepage model more thoroughly. Assessment involved comparing simulation results with measured water depths.

Description DCN-Zimb Reservoir --This reservoir is located in northwestern Kansas (Figure 2) approximately 3.5 miles from the St. Francis 8NW weather station. Annual precipitation at the weather station averages about 18 inches. The DCN-Zimb reservoir has a watershed area of 74 acres with an average land slope of seven percent. The stage-storage volume and stage-surface area relationship for the reservoir are in Figure 16. One-third of the watershed area is cropland with level-closed terraces in poor condition and the remaining two-thirds is grazed pasture/range. The primary soil type is a Colby silt loam with moderate permeability rates of 0.6 to 1.9 inches/hour. We estimated ETo to be 97% of the values from the Colby, Kansas station. The reservoir surface area at the spillway height is 1.2 acres.

Description of the DRA-Holste Reservoir--The DRA-Holste reservoir is located in the Rawlins County (Figure 2) about 6 miles from the Atwood 8SSE weather station. The contributing watershed area is approximately 430 acres. Average annual precipitation is about 21.6 inches. Silt loam soils at the site have moderate permeability rates of 0.6 to 1.9 inches/hour. Land use in the watershed area is about half cropland with level-closed terraces in good condition and half is pastured rangeland. The ETo was weighted between Colby, KS and Scandia, KS. The average annual ETo was about 60 inches. The reservoir surface area at the spillway height is 4.52 acres. The stage-storage volume and stage-surface area relationships for the reservoir are in Figure 17.

Soil at the DPL-Hogan reservoir contains less sand and more clay than the soils at the other two reservoirs (Table 4). Soil water characteristics from pedon transfer functions by Saxton et al. (1986) provided estimates of the saturated hydraulic conductivity for the soils (Table 4).

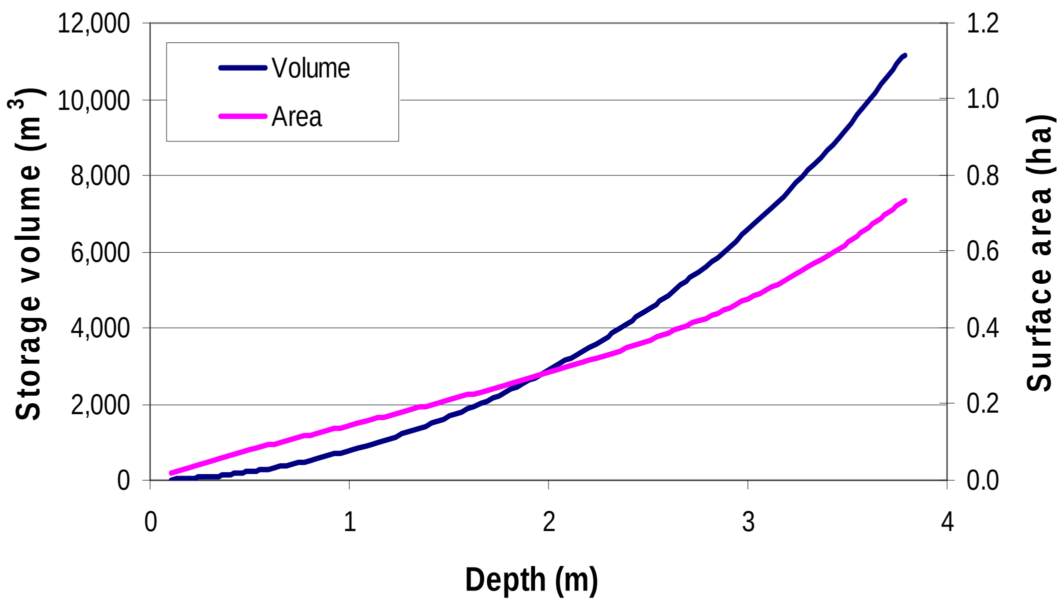


Figure 16. Stage-Storage Volume and Stage-Surface Area Relationship for the DCN-Zimb Reservoir.

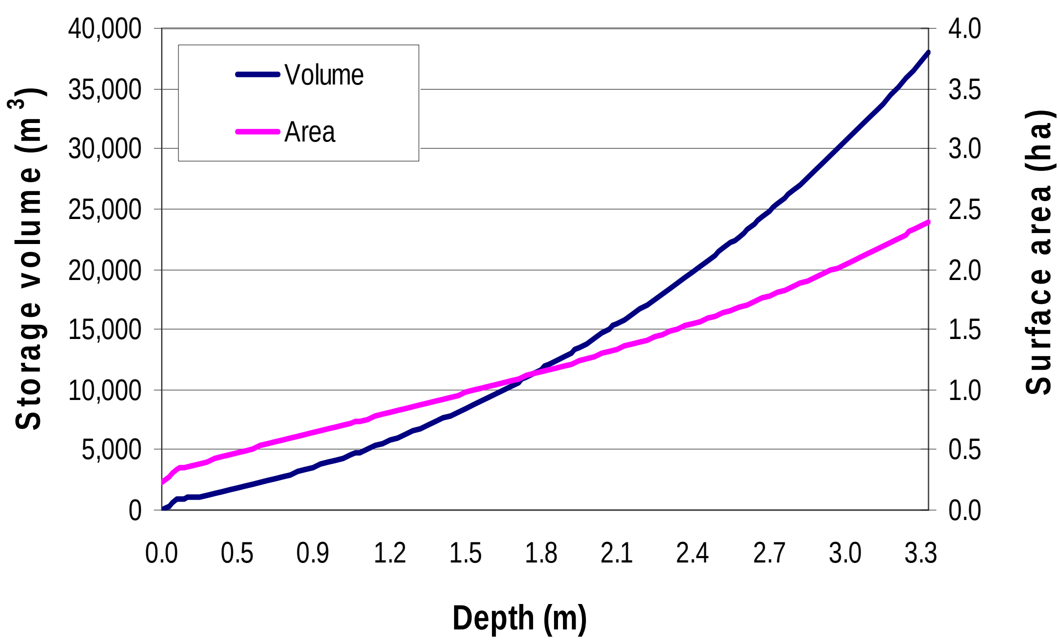


Figure 17. Stage-Storage Volume and Stage-Surface Area Relationships for the DRA-Holste Reservoir.

Table 4. Soil Characteristics at the Three Reservoirs and Estimated Seepage Rates.

Reservoir	Soil series	Approximate sand/silt/clay (percent)	Approximate hydraulic conductivity, inches/hour[a]	Rate of seepage depth vs. time, inches/day[b]
DPL-Hogan	Uly Penden	25/45/30	0.47	1.58
DCN-Zimb	Colby	30/47/23	0.51	6.7
DRA-Holste	Colby	30/47/23	0.51	22.5

[a] From Saxton et al. (1986)

[b] Determine from Individual Inflow Events for Each Reservoir.

We analyzed water depth patterns for the DCN-Zimb and DRA-Holste reservoirs following major inflow events (Figures 18 and 19). We initially used basic seepage rates determined from the DPL-Hogan Reservoir for the DCN-Zimb and DRA-Holste Reservoirs. The modeled and estimated seepage rates for the DCN-Zimb Reservoir agreed well except at lower inundation depths; therefore, we adjusted the basic seepage rate for levels 1-4 for the DCN-Zimb Reservoir.

Seepage rates were higher for the DRA-Holste reservoir. We increased the basic seepage rates for all levels in the DRA-Holste reservoir to represent these effects. The DRA-Holste reservoir is part of Highway US-36 and was constructed by filling the stream valley. This resulted in little disturbance of the surface soils in the reservoir storage area. The soils in the reservoir area are more typical of the surface soils than excavated materials from reservoir storage area. Hence, higher seepage rates were necessary to obtain agreement between simulated and measured water depths.

The basic seepage rates listed in Table 4 for the three reservoirs exhibit a large variation. The basic seepage rates as a function of water depth in the reservoirs are presented in Figure 20. The average difference between measured and simulated daily water depth was 4 cm for the DCN-Zimb reservoir and 1 cm for the DRA-Holste reservoir. Days with zero depths are included in the averages. These results demonstrate that the gross seepage module worked well after adjusting seepage parameters. The simulated water balances for these reservoirs in Table 5 show that the gross seepage is the dominant outflow of water from all reservoirs (about 70% of total inflow for Hogan and Holste, and about 80% for Zimb). Evaporation from the reservoirs averaged between about 7 and 15% of the total inflow. Overflow constituted the remainder of the water balance ranging from 5% to 23%.

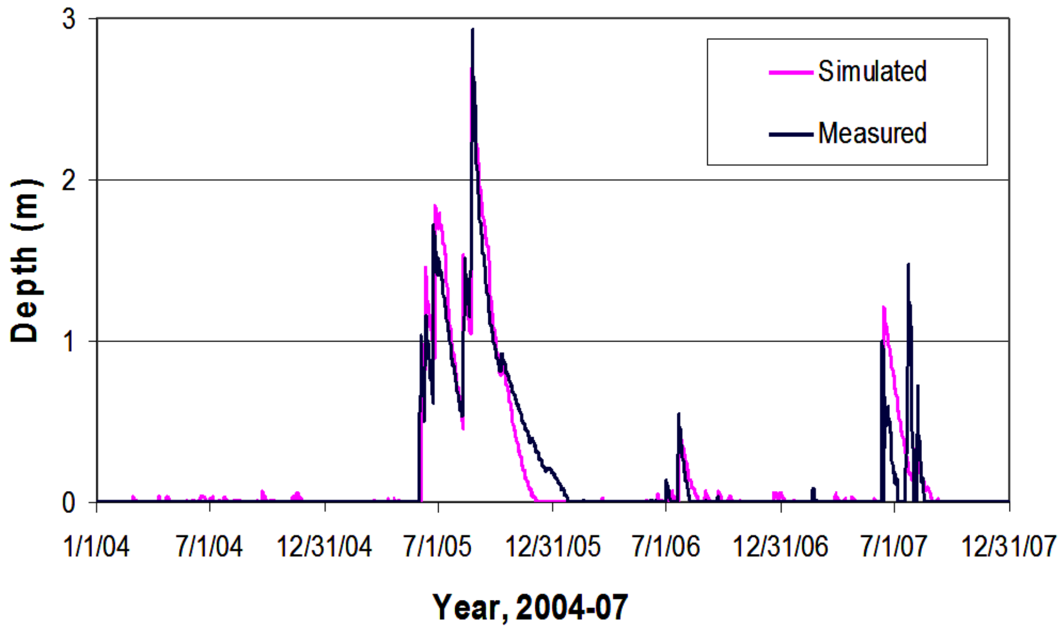


Figure 18. Simulated Versus Observed Water Depth Comparison for the DCN-Zimb Reservoir.

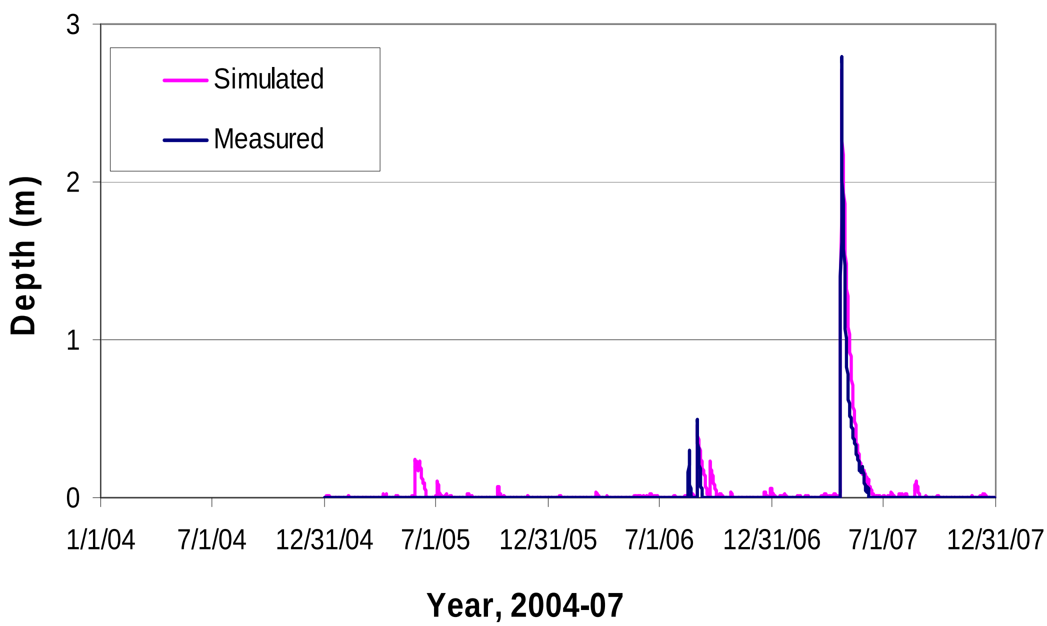


Figure 19. Simulated Versus Observed Water Depth Comparison for DRA-Holste Reservoir, 2004-07.

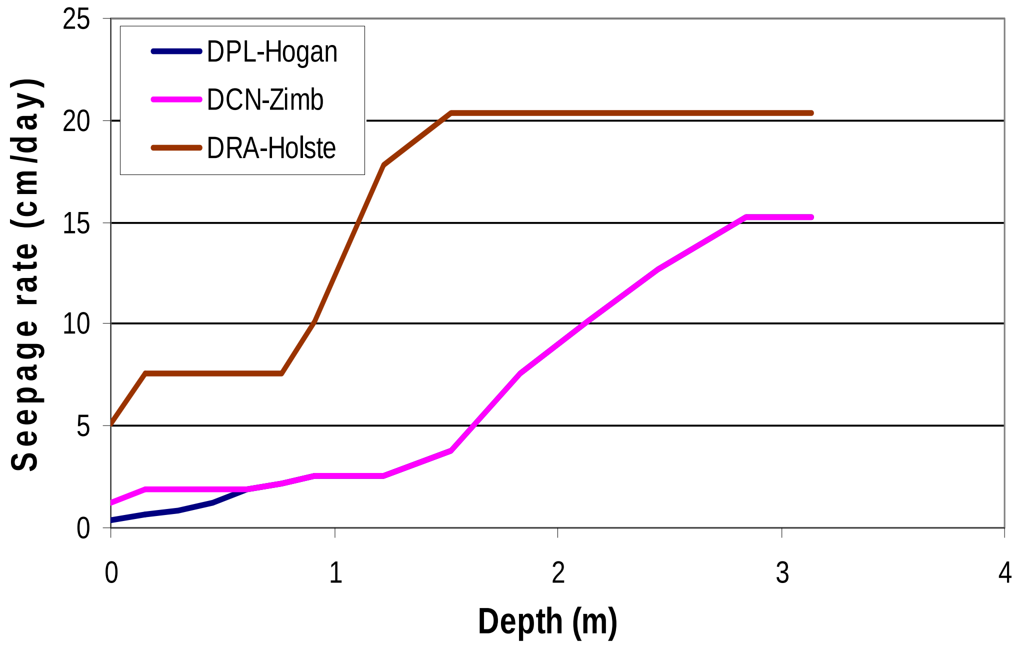


Figure 20. Calibrated Basic Seepage Rates Versus Water Depth for the Three Non-Federal Reservoirs.

Table 5. Simulated Water Balance for Reservoirs from 2004 through 2007.

Quantities	Volumes in acre-feet (1 acre-foot = 1234 m^3)		
	DPL-Hogan	DRA-Holste	DCN-Zimb
Inflow			
Inflow from the watershed	15.88	78.02	15.56
Precipitation on water surface	2.07	7.68	1.51
Total	17.95	85.70	17.08
Outflow			
Overflow	2.73	20.11	0.53
Evaporation from water surface	2.50	6.53	2.58
Gross seepage	12.72	59.07	13.97
Total	17.94	85.71	17.08

We simulated water budgets for the contributing drainage areas when reservoirs were present and absent. The difference between inflow from the watershed area without the reservoir and the overflow with the reservoir divided by the inflow from the watershed area without the reservoir represents the streamflow reduction percentage. Streamflow from the watershed decreased by 83% to 97% with the reservoirs in place (Table 6). The gross seepage ranged from 93% of inflow at the DCN-Zimb reservoir to 100% at the DRA–Holste reservoir.

Table 6. Contributing Area Water Balance for 2004 – 2007 when Reservoirs are Present or Absent.

Quantity	Volumes in m^3 (1 acre-foot = 1234 m^3)					
	DPL-Hogan		DRA-Holste		DCN-Zimb	
	Without reservoir	With reservoir	Without reservoir	With reservoir	Without reservoir	With reservoir
Inflows						
Inflow from watershed	19,870	19,600	97,280	96,310	19,460	19,210
Precipitation on reservoir	-	2,560	-	9,480	-	1,870
Total	19,870	22,160	97,280	105,790	19,460	21,080
Outflows						
Overflow	19,870	3,370	97,280	24,820	19,460	650
Evaporation	-	3,080	-	8,060	-	3,190
Gross seepage	-	15,700	-	72,920	-	17,240
Total	19,870	22,150	97,280	105,800	19,460	21,080
Streamflow change	-16,500		-72,460		-18,810	
Streamflow change (%)	-83.0		-74.5		-96.7	
Gross seepage increase	15,700		72,920		17,240	

Net Seepage Module

The net seepage module simulates the water balance on a daily basis. Net seepage is the water that percolates from the bottom of the root zone of plants that grow along the reservoir. This water may become groundwater recharge from the reservoir. Choodegowda (2009) developed the model and presented more details about the model and data requirements.

The soil profile was divided into three zones the: (1) upper 4-inch zone, (2) the middle zone from 4 to 12 inches, and (3) the lower 48-inch deep zone from 12 to 60 inches. The upper zone receives water from infiltration when not inundated and seepage when inundated. The upper zone loses water by evaporation from bare soil and runoff when not inundated and by percolation to the middle zone whenever the water content of the upper zone exceeds field capacity. The middle zone receives percolated water from the upper zone, loses water by transpiration when conditions are suitable for plant growth, and by percolation to the lower zone whenever the water content exceeds field capacity in the layer. The lower zone receives seepage from the middle zone and loses water by transpiration when conditions are suitable for plant growth and by percolation when the water content of the lower zone exceeds 90% of field capacity for the layer. The net seepage model does not include upward flow of water in the soil profile. The soil-water characteristics for the silt loam soil used in the simulation are included in Table 7.

Table 7. Soil-Water Characteristics of Silt Loam Soil.

Soil zone	Zone thickness , inches	Water content at (inches/zone)			
		FC	90% FC	PWP	50% PWP
Upper	4	1.42	NA	0.79	0.40
Middle	8	2.84	2.56	1.57	NA
Lower	48	16.8	15.0	9.61	NA

Evaporation from bare soil (BSE) may occur if water does not inundate a bench in the reservoir. We used the two-stage process found in FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) to describe evaporation for the soil. The first-stage, when the soil is wet, occurs at a constant rate equal to the amount of ETo that reaches the surface. This process occurs until the available soil water content in the upper soil zone drops to 70% of field capacity. The second stage of evaporation occurs when the hydraulic properties of the soil limit the evaporation rate. Second-stage evaporation begins when the available soil water drops below a threshold of 70% of field capacity. The evaporation rate decreases exponentially when the soil water is between 70% of field capacity and 50% of the permanent wilting point. Bare soil evaporation depends on the residue cover on the soil. Residue influences energy and water exchange between the soil surface and the atmosphere. We assume there is more residue cover during the non-growing season than during the active growing season.

Plants remove water from the middle and lower zones of the soil profile by transpiration during the growing season when water does not inundated a bench, except during periods following flooding events. The potential transpiration rate is the difference between ETo and the amount of bare soil evaporation. The transpiration rate equals the ETo rate as long as the root zone is wetter than a critical threshold. If the soil dries beyond the threshold the daily transpiration rate decreases.

Three scenarios occur in modeling the effects of inundation on soil-water movement. First, no soil evaporation or transpiration occurs from a bench when that level floods. The second scenario is when a bench is not flooded, but recent inundation lasted long enough to affect plant growth. Transpiration during this period does not reach the potential rate until plants regrow. Bare soil evaporation occurs when water does not inundate a bench, and transpiration slowly increases over time until plants reach the point that the potential transpiration rate is attainable. The third scenario occurs when plants grow to the stage where the potential transpire rate can be sustained if adequate soil water is present.

The net seepage module uses daily output from the gross seepage module. The daily inputs are gross seepage on each bench in the reservoir along with precipitation, ETo, and inflow from the watershed to the reservoir.

Results for the DPL-Hogan reservoir for the 4-year period used to simulate gross seepage provided data to simulate net seepage as summarized in Table 8. Remember bench 14 is above the spillway so seepage should not occur for that bench. Results show that there was no percolation during the four years for bench 14. Essentially equal amounts of bare soil evaporation and transpiration occurred. The sum, which is evapotranspiration, totaled 96% of the precipitation. Runoff and increases in soil water content in the root zone equaled two percent. Net seepage occurred on all 13 benches that inundated during part of the four-year period. Net seepage is nearly equal to gross seepage for most benches (Figure 21). The total height of the bars for each level in Figure 21 is the gross seepage and the lesser amount inside the bar is the net seepage for each level. Gross and net seepage both reached a maximum for benches 4 through 7. Net seepage for bench 1 was smaller because it had a lower basic seepage rate that limits gross seepage when inundated. The cumulative net seepage was 12 acre-feet compared to the gross seepage of 12.7 acre-feet for the DPL-Hogan reservoir during the 4-year period. Net seepage accounted for 95% of gross seepage, which is likely potential groundwater recharge. Average annual net seepage was about 3.0 acre-feet/year.

We used the net seepage model to simulate a 37-year period using historical weather data for the DPL-Hogan reservoir. The ratio of net seepage to gross seepage at different levels was similar to the results for the 4-year run of observed data (Figure 22). For this period, 93% of the gross seepage percolated below the lower zone of the soil profile and likely contributed to groundwater recharge. The average annual net seepage was 2.34 acre-feet for the 37-year period. The cumulative value of the water balance components for the 37-year period for the DPL-Hogan reservoir show that gross seepage is about 72% of the total inflow to the reservoir due to runoff from the watershed (Figure 23). About 28% of the inflow to the reservoir spilled through the spillway as overflow. The cumulative precipitation that fell on the reservoir is about equal to the amount of evaporation from the reservoir over the 37-year period.

Table 8. Water Balance from the Net Seepage Module for the DPL- Hogan Reservoir, 2004-2007.

Bench Number	Depth above bottom (m)	Gross seepage (cm)	Precipitation (cm)	Net seepage (cm)	Bare soil evaporation (cm)	Actual ET (cm)	Runoff (cm)	Change in soil water (cm)	Net seepage (%)
1	0.00	384	0	292	46	27	0	19	76
2	0.15	404	116	371	73	56	0	19	92
3	0.30	489	135	467	78	59	0	19	96
4	0.46	641	146	627	80	60	0	19	98
5	0.61	888	153	879	82	61	0	19	99
6	0.76	898	156	885	87	62	0	19	99
7	0.91	805	169	791	95	70	0	19	98
8	1.22	410	198	398	110	81	0	18	97
9	1.52	294	219	276	117	106	1	13	94
10	1.83	272	227	247	120	123	1	7	91
11	2.13	145	236	129	122	123	1	5	89
12	2.44	76	244	66	123	124	2	5	86
13	2.83	15	245	5	124	124	2	5	35
14	3.14	0	255	0	124	121	5	5	-

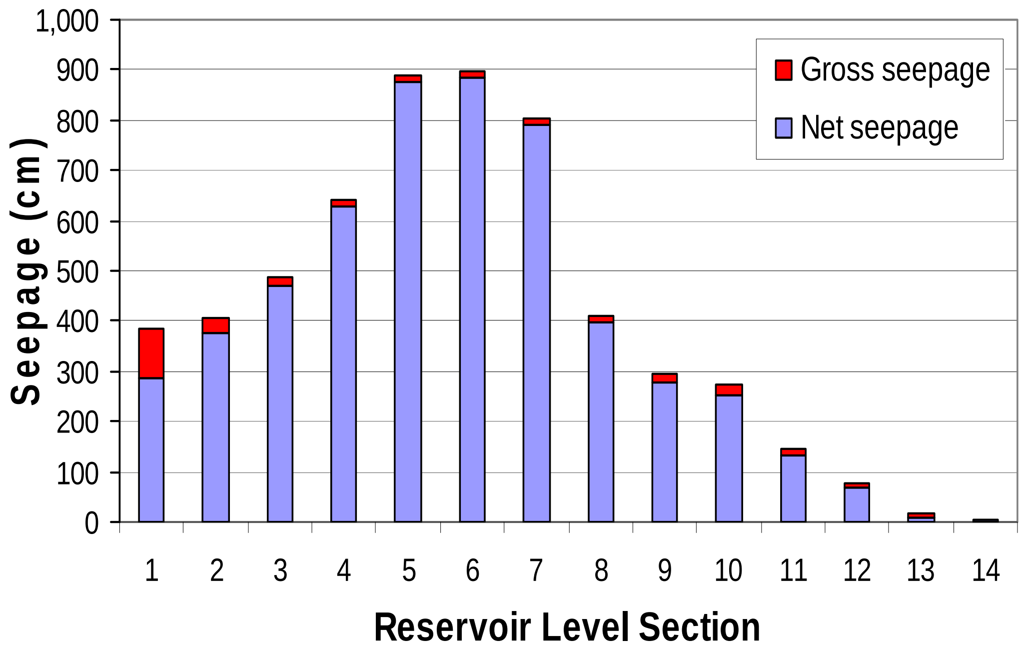


Figure 21. Simulated Gross and Net Seepage at Different Depths of the DPL- Hogan Reservoir, 2004 - 2007.

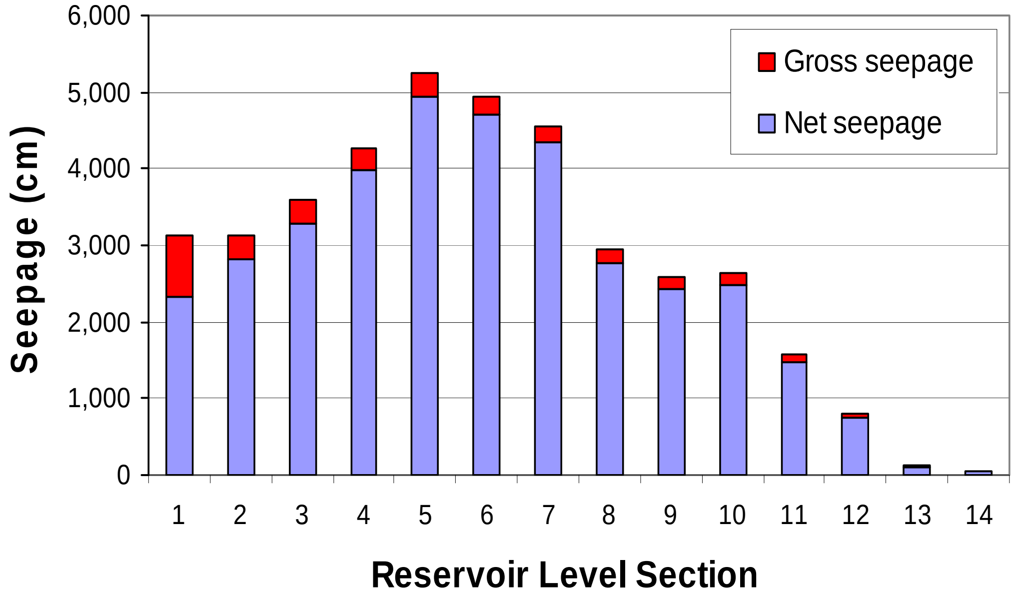


Figure 22. Simulated Gross and Net Seepage for the DPL- Hogan Reservoir, 1971-2007.

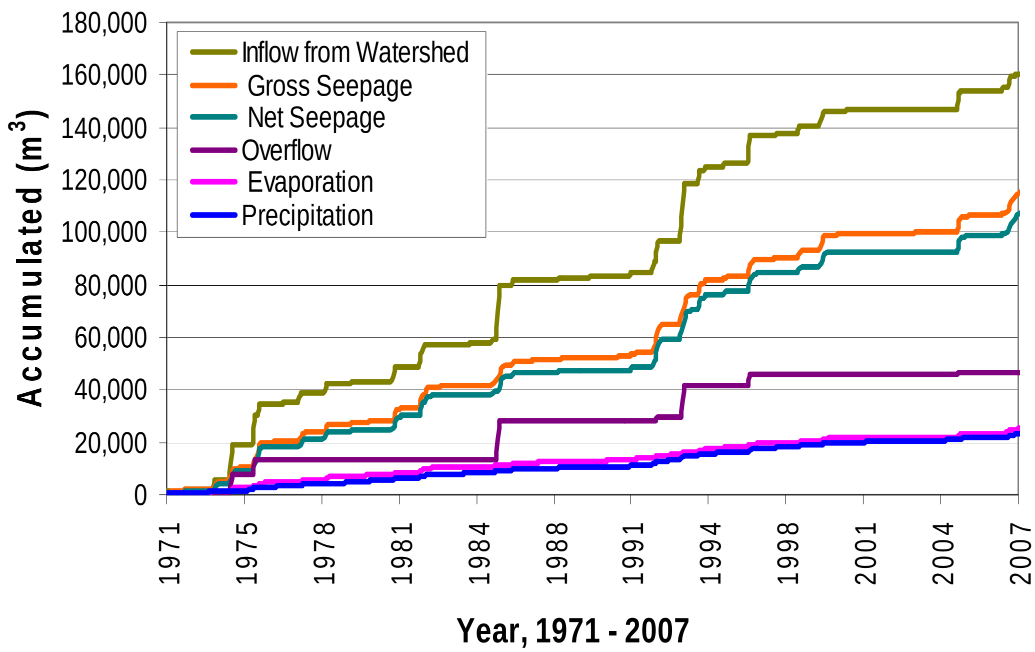


Figure 23. Accumulated Water Budget Components of the DPL-Hogan Reservoir, 1971-2007.

The water balances for the three monitored reservoirs for 2004 through 2007 are summarized in Table 9. Between 90% and 95% of the gross seepage percolated through the bottom of the lower zone to become potential groundwater recharge. The highest percent of contribution occurred in the DPL-Hogan reservoir, which stored water during most of the study period.

Table 9. Comparison of Net Seepage to Gross Seepage for Three Reservoirs for 2004 through 2007.

Quantity	DPL-Hogan	DRA-Holste	DCN-Zimb
Gross seepage, m^3	15,700	72,920	17,240
Net seepage, m^3	14,860	68,340	15,540
Ratio of net seepage to gross seepage (%)	94.6	93.7	90.1

Model Sensitivity Analysis

We conducted a sensitivity analysis to determine the influence of parameters on the water balance components for the reservoirs and watersheds. Simulations utilized historical weather data from 1971 to 2007. The water balance of reservoirs was evaluated for variations of the:

- Watershed area.
- Seepage rate.
- Water storage depth.
- Soil depth of the lower zone at each level section of the reservoir.
- Evapotranspiration rate from the water surface area.

The main source of water to the reservoir is runoff from the watershed area (inflow) so we varied the amount of inflow in 25% increments, from -75% to +100%, of the base inflow to assess impacts on net seepage and reservoir overflow. The seepage rate varied, for all levels of the reservoir, in increments of 25% between 75% less to 200% above base levels. The depth of the reservoir also involved 25% incremental steps so that surface area changed but the volume remained the same for the new depths. Lower zone soil depth is one of the crucial assumptions in estimating the effect of the amount of net seepage. It has no effect on overflow. To examine its effect on net seepage, the original lower zone soil depth of 48 inches ranged from 8 inches to 8 feet. Finally, evaporation from the water surface area and evapotranspiration demand were assumed to equal ETo. To test the effect of this assumption, the original daily ETo values changed in 25% increments from 75% below to 200% above the original values.

When inflow decreased by 50%, the net seepage and overflow declined by 30% and 83%, respectively. Smaller amounts of inflow remained in the reservoir but were subsequently lost as net seepage. When inflow increased by 100%, net seepage grew by 47% and overflow rose by 234% above original quantities. Changes in runoff from the watershed strongly affect net seepage and overflow.

Varying the seepage rate had less effect on overflow and net seepage. Net seepage and overflow respond in opposite patterns when seepage rates increase. Decreasing the seepage rate by 75% reduced net seepage by about 20% and increased overflow by about 20%. When the seepage rate increased to 200% of the original value, the net seepage rose by about 15% while the amount of overflow decreased by about 20%.

Variations of the depth of the reservoir, with a resulting increase in surface area, had limited impact on net seepage and overflow. As the depth decreased, the surface area increased to accommodate the storage volume, which increased evaporation from the water surface. This resulted in a reduction of both net seepage and overflow. Increasing the depth led to more water storage with a smaller surface area for evaporation and seepage that created more overflow and a slight decrease in net seepage. Again, relative changes are rather small compared to the changes caused by changes in inflow.

Net seepage and overflow were relatively insensitive to variations in the depth of the lower zone in the soil profile. Net seepage decreased as the depth of the lower zone increased because deeper zones increased soil water storage in the lower zone. More water is required to fill the soil storage before water percolates from the lower soil zone. Increasing soil water storage, in turn, provides more water for plants periods between inundations. Additionally, more gross seepage is required to refill the larger storage volume in the lower zone before percolation occurs. Conversely, a shallower lower zone is easy to refill resulting in percolation from minor inundation events. Of course, plant ET is limited when less soil water is available. Very shallow lower zones lead to percolation from areas that seldom flood during wet periods.

Evaporation losses from the reservoir depend on the rate of evapotranspiration compared to the amount of rainfall that falls on the reservoir. Varying ETo, which drives the rate of evaporation, only slightly affected overflow because it only influences evaporation during the time that water overflows the spillway. Net seepage was more sensitive to the changes in ETo because the changes affect bare soil evaporation and plant transpiration, which occurs over longer periods than overflow. Analyses show that precipitation on the reservoir provides water for evaporation so that the change of storage in the reservoir over a longer period is small.

Most of the annual inflow to a reservoir ultimately goes to either net seepage or overflows the spillway and flows downstream. The ratio of average annual inflow volume to the reservoir volume (I/V) provides a means to describe the relative rates of net seepage and overflow (Figure 24). The I/V ratio for the DPL-Hogan reservoir was 0.8. The fraction of inflow that becomes overflow was about 32% for the DPL-Hogan reservoir while the fraction that became net seepage was about 68%. The relationship in Figure 24 provides a basis to estimate the fraction of overflow and net seepage for other reservoirs in the region. The sum of the fractions is close to 1.0 in Figure 24, which indicates that nearly all of the inflow is lost as overflow or net seepage. Evaporation is the other important route of water loss from the reservoir; however, precipitation that falls on the water surface of the reservoir partially offsets evaporation. Evaporation minus precipitation is a small part of the total water budget for these reservoirs. Reservoirs in the western portion of the Basin are often empty or nearly empty, so the surface area is small. Finally, when the I/V ratio is small, overflow is unlikely and the net seepage fraction is greater than 1.0. This can occur because net seepage may arise from percolation within the reservoir area during wet periods for those parts of the reservoir that seldom flood.

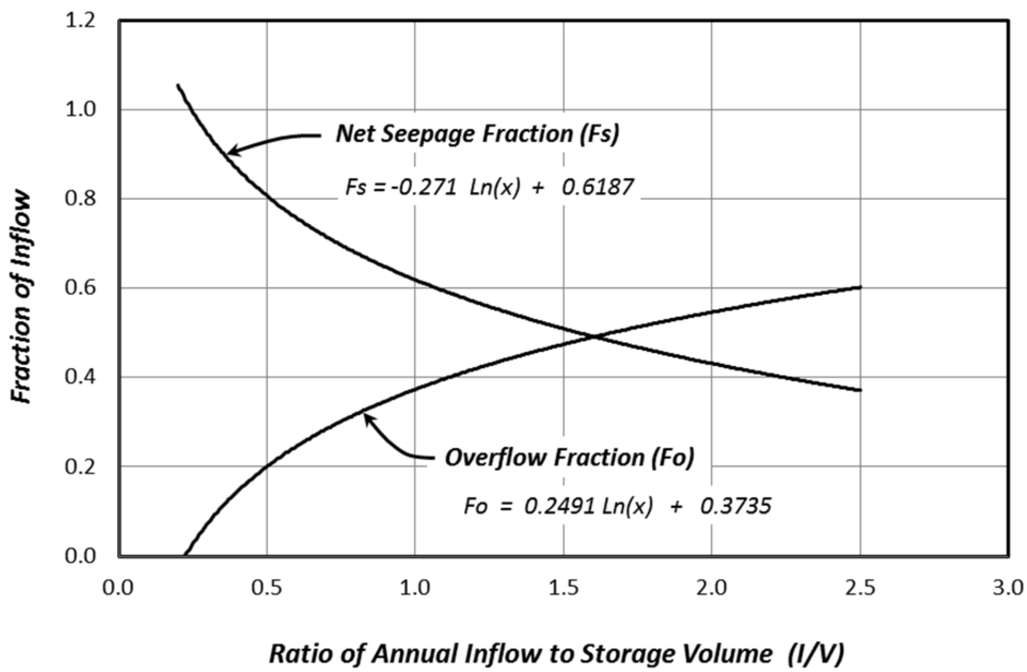


Figure 24. Effect of Ratio of Annual Inflow Volume to Reservoir Volume (I/V) on Fraction of Annual Inflow that Overflows and Net Seepages from the DPL-Hogan Reservoir.

Reservoir Summary

- The study of reservoirs by Choodegowda (2009) and data from monitoring selected reservoirs provided data and models for simulating the operation of small Non-Federal Reservoirs. Results of those developments show that:

- Reservoirs across the basin often retained little or no continuous storage. This limits empirical data for deriving water balances on a continuous basis and underscores the need to model reservoir performance.

- The three reservoirs that Choodegowda (2009) analyzed provided data to calibrate and verify reservoir model components.

- Most reservoirs do not have a continuous inflow. We assumed that runoff into reservoirs was from surface runoff. The exact inflow from an event may occur over several days; however, the total amount of inflow is most important.

- Most Non-Federal Reservoirs do not have pipe spillways, so they discharge infrequently through an overflow or emergency spillway. Therefore, when overflow occurs water is lost quickly. For modeling purposes, we assumed that the overflow occurred over a couple of days following the runoff event.

- The water balance for Non-Federal reservoirs shows that most of the inflow becomes net seepage, or groundwater recharge, while a smaller portion overflows the reservoirs. Some evaporation and evapotranspiration occurs, but precipitation that falls on the water surface largely offsets direct evaporation from the reservoir. Evapotranspiration does not occur from the permanent pool of the reservoir because vegetation does not grow in that area.

- We found that more than 90% of the water that infiltrates into the soil in the reservoir becomes -recharge below the rooting depth of the vegetation that grows in the pool area. We used this ratio in subsequent modeling of the water budget for reservoirs. Net recharge accounted for about 90% of the inflow. The remaining 10% of the inflow went to ET from vegetation near or in the reservoir or evaporation from the water surface in the reservoir.

- The seepage rate from reservoirs is high during those infrequent times when they completely fill. The average seepage rate is reasonably linear with the depth or fullness of the reservoir. Seepage rates are small for shallow water levels in the reservoir but increase substantially when reservoirs are nearly full. The seepage rate has a limited effect on partitioning inflow into net recharge or evaporative loss.

- We drew the following inferences for subsequent modeling of the performance of reservoirs throughout the basin:

- The minimum seepage rate for shallow water levels in the reservoirs is 0.10 inches per day. The rate increases linearly to 1.2 inches per day when the water level is near the top of the permanent storage pool.

- Information was available for the principal spillway height, total storage volume, surface area, average side slope, and bottom length and width for some reservoirs. We used these characteristics to derived relationships for "typical" reservoirs across the entire Basin.

Terrace Research

Description of Terrace Operation

Terrace systems capture runoff from the upland contributing area and temporarily store water in the terrace channel. Terrace systems with closed ends (Figure 25) retain water behind the terrace berm and in the channel. Water retained in the channel eventually infiltrates or supplies evapotranspiration (Figure 26). Other types of terraces are open on the ends to allow detained water to slowly flow from the terrace. Runoff from the contributing area may exceed the storage capacity of the channel for large storms and some water may overtop the terrace end or ridge. A significant portion of the water that overtops terraces, or that flows from the ends of open-ended terraces, will likely end up in streams; however, some of the water also seeps into dry channels between the field and the stream. Crops use some of the water retained in the terrace channel while the remaining water percolates below the root zone of crops grown in the channel. Deep percolation ultimately reaches the local groundwater where it may (1) Return to the stream as baseflow, (2) Be pumped for irrigation, or (3) Be stored in the ground water system. The goal for this portion of the project was to determine the amount of water that runs into terrace channels and to partition the captured water into either deep percolation or evapotranspiration. We also estimated the amount of deep percolation, evapotranspiration and runoff for the contributing areas. This analysis depends on the amount of land terraced, the condition of terraces, and the distribution of terrace types across the basin. The following sections describe the procedures used to determine these quantities.

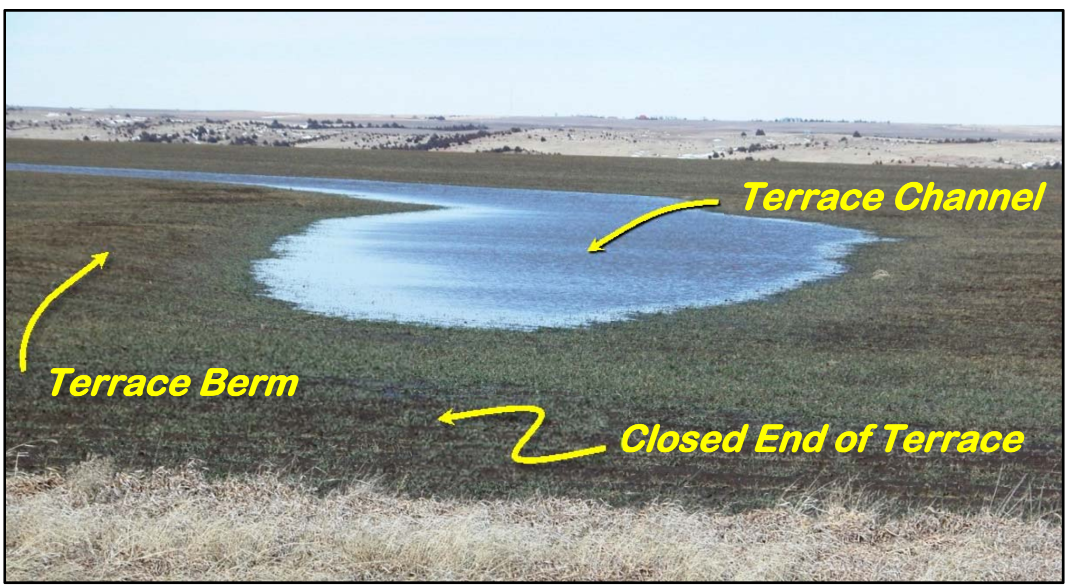


Figure 25. Picture of the Closed End of a Conservation Terrace.

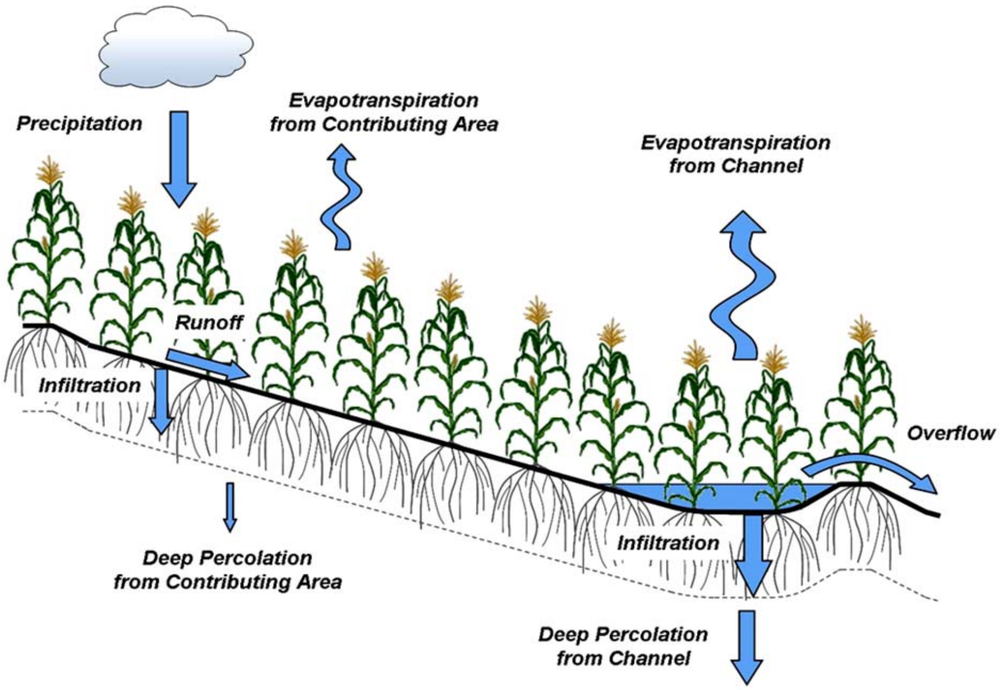


Figure 26. Water Balance Components of Terraced Land.

The terrace cross section and the system to remove water from the terrace characterized the type of terrace. The more traditional cross-section shape in the Republican River Basin is the broad-based channel shown in Figure 27. An alternative is to make the terrace channel wider to store more runoff and to distribute the water to a shallower depth across the channel to encourage crop water use and avoid crop death due to prolonged inundation in the channel. The slope along the channel can be nearly flat or the channels can be sloped gradually to encourage water to run to an outlet either in the terrace channel or to flow toward the end of the terrace. Water exits from the terrace channel in two ways. One method simply slopes the terrace channel toward the end of the terrace to allow water to flow from the terrace at a nonerosive velocity. In some cases, vertical risers installed in the terrace channel quickly drain water from the channel. The riser connects to an underground pipeline to channel the water to a desired outlet location. When the slope along the terrace channel is flat, the ends of the channel may be even with the terrace channel to allow the water to flow from the terrace. The end of flat terraces can also be elevated to retain water indefinitely in the terrace channel. The latter type of terrace is a conservation terrace.

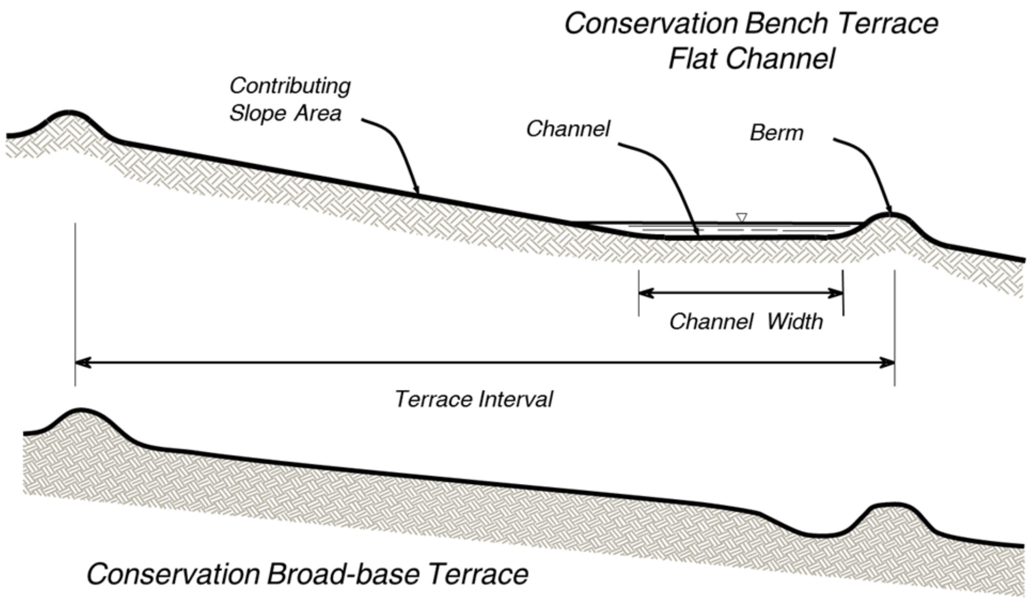


Figure 27. Cross-Sectional Patterns and Terminology for Conservation Bench and Broad-Base Terraces.

Terraced Land

The location and amount of terraced lands in the Republican River Basin was determined by digitizing terraced fields using the 2006 National Agriculture Imagery Program (NAIP, 2006) digital orthophotographs from the USDA-NRCS (available at http://datagateway.nrcs.usda.gov/). We traced the boundary of terraced lands for the entire basin. Originally, the Nebraska Department of Natural Resources digitized land in Nebraska using high altitude aerial photographs for 1999. We updated the original coverage to photographs from 2006. The example in Figure 28 illustrates the result of the digitization process. The 2006 update also utilized the Common Land Use coverage for Nebraska to align digitized parcels to land ownership boundaries. The land above the initial terrace was included into the land treated with terraces in this process.

The digitization process was similar for portions of the Basin in Kansas and Colorado. Personnel at the University of Nebraska digitized some portion of Kansas as well. Personnel from the Bureau of Reclamation digitized portions of Kansas and all of the terraced lands in the Basin in Colorado. The process was slightly different for the entities tracing terraced lands. Given the different groups and digitization processes, we edited coverages from each group for consistency and adequacy. For example, orthophotographs at a scale of 7.5-minute quadrangles were the basis for the digitization in parts of Kansas and Colorado. Merging traced parcels to construct coverages for counties, states and hydrologic units produced some overlaps of coverages. We eliminated the overlaps in the coverages. In addition, we used common land use coverages to reflect field boundaries for only Nebraska, and not for Kansas or Colorado. Some digitized parcels in Kansas and Colorado include several fields. The size of digitized parcels in Kansas and Colorado therefore do not represent the actual distribution of field sizes for terraced fields. The size distributions for Nebraska better reflect field sizes.

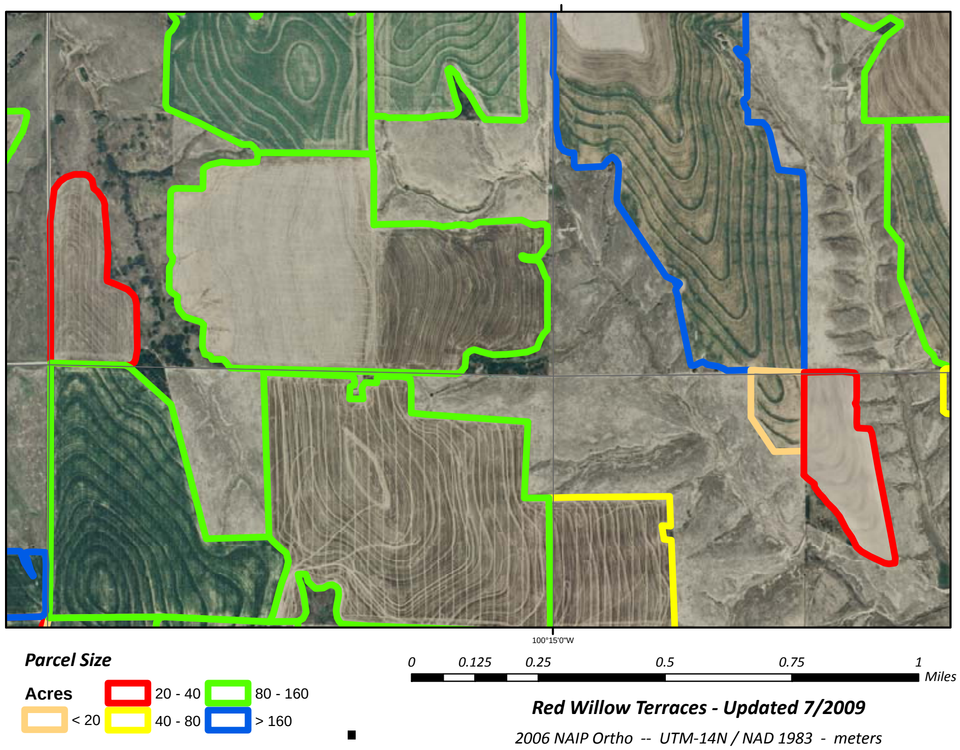


Figure 28. Illustration of Digitized Terraced Fields in Red Willow County Nebraska.

The map in Figure 29 shows the aggregated coverage and location of terraced lands in the Republican River Basin. The total amount of terraced lands in the basin above the gaging station near Hardy, NE is approximately 2,132,500 acres. The United States Geological Society (USGS) reports that the drainage area above the gage at Hardy is 14,336,640 acres and the contributing area for runoff is 9,536,640 acres (USGS, 2012). Thus, the amount of terraced land is approximately 15% of the total drainage area of the Republican River Basin above the gaging station near Hardy Nebraska and about 22% of the drainage area contributing runoff to the gage at Hardy. The amount of terraced land is about the same in Kansas and Nebraska (approximately 923,000 and 919,000 acres, respectively, see Table 10). Terraced lands in Colorado are about 31% of that in Kansas. The majority of the terraced land occurs in the middle of the Basin from Hitchcock to Harlan Counties in Nebraska, and from Rawlins to Phillips Counties in Kansas.

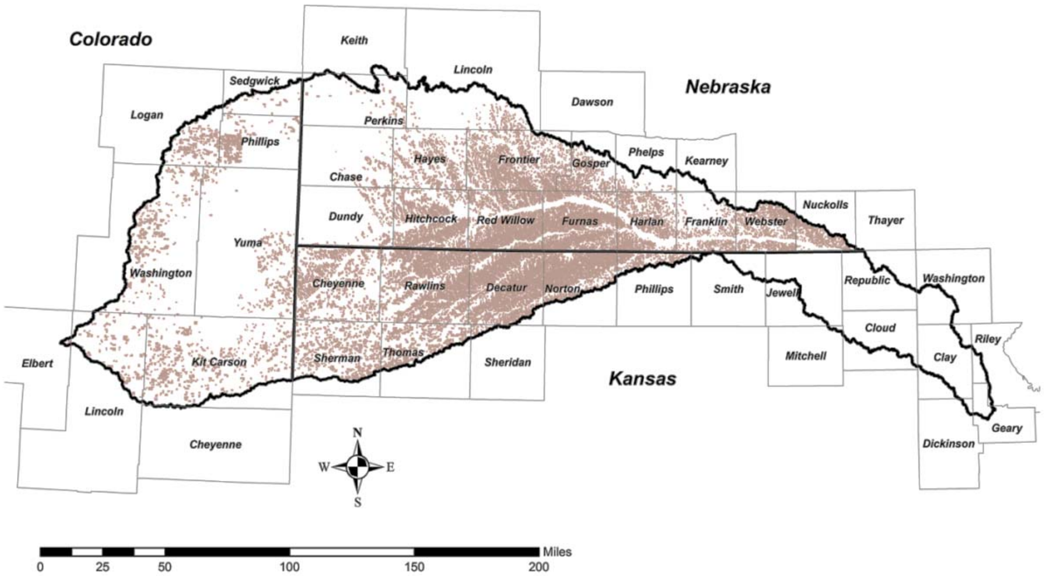


Figure 29. Distribution of Terraced Lands in the Republican River Basin.

Table 10. Summary of Terraced Lands in the Counties in the Republican River Basin.

Nebraska		Kansas		Colorado	
County	Acres	County	Acres	County	Acres
Chase	12,112	Cheyenne	108,345	Elbert	97
Dundy	24,061	Decatur	235,087	Kit Carson	88,863
Franklin	26,213	Norton	149,303	Lincoln	25,787
Frontier	125,645	Phillips	27,160	Logan	35,193
Furnas	160,898	Rawlins	239,957	Phillips	38,890
Gosper	37,694	Sheridan	4,034	Sedgwick	6,059
Harlan	74,644	Sherman	83,137	Washington	56,084
Hayes	58,192	Smith	811	Yuma	38,934
Hitchcock	131,912	Thomas	75,400	Total	289,908
Kearney	164	Total	923,234		
Keith	62				
Lincoln	11,800				
Nuckolls	27,996				
Perkins	10,929	Total Terraced Lands		2,132,464	acres
Phelps	4,771				
Red Willow	154,803				
Thayer	147				
Webster	57,283				
Total	919,322				

Terrace Condition Survey

Procedure

The size and location of terraced fields across the Republican Basin affect the hydrologic impact of terraces. The condition of terraces also plays a significant role in determining the amount water retained in the terrace and the ultimate fate of retained water. We conducted a survey to determine the storage conditions of a sampling of terraces across the basin. We initially planned to select approximately 1% of the fields across the basin to survey. The type of terrace was also determined in the survey.

Field Selection Process--A list of terraced lands provided the basis to select a random set of fields to survey. We also developed an alternate list when we could not survey a selected field. A technician started at the top of the list, made contact with the property owner, and arranged to survey the farm. If the property owner did not wish to participate or could not be contacted, the technician moved to the next farm on the alternate list. After surveying 1% of the terraced farms in a county, the technician moved to the next county. Since the selection process was random, the size of the fields, type of terrace, condition of terraces and management practices varied greatly.

Although we could not survey 1% of the terraced fields in all counties, we did develop a representative sample of terrace conditions across the Basin. A total of 167 fields were surveyed with the distribution shown in Table 11. Eleven fields were in Colorado, 47 in Kansas and 109 fields in Nebraska. Based on the surveyed fields, about eighty percent of the fields are broad-based terraces and twenty percent are flat channel (*i.e.,* conservation bench terraces). Appendix C contains more information about the properties of some of the surveyed fields.

Survey Process--The survey used a survey-grade GPS system installed on an all-terrain vehicle. The survey-grade GPS provided accurate spatial and vertical resolution of the field topography. The GPS system logged the horizontal location and the elevation within the field. The GPS system provided data to define field boundaries and develop estimates of storage capacities of terraces in surveyed fields.

Field Equipment--Field equipment consisted of a survey grade GPS system and an all-terrain utility vehicle. The unit was a Sokkia model GSR2700IS GPS unit (Figure 30). Sokkia's GSR2700IS is a L1/L2 GPS system with a high precision, dual-frequency GPS receiver and an internal data link for RTK surveying. The receiver used Bluetooth wireless technology for communication with data logger making the system cable-free. The listed accuracy of the unit was +/- 1 cm in the horizontal direction and +/- 2 cm in the vertical direction.

We mounted the GPS on a 2007 Yamaha 450 Rhino ATV Utility vehicle (Figure 31). The GPS receiver attached to the driver's side roll bar of the ATV and above the vehicle to assure there would be no obstructions of the signal. This mounting method allowed the driver to place the driver's side of the ATV directly over the desired topography or profile when surveying.

Table 11. Summary of the Location and Type of Terraces Includeed in the Field Survey.

State	County	Fields Surveyed	Terrace Type: Broad-base	Terrace Type: Flat Channel	Terrace Type: Unknown
Colorado	Kit Carson	4	3	1	
Colorado	Lincoln	1	1		

Colorado	Logan	1	1		
Colorado	Phillips	1		1	
Colorado	Washington	2	1	1	
Colorado	Yuma	2	2		
Kansas	Cheyenne	6	5	1	
Kansas	Decatur	8	2	5	1
Kansas	Norton	11	6	1	4
Kansas	Phillips	7	6		1
Kansas	Rawlins	13	10	3	
Kansas	Thomas	2	2		
Nebraska	Frontier	20	16	2	2
Nebraska	Furnas	34	27	1	6
Nebraska	Harlan	11	4	2	5
Nebraska	Hayes	9	5	2	2
Nebraska	Hitchcock	16	5	6	5
Nebraska	Red Willow	19	16	2	1
Total		167	112	28	27

Figure 30. Sokkia GSR2700IS Receiver and Data Logger for GSR2700IS GPS Unit.

Figure 31. 2007 Yamaha Rhino 450 ATV with GPS Unit Attached.

Field Operations: Upon arriving at a field site, the technician set a benchmark. Then he centered the GPS over the benchmark and aligned with the driver's side of the ATV. A relative coordinate system of 1,524 meters (5,000 feet) by 1,524 meters (5000 feet) was established. The benchmark elevation was set to match the estimated USGS MSL elevation as recommended by a technical representative of Sokkia to ensure the best elevation data. The technician measured the height of the antenna above the benchmark while the driver and all equipment were in the ATV. This accounted for any compression of tires or suspension. If the driver needed to increase the contents of the ATV or add a passenger, he resurveyed the benchmark and adjusted the data.

After the initial setup, the technician drove the perimeter of field to define field area. While driving the perimeter, he visually scouted the field and determined the number of terraces, terrace types and management system. Based on the visual observation, the technician would select terraces to use for volume calculations. The number of terraces selected depended on the total number of terraces in the field. If there were three or less terraces in the field, he only selected a single terrace to determine the storage volume. If there were four to eight terraces in the field, then he selected two terraces for analysis. He surveyed three terraces when the field contained nine or more terraces.

After driving around the perimeter of the field and selecting terraces for volume calculations, the technician would start the terrace survey at the top portion of the field. A profile along the length of each individual terrace berm in the field was driven and kept as a separate feature in the survey. When he arrived at a terrace that was to be used to calculate storage volume, he drove additional profiles along the length of the terrace. We developed six profiles by driving along: (1) the back slope of terrace, (2) the berm top, (3) the intermediate position between berm and terrace channel, (4) the terrace channel, (5) the middle of cut slope, and (6) the upland slope of terrace (see Figure 32).

While doing the survey, the technician filled out an assessment data sheet. The assessment sheet summarized all visual observations about the field and terrace conditions, terrace types, and management systems used on the field.

An application to a field owned by a producer cooperating with the field experiments will illustrate the process. The aerial photograph for the field shown in Figure 33 illustrates that there are seven terraces in the field. For this field the technician drove the ATV around the boundary of the field as indicated by the open diamonds in Figure 34. He also drove along the berm of each terrace to determine the location and layout of individual terraces. The resulting relative topographic map for the field is in Figure 34. The topographic map helps characterize the field but it is not helpful in determining the storage capacity of the terraces. To determine the storage capacity the technician drove paths parallel to two terraces in this field similar to Figure 32. The paths for the survey of the third terrace in the field are illustrated in Figure 35.

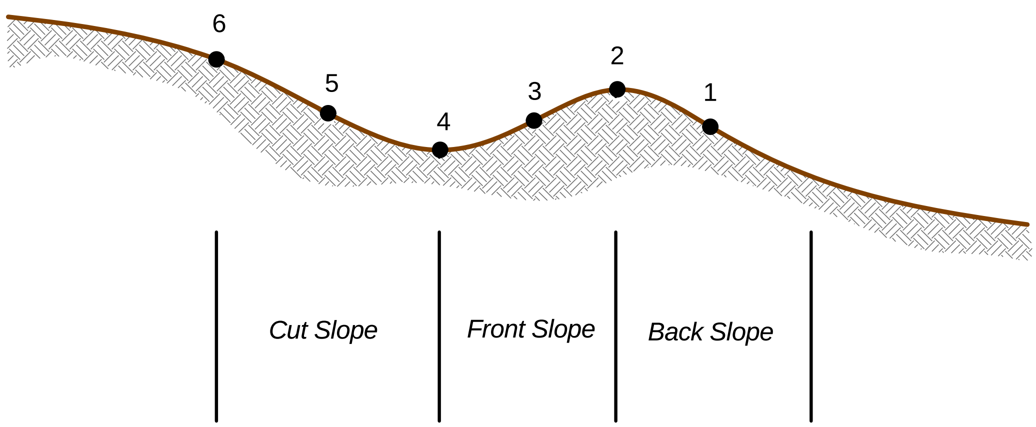


Figure 32. Location of GPS Profile Lines Along the Length of the Terrace from Driving the ATV Parallel to the Terrace.

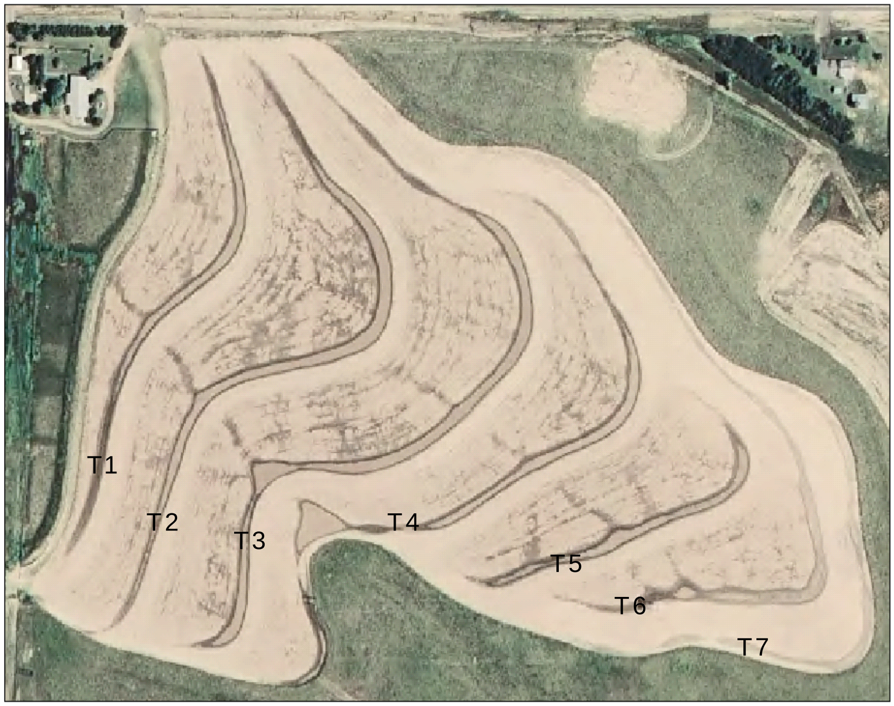


Figure 33. FSA Digital Photograph of a Terraced Field Used to Illustrate the use of a Field-Grade GPS System to Characterize Field Conditions and Terrace Storage.

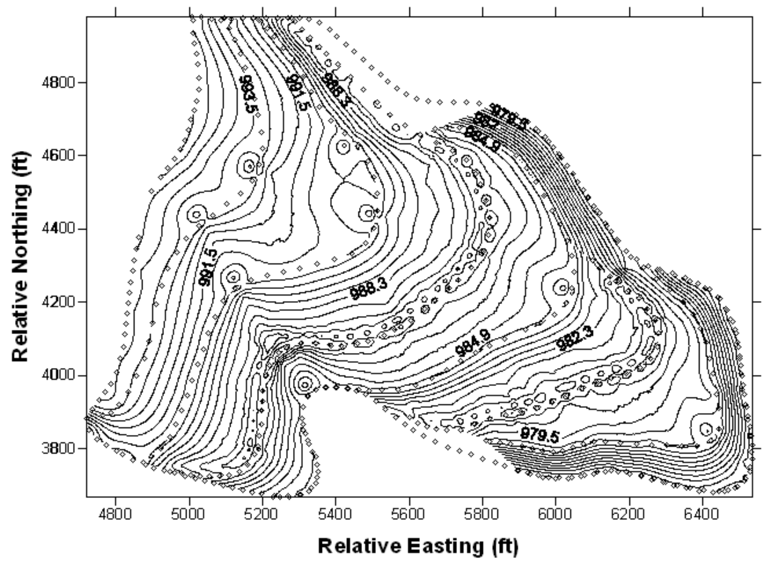


Figure 34. Relative Topographic Map of the Producer's Field as Developed from Driving the Paths in the Field Depicted by the Open Diamonds.

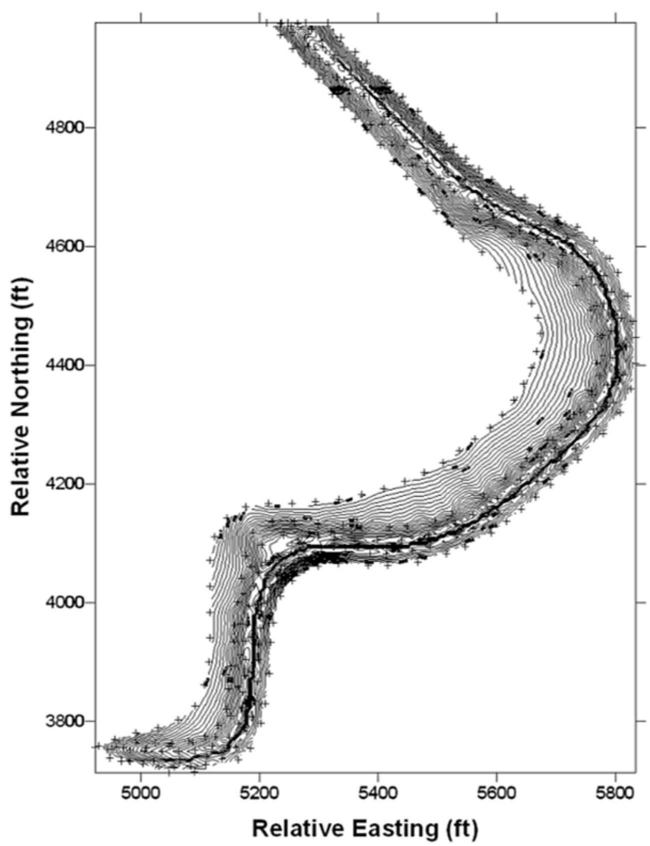


Figure 35. Topography for the Third Terrace in a Cooperator's Field.

The goal of the terrace conditions survey was to determine the volume of water that could be stored in a conservation terrace channel and to integrate results from a few terraces in the field to determine the total volume of water that could be stored in the field. We conducted a pilot test in August of 2007 to evaluate survey methods. The pilot study involved a 35-acre field in Norton County, KS. The pilot study allowed us to become familiar with the survey grade GPS/ATV combination and to assess the best method of surveying the field to obtain data to calculate area and volume. The field had been in wheat, which was harvested the prior month. The wheat stubble was still present. The farm consisted of seven broad-base terraces with closed ends.

We set a benchmark, drove around the perimeter of the field, and followed the profiles of 7 terraces. We selected two terraces to determine the storage volume. We evaluated two methods of determining the storage volume of terrace channels. The average end-area method used equally spaced cross sections of the terrace. The area under the cross section and the average volumes between cross sections were calculated and summed. We drove the GPS/ATV system across each cross section and compared the data to that obtained with a total station.

The second method involved driving parallel profile lines along the terrace. Six profile lines define key features of the terrace as shown in Figure 32. We entered the data from these profiles into a contouring and 3-D mapping program (SURFER) to calculate the retention volume of the terrace.

Results in Figures 36 and 37 compare the methods. Three cross sections were plotted; 1) the cross section measured by total station and rod, 2) the cross section driven by the ATV, and 3) the cross section that was calculated from the profile data processed with the contouring software (SURFER). The plots show that the GPS/ATV system did an acceptable job of surveying the terrace. The cross sections made from driving the ATV perpendicular to the terrace are similar to the profile from driving parallel to the terrace berm. The plots show the SURFER software could adequately develop a contour map from the profile data that can then be used to calculate the storage volume in the terrace. A comparison of the volumes calculated using the SURFER software verses the cross section method (Table 12) shows that the results are within +/- 4%. These comparisons demonstrate that fields could be surveyed using the profile method rather than the cross-section method.

We selected the second method because of two benefits over the average end-area method. First, it was more time efficient. The technician was able complete the survey in about 2/3 of the time because he was able to continuously drive the survey with few stops. This was a major benefit given the number of farms be surveyed. The first method required the technician to drive the terrace initially, then calculate the length, and finally to calculate, locate, and measure the cross section intervals. The second method allowed us to identify features such as breaches, low spots, or silted-in areas that we might have missed with the first method.

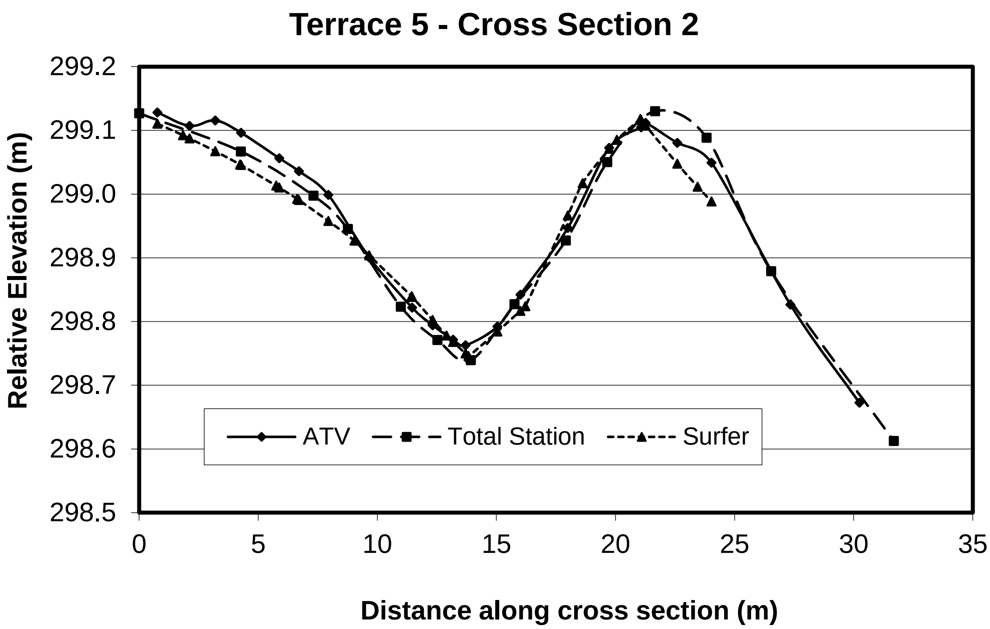


Figure 36. Cross Section Comparison of Two Survey Methods at Cross Section 2.

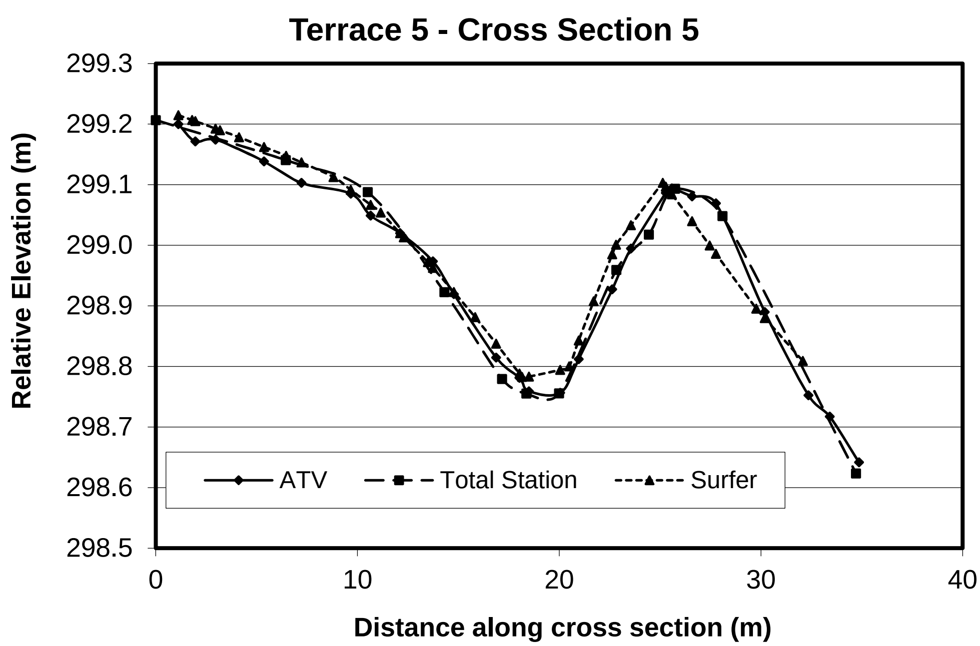


Figure 37. Cross Section Comparison of Two Survey Methods at Cross Section 5.

Table 12. Comparison of Surfer Method and Cross Section Method.

Terrace I.D.	Max. Storage Volume Surfer Method (m^3)	Runoff Needed to Fill Terrace (mm)	Max. Storage Volume Cross Sec. Method (m^3)	Difference
T3	712.8	22.36	686.2	3.9%
T5	371.7	26.6	383.4	-3.0%

Analyzing the field survey data to determine the field and terrace area and storage volume involved digitizing, contouring and 3-D surface mapping using the SURFER (version 8.06) software by Golden Software and Arc-Map by ESRI (version 9.3). We calculated the field area, individual terrace areas and terrace lengths. Surfer routines provided a means to determine the volume of terraces for estimating field storage volumes.

A digital elevation model (DEM) of the field created from survey data collected from the GPS/ ATV system allowed calculation of the volume of storage in individual terraces. A contour map generated from the DEM allowed analysis of terrace storage. We cropped the area for each terrace used for volume calculation from the field file to isolate the respective terrace. The profile of the berm of the selected terrace and the berm profile of the immediate upslope terrace defined the boundaries for cropping. The profile of the berm determined the maximum storage elevation. The elevation at which the terrace would allow water to be released (i.e. overtop) was determined from the profile. The Surfer's Cut/Fill routine for a 3-D surface provided a means to use that elevation to calculate the maximum volume of water held in the respective terrace. If a terrace was in poor condition or if there was an obvious breach of the terrace, the elevation of an un-breached or new condition terrace provided the elevation needed to estimate the storage volume. SURFER produced data to determine the amount of runoff from a rainfall event that was necessary to fill the terrace, the average slope of the field, the average terrace spacing, and area not containing terraces. We computed the capacity or depth of runoff that could be stored in a channel by dividing this storage volume by the area of land between the surveyed terrace and terrace immediately above the surveyed terrace.

We estimated the amount of the field area below the bottom terrace in the field using data from the survey. The area below the bottom terrace does not retain water thus we discounted that area from the total terraced area determined from digitizing terraced lands.

Most of the surveyed fields (128 of 160 fields) utilized broad-base terraces. Within these fields, we selected 277 representative terraces for volume measurement. The median field slope was 3.2 percent with the 10th and 90th percentiles being 1.8 and 7.2 percent, respectively (see Figure 38). The line inside the box plot in Figure 38, and all the following box plots, represent the median value. The bottom and top of the box represent the 25 and 75th percentiles, respectively. The bottom and top whisker caps are the 10th and 90th percentiles, respectively. The median spacing of broad-base terraces was 42 m with the 10th and 90th spacing percentiles of 26 and 68 m, respectively (Figure 39).

Thirty-two fields with flat-channel terraces were surveyed that included 64 representative terraces for volume calculations. The median field slope of the flat-channel terraces was 2.3 percent and the 10th and 90th percentiles were 1.1 and 4.5 percent, respectively (see Figure 40). Terrace spacings for flat-channel terraces were 76 m, 54 m, and 105 m for the median, 10th percentile, and 90th percentile spacings respectively (see Figure 40). The terrace spacing data are consistent with the field slope data, as horizontal terrace spacing varies inversely with field slope. In addition, installation of flat-channel terraces usually requires more earthwork than broad-base terraces making flat-channel terraces much more expensive for fields with steeper slopes.

We conducted a frequency analysis of the terrace capacity data (Figures 41 and 42). Approximately 11 percent of the broad-base terraces had no storage even though the terraces had closed ends. The median runoff storage capacity for all broad-base terraces was 7 mm while the 10th and 90th percentiles were 0 and 60 mm, respectively. The data fit a log Pearson Type III frequency distribution quite well. Results of the frequency analysis for flat-channel terraces show that approximately 1.6% of the flat-channel terraces had no storage (Figures 42). The Pearson Type III distribution fit the data reasonably well. The median storage of flat-channel terraces was 26 mm while the 10th and 90th percentiles were 7.2 and 99 mm, respectively. As expected, the median storage of flat-channel terraces was higher than that for the broad-base terraces (Figure 40).

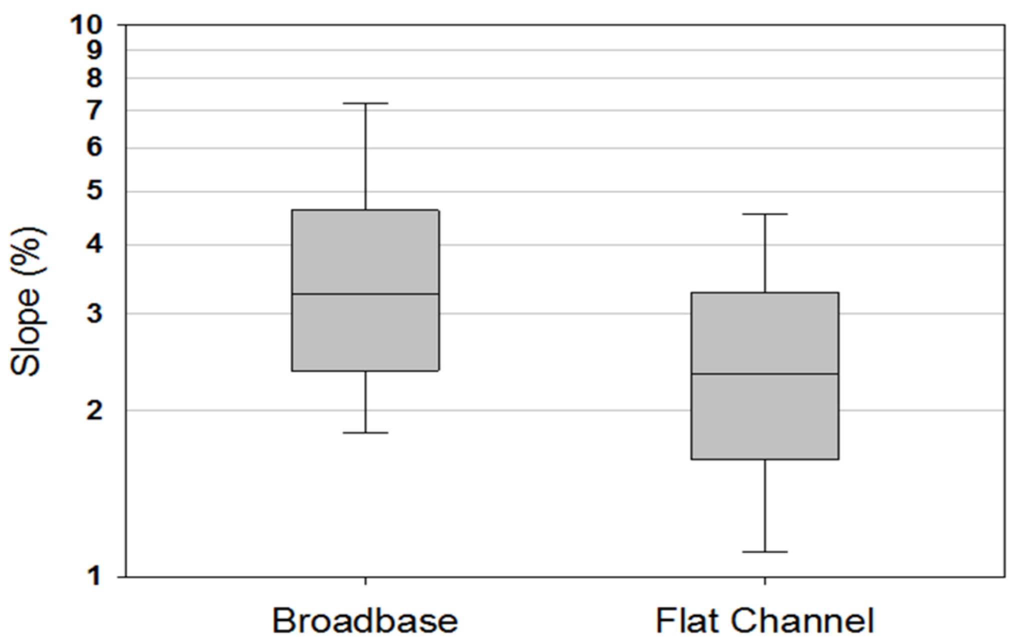


Figure 38. Field Slopes for Fields with Broad-Base and Flat-Channel Terraces

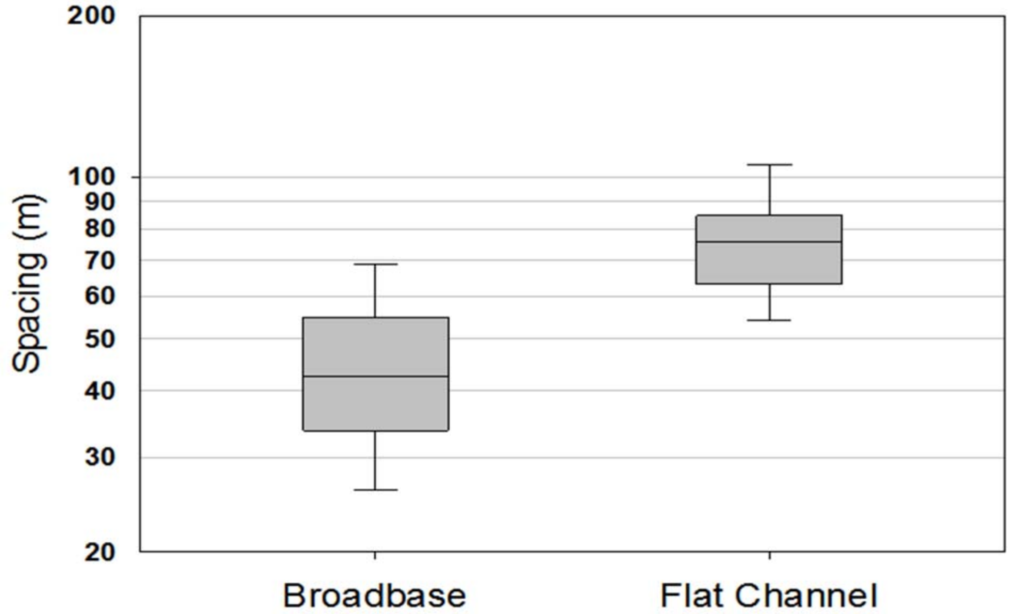


Figure 39. Terrace Spacing for Fields with Broad-Base and Flat-Channel Terrace.

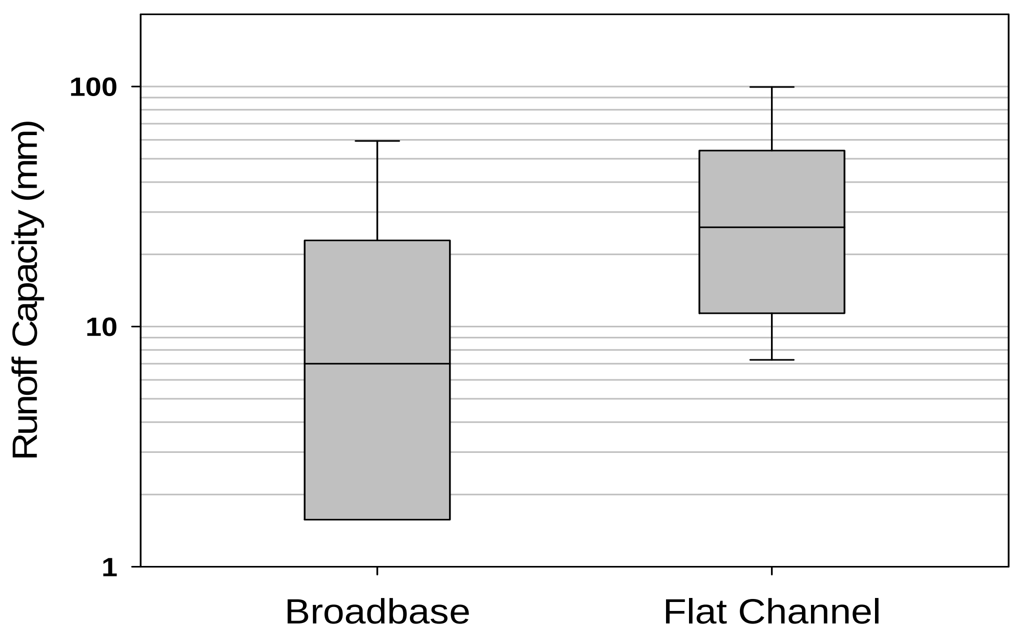


Figure 40. Runoff Storage Capacity for Fields with Broad-Base and Flat-Channel Terrace.

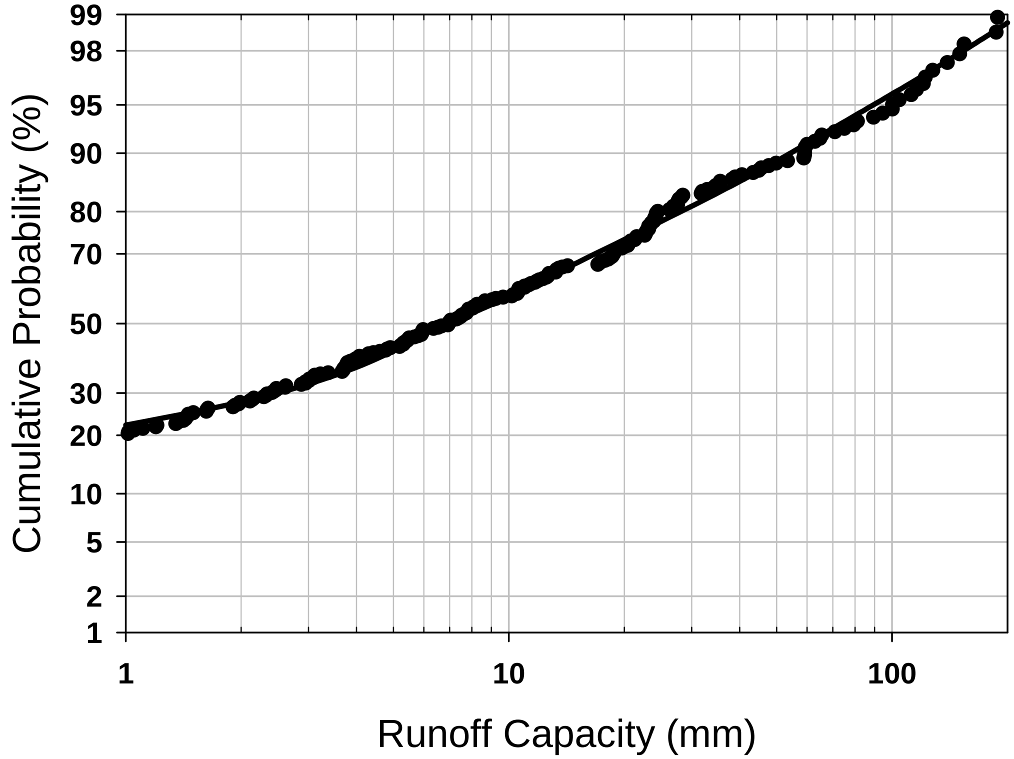


Figure 41. Cumulative Probability Distribution of runoff Storage Capacity for Fields with Broad-Base Terraces. Solid Line Represents the Log Pearson Type III Distribution.

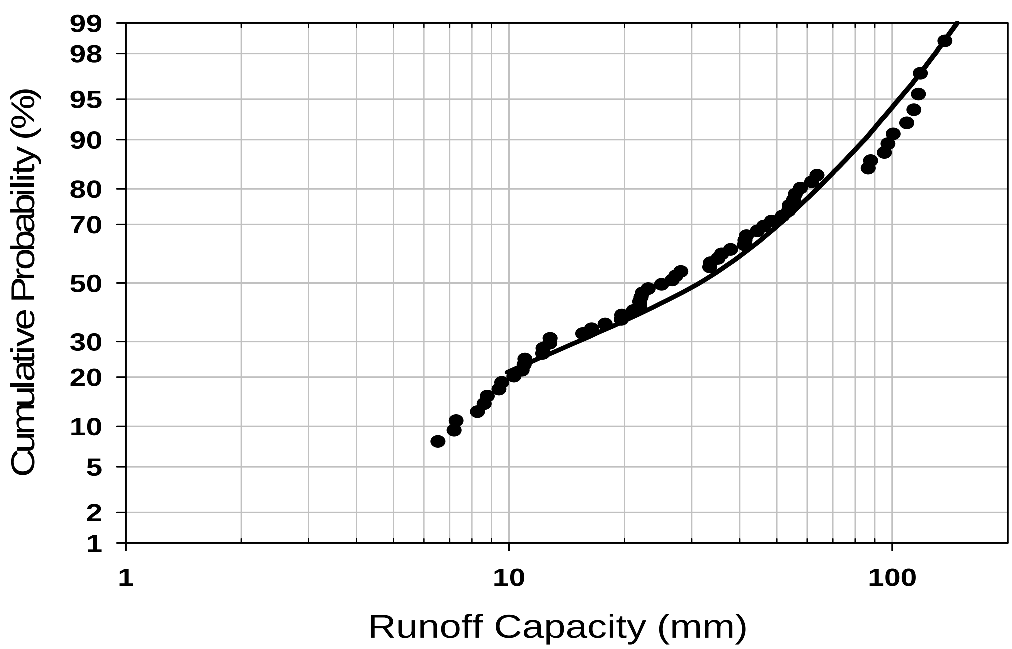


Figure 42. Cumulative Probability Distribution of Runoff Storage Capacity for Fields with Flat-Channel Terraces. Solid Line Represents the Pearson Type III Distribution.

Field Water Balance

We established five field sites to research the impact of terraces on field water balances. Two sites had conservation bench (*i.e.,* flat-channel) terrace systems located near Culbertson, Nebraska and Colby, Kansas. Two sites had broad-based (level) terrace systems with closed ends located near Curtis, Nebraska and Norton, Kansas. The fifth site located near Stamford, Nebraska had a broad-based (level) terrace system with open end(s) (see Figure 43).

Precipitation in the western Great Plains is often insufficient to produce acceptable crop yields every year. Historically, the traditional cropping practice was a wheat-fallow rotation that produced one winter wheat crop every other year. This rotation included a 14-month fallow period to allow soil moisture for the subsequent wheat crop to accumulate in the soil. However, only about 25% of the precipitation that fell during the fallow period was actually stored in the crop root zone for the next crop (Peterson and Westfall 1996). Ecofallow cropping is an intensification of the traditional wheat-fallow rotation that produces two crops in three years with a summer annual row crop such as corn or grain sorghum rotated with winter wheat. The timing of the two fallow periods and crops of the ecofallow rotation system often provides an opportunity to store a larger portion of the annual precipitation in the crop root zone; *i.e.* a better fallow efficiency, than traditional wheat-fallow rotations (Peterson et al. 1996). Figure 44 shows the cropping sequence for the ecofallow system.

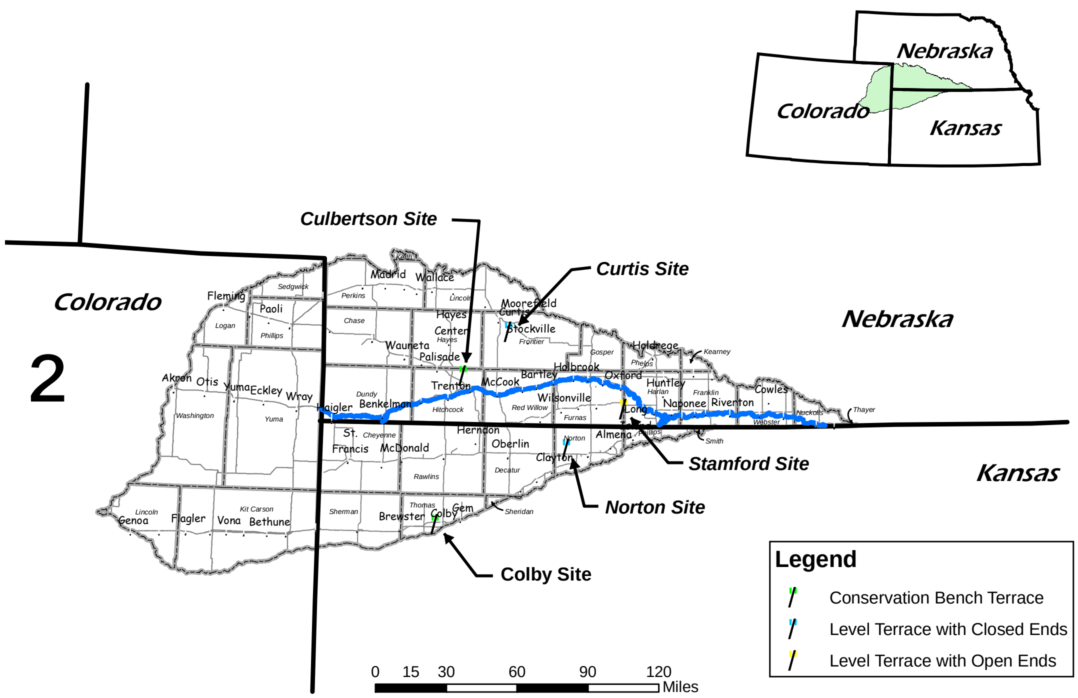


Figure 43. Location of Terraced Field Research Sites.

The arrows in Figure 26 illustrate the water cycle components that we monitored at the field sites. We measured the following parameters using the listed instrumentation at the five sites:

- Rainfall rate and amount using 8-inch diameter tipping bucket rain gauges,
- Alfalfa reference evapotranspiration (ET) using a Model E atmometer,
- Inflow into terrace channels using water level loggers,
- Outflow from terraces with open ends is measured with a velocity-area meter, and
- Soil water in and below the crop root zone utilizing various instruments.

Data from field sensors were continuously stored in data loggers. We downloaded data from the loggers during monthly field visits. We installed equipment during the spring of 2006 and monitored the fields for three growing seasons. The Natural Resource Conservation Service (NRCS, 2009) identified the dominant soil series at each location as listed in Table 13. Hydraulic conductivity values from the NRCS are included in Table 13 along with the particle-size distributions for soil samples taken in 2006. All soils formed in an upland landscape setting within loess parent material.

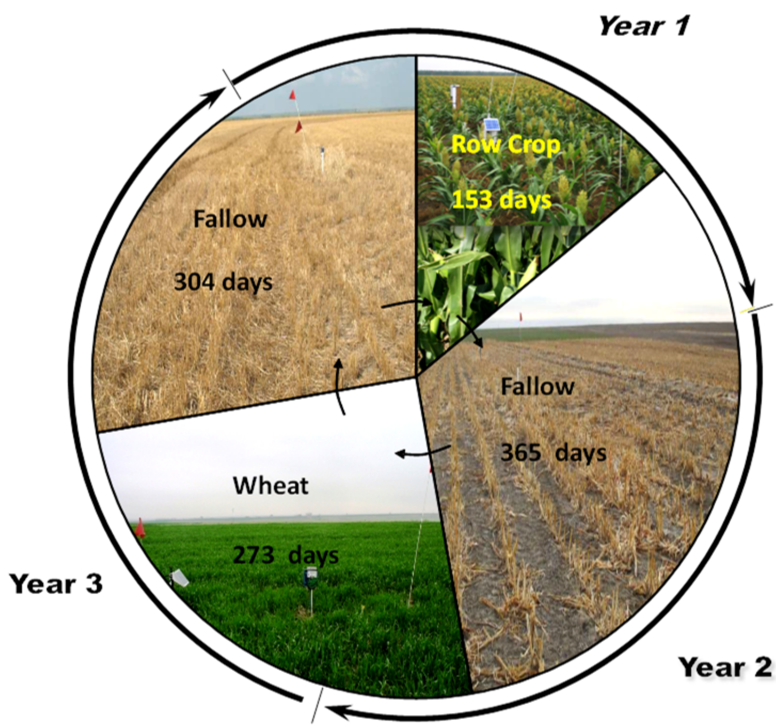


Figure 44. Ecofallow Cropping Sequence.

All study sites used a no-till ecofallow cropping rotation during each of the three years of the study (Table 14). Sweep tillage at the Colby and Curtis sites occurred during the fallow period after the row crop. Tillage at the Stamford site included disking prior to drilling wheat. The Norton and Culbertson sites were no-till systems. Colby was the only site to utilize sorghum in the rotation; all other sites produced corn during the row crop phase.

Tipping bucket rain gauges located at each site recorded precipitation. We obtained additional precipitation data from the High Plains Regional Climate Center. The average annual precipitation and recorded rainfall appear in Table 15. Only Curtis, NE in 2006 and Colby, KS in 2007 received less than average precipitation. Curtis, NE was considerably above average in 2007 and 2008 as were Norton, KS and Stamford, NE in 2008.

The five study sites all had terraces in place to control soil erosion and pond water in the channels for infiltration. The list in Table 16 describes the type of terraces used at each site. The Colby, KS and Culbertson, NE locations utilized a terrace with a level, wide flat channel that spreads runoff water over a large area for increased infiltration. The other three sites had level broad-based terraces. The terraces at Curtis, NE and Norton, KS have closed ends to contain runoff on the field, whereas, the Stamford, NE site terraces were level but they open on one end to allow water to slowly drain from the channel.

Students used data from field measurements in their projects to calibrate and validate simulation models for partitioning runoff from the contributing area into seepage, ET or overland flow.

Table 13. Characteristics of Soils at the Research Sites.

Location	Soil Series	K_{sat} (inches/hr)[1]	Sand (%)	Silt (%)	Clay (%)
Colby, KS	Ulysses	1.26	20	60	20
Culbertson, NE	Blackwood	1.26	25	55	20
Curtis, NE	Holdrege	1.30	27	53	20
Norton, KS	Holdrege	1.26	21	54	25
Stamford, NE	Holdrege	1.30	22	56	22

1. From NRCS Web Soil Survey (NRCS, 2009).

Table 14. Crops Harvested at Each Location.

Location	2006 Crop	2007 Crop	2008 Crop
Colby, KS	Sorghum	Fallow	Wheat
Culbertson, NE	Wheat	Corn	Fallow
Curtis, NE	Corn	Fallow	Wheat
Norton, KS	Wheat	Corn	Fallow
Stamford, NE	Fallow	Wheat	Corn

Table 15. Average Annual and Measured Precipitation during Experimental Years.

Location	Average Annual Precipitation (inches)[†]	Measured Precipitation (inches)		
		2006	2007	2008
Colby, KS	19.2	21.1	18.2	20.6
Culbertson, NE	19.8	20.4	24.3	22.4
Curtis, NE	21.0	18.0	31.7	31.0
Norton, KS	22.8	27.6	24.6	33.6
Stamford, NE	22.3	27.4	27.0	33.2

[†] SCS, 1970, 1974, 1977, 1978, 1980, and HPRCC, 2008.

Table 16. Type of Terrace at each Research Site.

Location	Type of Terrace
Colby, KS	Conservation Bench (flat channel)
Culbertson, NE	Conservation Bench (flat channel)
Curtis, NE	Level Broad-base w/ Closed Ends
Norton, KS	Level Broad-base w/ Closed Ends
Stamford, NE	Level Broad-base w/ Open Ends

Simulating Terrace Performance

We used the NRCS Curve Number method in the POTYLDR model to simulate runoff from contributing areas and infiltration for the terraces throughout the basin. Seepage and infiltration rates depend on the field saturated hydraulic conductivity of the soil. As a part of the field study, we conducted several field and simulation studies to improve estimates of these quantities for water balance modeling. One of the main objectives was to determine the variability of curve numbers within an ecofallow cropping system.

Curve Numbers for Ecofallow

The curve number method developed by the Soil Conservation Service, now the Natural Resources Conservation Service (NRCS), provides for estimation of runoff from storm rainfall (Ponce and Hawkins 1996). The method uses precipitation depth and a term called maximum potential retention to determine the amount of runoff. The maximum potential retention varies inversely with the curve number. The curve number varies from 0-100 where 100 is an impervious surface. The NRCS (2004) developed tables of curve numbers for various land uses and farming practices. The method historically included an adjustment for antecedent moisture condition, AMC. A dry condition corresponded with AMC-I, AMC-II for average conditions, and for wetter conditions, AMC-III is used. Antecedent moisture conditions depended on the rainfall during the previous 5 days to account for runoff variability. Recent studies demonstrate that prior rainfall does not explain all of the variability (Woodward et al. 2002). Recent versions of the National Engineering Handbook from the NRCS have removed the 5-day rainfall adjustment. The new terminology is antecedent runoff condition (NRCS 2004). This includes effects that cause variability in runoff prediction.

Crop residue generally decreases runoff and lowers curve numbers by 5-10% (Onstad and Otterby 1979; Rawls et al. 1980). Hauser and Jones (1991) derived curve numbers for a conservation tillage system with a wheat-sorghum-fallow rotation. The study site was in a semi-arid climate in the southern High Plains. They analyzed each phase of the rotation separately and compared results to SCS handbook curve numbers. Results showed that the handbook value for wheat was accurate at 80, while a value of 82 was more appropriate for grain sorghum. A larger discrepancy occurred with the fallow values. The handbook value for fallow with good conservation methods is 90 while the curve numbers derived from their study were 77 and 82 for fallow after wheat and fallow after sorghum, respectively. Steichen (1983) also studied curve numbers for the wheat-sorghum-fallow rotation. They considered three levels of tillage for comparison: no-till, stubble-mulch, and clean tillage. The study found that the curve numbers estimated from the SCS handbook accurately predicted runoff under the three conditions. The SCS adjustments for crop residue adequately accounted for the increase in infiltration for the observed conditions.

We conducted a study to determine the temporal variability of runoff curve numbers within an ecofallow cropping system at our five sites. We used the lognormal method used by Hjelmfelt (1991) to calculate curve numbers. The curve numbers of 85 and 84 for the fallow after row crop and fallow after wheat phases of the rotation, respectively, match well with the NRCS (2004) tabulated value for fallow of 83. However, the curve number of 85 calculated for the row crop phase was higher than the tabulated value of 75. In addition, the tabulated curve number for wheat of 72 was much lower than the value obtained from these data of 92. This is most likely due to using all runoff events in the analysis instead of removing smaller precipitation events. There were significant differences between curve numbers obtained for the phases. The curve numbers for the wheat phase of the rotation were significantly higher than the curve numbers for the two fallow periods.

The objective of this portion of the project was to determine the temporal variability of field saturated hydraulic conductivity in an ecofallow cropping system. Infiltration rates for soils depend on the saturated hydraulic conductivity, K_s. Shaver et al. (2002) studied infiltration under different cropping systems, including ecofallow. That study analyzed soil sorptivity with Smith's (1999) method using a single ring infiltrometer from long-term no-till plots in wheat-fallow, wheat-corn-fallow, and continuous cropping. They found no differences between infiltration rates under the different cropping systems. The study reported a sorptivity value for wheat-corn-fallow of 0.21 $cm/s^{1/2}$.

We measured the field saturated hydraulic conductivity on all field sites one time each year for three years. We performed six tests in each contributing slope using a randomization procedure to choose quadrants for tests. We considered the impact of equipment wheel tracks and crop rows on infiltration. We divided plots evenly between wheel tracks rows, non-wheel track rows, and crop rows for tests performed during the row crop-growing season and the fallow period after row crops. One out of three tests performed in fallow after wheat was in a wheel track. We conducted tests below the tillage zone following sweep tillage at Colby, KS and Curtis, NE in 2007.

A variation of the method proposed by Smith (1999) allows the use of a single ring infiltrometer to measure hydraulic conductivity. Rings 15 cm in diameter were driven 10 cm into the soil. A coffee filter placed inside the ring prevented damage to the soil surface when adding water. Removing the filter immediately after ponding maintained soil surface conditions. Ponding water to a depth of 1-2 cm inside the ring ensured one-dimensional flow. We recorded the elapsed time required for water to infiltrate until approximately half of the soil surface was exposed. The test method varied in the depth of water applied as the study progressed. In 2006, one cm of water was ponded but if infiltration occurred rapidly, we added a second cm of water. In 2007, we used a consistent depth of

1.5 cm for each test. In 2008, we used the depth of 1.5 cm, but after 3 minutes, we removed excess water until half of the soil surface was exposed. We also obtained soil samples, 5.375 cm in diameter and 6 cm long, adjacent to the ring infiltrometers for determination of bulk density and initial moisture content.

Because measurements were not taken in each phase at each location each year, there may be differences in the rainfall prior to infiltration tests. This may bias measurements higher when less rainfall occurred prior to the infiltration tests or it may be lower for larger amounts of precipitation. We developed a procedure to remove the effect of rainfall impact energy on hydraulic conductivity and produce adjusted curves similar to that one used by the WEPP model from Risse (1994).

The original calculated hydraulic conductivity was not significantly different between the three phases of the rotation. However, precipitation prior to infiltration tests may affect the measured values. A procedure to adjust hydraulic conductivity depending on the amount of precipitation recorded during the 90 days prior to measurement accounted for these effects. The adjusted hydraulic conductivity values were different between the phases of the rotation. The hydraulic conductivity for the fallow after wheat phase was significantly higher with a value of 3.54 cm/hr than for the row crop phase of 1.13 cm/hr and the fallow after row crop condition was 1.41 cm/hr.

The Water Erosion Prediction Project (WEPP) model can simulate changes of infiltration rates over time, which provided a method to predict the variability of hydraulic conductivity within an ecofallow cropping rotation. A routine to relate hydraulic conductivity to curve numbers allowed us to simulate the temporal variability of curve numbers. Hydraulic conductivity measurements conducted annually at each of the five field study locations permitted us to determine curve numbers for runoff events at each location. We compared WEPP simulations to field measurements.

Integration of weather data from the High Plains Regional Climate Center (HPRCC) with rainfall information recorded at each research site produced weather files for WEPP model. The HPRCC data results from data recorded by National Weather Service at cooperative observer locations. We installed tipping bucket rain gauges at each research site (Yonts 2006) to collect precipitation in 0.04 mm tipping events. The collectors have a 20-cm diameter. HOBO dataloggers recorded the time and depth of precipitation for the 0.04-mm tipping gauge. The rain gauges operated from late March until late November; therefore, snowfall precipitation was unrecorded. We combined the maximum and minimum daily air temperatures and winter precipitation from the HPRCC data with the rainfall recorded at each site to provide inputs for the CLIGEN weather simulator used in the WEPP model. Results from the CLIGEN simulator provided weather files for simulation with the WEPP model.

The WEPP model has the option of either using a constant hydraulic conductivity or a time-variable hydraulic conductivity. The time-variable hydraulic conductivity method provides the changes in hydraulic conductivity and, therefore, curves numbers for the period of simulation. This method uses an exponential decay equation developed by Risse et al (1995):

$$K_e = K_b \left[MA + (1 - MA) \, e^{-C \times KEcum \times \left(1 - \frac{rr}{4}\right)} \right] \tag{3}$$

where

K_e	= the effective hydraulic conductivity,
K_b	= a baseline conductivity following tillage,
MA	= the maximum adjustment to conductivity,
C	= a soil stability factor,
KEcum	= the cumulative rainfall energy
rr	= the random roughness following tillage.

We used a single storm to predict runoff with various hydraulic conductivities. These data give runoff datasets to calculate curve numbers. The storm used was a 100-year return period storm for Colby, KS. It had a total storm depth of 10.6 cm. We used a surface storage of 0.1 cm, a wetting front suction of 17 cm and $\Delta\theta$ equal to 0.27 for the Green-Ampt method in the WEPP model to develop a relationship between hydraulic conductivity and curve number as shown in Figure 45.

Data from the field terraces include runoff data that we used to evaluate the curve number method. Water level loggers used pressure transducers made by Solinst recorded ponded water depth in each channel (Yonts 2006). The transducers hung from a chain attached to a cap on top of a 5.1 cm schedule 40 PVC pipe standing vertical in the lowest point in the channel. Holes drilled into the PVC pipe allowed water to enter the pipe. Transducers located below the soil surface allowed measurement of small depths of ponded water for 15-minute recording intervals. Another pressure transducer installed at each site measured the atmospheric pressure. Compensation of the readings from the pressure transducers in the channels removed the effects of changes in atmospheric pressure. Pressure transducers operated from late March through late November.

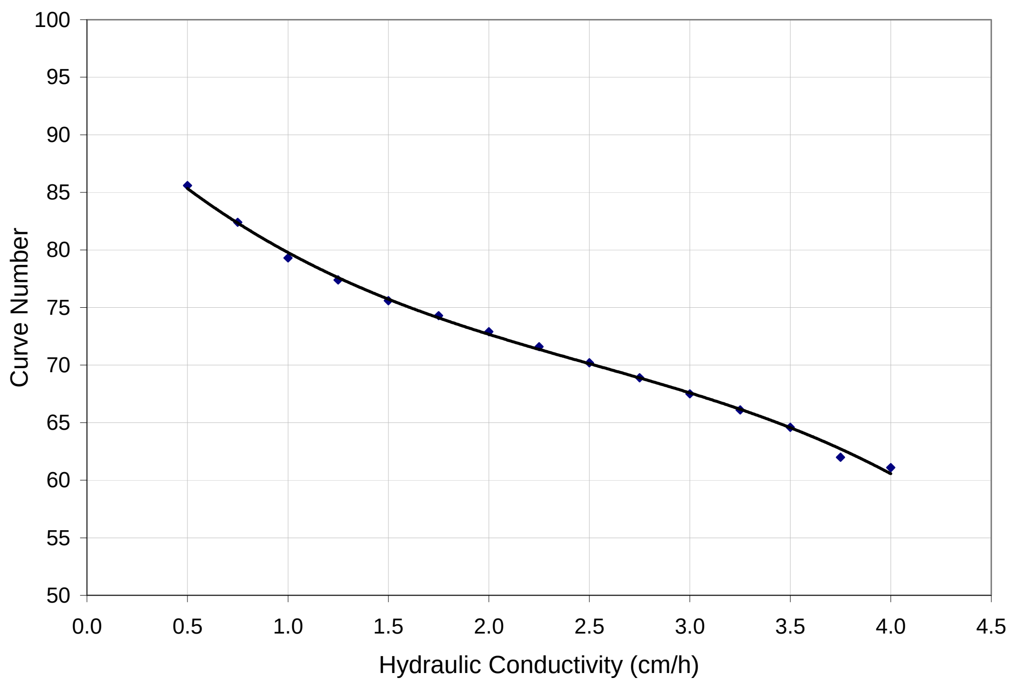


Figure 45. Hydraulic Conductivity/Curve Number Relationship.

Water does not accumulate in the channel of terraces that are open at the ends of the terrace channel. Thus, pressure transducers do not work to measure runoff from the contributing area for the level broad-base terraces with open ends at the Stamford, NE site. We installed flumes with velocity-area sensors to record runoff information at the Stamford site. The flume consisted of plywood sheets placed in the channel to create a flume that was level in the center section with outer sections inclined to match the slope of the terrace channel. Cinder blocks buried below the soil surface anchored the plywood in place. Plywood inserted vertically on both the upstream and downstream ends of the flume blocked the flow of water under the flume. The terraces were surveyed with a global positioning system (GPS) mounted on an all-terrain vehicle. Driving the all-terrain vehicle along transects parallel to the channel at various positions along the slope provided elevation data to map the topography of land around the monitored terraces. We used a software program to analyze the survey information obtained with the GPS. The survey provided data to develop a relation between the depth and volume of water in the channel. We also developed a relation between the depth of water in the channel and surface area of water in the channel.

The conditions of the studied terraces varied substantially. For example, the length along terrace berms varied from about 700 feet at Colby to 5000 feet at Norton (Table 17). The cross-sectional areas of terrace channels calculated from survey information provide the volume of water that can be stored and represents the amount of soil used to construct the berm. Combining the maximum depth of water before a terrace overtopped the berm with the cross-sectional area as a function of depth provided an estimate of the maximum storage volume for the channel. Dividing the maximum volume by the land area between the berm of the terrace above and the berm of the terrace produced the depth of runoff to fill the channel before the berm is overtopped.

Table 17. Terrace Properties.

Location	Length, Ft	Area, ft^2	Maximum Volume, Acre-feet	Depth of Runoff to Fill the Channel, inches
Colby, KS	705	3.17	0.56	2.14
Culbertson, NE Upper	2585	17.46	0.85	0.58
Culbertson, NE Lower	2030	13.68	1.54	1.35
Curtis, NE Upper	1073	2.68	0.09	0.39
Curtis, NE Lower	1309	3.25	0.43	1.58
Norton, KS Upper	3401	11.68	2.48	2.55
Norton, KS Lower	5005	16.65	2.99	2.15
Stamford, NE Upper Stamford, NE Lower	Open-ended Terraces			

Data for the 15-minute recording intervals allows computation of the runoff depth. The change in channel volume is the difference in the volume of water in the channel between transducer readings. The rainfall volume accounts for the rainfall that falls directly onto ponded water in the terrace channel. The infiltration volume is the water that infiltrated from the ponded water in the channel. We assumed a uniform infiltration rate of 1.0 cm/hr. We computed the volume of infiltration for each 15-minute interval as the surface area times the satiated hydraulic conductivity and an elapsed time of 0.25 hours. The contributing area from which the runoff for each interval originates also changes with depth of water in the channel. As the water in the channel increases, the amount of exposed land decreases. The contributing area was total area for the terrace minus the surface area of water in the terrace channel.

The sum of the interval runoff depths provides the total storm runoff depth that allowed for calculating curve number values. The curve number method predicts runoff using the precipitation depth, initial abstraction, and maximum potential retention (S). We computed the maximum potential retention from the precipitation and runoff depths for each storm (Hawkins 1973). This relationship assumes that the initial abstraction equals the historical value of $0.2S$.

We used two methods to calculate curve numbers from the maximum potential retention derived from rainfall and runoff information. The first was the lognormal method developed by Hjelmfelt (1991). The basis of this method is that maximum potential retention is log-normally distributed. It uses the assumption that the median of the maximum potential retention values, S, corresponds to the ARC-II curve number. This median calculated as the mean of the logarithms of the maximum potential retention.

The hydraulic conductivity results from WEPP simulations and the corresponding curve numbers shown in Figures 46 through 50 illustrate variation of runoff conditions in the region during a cropping sequence. Field measurements for computing hydraulic conductivities compare to WEPP simulations reasonably well as do the resulting curve numbers from runoff producing events.

The hydraulic conductivity at Colby (see Figure 46) decreased due to freezing in the fallow after wheat and wheat phases. The two spikes during the fallow after the row crop phase are due to sweep tillage. Curve numbers inversely relate to the hydraulic conductivity thus curve numbers increase for frozen conditions and decrease following tillage. Overall, curve numbers ranged from approximately 60 to 90 during the three-year rotation. This location only had two runoff events during the three years of study. Both runoff events occurred during the fallow after row crop phase. The hydraulic conductivity calculated in the row crop and fallow after wheat was much higher than the simulated values. The hydraulic conductivity calculated for the fallow after row crop phase was for the soil below the tillage layer.

The hydraulic conductivity was very consistent during the cropping rotation except when the soil froze at Culbertson (Figure 47). This site experienced no tillage during the study and the baseline hydraulic conductivity was less than simulated values. The hydraulic conductivity seemed to be consistent in each phase of the rotation at approximately 2 cm/hr. This resulted in a consistent curve number of approximately 75. Again, low hydraulic conductivities and high curve numbers occur when the soil freezes.

Results in Figure 48 show the variation of hydraulic conductivity and runoff curve numbers for the Curtis, NE site using the WEPP simulation program. This location, similar to the Colby, KS site, experienced two sweep tillage events during the fallow period after the row crop phase. These events produced sharp increases in hydraulic conductivity and decreases in curve number. The simulated hydraulic conductivity matches well with the calculated values. The measured curve numbers are higher than calculated from the simulated hydraulic conductivity. This is likely because the upper terrace at Curtis overtopped in 2007, which caused a breach in the terrace berm. This reduced the usable runoff events to the smaller events that did not overtop the cut berm and smaller events usually result in larger curve numbers. Overall, the curve numbers range from approximately 60 to 90 while hydraulic conductivity ranges from less than 0.5 cm/hr during the winter to the baseline hydraulic conductivity of 4 cm/hr.

No tillage occurred at the Norton, KS site during the three years of this study; however, results from WEPP simulation of the hydraulic conductivity and curves number were more variable at this site than other no-till locations (Figure 49). The hydraulic conductivity of the row crop phase appears to be lower than that of the other three phase of the rotation. The measured hydraulic conductivity values for the fallow after wheat phase are much higher than the simulated values.

Figure 50 shows the results of the simulation from the WEPP model for the Stamford, NE site. This site was tilled prior to planting wheat which caused the WEPP model to increase hydraulic conductivity to the baseline value of 4 cm/hr. Overall the hydraulic conductivity predicted by WEPP matched the measured values well. Simulated hydraulic conductivities ranged from less than 0.5 cm/hr to 2 cm/hr when no tillage had occurred. The curve numbers related to this simulated hydraulic conductivity ranged from 60 following tillage to 90 when the soil was frozen.

The WEPP model predicts the temporal variability of hydraulic conductivity within an ecofallow rotation. We developed a relationship to convert hydraulic conductivities to curve numbers and compared to hydraulic conductivities and curve numbers calculated from field measurements taken at five locations in southwest Nebraska and northwest Kansas. Predicted hydraulic conductivities range from 4 cm/hr following tillage to less than 0.5 cm/hr when the soil was frozen. When no tillage had occurred, hydraulic conductivity was approximately 2 cm/hr. Curve numbers related to the simulated hydraulic conductivity ranged from 60 following tillage to 90 for frozen soil. The curve numbers were approximately 75 during the growing season when no recent tillage had occurred.

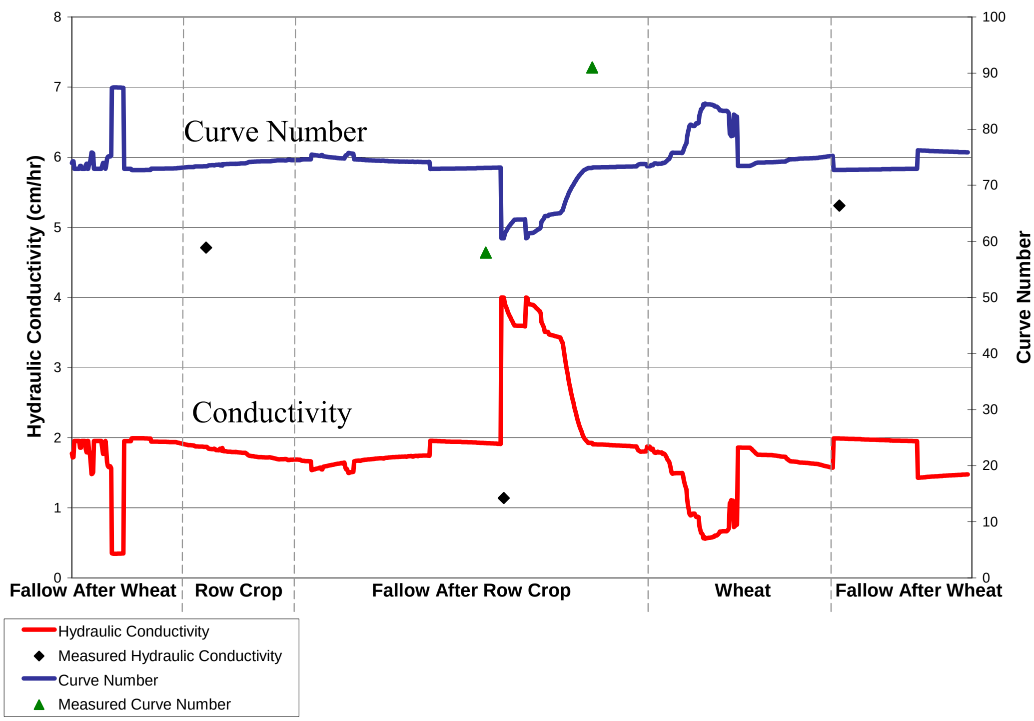


Figure 46. Hydraulic Conductivity and Curve Numbers for the Colby, KS site.

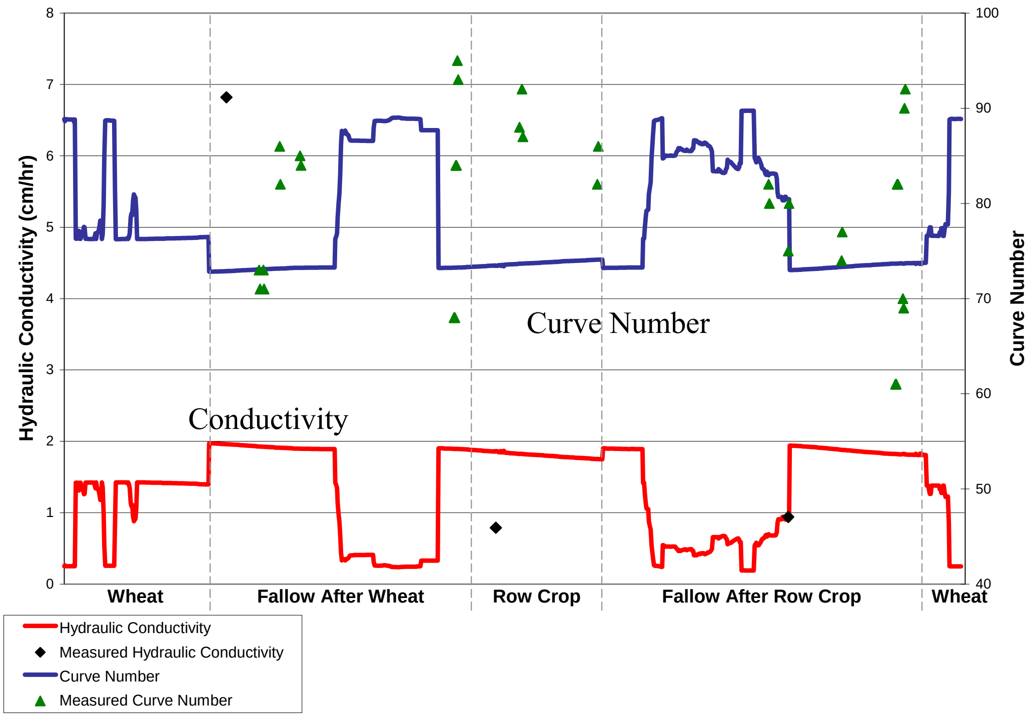


Figure 47. Hydraulic Conductivity and Curve Numbers for the Culbertson, NE site.

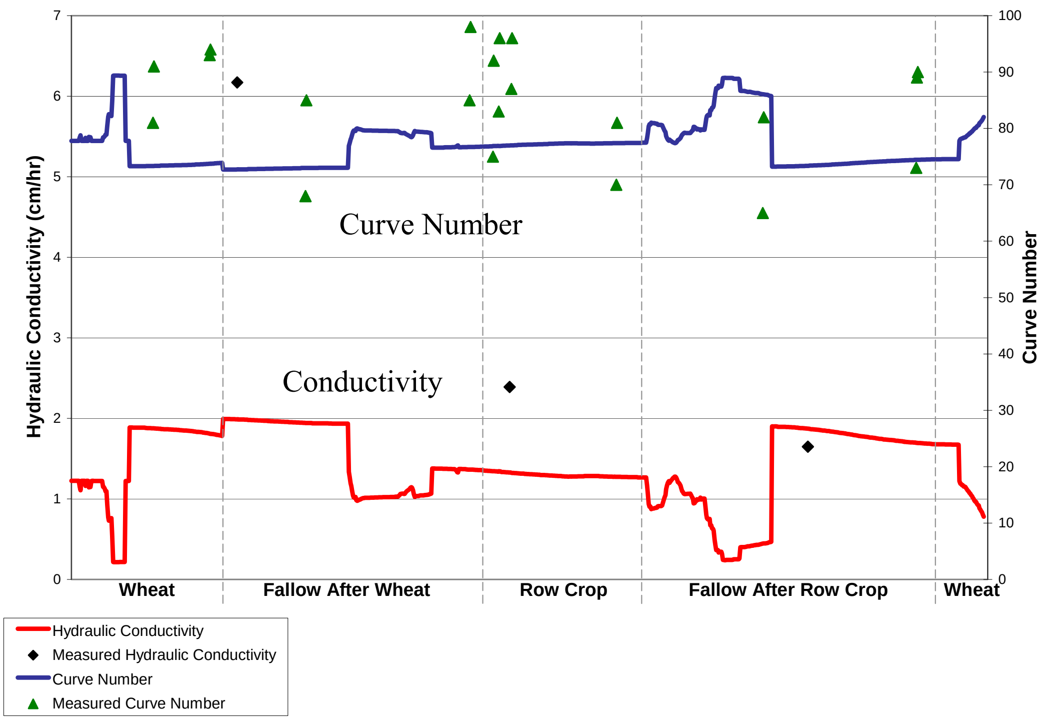


Figure 48. Hydraulic Conductivity and Curve Numbers for the Curtis, NE site.

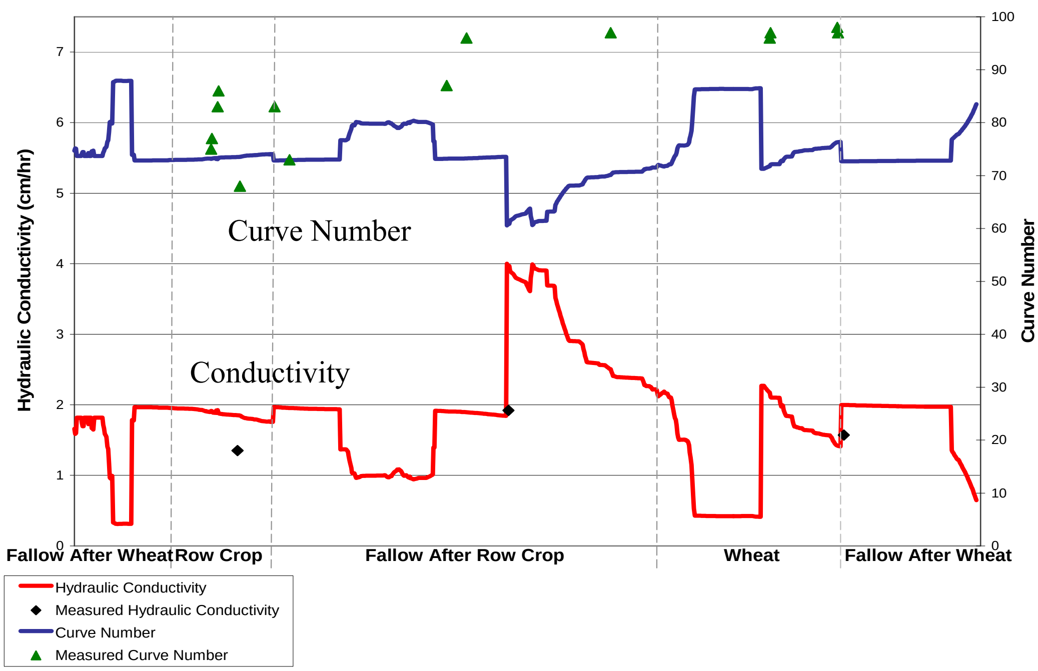


Figure 49. Hydraulic Conductivity and Curve Numbers for the Norton, KS site.

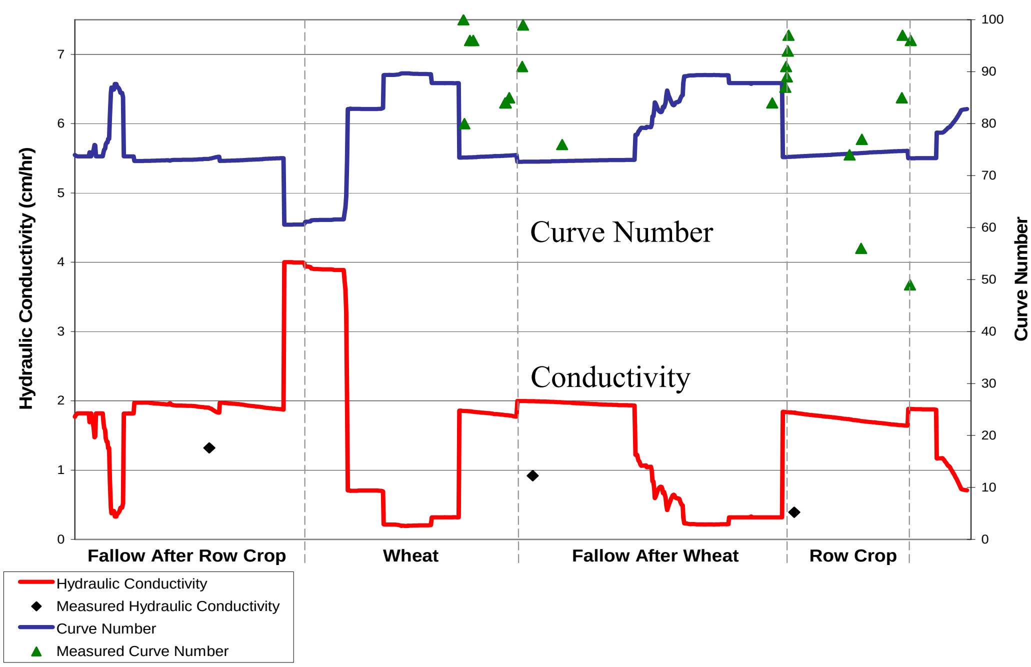


Figure 50. Hydraulic Conductivity and Curve Numbers for the Stamford, NE site.

Root Zone Water Quality Model

The Root Zone Water Quality Model (RZWQM) (Ahuja et al., 2000) version 2 released on January 6, 2008 is a simulation model used to assess the hydrology of field sites and to partition infiltration into increased crop evapotranspiration and deep percolation. We calibrated the RZWQM model with data from the instrumentation at the Colby south terrace and the Norton lower terrace. After calibrating the model, we simulated a 30-year period at these sites. The Colby calibration period was from April 6, 2006 to August 19, 2008 and the Norton calibration period was from January 1, 2005 to December 31, 2007. Input parameters came from data measured at the field sites and from GeoProbe soil core characteristics as described in a following section.

The RZWQM model includes routines to generate weather files to simulate terrace performance. Data collected from the research sites also provides information to build weather data files. The model requires breakpoint rainfall, meteorological, and snowfall precipitation data. The meteorological files include daily maximum and minimum air temperature, average wind speed, shortwave solar radiation, pan evaporation, and relative humidity. These files were developed using a combination of data measured in the field and at nearby locations.

The RZWQM model simulates the water balance at a point in the field. Simulations are required for the contributing slope and the terrace channel to account for field conditions. We assumed that no water ran off the terrace channel. In the field, some water may move within the channel itself because it may not be perfectly level; however, the slope along the terrace channel is generally small so we simulated level channels. The weather files were the same for both scenarios except for the snow weather file where the fraction of snowmelt infiltrating can be included.

After calibrating the model, we simulated thirty-year simulation scenarios for the Norton and Colby sites. Results of the 30-year simulations provide data for the long-term ET, deep percolation and runoff. The soil properties, initial conditions, and management practices determined while calibrating the model for the sites provided parameters for long-term simulations. No-till farming is popular for rainfed rotations in this region so we used that practice in our simulations. We assumed that the crops in the terrace channel did not drown out even though field observations indicate that some crop drowning occurs during wet years.

An average of several terrace cross-sections furnished data for terrace characteristics. Yonts (2006) surveyed the terraces for the Colby and Norton sites and provided several cross sections along the terraces. Figures 51 and 52 show the averaged cross sections for Colby and Norton, respectively. The terrace channel at Norton has a parabolic cross-section rather than a trapezoidal shape. The survey data points used in making the cross sections are also in Figures 51 and 52.

Each 30-year simulation covers ten cycles of the ecofallow rotation. The simulation spanned a total of 39 years to allow the effect of the initial conditions to dampen out. The cumulative ET for the terrace channels exceeds that for the contributing areas for Colby and Norton (see Figures 53 and 54 respectively). The cumulative ET in the channel is for the deepest point in the channel. These data show that evapotranspiration increases by about 7 cm/year for broad-base terraces and 3.5 cm/year for the conservation bench terrace at Colby compared to the contributing area. Terraces had a larger impact at the Norton site with increased evapotranspiration of approximately 18.5 cm/year for broad-base terraces and 12 cm/year for the conservation terraces over that for the contributing area.

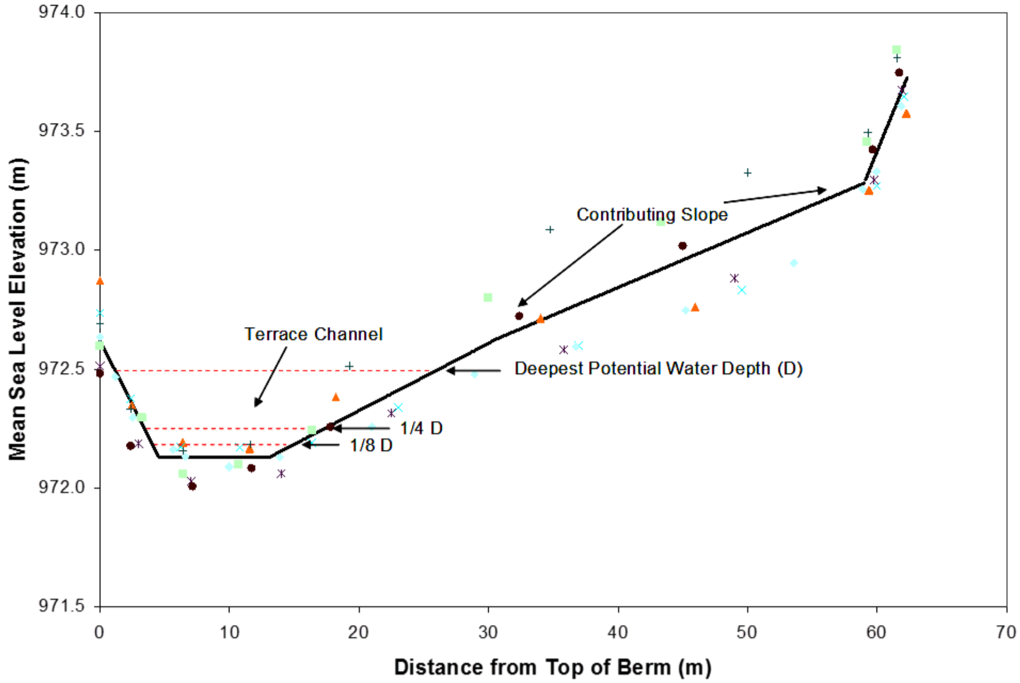


Figure 51. Average Cross Section for the Colby Terrace (Conservation Bench Terrace).

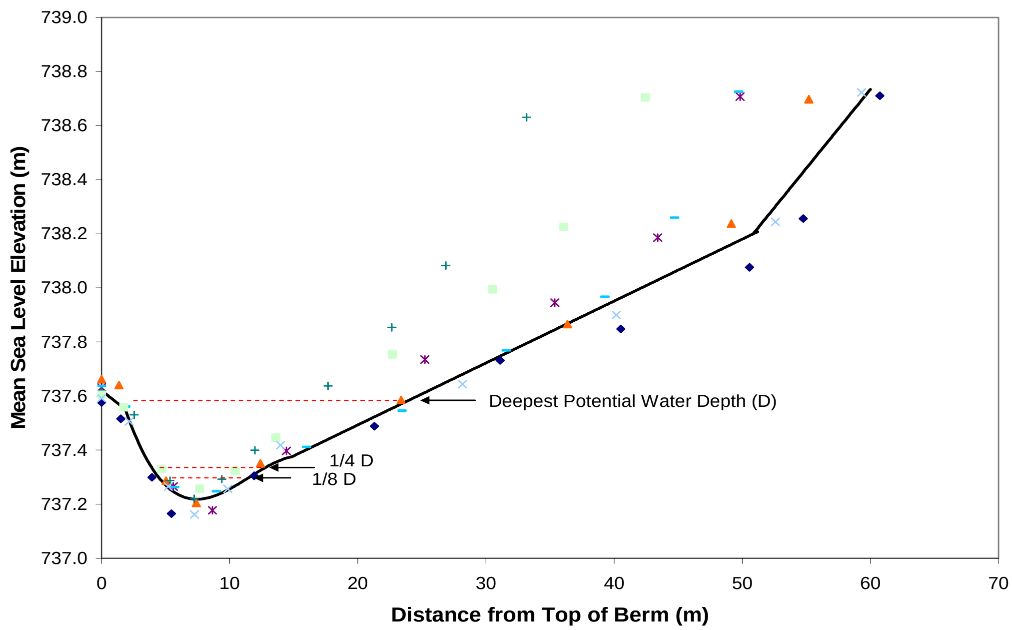


Figure 52. Average Cross Section for the Norton Terrace (Broad-Base Terrace).

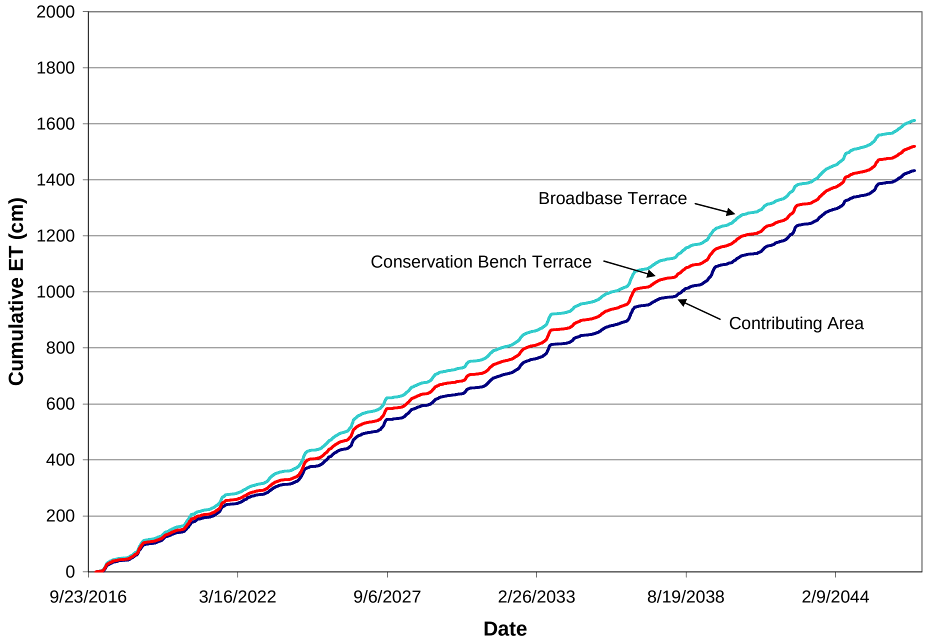


Figure 53. Modeled ET at the Colby Site. Terrace Channel Data is for the Lowest Point in the Channel.

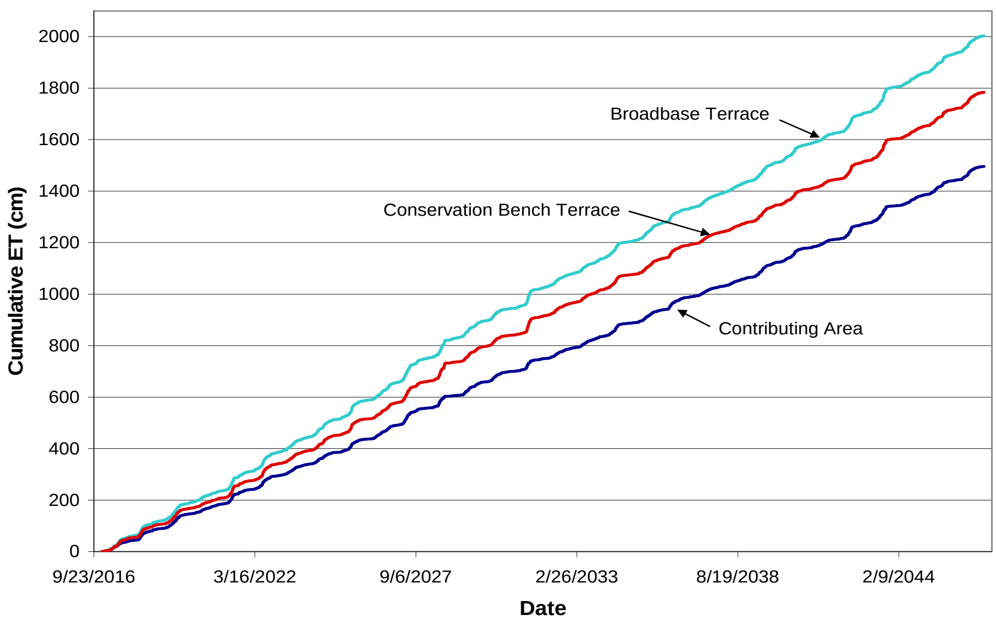


Figure 54. Modeled ET at the Norton Site. Terrace Channel Data is for the Lowest Point in the Channel.

Cumulative deep percolation at Colby and Norton (Figures 55 and 56) represents water that leached below the crop zone depth of 203 cm. Water moved upward during some periods resulting in a negative water flux rather than deep percolation during that time. This occurred primarily in the contributing slope areas. The deep percolation in the terrace channel is for the lowest point in the channel. Deep percolation for the broad-base terrace at Colby exceeded that for the contributing area by approximately 16 cm/year while the conservation base terraces provided an increase of deep percolation of about 10 cm/year above that for the contributing area. The cumulative deep percolation for the contributing area at Norton is quite small. Increases in deep percolation for the terraces compared to the contributing area are about the same as for Colby. Deep percolation amounts illustrate the increased groundwater recharge expected for the terraces.

Deep percolation was very episodic. The most significant events over the simulation period occurred for weather data generated for 2039 at Colby and 2042 at Norton. Deep percolation from May 30 to July 5, 2039 represented 14.1% of the total deep percolation for the 30-year period for broad-base terraces at Colby. Deep percolation for that period was 25.4% of the total for the 30-year period for conservation bench terraces at Colby. About 49 cm of rain fell from May 27 to June 10 producing the deep percolation. At Norton, 12.9% of the total deep percolation for the 30-year period occurred over a 42-day period from June 18 to July 29, 2042 for broad-base terraces. Deep percolation for conservation bench terraces during that period accounted for 15.4% of the 30-year deep percolation at Norton. Deep percolation for the field cropped to wheat resulted from 42 cm of rain in four storms from June 10 to 18.

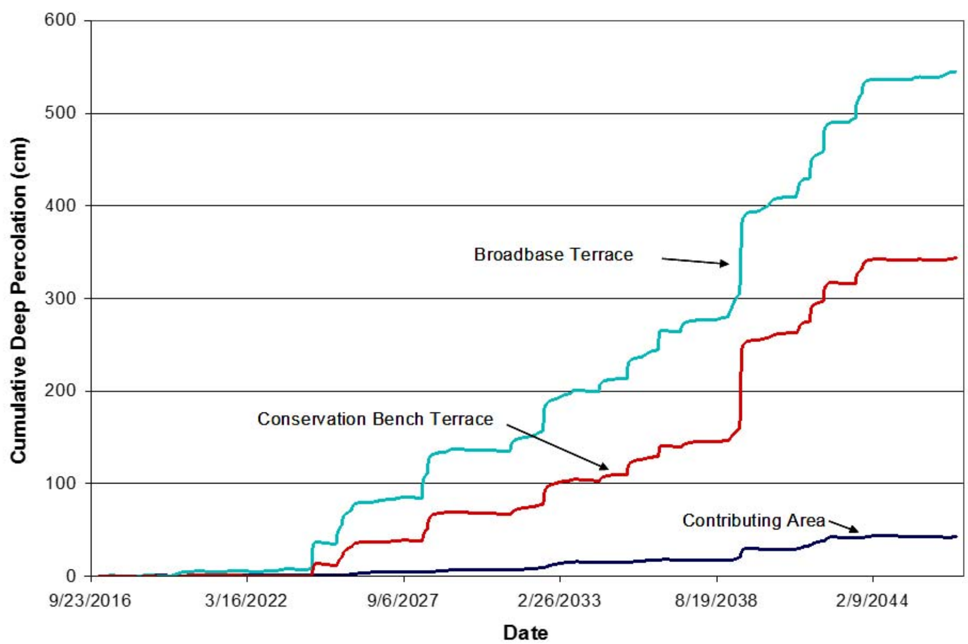


Figure 55. Deep Percolation at 203 cm at the Colby Site. Channel Data is for the Lowest Point in the Channel.

The time series of ET and deep percolation for the contributing areas and the terrace channels at their lowest points shown in Figures 53 to 56 represent two locations in the terraced fields. However, especially for the broad-base terrace, the lowest point in the terrace channel is a small portion of the cross section. The impact of terraces requires the averaged depth of stored water, ET, and deep percolation across the channel, not just at the lowest point. The design of these terraces included a lower section (drain) in the berm where water discharges if water rises too high in the channel. The drain protects the terrace from damage due to overtopping. The drain is generally next to the edge of the field so, if the terrace is overtopped, it will only wash out at the edge of the field. The elevation of the drain corresponds to the deepest potential water depth of the terrace cross-sections shown in Figures 51 and 52. The drain is the lowest elevation along the terrace berm and defines the deepest water storage possible for the terrace. The deepest depth was 30 cm at Colby and 32.2 cm at Norton.

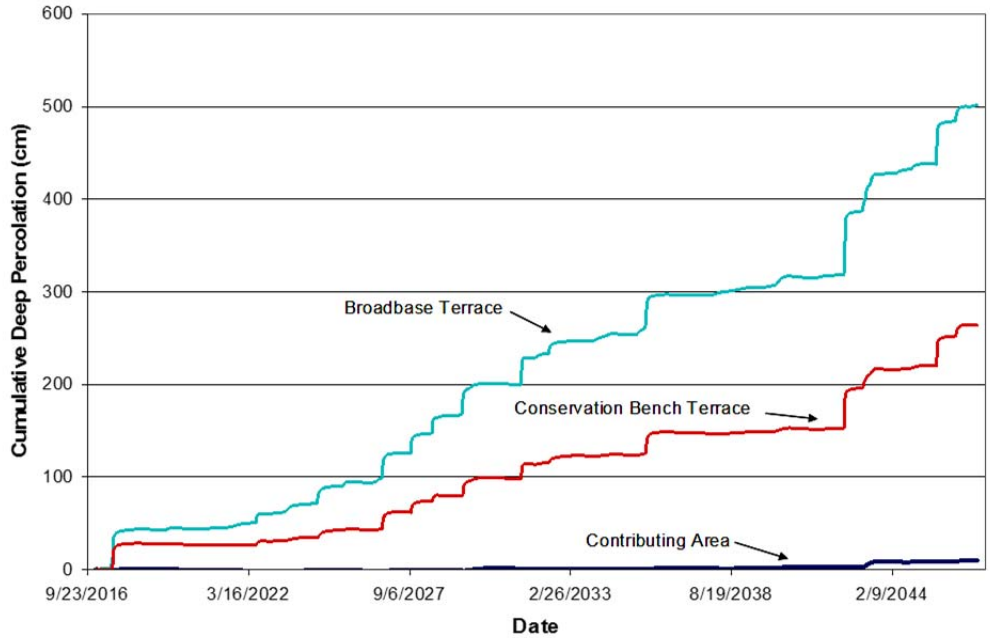


Figure 56. Deep Percolation at 203 cm at the Norton Site. Channel Data is for the Lowest Point in the Channel.

Estimating the weighted average depth of storage, ET, and deep percolation required several simulations to represent conditions across the terrace channel as the depth of water varied with the location in the channel. Terrace channel characteristics were the same for all simulations except that run-on water depth corresponded to a quarter and an eighth of the depth for the lowest location in the channel. We plotted results for the cumulative depth of storage, ET, and deep percolation to produce profiles (see Figures 57 and 58) for assessment of these processes. Integration of the profiles allowed calculation of the total weighted depth of water either stored (or lost from storage), evaporated or percolated per meter of channel length. We computed the weighted depth of water across the terrace channel by integrating the ET, evaporation, deep percolation, or storage profile and then dividing by the top width of the terrace channel

We also computed the proportions of the annual volume of water for the terraces at each experimental site. Computing the volumes per unit length for the contributing area involved multiplying the runoff, ET and deep percolation depths for the contributing area by the width of the contributing area. The width of the contributing area is the distance perpendicular to the terrace channel between successive terrace berms, minus the width of the terrace channel. The volume per unit length for the terrace channel equaled the product of the weighted depth of each water quantity times the width of terrace channel. The average annual volume for the terraces is the volume per unit length times the length of the terrace. We separated evapotranspiration of crops from the evaporation of standing water in the terrace channel. Results show that the volumes are quite different for the contributing slopes and the terrace channels (Tables 18 and 19). Precipitation and runoff volumes are much larger for the contributing slope due to the sizes of the areas. There is little deep percolation for the contributing area, especially at the Norton site. The broad-base and CBT slopes have different volumes because they have different sizes of terrace interval.

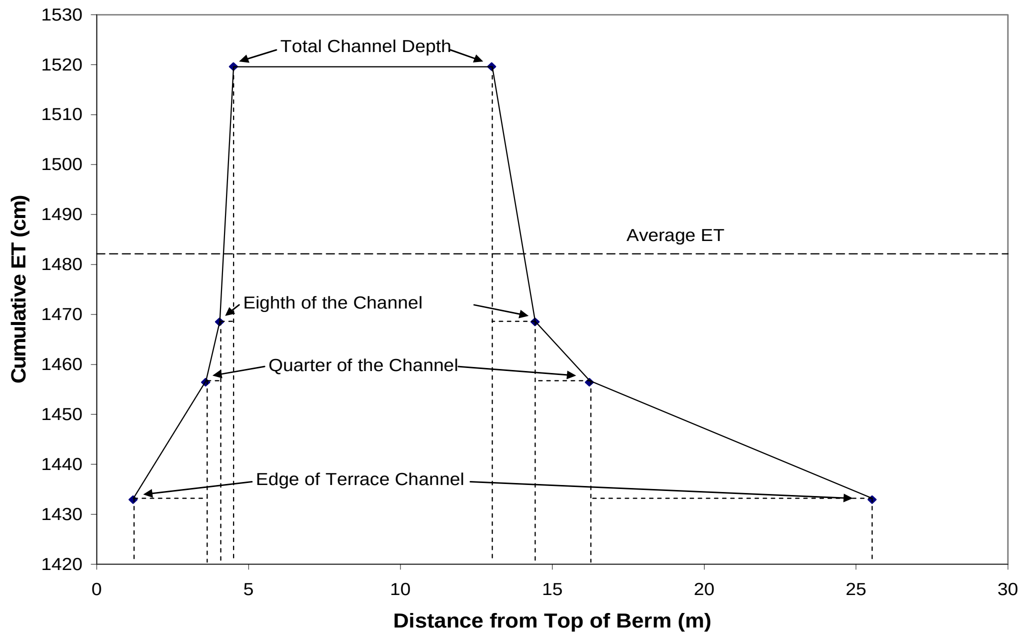


Figure 57. Thirty-Year ET Profile in the CBT Channel at the Colby Site.

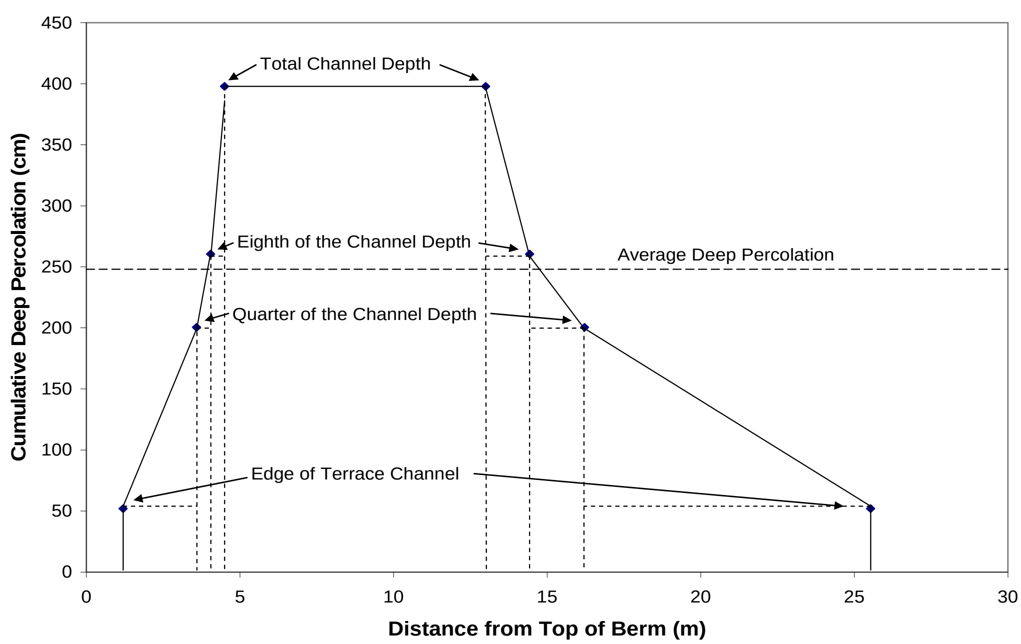


Figure 58. Thirty-Year Deep Percolation Profile in the CBT Channel at the Colby Site.

Table 18. Volume-Based Average Yearly Water Balance at the Colby Site.

Quantity	Broad-Base Contributing Slope	Broad-Base Channel	CBT Contributing Slope	CBT Channel
Precipitation (m^3)	20.7	10.5	19.8	12.6
Runoff (m^3)	1.3	0.1	1.3	0.0
Run-on (m^3)	0.0	1.3	0.0	1.3
ET (m^3)	19.0	9.9	18.2	12.0
Evaporation (m^3)	0.0	0.1	0.0	0.1
Deep Percolation (m^3)	0.6	1.8	0.5	2.0
Change in Storage (m^3)	0.021	-0.005	0.020	-0.006

Table 19. Volume-Based Average Yearly Water Balance at the Norton Site.

Quantity	Broad-Base Contributing Slope	Broad-Base Channel	CBT Contributing Slope	CBT Channel
Precipitation (m^3)	21.5	10.9	20.5	13.1
Runoff (m^3)	1.8	0.2	1.7	0.1
Run-on (m^3)	0.0	1.8	0.0	1.7
ET (m^3)	19.9	11.1	19.0	13.4
Evaporation (m^3)	0.0	0.1	0.0	0.1
Deep Percolation (m^3)	0.1	1.2	0.1	1.4
Change in Storage (m^3)	-0.023	0.013	-0.022	0.004

At Colby, 2.7% of the precipitation falling on the contributing slope resulted in deep percolation. Distributing the extra deep percolation caused by the terrace over the contributing slope and terrace channel would result in 2.1 cm per year of additional percolation for broad-base terraces and 2.3 cm per year of additional percolation for conservation bench terraces. At Norton, 0.6% of the precipitation falling on the contributing slope resulted in deep percolation. Spreading the extra deep percolation caused by the terrace over the contributing slope and terrace channel would result in 2.0 cm per year of additional percolation in the broad-base channel and 1.7 cm per year of additional percolation in the CBT. These values are comparable to results obtained by Koelliker (1985). In his research, conservation bench terraces increased deep percolation by 1.6 cm per year while broad-base terraces enlarged deep percolation by about 2.4 cm per year.

Simulation results also provided data to determine the ET and deep percolation that occurs during each phase of the crop rotation as shown in Figures 59 to 62. The terrace channel had more ET than the contributing slope except when fallow followed wheat at the Colby site. Deep percolation was always higher in the terrace channel than the contributing slope. The deep percolation shown in Figures 61 and 62 had large ranges in the exceedance probabilities. This is a result of the episodic nature of deep percolation.

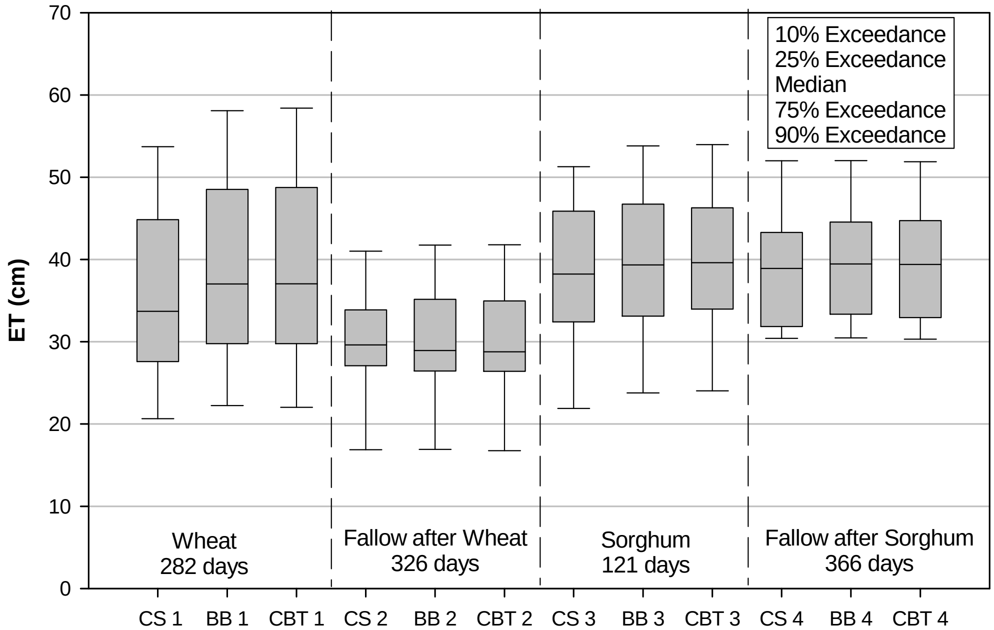


Figure 59. ET for the Contributing Slopes and Terrace Channels at Colby. Terrace Channel ET is the Average Across the Channel (CS = Contributing Slope, BB = Broad-Based Terraces and CBT = Conservation Bench Terraces).

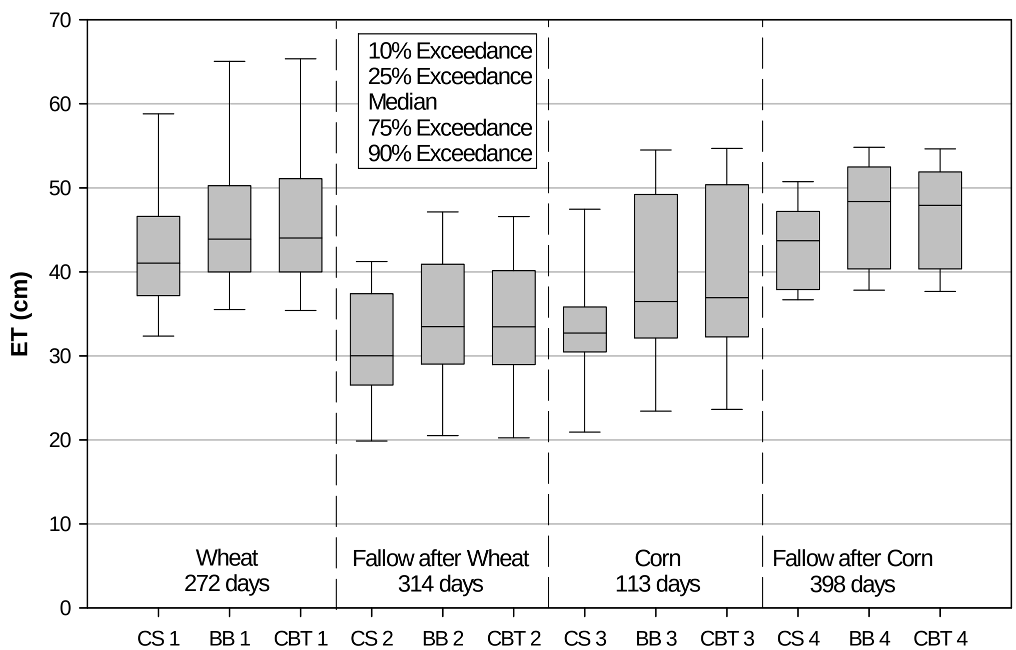


Figure 60. ET for the Contributing Slopes and Terrace Channels at Norton. Terrace Channel ET is the Average Across the Channel (CS = Contributing Slope, BB = Broad-Based Terraces and CBT = Conservation Bench Terraces).

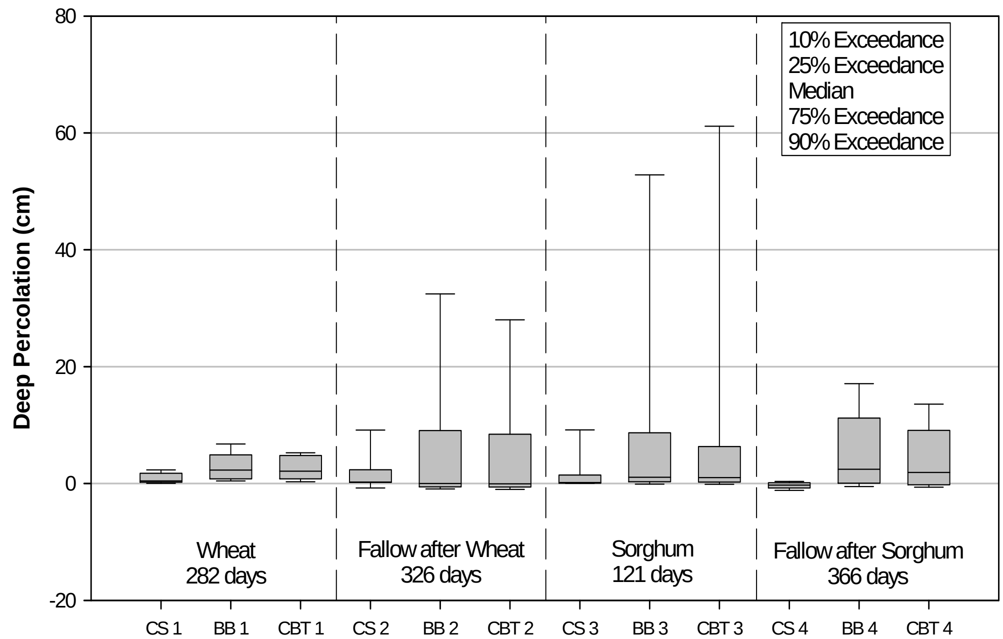


Figure 61. Deep Percolation for the Contributing Slopes and Terrace Channels at Colby. Terrace Channel Deep Percolation is the Average Across the Channel (CS = Contributing Slope, BB = Broad-Based Terraces and CBT = Conservation Bench Terraces).

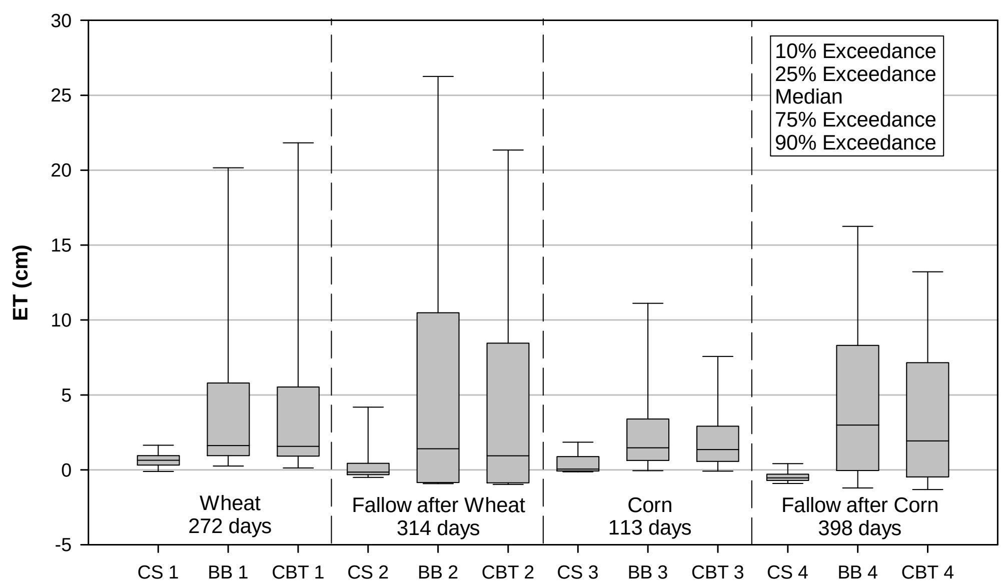


Figure 62. Deep Percolation for the Contributing Slopes and Terrace Channels at Norton. Terrace Channel Deep Percolation is the Average Across the Channel (CS = Contributing Slope, BB = Broad-Based Terraces and CBT = Conservation Bench Terraces).

Thirty-year simulations for the Colby and Norton, Kansas field sites involved modeling the broad-base and conservation bench terraces at each site. The long-term simulation modeling used the parameters determined through calibration. The Colby broad-base terrace retained 2.7 cm of runoff water per year, and the Colby CBT terrace retained 2.8 cm of runoff per year. The Norton broad-base terrace retained 2.9 cm of runoff water per year, and the Norton CBT terrace retained 3.5 cm of runoff per year. Over the course of the simulations, broad-base terraces retained 90% of the contributing slope runoff, while CBT terraces retained 100% of the contributing slope runoff at the Colby site. At Norton, broad-base terraces retained 91% of the runoff from contribution slope while CBT terraces retained 95% of the runoff from the contributing slope.

Evapotranspiration and deep percolation in the terrace channels consistently exceeded that for the contributing slope. Runoff retained in terrace channels primarily went to ET and deep percolation. Approximately 80% of the run-on water retained by broad-base bench terraces at Colby ended up as deep percolation. About 79% of the run-on water retained by conservation bench terraces deep percolated at the Colby site. About 17% of the water retained by the broad-base terrace and 19% of the water retained by conservation terraces became ET at Colby. At Norton, 45.5% of the water retained by the broad-base terrace and 47.4% of the water retained by the CBT deep percolated, whereas 42.4% of the water retained by the broad-base terrace and 47.7% of the water retained by conservation bench terraces became ET.

Deep percolation occurred primarily from specific precipitation events. At Colby, 49 cm of rain fell over a 14-day period resulting in 25.4% of the deep percolation under the CBT during the 30-year simulation. At Norton, 42 cm of rain fell over an 8-day period and produced 12.9% of the deep percolation under the broad-base terrace during the 30-year simulation.

The distribution of ET within the ecofallow cropping rotation is uniform among the two fallow periods, and the wheat and row crop growing periods. At Colby, the ET of each of the four phases of the rotation ranged from 20 to 28% of the total ET, and at Norton, the ET of each of the four phases of the rotation ranged from 21 to 29% of the total ET. Higher daily ET occurred during the row crop and wheat growing periods, but the fallow periods were longer in duration resulting in similar cumulative amounts of ET.

GeoProbe Results

We used a Geoprobe direct push sampler (see Figure 63) to gather soil samples near each set up of instruments in the field in April 2006 and again in 2009. The GeoProbe takes an undisturbed core of soil to a chosen depth. Two samples taken in the contributing area and two in the terrace channel provide a pattern of soil profiles for the fields. We sampled the soil to a depth of 25 feet and stored the samples in sealed plastic tubing. The goals of these cores are twofold: to obtain a water content profile to a depth of 25 feet and to collect undisturbed samples for lab determination of hydraulic conductivity.

Analysis of the results of the probing provides a depiction of the soil water profile throughout the 25-foot depth. The soil water profiles at the sites in 2006 (Figures 64 – 68) show that the regions below the terrace channel are consistently wetter than beneath the contributing area. The difference in soil profile water is more substantial for the conservation broad-base terraces at Curtis and Norton (Figures 64 and 65) than for the flat channel conservation terraces at Culbertson and Colby (Figures 66 and 67). Note that the second terrace at the Colby site had breached prior to setting up the equipment at the field site and did not produce results as expected for a conservation terrace. The open-ended terraces at Stamford show less difference between the soil below the terrace channel and the contributing area (Figure 68). We resampled the profiles in 2009. The results for contributing areas at Curtis were markedly similar between 2006 and 2009 (see Figure 69.)

These data provide strong evidence that the terrace channels beneath conservation terraces contribute to groundwater recharge in the area. It is important to partition runoff that is stored behind the terrace channel between deep percolation that goes to groundwater recharge, evapotranspiration and that overflows the terrace berm and flows toward ephemeral streams and waterways.

Figure 63. Geoprobe Sampling of Soils to 25 feet in the Spring of 2006.

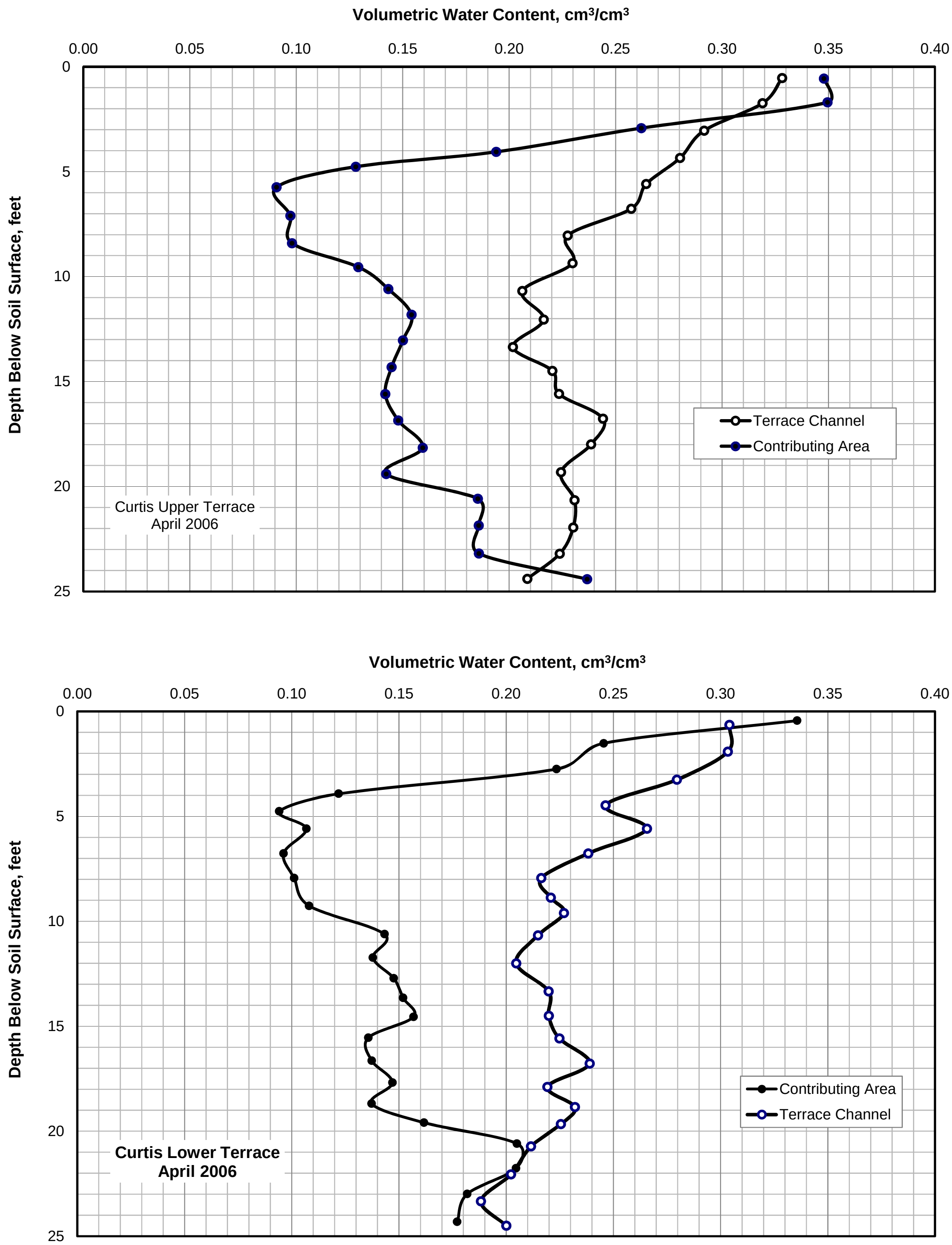
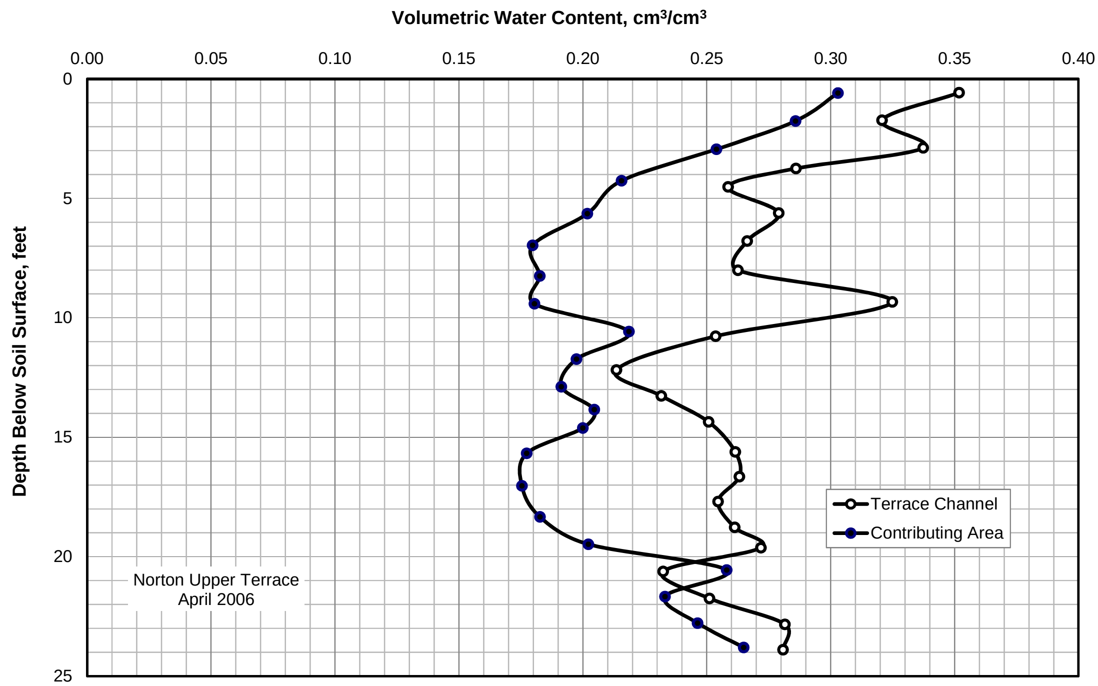


Figure 64. Soil Water Profile Beneath the Contributing Area and the Terrace Channel at the Curtis Site in 2006.



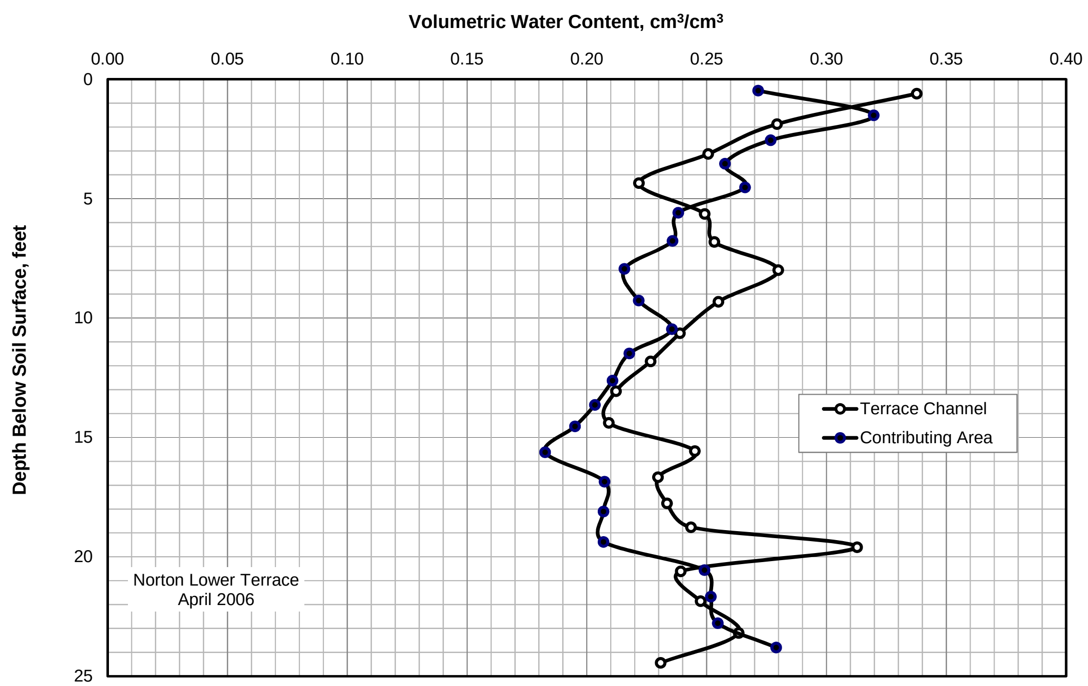
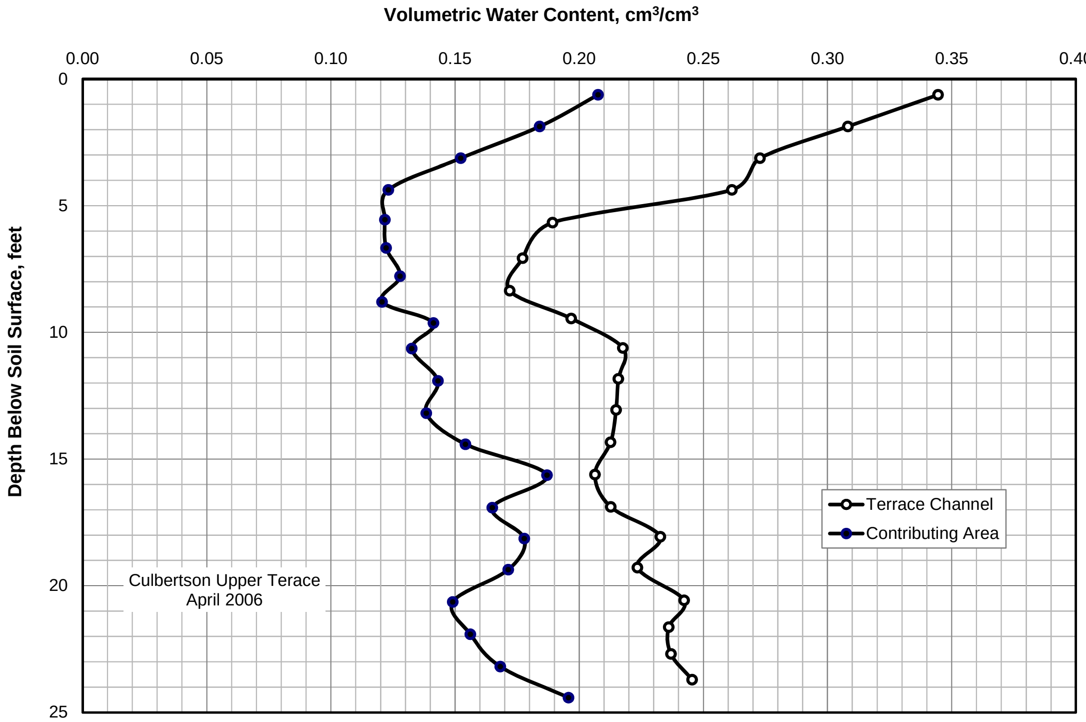


Figure 65. Soil Water Profile Beneath the Contributing Area and the Terrace Channel at the Norton Site in 2006.



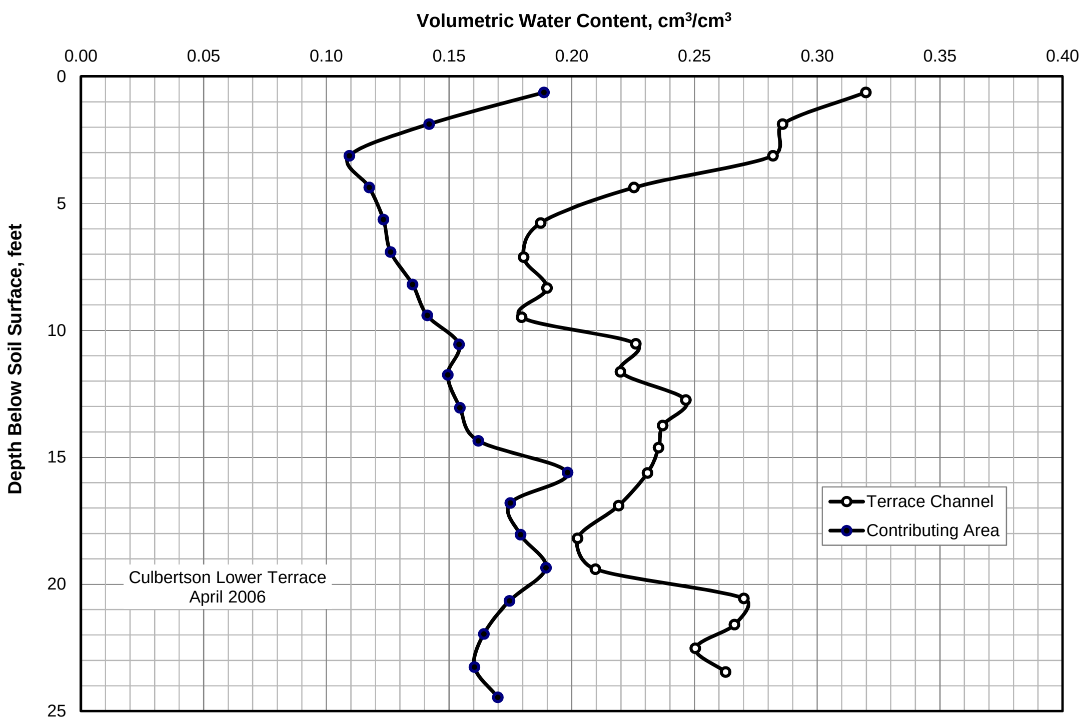


Figure 66. Soil Water Profile Beneath the Contributing Area and the Terrace Channel at the Culbertson Site in 2006.

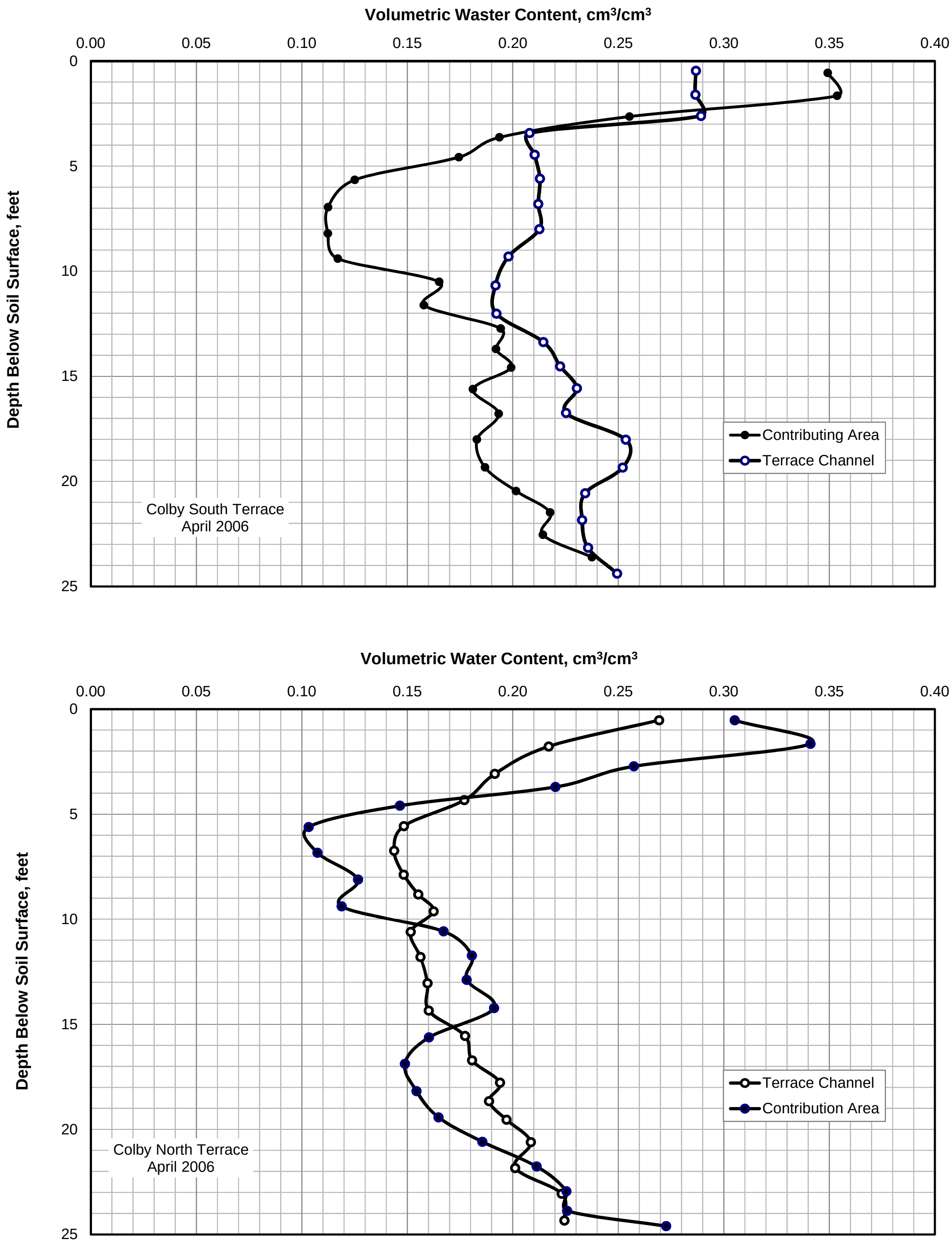
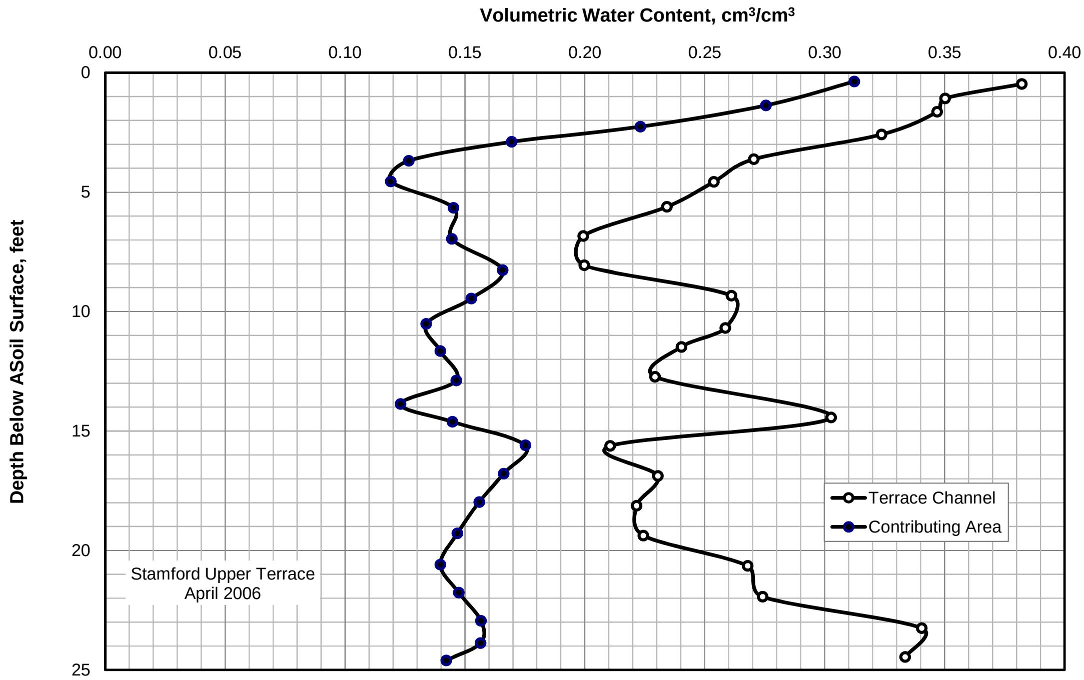


Figure 67. Soil Water Profile Beneath the Contributing Area and the Terrace Channel at the Colby Site in 2006.



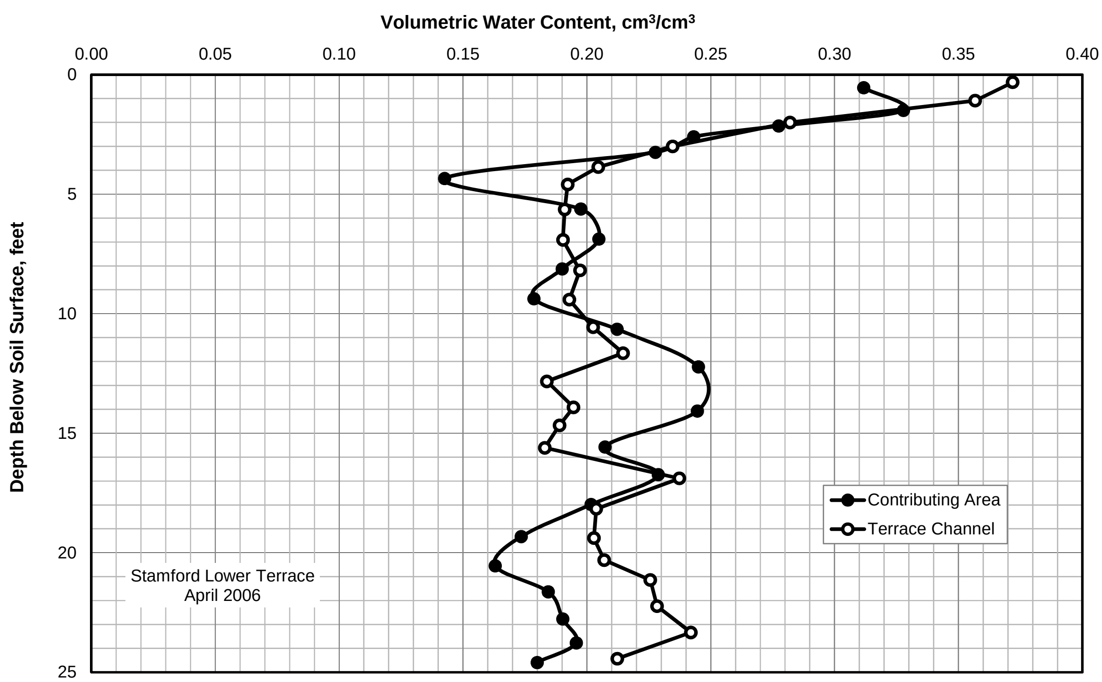


Figure 68. Soil Water Profile Beneath the Contributing Area and the Terrace Channel at the Stamford Site in 2006.

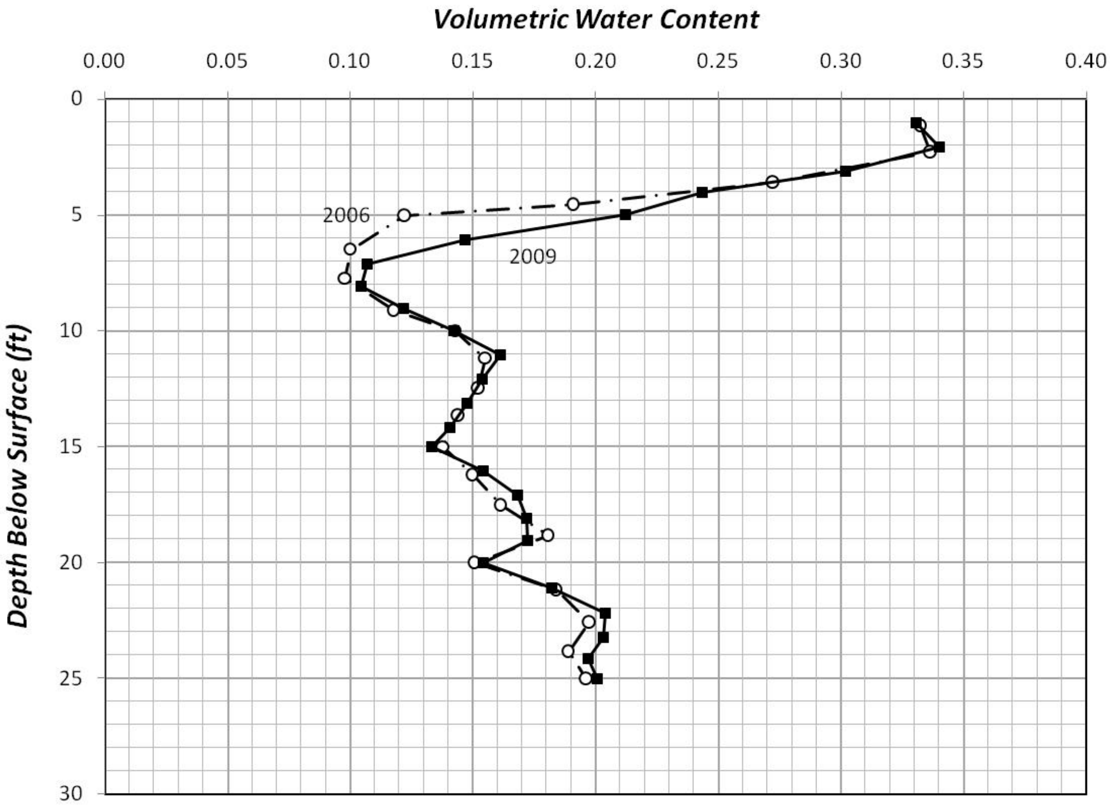


Figure 69. Soil Water Profiles for the Upper Contributing Area at the Curtis Site in 2006 and 2009.

Transmission Losses

Transmission losses in the stream network decrease the relative upstream impact of small reservoirs and land terraces. Streamflow is lost to the unsaturated materials in the stream valley by infiltration into the banks, into the floodplain for out-of-bank flow after water leaves the small reservoir, and land terraces. Jordan (1977) estimated losses of ~ 2% of the flow volume per mile of stream length in the 1960s for relatively large flow events at paired stations. An example of transmission loss appears in Figure 70. The total flow of water into this reach of the Republican River during two weeks in August 2010 was 2,023 acre-feet. The outflow at the gaging station near Stratton on the Republican River was only 1,157 acre-feet. Precipitation occurred early in the period, but there was no significant precipitation during the last week of the period. There was no significant storage of water within the reach and no delayed flood flows or bank storage. The tributaries in this region were losing streams. A second example of transmission loss occurred for a rainfall event on the South Fork of the Republican above Benkelman, NE in August 2008. The storm produced a total flow of 3,300 acre-feet at the CO-KS border. Eight days later, flow reached the gaging station at the KS-NE border.

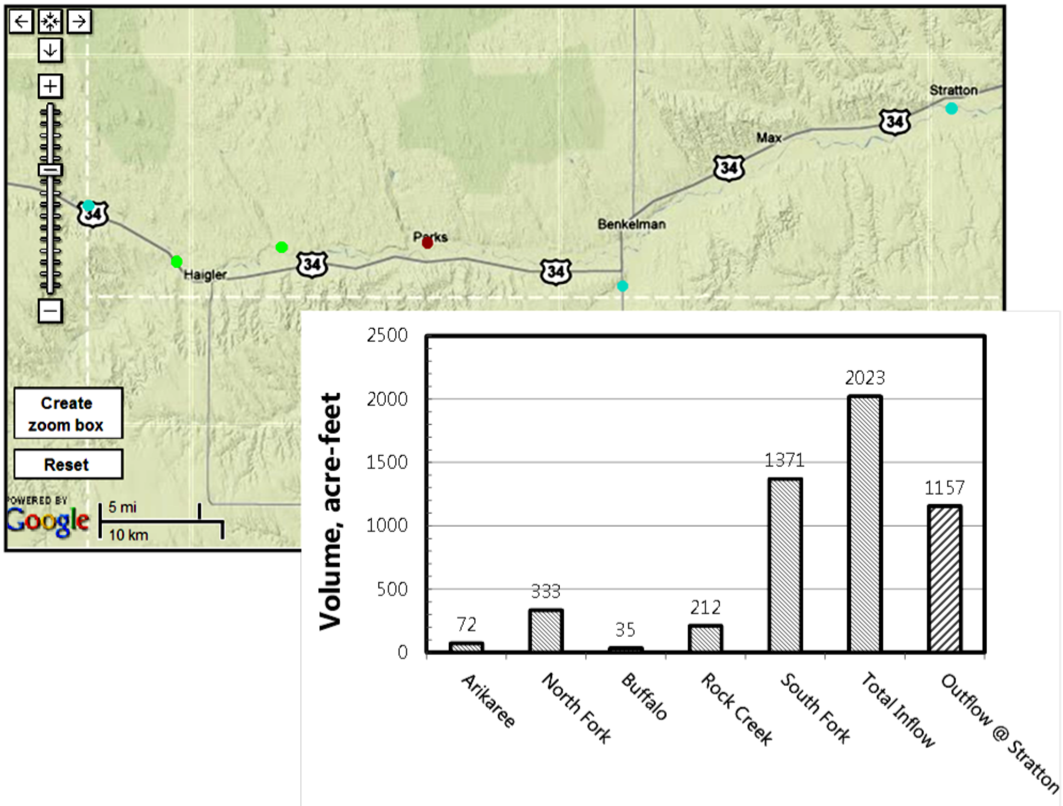


Figure 70. Illustration of transmission loses in streams in southwest Nebraska during August in 2008. Volumes represent the cumulative flow past gaging stations and the total inflow and outflow for the reach.

Only about 200 acre-feet made it past this point. The average transmission loss in the dry stream was more than 7% per mile. This value is probably a higher loss than the average loss across the basin. Analysis of radar-estimated precipitation in the Prairie Dog Creek above Sebelius Reservoir produce an estimated 3.5% loss for an estimated 180 acre-feet of runoff that resulted in 40 acre-feet of flow at the gage about 40 miles downstream over the following 12-day period.

Transmission losses depend on the loss rate in percent of flow per mile of travel and the distance that water travels (Figure 71). For example if the transmission loss rate was 2%/mile and water flows over 10 miles, then 80% of the water would reach a stream. If the same loss occurred per mile but the stream was 30 miles away, then only about 55% of the field runoff would reach the stream.

The travel distance used to determine the transmission loss was from the centroid of the HUC-12 to the outlet of the HUC-12. An example in Figure 72 illustrates the process for the Medicine Creek Basin. The National Hydrographic Dataset includes GIS coverages useful in computing the average distance of travel to the outlet. Modeling required estimates of streamflow at the outlet of various subbasins, so the total travel length used to estimate transmission losses was from the centroid of each HUC-12 to the outlet of its particular subbasin. For the Medicine Creek watershed, the travel lengths from the centroid of the HUC-12s ranged from less than 2 miles to over 70 miles. The median distance was 46 miles.

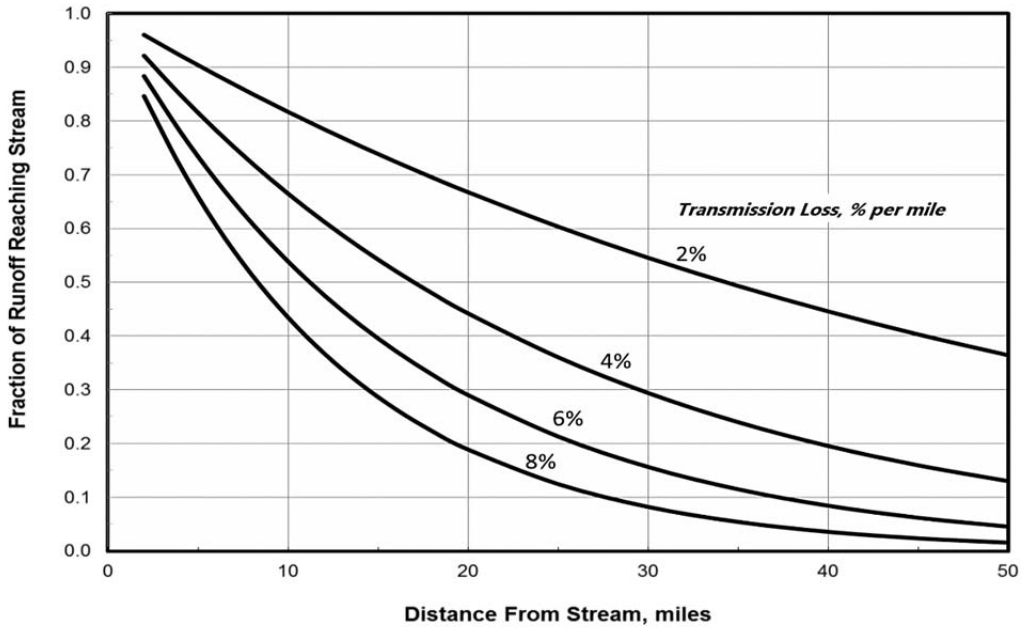


Figure 71. Fraction of Runoff Water that Reaches a Stream Based on Transmission Losses.

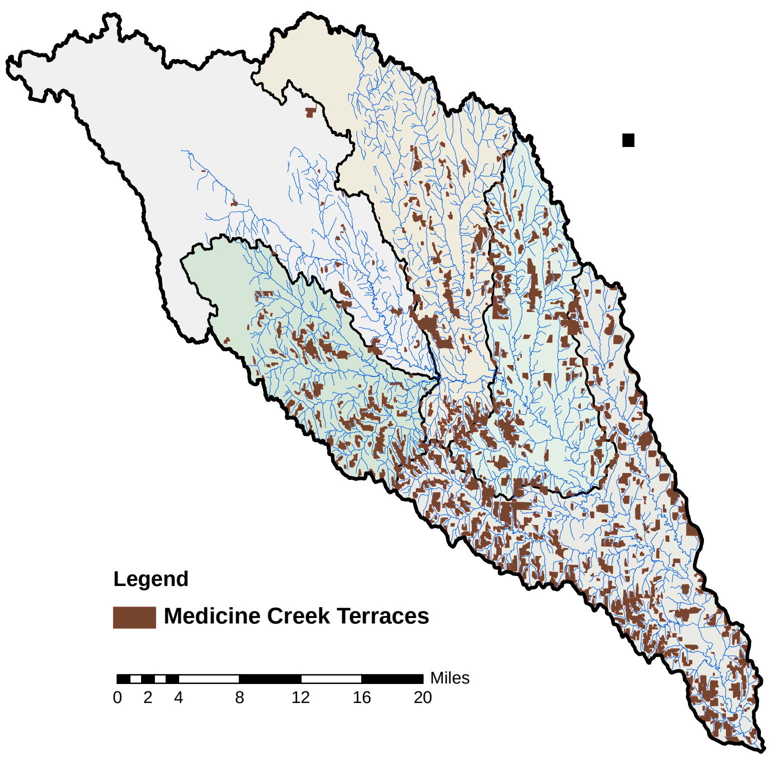


Figure 72. Map of Terraced Land and Streams in the Medicine Creek Watershed.

Databases

Watershed - Hydrologic Unit Codes

The United States consists of 21 major water basins represented by a two-digit code. Each major basin (*i.e.,* the two-digit code basins) encompasses subregions described by four-digit, eight-digit and twelve-digit hydrologic unit codes (HUC). For example, the Missouri River Basin is HUC 10. The four-digit HUC designation for the Republican River Basin is 1025. The Republican River Basin includes 17 subbasins represented by eight-digit HUC units. For example, the HUC-10 code for Prairie Dog Creek is 10250015. Finally, the HUC-12 representation further divides the watershed into smaller subbasins. For example, Prairie Dog Creek contains 25 HUC-12 subbasins. There are 617 HUC-12 subbasins in the Republican River Basin. About 569 HUC-12 subbasins are located above the stream gage near Hardy Nebraska. The average size of HUC-12 subbasins in the Republican River Basin is about 40 square miles. We considered this an adequate size to represent the variability of climates, soils, crops and terrace conditions to use for characterizing hydrologic response units (HRUs) for the POTYLDR model. The HUC system also provides a reliable method to aggregate HUC-12 response to address the issue of depleted streamflow at the HUC-8 subbasin level.

We used the National Hydrologic Dataset (NHD) from the USGS as the basis for our work. We used the UTM NAD1983 projection for Unit 14N for our work. The NHD dataset also provides information for the location of steams, water bodies, and other hydrologic units. This provided an integrated system to represent the Basin.

The HUC-12 subbasins coverages were the foundation for representing the hydrologic characteristics of small watersheds for simulating the impact of terraces and small reservoirs across the entire basin. The POTYLDR model utilizes hydrologic response units for simulating the impact. This involves dividing a watershed into a set of hydrologic response units. Modeling treats land conditions and use within a hydrologic response unit as homogeneous units for a given practice and soil. The process requires definition of a finite set of land uses for the model. We superimposed practices over soil types, terraced land, climate conditions and other factors to define the hydrologic response units. Once the characteristics of the hydrologic response units are defined then the amount of land assigned to each HRU must be determined. Superposition involved overlaying various GIS coverages at the HUC-12 level similar to the process shown in Figure 73.

The GIS coverages that were required for defining the characteristics of the HRU and the aerial expanse of each HRU included coverages for the:

- HUC-12 boundaries
- Soil types
- Plant-land use distributions
- Terraced land distribution and characteristics
- Irrigated land distribution
- NHD data for watercourse locations
- Location and characteristics of small Non-Federal Reservoirs
- Location of weather stations

The following sections describe the development and use of datasets to build the datasets for the HRU characteristics and distribution.

We developed databases for simulating the hydrologic impact of small reservoirs and terraces. The sketch in Figure 73 shows some of the needed geospatial data layers. Geodatabases were developed that include the location of Non-Federal Reservoirs, the amount and location of terraced lands, the delineation of watershed and subwatershed (HUC12 level) boundaries and the location of waterways and water bodies using the National Hydrographic Dataset (NHD).

Personnel from Nebraska originally digitized the location of terraced land in Nebraska and the Sappa Creek watershed in Kansas based on 1994 DOQQ images. We updated these data to match the period for the areas of the watershed digitized by the Bureau of Reclamation in Kansas and Colorado. The FSA data and field boundaries from common land unit (CLU) data helped in creating the updated terrace shapefiles. We updated coverages on a county-by-county basis in NE. With the new procedure, each shape had a unique ID within each county. The updated data relied on the FSA dataset that contains photographic information obtained for the National Agricultural Imagery Program (NAIP) for 2006.

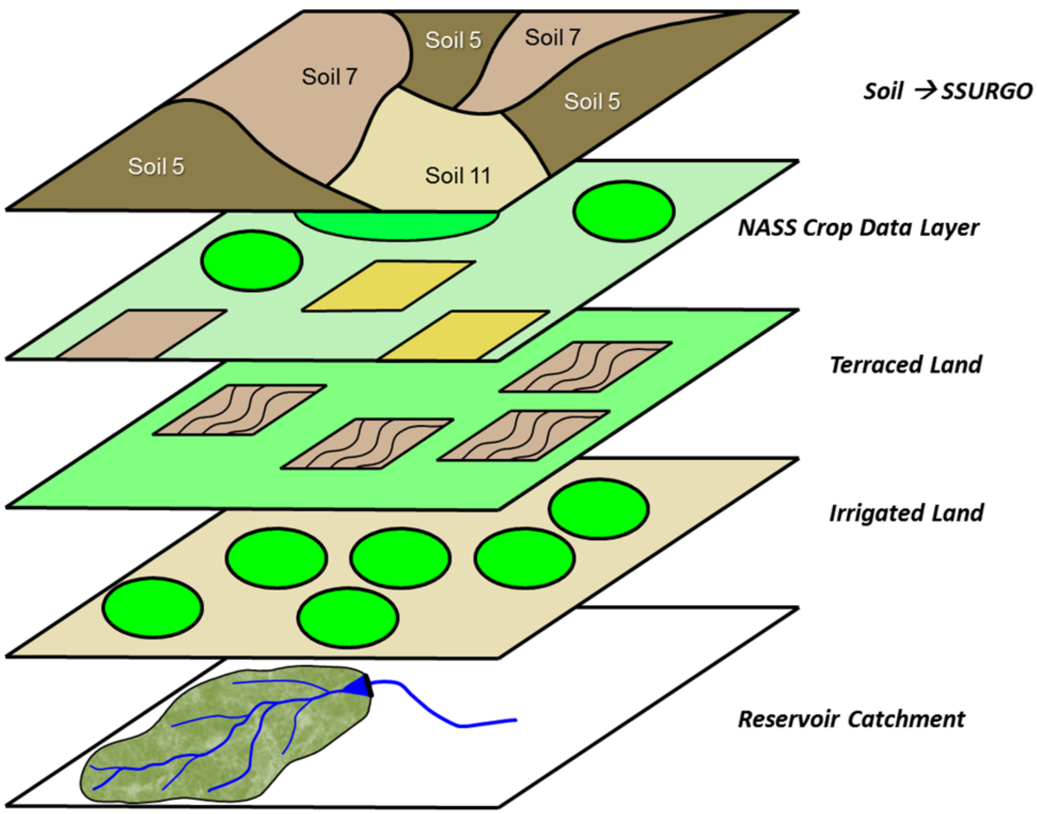


Figure 73. Sketch of Data Layers of some Information for Simulating Impact of Terraces and Reservoirs.

Weather Data

We assembled two types of weather data. Data from the automated weather data network (AWDN) operated by the High Plains Regional Climate Center and data from the Colorado Agricultural Meteorology network were used to compute reference crop evapotranspiration using the hourly Penman-Monteith method. Nineteen AWDN stations across the Republican River Basin supplied data for simulation. Filtering of the data from the stations removed periods when solar radiation data indicated sensor malfunction and when the difference between daily minimum temperature and the average daily dew point was greater than four degrees Celsius. We calibrated the Hargreaves equation for the Great Plains to the filtered reference crop ET data for each month. The Hargreaves method only requires the daily maximum and minimum air temperature to estimate reference crop ET. We then used the calibrated Hargreaves method with data from the Cooperative program operated by NOAA and the National Weather Service (NWS), referred to as the NWS data. These records only include the daily maximum and minimum air temperature and the amount of precipitation received for the day. The data for the NWS stations came from the High Plains Regional Climate Center. The Hargreaves method and NWS data provided estimates of reference crop ET for the NWS sites shown in Figure 74. The NWS data provide a continuous record of data since 1950 for the stations. These data are available for use in the POTYLDR model. The HPRCC also conducts data quality evaluations to fill periods of missing data and to adjust original data if reported data lies outside an expected range based on historical records and conditions at surrounding weather stations. These procedures improve the completeness and reliability of the data.

The excerpt of a weather file in Table 20 shows the format of the data files. The file is comma delimited with two header lines and then data starting on the first day that data is available or on January 1, 1948 whichever is later. The first header line gives the station name, two-character state abbreviation, the NOAA code number, and of the latitude, longitude and elevation of the site. The second header line describes the daily data columns that follow. Daily data starts on the third line. The month, day, year, day of the year and the week for the line are contained in the first five data items. The maximum and minimum daily temperatures in degrees Fahrenheit are next, followed by the daily precipitation in inches per day. The next three columns represent the daily reference crop evapotranspiration in inches per day. The column under EToHG represents the reference ET for a grass crop using the Hargreaves method. The column under EToPM is for a grass reference crop using the ASCE Penman-Monteith method. The last column is the daily reference ET for an alfalfa crop using the ASCE Penman-Monteith method.

The column under EToPM represents the reference ET for grass as computed in the FAO-56 publication by Allen et al. (1998). We conducted a regression analysis from automated weather stations across the Republican Basin including networks operated by the High Plains Regional Climate Center at UNL, the Colorado AgMet network and stations in Kansas that are part of the High Plains Center. The regression correlated the Hargreaves method to the Penman-Monteith method (Mortensen, 2011).

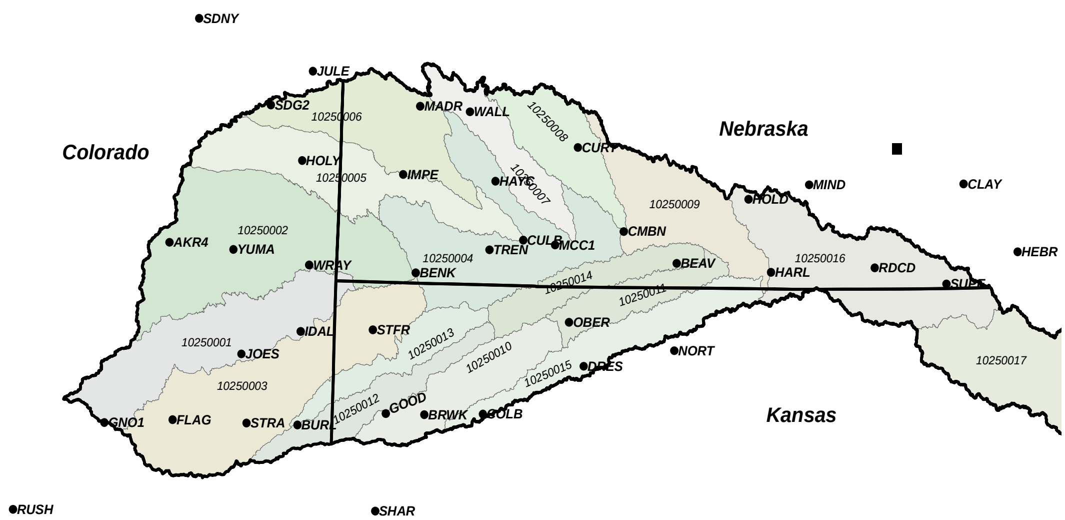


Figure 74. Location of NWS Weather Stations and HUC Units for Simulation of Terrace and Reservoir Impacts.

Table 20. Example of Weather Data Format for the National Weather Service Stations.

COLBY 1 SW		KS c141699		39.38	101.07	3168	<---- Latitude, Longitude, Elevation-Feet			
Month	Day	Year	DOY	Week	Tmax F	Tmin F	Precip in/d	EToHG in/d	EToPM in/d	ETrPM in/d
1	1	1950	1	1	57.06	22.1	0	0.051	0.065	0.092
1	2	1950	2	1	45.41	16.21	0	0.036	0.045	0.062
1	3	1950	3	1	19.37	-4.96	0	0.008	0.015	0.018
1	4	1950	4	1	25.43	-12.62	0	0.009	0.015	0.019
1	5	1950	5	1	31.43	-5.31	0	0.018	0.023	0.030

Reservoir Association

Simulation of individual reservoirs is beyond the scope of this project given the amount of information available for the 709 reservoirs across the Basin. Instead, we simulated the performance of representative reservoirs for regions across the Basin. This required an association of individual reservoirs to the NWS weather stations. We used the Thiessen polygon method to define polygon regions around each weather station. Overlaying the reservoir locations on the Thiessen polygons determined how to associate weather stations to each reservoir (Figure 75). Linking characteristics from the weather station with the reservoir coverage provided data needed to simulate the performance of a typical reservoir in each polygon. These results provided direct input for the reservoir simulation component of the project.

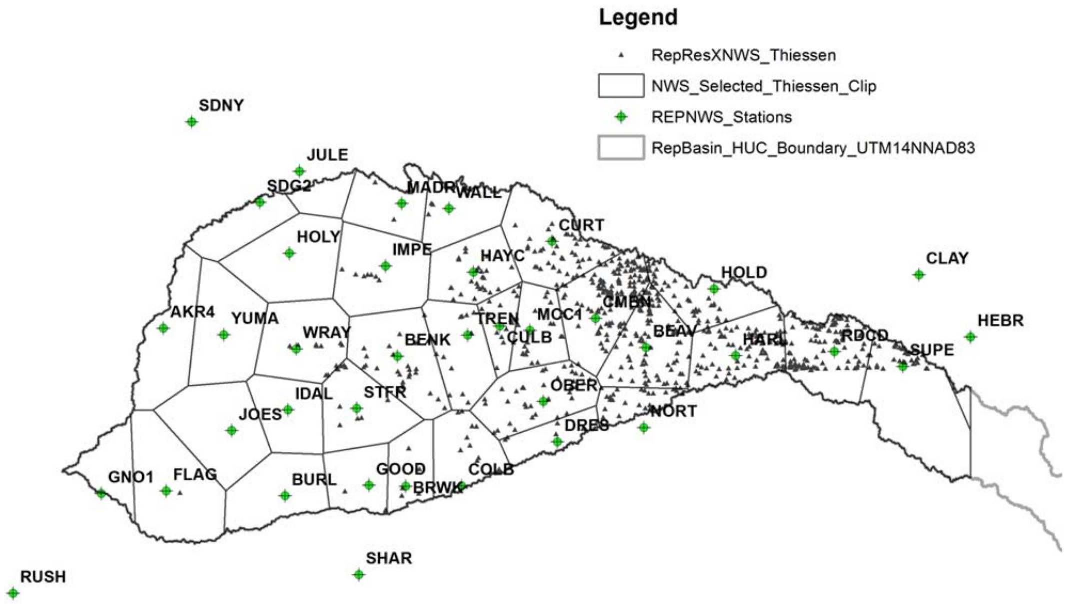


Figure 75. Thiessen Polygons used to Provide Weather for Non-Federal Reservoirs.

Distribution of Terrace Types

Simulation of terrace impacts required a distribution of terrace characteristics across the basin. We used results from the field survey to identify the types of terraces distributed across the basin. The first characterization was the slope of the terrace channel. We divided the terraces into either flat or gradient terraces. Flat-channel terraces retain or detain water in terrace channels to minimize soil erosion by water and provide water for crop grown in and adjacent to the channel.

The fraction of the terraces at a given longitude that have flat channels is given in equation 4 while the relationship for computing the fraction of the terraces that are broad-based is given in equation 5. The relationships in Figure 76 illustrate the nature of the functions compared to the original data. Nonlinear regression provided values for the parameters needed in equations 4 and 5 (Table 21).The coefficients of determination in Table 21 show that the relationships are reasonable.

$$Level\ Fraction = 1 - Min\left(-GRTa \times \left(Long - GRtlongo \right)^{GRTb}, 1 \right) \qquad (4)$$

$$BB\ fraction = BBa + BBb \times \left(MIN\left(1, \frac{Long + BBd}{Range} \right) \right)^{BB\exp} \qquad (5)$$

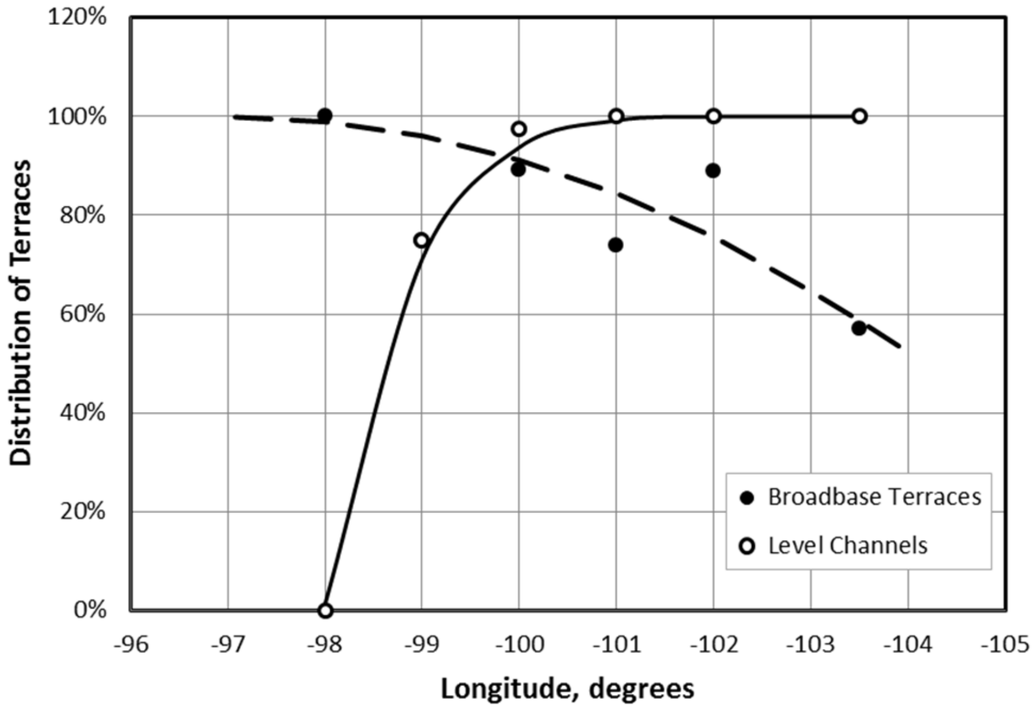


Figure 76. Percentage of Broad-Based and Level Channel Terraces Based on the Longitude.

Table 21. Parameters for Terrace Distributions Described in Equations 4 and 5.

Parameter	Value	Parameter	Value
GRtlongo	-103.6	BBa	1.0
GRTa	-2.074E-05	BBb	-0.117
GRTb	6.251	Range	3.461
R^2	0.99	Longo	97.0
		BBexp	2.0
		R^2	0.71

Terrace types can be divided into flat or gradient, broad-based or flat channel, and closed or open at the end of the terrace. Essentially all of the gradient terraces are broad-based and have open ends. The relationships in equation 6 provide estimates of the fraction of level channel terraces for two types of channels and end conditions. The results in Figure 77 show the distribution of terrace conditions across the basin while the values of the parameters for equation are in Table 22.

$$\begin{aligned} BB\,level\,open\ fraction &= \left(Level\ Channel\ \ fraction \right) \times BB\,open\ fraction \times BB\ fraction \\ BB\,level\ closed\ fraction &= \left(Level\ Channel\ \ fraction \right) \times BB\,closed\ fraction \times BB\ fraction \\ FClevel\,open\ fraction &= \left(Level\ Channel\ \ fraction \right) \times FC\,open\ fraction \times \left(1 - \ BB\ fraction \right) \\ FClevel\,closed\ fraction &= \left(Level\ Channel\ \ fraction \right) \times FC\,closed\ fraction \times \left(1 - \ BB\ fraction \right) \end{aligned} \quad (6)$$

where:

BB = broad-based terraces, fraction
FC = flat-channel terraces, fraction

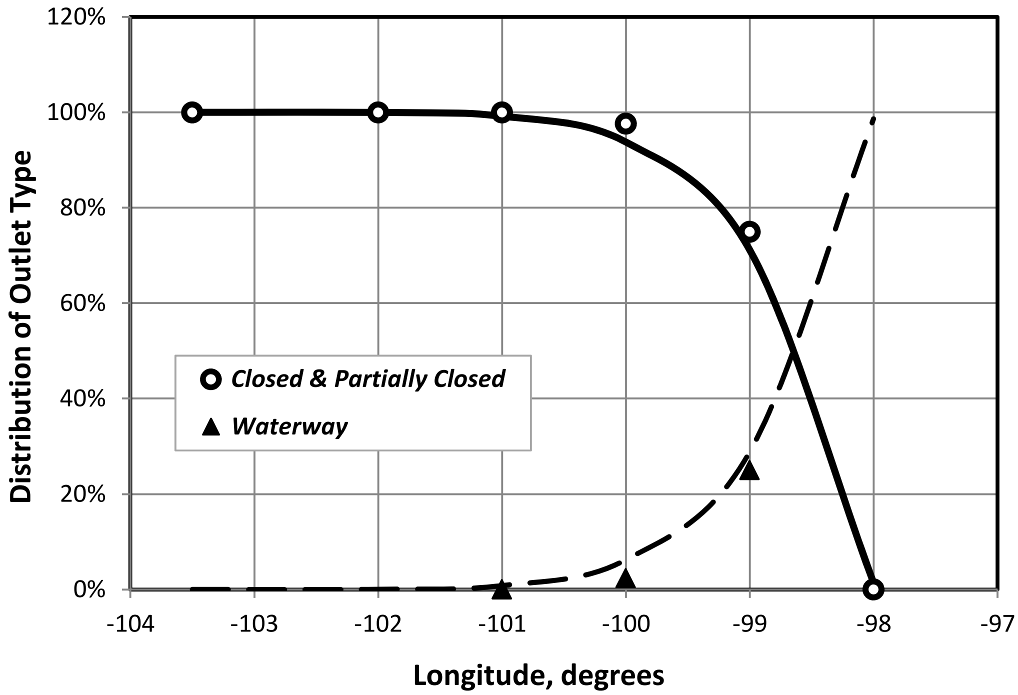


Figure 77. Distribution of Types of Terrace Outlets Based on the Longitude of the Field.

Table 22. Distribution of Terrace Types (Fraction) across the Basin.

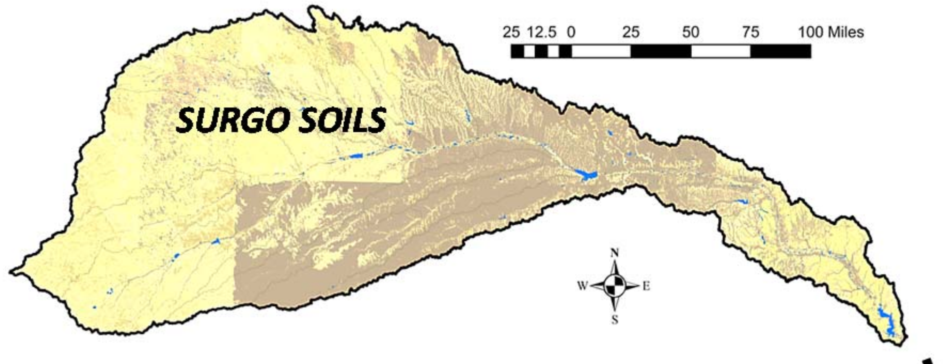
	Broad-Base Terraces			Flat-Channel Terraces		
Longitude	Gradient	Level-Open	Level-Closed	Level-Open	Level-Closed	Total
-97	1.000	0.000	0.000	0.000	0.000	1.00
-98	0.986	0.002	0.012	0.000	0.000	1.00
-99	0.288	0.101	0.583	0.001	0.027	1.00
-100	0.062	0.126	0.729	0.002	0.080	1.00
-101	0.008	0.123	0.713	0.005	0.151	1.00
-102	0.000	0.111	0.644	0.007	0.237	1.00
-103	0.000	0.095	0.552	0.011	0.342	1.00
-104	0.000	0.077	0.444	0.014	0.465	1.00

Soils

We derived information for soil characteristics from the Soil Survey Geographic Database (SSURGO) provided by the USDA-NRCS. The SSURGO database includes the digital soil survey prepared for each county and the associated spatial and tabular data for the soil series in a county. The spatial data component is available as an ESRI ArcGIS shape file. The mapping unit keys represent the soil types in the attribute tables. The attribute tables include soil properties associated with soil series in the shape file. The required soil properties for the POTYLDR model are in the map unit, component, and chorizon tables. We reclassified the soil data because each polygon in the SSURGO shapefile or coverage represents a different soil type, which may appear more than once throughout the dataset. In addition, a single record in the shapefile or coverage may fall into an association of multiple horizons. Reclassifying soil data provides delineation of representative hydrologic response units in the watershed. Each county also has some unique soil series names but the soil is essentially the same across the county line. The POTYLDR model only considers general soil types. We processed the SSURGO spatial data to develop a map of the soil types used in the POTYLDR model. The AWHCCode represents a range of available water holding capacities for soil types, which we computed from SSURGO information. We grouped soils with the same AWHCCode into categories that match soil types in the POTYLDR model. The correspondence of the codes is in Table 23. The map of the correspondence in Figure 78 shows the distribution of soil types for the POTYLDR model. The results show that the majority of the Basin is a deep silt loam soil that corresponds to soil type 5 in the POTYLDR model.

Table 23.Correspondence of Water Holding Capacity Codes Derived from the SSURGO Database and Codes for the POTYLDR Model.

AWHCCode	POTYLDRcode
1	11
2	11
3	11
4	11
5	11
6	7
7	7
8	7
9	5
10	5
11	5
12	0
99	0



POTYLDcode	Soil	Acres	Sq. Miles
0	Other	73,231	114
5	Silt Loam	9,764,730	15257
7	Sandy Loam	3,749,360	5858
11	Sandy Soils	2,362,816	3692
Total		15,950,137	24,922

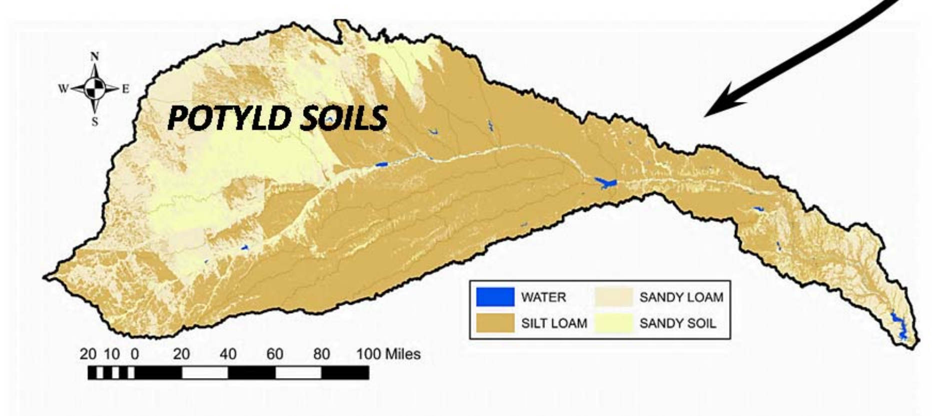


Figure 78. Mapping of SSURGO water-holding capacities to the soil types used with the POTYLDR model.

The Soil Coverage using the POTYLDR Soil Codes Overlaid with the HUC-12 Coverage Provided the Distribution of Soil Types Within Each HUC-12.

Crops

Representation of the HRU requires the distribution of crop types across the basin. The USDA has developed a cropping database called the Crop Data Layer (CDL), which includes GIS coverages of the types of crops grown across the United States. The Crop Data Layer was from the USDA-NASS for the 2009 crop-growing season. Since that time, a new delivery platform has been develop and is now available at http://nassgeodata.gmu.edu/CropScape/. The database is available across the entire basin in a geographical format. We believe that the accuracy of the CDL is adequate for the scale of this study. The POTYLDR model does not simulate the same crops that are available in the CDL database. We developed a cross listing of crops from the CDL to crops simulated with the POTYLDR as listed in Table 24. The map in Figure 79 and summary in Figure 80 illustrate the distribution of land uses across the Basin. Pasture is dominant representing about 47% of the Basin. Corn and small grains are the largest farmed land use. Soybeans and grain sorghum individually represent less than 2% of the Basin and these land uses were included with the acreage for corn to represent row crops for the Basin.

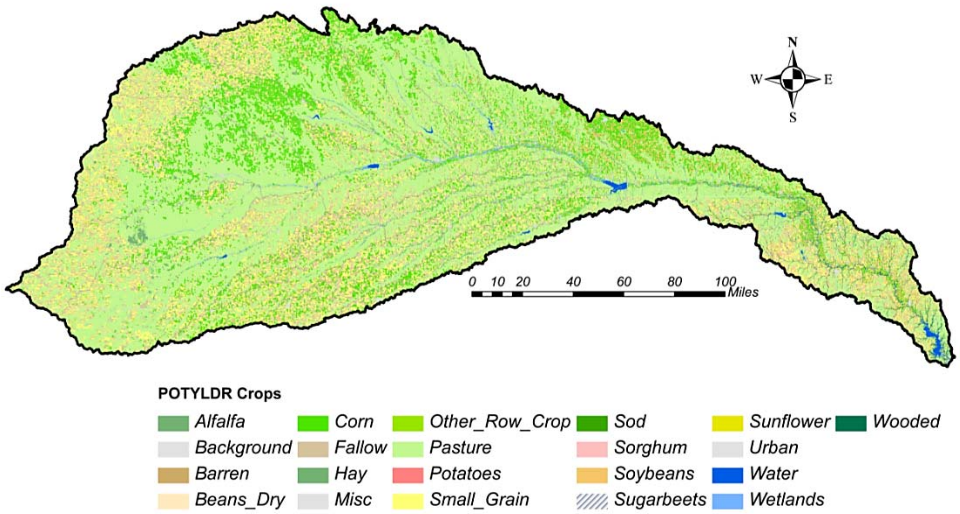


Figure 79. Spatial Distribution of Crop Types for the POTYLDR Model.

Table 24.Correspondence of Codes Between the Crop Data Layer Dataset and POTYLDR Crop Codes.

Code	POTYLDR_Code	Crop Data Layer	POTYLDR_Crop	ID
0	PC02	Background	Misc.	1
1	PC05	Corn	Row Crop	2
2	PC10	Cotton	Row Crop	3
3	PC10	Rice	Row Crop	4
4	PC15	Sorghum	Row Crop	5
5	PC16	Soybeans	Row Crop	6
6	PC18	Sunflowers	Row Crop	7
10	PC10	Peanuts	Row Crop	8
11	PC10	Tobacco	Row Crop	9
12	PC05	Sweet Corn	Row Crop	10
13	PC05	Pop. or Orn. Corn	Row Crop	11
14	PC10	Mint	Row Crop	12
21	PC13	Barley	Small Grain	13
22	PC13	Durum Wheat	Small Grain	14
23	PC13	Spring Wheat	Small Grain	15
24	PC13	Winter Wheat	Small Grain	16
25	PC13	Other Small Grains	Small Grain	17
26	PC13	W. Wht./Soy. Dbl. Crop	Small Grain	18
27	PC13	Rye	Small Grain	19
28	PC13	Oats	Small Grain	20
29	PC13	Millet	Small Grain	21
30	PC13	Speltz	Small Grain	22
31	PC10	Canola	Row Crop	23
32	PC10	Flaxseed	Row Crop	24
33	PC10	Safflower	Row Crop	25
34	PC10	Rape Seed	Row Crop	26
35	PC10	Mustard	Row Crop	27
36	PC01	Alfalfa	Hay & Forage	28
37	PC07	Other Hays	Hay & Forage	29
38	PC10	Camelina	Row Crop	30
41	PC17	Sugar beets	Row Crop	31
42	PC04	Dry Beans	Row Crop	32
43	PC12	Potatoes	Row Crop	33
44	PC10	Other Crops	Row Crop	34
45	PC08	Sugarcane	Misc.	35
46	PC08	Sweet Potatoes	Misc.	36
47	PC08	Misc. Vegs. & Fruits	Misc.	37
48	PC08	Watermelon	Misc.	38
49	PC08	Onions	Misc.	39
50	PC08	Pickles	Misc.	40
51	PC08	Chick Peas	Misc.	41
52	PC08	Lentils	Misc.	42
53	PC08	Peas	Misc.	43
54	PC08	Tomatoes	Misc.	44
55	PC08	Cranberry	Misc.	45
56	PC08	Hops	Misc.	46
57	PC08	Herbs	Misc.	47
58	PC08	Clover/Wildflowers	Misc.	48
59	PC14	Seed/Sod Grass	Misc.	49
60	PC19	Switch grass	Hay & Forage	50
61	PC06	Fallow/Idle Cropland	Fallow	51
62	PC11	Pasture/Grass	Pasture	52

63	PC23	Woodland	Wooded	53
64	PC23	Scrublands	Wooded	54
65	PC03	Barren	Fallow	55
66	PC09	Cherry Orchard	Wooded	56
67	PC09	Peaches	Wooded	57
68	PC09	Apples	Wooded	58
69	PC09	Grapes	Wooded	59
70	PC23	Christmas Trees	Wooded	60
71	PC09	Other Tree Nuts	Wooded	61
72	PC09	Citrus	Wooded	62
73	PC09	Other Tree Fruits	Wooded	63
74	PC09	Pecans	Wooded	64
75	PC09	Almonds	Wooded	65
76	PC09	Walnuts	Wooded	66
77	PC09	Pear	Wooded	67
80	PC23	Other Non-Tree Fruit	Wooded	68
81	PC02	Clouds	Misc.	69
82	PC20	Urban/Developed	Misc.	70
83	PC21	Water	Misc.	71
87	PC22	Wetlands	Misc.	72
92	PC21	Aquaculture	Misc.	73
111	PC21	NLCD - Open Water	Misc.	74
112	PC08	NLCD - Perennial Ice/Snow	Misc.	75
121	PC20	NLCD - Developed/Open Space	Misc.	76
122	PC20	NLCD - Developed/Low Intensity	Misc.	77
123	PC20	NLCD - Developed/Medium Intensity	Misc.	78
124	PC20	NLCD - Developed/High Intensity	Misc.	79
131	PC03	NLCD - Barren	Misc.	80
141	PC23	NLCD - Deciduous Forest	Wooded	81
142	PC23	NLCD - Evergreen Forest	Wooded	82
143	PC23	NLCD - Mixed Forest	Wooded	83
152	PC23	NLCD - Scrublands	Wooded	84
171	PC11	NLCD - Grassland Herbaceous	Pasture	85
181	PC11	NLCD - Pasture/Hay	Pasture	86
182	PC10	NLCD - Cultivated Crop	Row Crop	87
190	PC22	NLCD - Woody Wetlands	Misc.	88
195	PC22	NLCD - Herbaceous Wetlands	Misc.	89

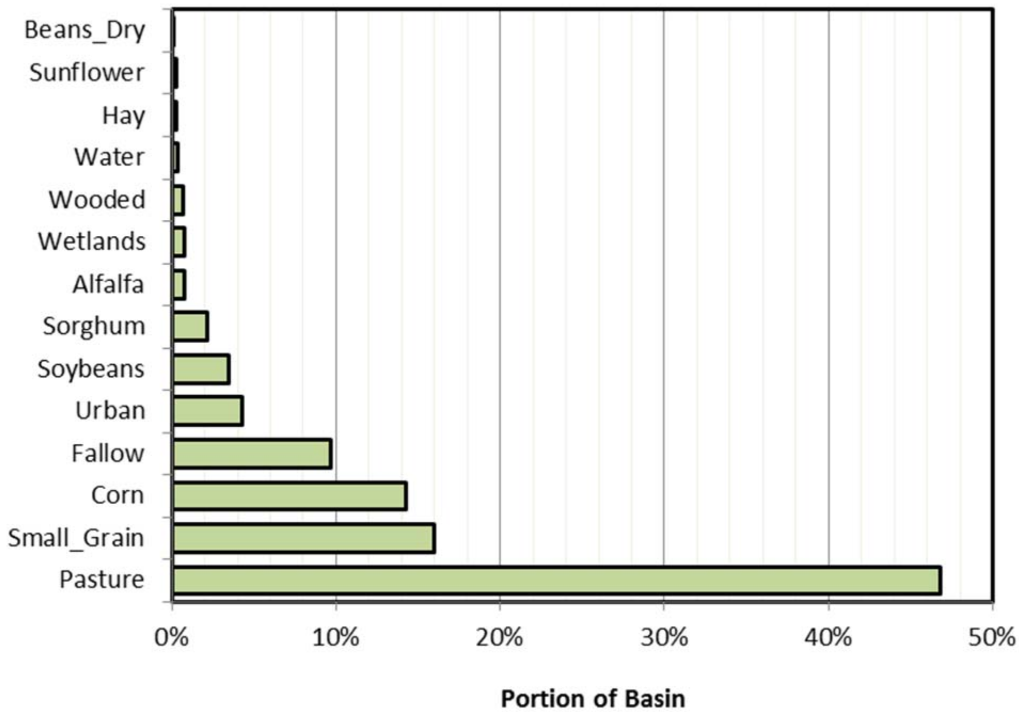


Figure 80. Land use Percentages for the Republican River Basin based on the 2009 USDA-CDL Data.

The crops listed as small grains in Table 24 are primarily wheat. The POTYLDR water balance model represents results for small grains by simulating three rotation practices for wheat. Some land in the basin grows wheat annually, *i.e.,* continuously cropped. Cropping rotations that employ some amount of fallowing to recharge the root zone occur in the western portions of the basin. A survey by Wicks et al (2003) provided data to determine the percentage of the wheat cropping practices across the Nebraska portion of the basin. Data from the USDA National Agricultural Statistical Service (USDA NASS, 2007) provided the amount of continuously cropped wheat across the basin. These fractions applied to data from the USDA Crop Data Layer database allowed computation of the distribution of each type of wheat production for the hydrological response units across the basin.

The distribution of wheat cropping practices from the survey by Wicks et al. (2003) as a fraction of the land planted to wheat that is in a wheat-fallow rotation (WF_f), fraction of wheat that is grown in a continuous cropping system (CC_f), and an eco-fallow rotation of wheat, corn and fallow (WCF_f) is listed in Table 25. The fractional distribution was regressed against the average annual precipitation (P_m) at the locations used in the survey. The resulting functions are:

$$WF_f = 47.98\, e^{\left(-0.03932\, P_m^{1.691}\right)} \tag{7}$$

$$CC_f = 7.537\, e^{\left(0.0003721\, P_m^{2.664}\right)} \tag{8}$$

$$WCF_f = 1 - WF_f - CC_f \tag{9}$$

Results in Figure 81 illustrate the variations of the cropping patterns from the Wick's survey.

Table 25. Distribution of Wheat Rotations in Nebraska (from Wicks et al 2003 - Survey in 1998).

Rotation	Western: Panhandle and Perkins, Chase, Dundy	South-Central: Hitchcock to Harlan	Southeastern: Franklin to Thayer	Fallow Period before Wheat, months
	Two-Year Fallow Rotation			
Wheat–fallow	40%	5%	3%	14
	Three-Year Fallow Rotation			
Wheat–corn–fallow	44%	69%	20%	11
	Continuous Cropping			
Wheat–wheat	2%	5%	23%	2
Wheat–corn or grain sorghum	10%	5%	5%	0
Wheat–corn–soybean	2%	7%	49%	0
Wheat–corn–spring grain	2%	9%	0%	5
Total Continuous Cropping	16%	26%	77%	7

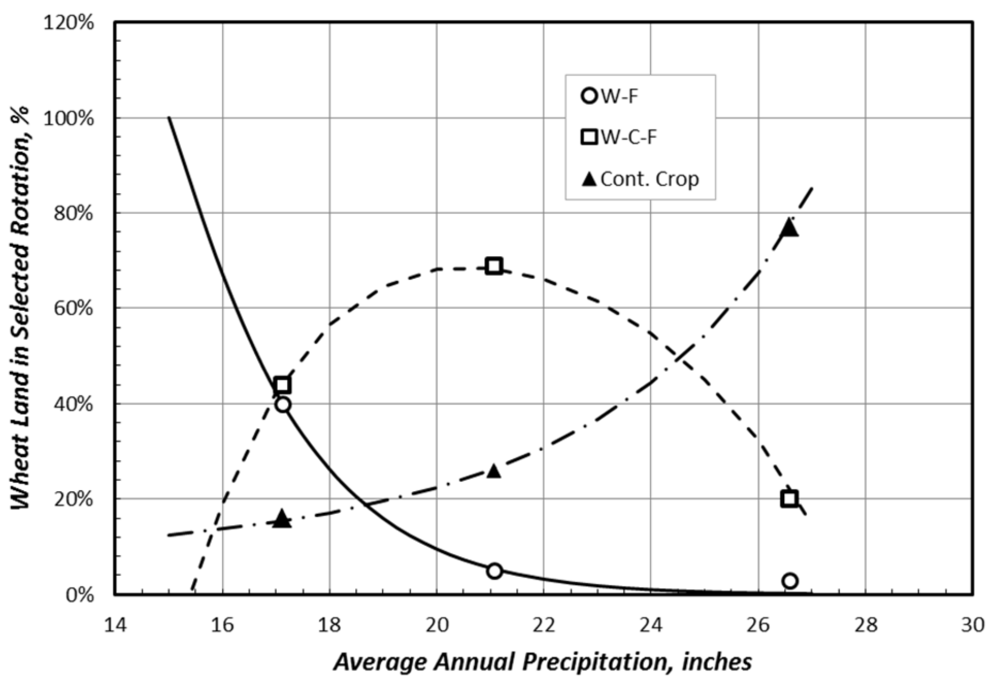


Figure 81. Figure Used to Determine Type of Wheat Cropping Across the Basin.

These relationships enable computation of the fraction of the total fallowed wheat land that used a wheat-fallow rotation, *i.e.* $WF_r = WF_f \,/\, \left(WF_f + WCF_f \right)$.

Data from Wicks et al. (2003) only applies to Nebraska. We used data from the USDA National Agricultural Statistical Survey (NASS) for 2007 and the above relationships to determine the fraction of continuously cropped wheat land across the basin. We used cropping pattern data from counties that are completely contained in the basin to determine the fraction of the continuously cropped wheat land as a function of the average annual precipitation. The resulting relationship was:

$$CC_{ww} = 0.0619 \; P_m - 0.8954 \tag{10}$$

The fraction of the wheat land in a wheat-fallow rotation is:

$$WF_{ww} = W_r \left(1 - CC_{ww}\right) \tag{11}$$

We computed the fraction of wheat land that employed an eco-fallow rotation as:

$$WFC_{ww} = 1 - CC_{ww} - WF_{ww} \tag{12}$$

Data in Figure 82 and Table 26 illustrate the results of partitioning wheat land by practice, where:

CC_f = fraction of wheat that is grown in a continuous cropping system
CC_{ww} = fraction of winter wheat that is grown as continuous cropping
P_m = annual precipitation in inches
WCF_f = fraction of wheat that is grown in an eco-fallow rotation of wheat, corn and fallow.
WFC_{ww} = fraction of winter wheat in a wheat-corn fallow rotation
WF_f = fraction of the land planted to wheat that is in a wheat-fallow rotation
WF_{ww} = fraction of the winter wheat grown in a wheat-fallow rotation
W_r = fraction of the total fallowed wheat land that used a wheat-fallow rotation

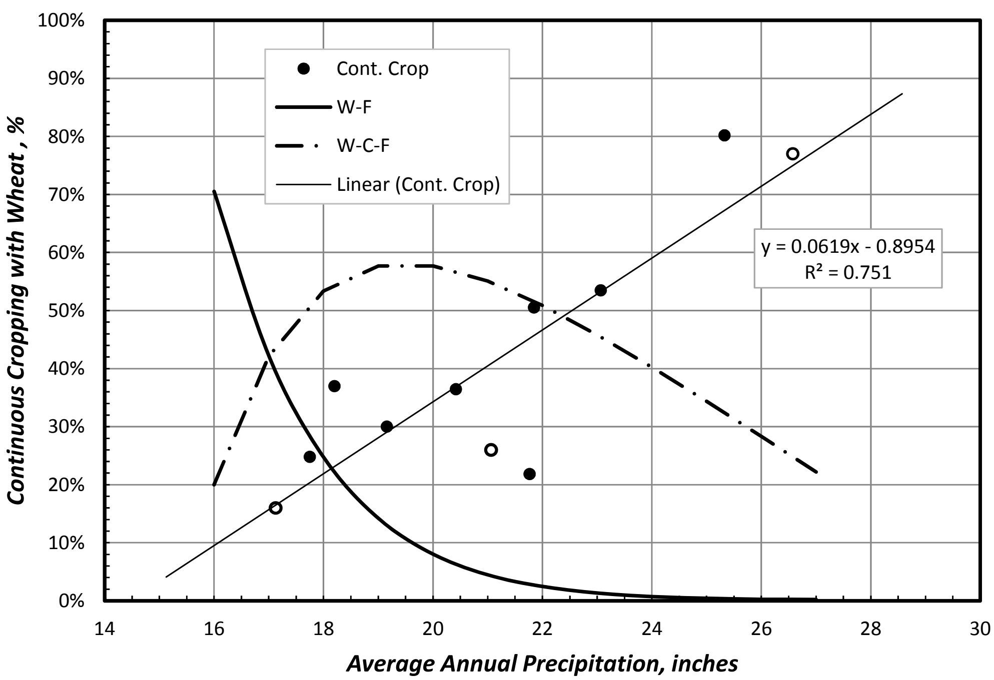


Figure 82. Functions to Predict Distribution of Wheat Cropping Practices.

Table 26. Distribution of Wheat Cropping Practices Based on Average Annual Rainfall.

Zone	Average Annual Precipitation Range, inches	Mean Annual Precipitation, inches	Distribution of Wheat Cropping Practices		
			Continuous	Wheat-Fallow	Wheat-Corn-Fallow
1	< 16	15	3%	97%	0%
2	16 - 18	17	16%	42%	42%
3	18 - 20	19	28%	14%	58%
4	20 - 22	21	40%	4%	55%
5	22 - 24	23	53%	1%	46%
6	24 - 26	25	65%	0%	35%
7	26 - 28	27	78%	0%	22%
8	28 - 30	29	90%	0%	10%

Irrigated Land

Irrigated land is important in assessing the effect of land use practices on streamflow depletions. Irrigation is important in two ways. The simulation of reservoirs requires an estimate of the surface water yield that reaches the reservoir. Irrigation is also important because some land originally terraced is now irrigated. Thus, the runoff and recharge from the irrigated land affects the impact of terraces and reservoirs. Employment of two data sources allowed determination of the amount and location of irrigated land in the basin. Accounting documents from the settlement of the Republican River Compact Administration provide data to determine the amount and location of irrigated land for 2007 (http://www.republicanrivercompact.org/2007/index.html). Data supplied annually by each state for accounting modeling provides information about irrigated data. Independent irrigation coverages were available for Kansas and Nebraska that provided a means to map the irrigated land. Finally, the locations of irrigation wells within the Republican Basin allowed assessment of the spatial distribution of irrigated land.

The dataset for Nebraska was from a remote sensing survey by the Center for Advanced Land Management Information Technologies (CALMIT) in 2005 (http://calmit.unl.edu/2005landuse). This coverage included the distribution of land irrigated by center pivots and by other methods. The coverage shows circles and polygons for each class of irrigated land as illustrated in Figure 83. The locations of active registered irrigation wells originated from the Nebraska Department of Natural Resources (http://dnrdata.dnr.ne.gov/wellscs/Menu.aspx). The plot in Figure 83 illustrates the nature of the data for a portion of the Basin.

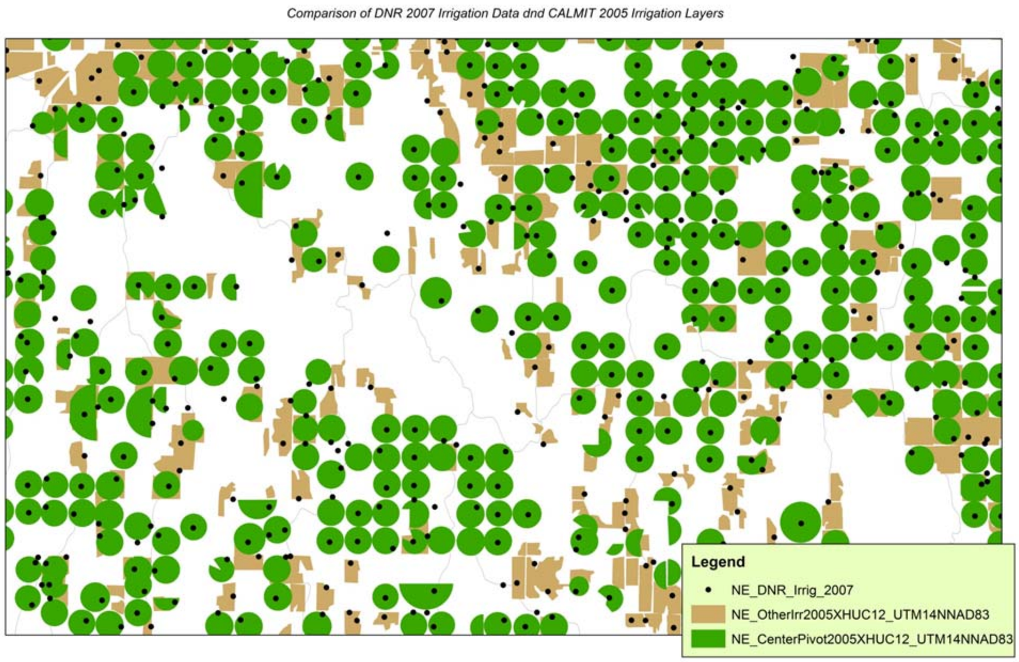


Figure 83. Spatial Comparison of Irrigated Lands From the CALMIT Image Processing and the Location of Wells from the DNR Well Registration Database.

We clipped the statewide GIS coverage for the distribution of the irrigated land to the boundaries of the Republican Basin. We then partitioned both data sources by HUC-12 boundaries and totaled the amount of irrigated land within each HUC-12 (Figure 84). Results in Figure 84 show an excellent correlation between the two data sources. This provided support for use of the GIS coverage that provided a spatial distribution of the irrigated land, which allowed us to overlay coverages to determine the aerial extent of land use combinations.

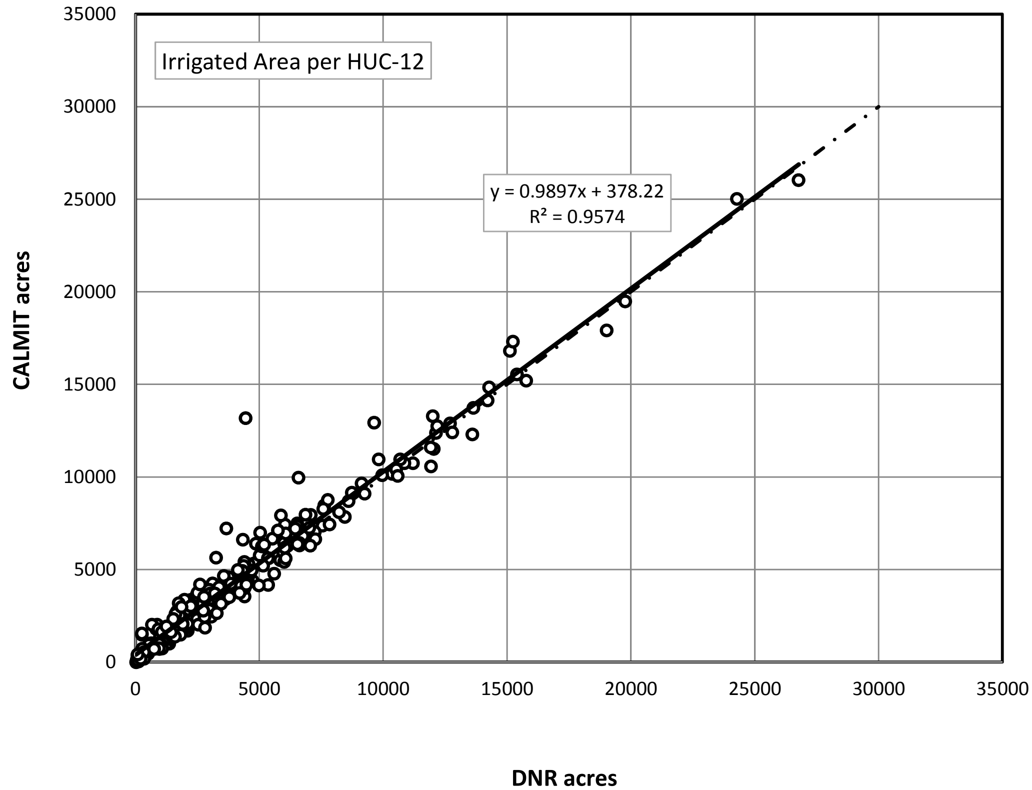


Figure 84. Comparison of Irrigated Area per HUC-12 in Nebraska for the Data Reported by DNR in 2007 and as Digitized by CALMIT.

Kansas has developed a Place-of-Use coverage for irrigated land. The database includes forty-acre tracts of land that receives some irrigation. We clipped the coverage to the boundary of the Republican Basin and overlaid the coverage with the irrigation well dataset derived from the annual report for the Republican River Settlement (see example for Thomas County in Figure 85). This database provides location information for irrigation but does not identify the actual amount of irrigated land in the forty-acre tract. For example, if a center pivot was centrally located on four contiguous forty-acre tract then the total area for the four forty-acres tracts would be 160 acres while a traditional center pivot would only irrigate about 130 acres in a quarter section. Clearly, using the total land area from the Place-of-Use data would overstate the amount of irrigation. We obtained the amount of irrigated land from the Republican River Compact Administration website (http://www.republicanrivercompact.org/) for Kansas in 2007. One of the available files included a record of irrigation water pumpage in 2007. This file does not include GIS coverages but does include an identification index for each well and a reported amount of land irrigated for the well in 2007. We obtained the list of active irrigation wells from the Kansas Water Information Management and Analysis System (WIMAS at http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm). We joined the data from the 2007 compact administration file to the location information available in WIMAS for active irrigation wells. We eliminated irrigation wells from the database for wells that reported no irrigation in 2007. We then overlaid the active well database with the HUC-12 coverage to determine the amount of land irrigated in each HUC-12 for 2007.We computed the irrigated acreage per HUC-12 from the Point-Of-Use coverage and used the ratio between acreage reported for the Settlement and the total area from the Point-Of-Use data to determine the irrigated area per HUC-12. We used the acreage ratio to determine the areas for overlays of other properties in building input files for POTYLDR simulation. We do not have an independent check on the amount of land irrigated in Kansas as was available for Nebraska. However, the amount of irrigated land is equal to what Kansas reported for Compact administration in 2007.

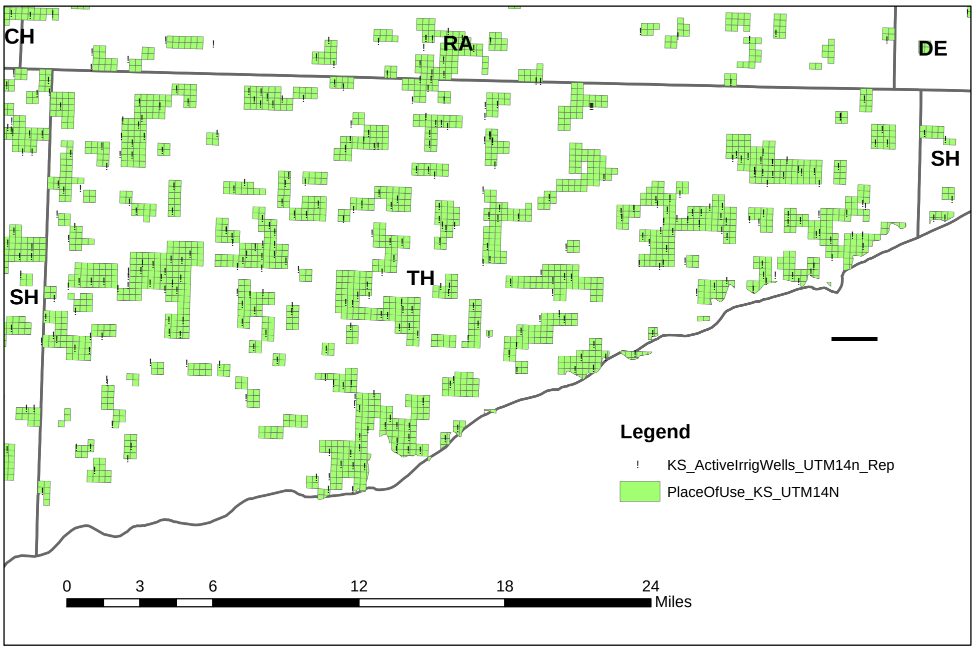


Figure 85. Correspondence of the Location of Irrigation Wells from the WIMAS System and the Place-Of-Use Coverage for Thomas County Kansas

We were unable to locate a digital coverage of irrigated land for Colorado. The data provided by Colorado for Compact accounting in 2007 included the amount of groundwater pumped and applied to sprinkler and furrow irrigated land. The data file included the location of the well based on the cell of the groundwater model. We converted location information for the groundwater model cells into geographic coordinates for mapping with GIS. We summed the irrigation acreage for sprinkler and surface irrigation to provide a shapefile of irrigated land. The point coverage did not include the area of coverage so we could not superimpose the irrigation shapefile over other coverages to compute characteristics of the irrigated land. We used a buffer around the points found for the irrigation wells to provide an area surrounding the well. An example of the overlap for irrigated and terraced land in Figure 86 shows an application of the method. The amount of terraced land is much less extensive in Colorado and the procedure described here seems to be adequate for determining the interaction of irrigation and terracing in Colorado. The buffer seemed to be adequate for overlaying crop and soil coverages to develop characteristics for the HUC-12 for input into the POTYLDR model.

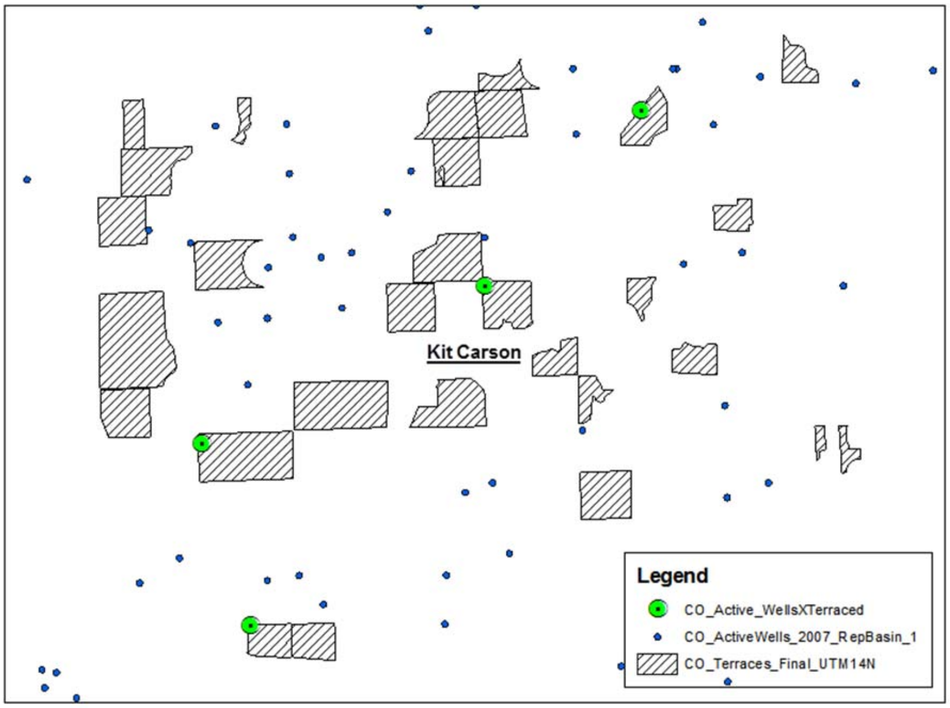


Figure 86. Example of Procedure to Determine if Terraced Land in Colorado was also Irrigated.

Catchment Area for Small Reservoirs

We had to develop characteristics for the catchment areas of the small Non-Federal Reservoirs distributed across the Basin. The characteristics of the catchment areas are different from the characteristics of the HUC-12 where the reservoir is situated. Reservoirs are located in drainage valleys where a high percentage of the surrounding area is steep enough to contribute adequate runoff for water use in the reservoir. The uplands in the general HUC-12 include flat plateaus where a higher percentage of the land is farmed. The runoff characteristics of that area is different than for the catchment area of the reservoir that usually contains more pasture land than in the surrounding HUC-12. To develop characteristics of the reservoir catchments we used data from the NHD Plus database (http://www.horizon-systems.com/nhdplus/). The database is similar to the general NHD database but is at a much finer resolution. We followed the procedure for the database development previously described and applied those techniques to the refined coverage for the NHD Plus database. An example in Figure 87 illustrates the procedure for a catchment. The figure shows that the catchment areas are close to the drainage way associated with the reservoir. The figure also shows that reservoirs in series over a short distance on one stream occur frequently.

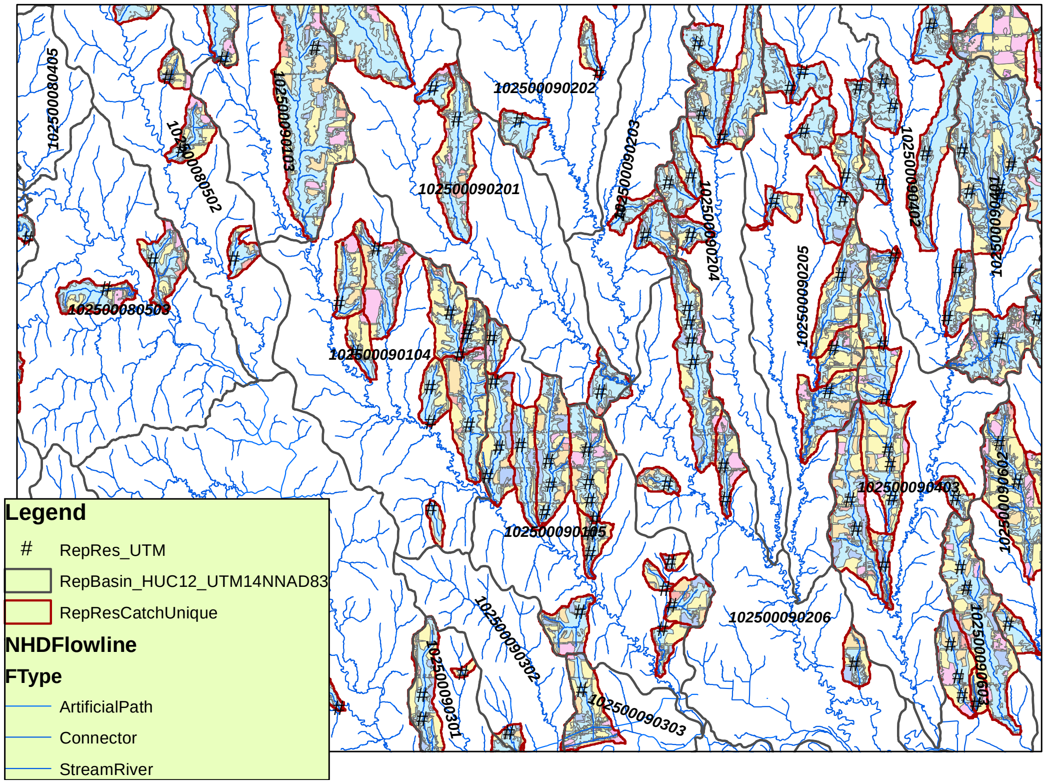


Figure 87. Example of Catchment Areas for Non-Federal Reservoirs using the NHD Plus Dataset.

We did not simulate the performance of individual reservoirs; instead, we simulated representative reservoirs for HUC-12 units that contained reservoirs catchments. This required additional analysis of the characteristics for the catchment areas. We used the Thiessen polygon method to associate reservoirs to weather stations. We then computed the characteristics for reservoirs associated with a weather station. We used an Excel Pivot Table to aggregate characteristics for catchment areas for small Non-Federal Reservoirs. We simulated 24 large reservoirs separately from the smaller reservoirs, which required datasets for the catchment areas for the large reservoirs. Datasets for the larger reservoirs were similar to that for terraced land within a HUC-12.

Combined Datasets

Combining data from the various datasets with GIS allowed us to determine input values needed for simulation with the POTYLDR model. An example of a dataset of soil types, HUC boundaries, county areas, terraced land and irrigated land in Red Willow County Nebraska in Figure 88 illustrates the GIS combined data overlay. These combined data overlays provided a series of files for input for the model and datasets for post processing simulation results.

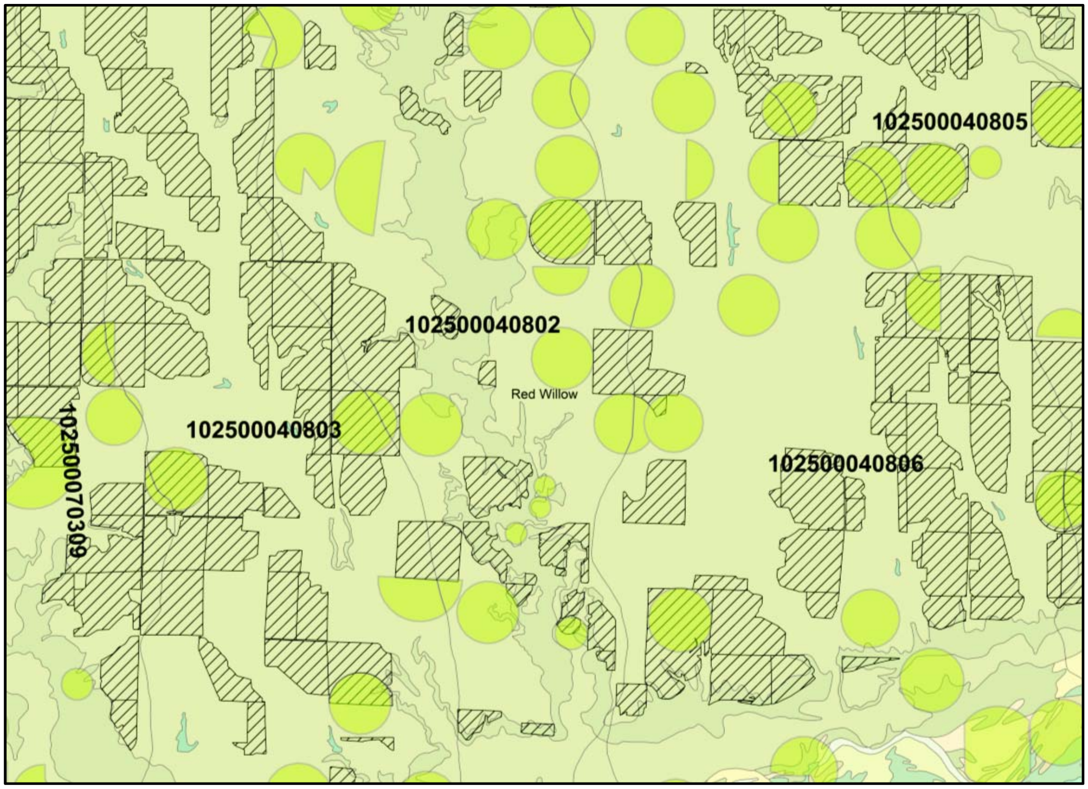


Figure 88. Example Overlay of Soil, HUC-12, Terrace and Irrigation Coverages used to Build Input Datasets.

Water Balance Modeling for the Project

We studied components of the water balance of selected subbasins to build an understanding of the performance of terraces and reservoirs. This section and those that follow describe various parts that we examined. Results in Table 27 summarize the water balance components for a portion of the Prairie Dog Creek Basin.

Table 27. Selected Water Balance Model Output for a Portion of Prairie Dog Creek Subbasin, Values are acre-feet/square mile of Land.

					With No Terraces								
			inches/yr		Continuous Dryland Corn			Continuous Dryland Wheat			Wheat-Corn-Fallow		
Weather Station	STSTN ID	Soil	Precip	Ref ETo	ET	Runoff	Deep Perc	ET	Runoff	Deep Perc	ET	Runoff	Deep Perc
Dresden, KS	142213	5	21.65	50.15	1096.43	59.46	1.84	1095.94	46.81	12.67	1058.63	58.88	37.58
	142213	7	21.65	50.15	1095.40	56.72	4.13	1087.83	44.28	22.16	1031.48	56.74	65.84
	142213	11	21.65	50.15	1076.99	44.90	32.23	1058.64	34.05	60.50	957.72	41.87	153.89
Norton, KS	145856	5	22.36	48.90	1126.77	62.85	4.32	1119.99	55.09	15.99	1069.86	64.82	57.03
	145856	7	22.36	48.90	1122.51	59.34	10.72	1109.36	52.54	29.01	1039.05	62.33	89.44
	145856	11	22.36	48.90	1091.68	46.14	53.36	1071.69	40.47	79.14	963.09	45.61	182.53
Oberlin 1E, KS	145906	5	21.25	50.66	1079.90	57.61	0.28	1082.38	45.67	7.30	1044.88	57.29	32.94
	145906	7	21.25	50.66	1078.75	54.89	2.72	1075.73	43.42	15.26	1019.24	55.28	59.58
	145906	11	21.25	50.66	1057.39	40.81	36.12	1046.35	32.72	54.33	949.71	39.36	144.05

Land Terracing

We examined terrace characteristics including the storage capacity for storage terraces in the basin, and the infiltration rate in terrace channels and contributing areas. The surface area for infiltration and evaporation varies with the depth of water in a terrace channel. The soil below inundated areas of a terrace channel is wetter than near the upper edge of the terrace. The upper levels of the channel are frequently empty. These and other factors require separate water balances for portions of the terrace channels. We represented terrace channels as a series of level areas to simulate the amount of ET and deep percolation that occurs in the terrace storage area (Figure 89). Summation of results from all levels provided estimates of the water balance for the whole terrace.

Daily output from POTYLDR for the HRUs without terraces, along with other input data, provided input for two other simulation programs to estimate the amount of runoff from land uses above terraces and groundwater recharge from the land terraces. Previous applications of the POTYLDR model to simulate the operation of various types of terraces utilized the Runoff Curve Number method for terraced and non-terraced land. This was appropriate for estimating the effects on surface runoff, but not for estimating the amount of groundwater recharge from storage terraces. Therefore, we developed a program, TERRACEPOND, to simulate the operation of the terrace channel using the multilayer representation illustrated in Figure 89.

TERRACEPOND simulates the storage area of a terrace as a series of level surface areas or steps that would or would not be inundated depending upon the volume of water in the storage area. The procedure to estimate the outflow from the area above the terrace ridge was the same as overflow for a small reservoir. The program accounts for inflow of runoff from the drainage area above the terrace, infiltration in inundated areas, and evaporation from and precipitation onto the free-water surface when water is stored in the terrace storage area. Terrace channel characteristics define the amount of water stored at various depths in the terrace channel. The Sensitivity Analysis section of this report provides additional discussion and details of the operation of this program.

The TERRACEPOND program produced output for each level in the channel and the output served as the input to the second program (TERRACECHANNEL). TERRACECHANNEL simulates the water budget for each level in the terrace channel on a daily basis. It provides an estimate of the water budget for each of the levels to estimate the amount of evapotranspiration and groundwater recharge. Accumulating results for all levels determines the total amount of each value for the terrace channel. Finally, this program provides the change in the amounts of evaporation, groundwater recharge, and runoff at the edge of the field above the terraced portion. The output units are the average annual amounts in acre-feet per square mile of area. Differences in runoff and groundwater recharge provide the basis to scale-up water balance results for each HUC-12 for non-terraced land and terraced land.

The field survey and subsequent analyses of the data provided storage capacity information for closed-end terraces. Results of the survey allowed development of a stage-area relationship between the depth of stored water in the terrace and the width of the water surface. This information along with the volume of water at various depths of storage provided a basis to create an equivalent stage-storage relationship for a series of levels. Results in Figures 90 and 91 show the comparison of the field measured and modeled terrace storage channels for the two terrace types. Data show the amount of storage in the two types of terrace channels at various depths (Table 28).

The overflow level for broad-base terraces with closed ends occurs at Level 8 or 13.2 inches of depth in the channel. This depth represents 0.48 inches of runoff storage over the terrace interval that was determined from the field survey data. It was slightly less than the 0.57 inches (14.3 mm) used earlier, but the general conclusions are little different. If the terrace completely filled, then the combination of infiltration and evaporation required about 10-14 days to completely empty the stored water provided no additional water from rainfall or runoff entered the channel. The rate of seepage into the various levels was 0.5 inches per day for Levels 1 and 2, and 1.0 inches per day for all other levels. These rates were low, but experience and observations of these terraces showed that ponded water remains for several days following a runoff event. Sensitivity analyses in a later section will show how changing the seepage rate affects overall results.

The overflow level for flat channel terraces with closed ends occurs at Level 10 for 11.3 inches of depth in the channel. This represents 0.99 inches of runoff storage over the terrace interval (see Table 28). Again, this value is slightly lower than the 1.25 inches (31.8 mm) used earlier in this report. If the terrace filled completely, about 10-14 days of infiltration and evaporation would deplete the stored water as long as rainfall or runoff did not enter the channel. The seepage rates varied for specific levels as for broad-base type.

For level terraces with open ends or breaches, the overflow level in Figures 91 and 92 is six for both types of terraces. For broad-base terraces, the storage depth is 0.20 inches of water over the terrace interval and the time required for the retained water to infiltrate and evaporate is about 7 days. Most of these types of terraces have low areas that retain water that will not drain by gravity, so the opportunity time for infiltration is substantial. For flat-channel terraces, the storage depth is 0.25 inches of water over the terrace interval and the time for the retained water to infiltrate and evaporate is about 7 days.

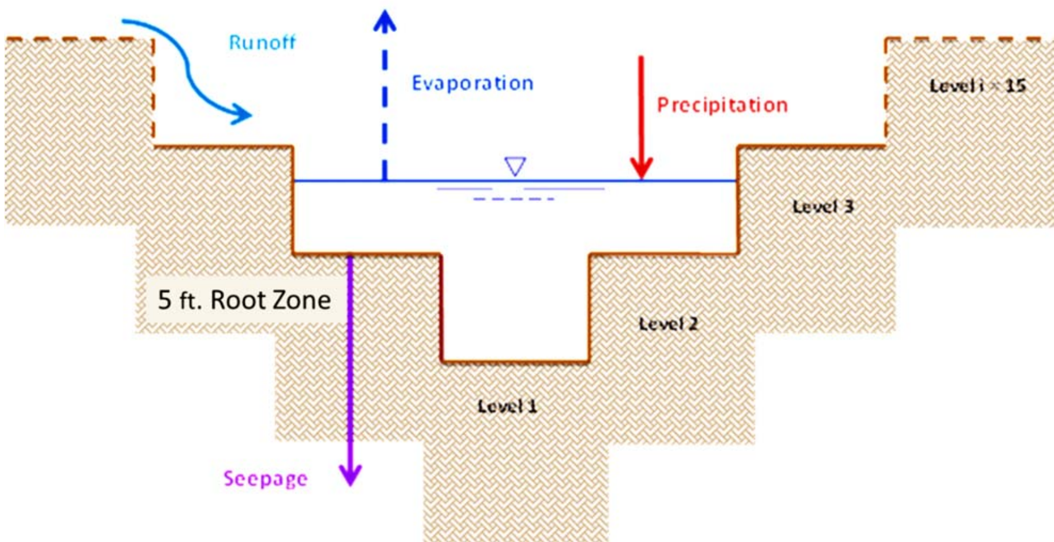


Figure 89. Terrace Channel Representation by Level Sections when Runoff Occurs and Stored Runoff is Present.

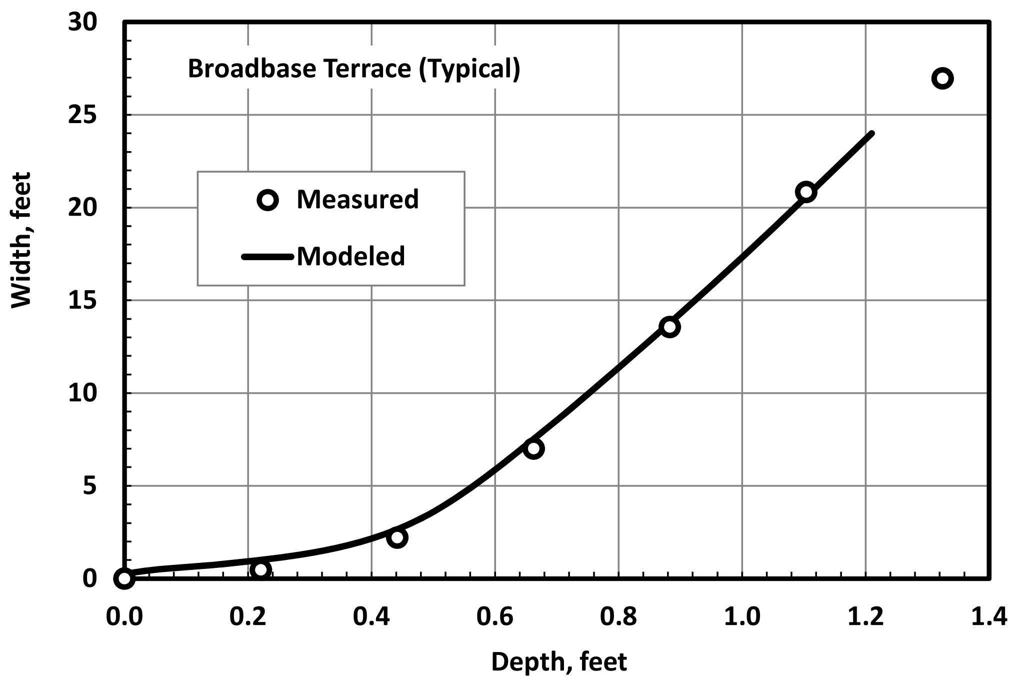


Figure 90. Depth-Width Relationship Measured for a Typical Broad-Base Terrace.

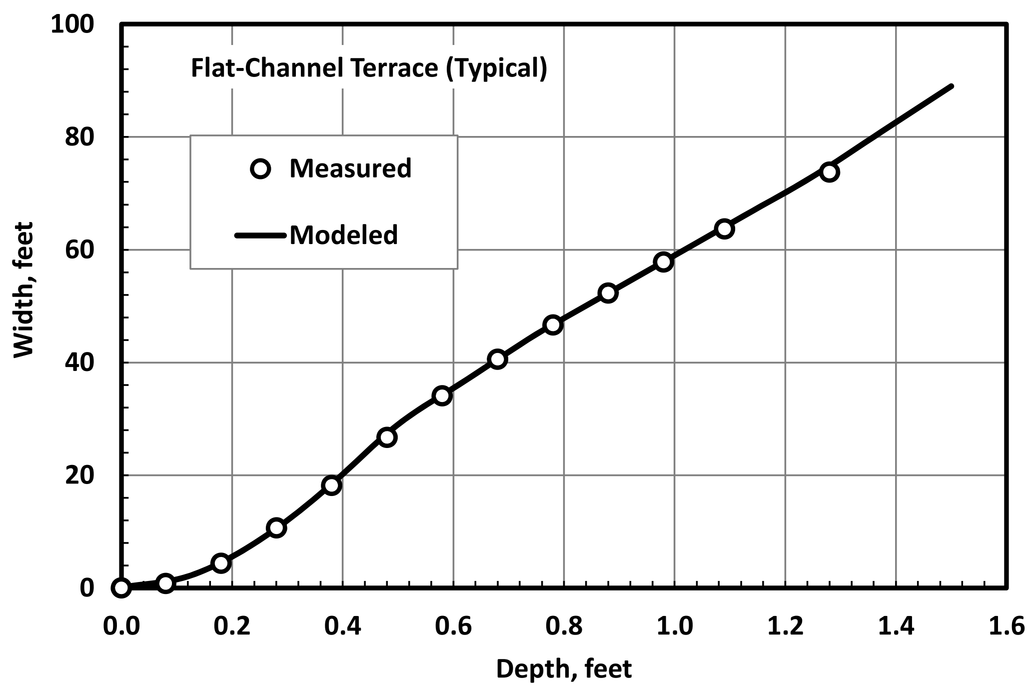


Figure 91. Depth-Width Relationship for a Typical Flat Cannel Terrace.

Table 28. Accumulated Storage Capacity at Level No., Closed-End Terraces Over the Terrace Interval.

Level No.	Broad-base, inches	Flat Channel, inches
1	0.00	0.00
2	0.0018	0.0005
3	0.014	0.017
4	0.050	0.058
5	0.11	0.13
6	0.20	0.25
7	0.32	0.39
8	0.48	0.57
9	0.74	0.76
10	1.29	0.99
11	1.98	1.33
12	2.80	1.77
13		2.53
14		4.25

Note: The Average Intervals for Broad-Base and Flat-Channel Terraces are 165 and 293 feet, Respectively.

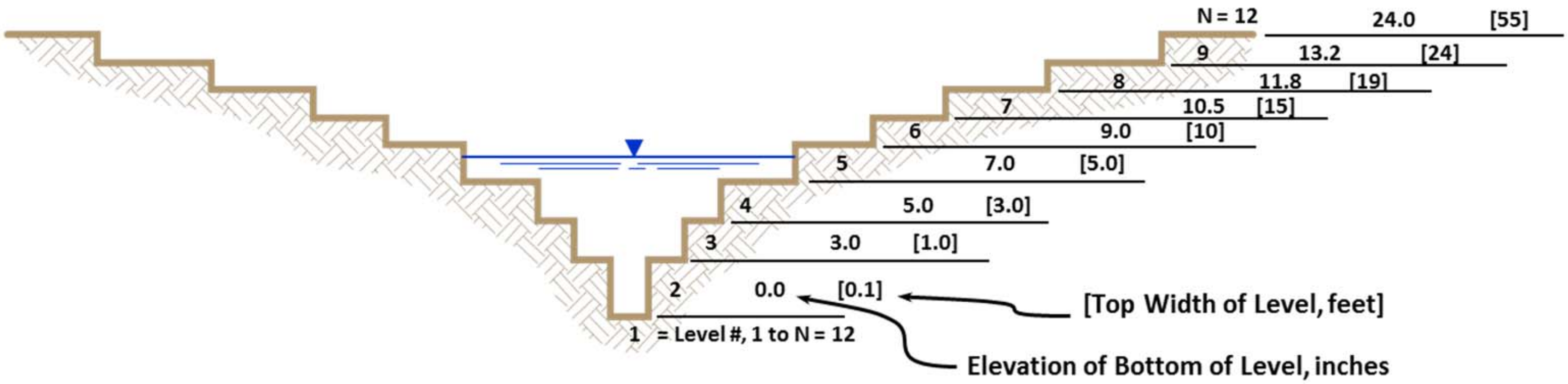


Figure 92. Representative Cross-Section of a Broad-Base Terrace from Survey as Modeled with the Subprogram, TERRACEPOND. (Drawing is not to scale).

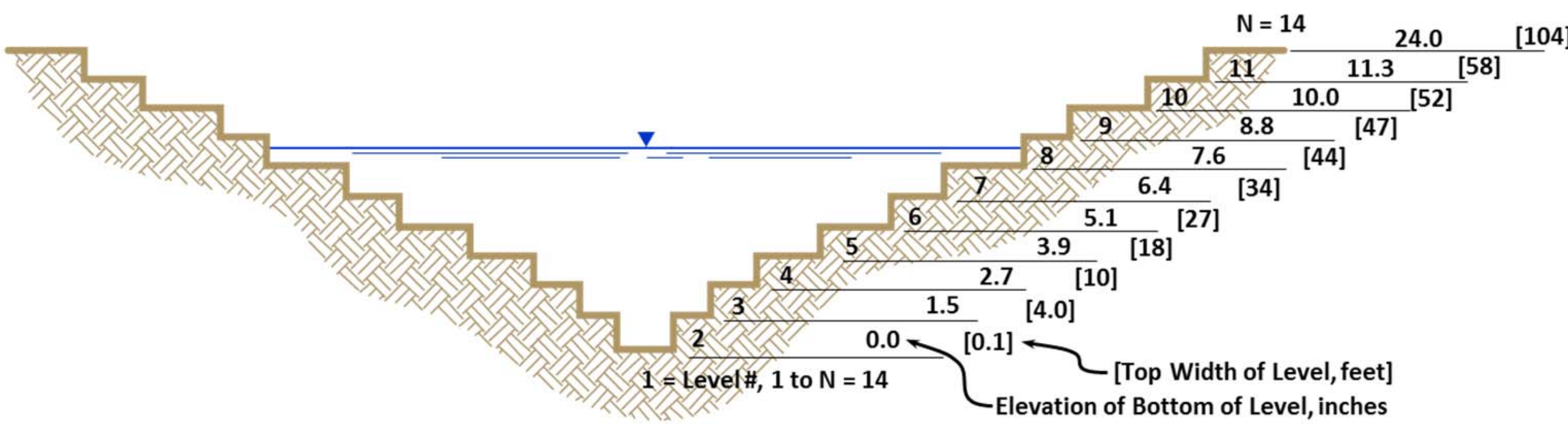


Figure 93. Representative Cross-Section of a Flat-Channel Terrace from the Field Survey as Modeled with the Subprogram, TERRACEPOND. (Drawing is not to scale).

We specified the fourth level in the terrace as the depth where overflow began for graded broad-base terraces. This resulted in a retained water volume equivalent to 0.05 inches over the terrace interval. We selected the fourth level based on the effect of water depth on the reduction of runoff predicted using the NRCS runoff method. The 0.05 inches of retained runoff agreed well with the difference in runoff that occurred for curve numbers traditionally used for unterraced land and terraced land. This procedure allowed us to estimate evapotranspiration and recharge based on the amount of retained water. Some water usually remains in graded terraces for several days because low spots do not drain. It turns out that about half of the retained water goes to ET and half becomes recharge for graded broad-base terraces.

Simulation results presented in Table 29 illustrate typical water balances for the median storage capacity of the two types of terraces at two locations and three land uses. Wheat-corn-fallow rotations are common practices for dryland cropping in the region. Range-pasture is indicative of terraced land that is now in permanent cover such as the conservation reserve program while irrigated corn represents terraced lands that are now under center-pivot irrigation. The evapotranspiration increase is the additional ET for crops plus water that evaporates directly from the terrace channel following runoff events. Runoff at the edge of the field decreased about 90% due to terracing for flat-channel terraces and over 80% for broad-base terraces. In general, about 40% of the retained runoff for the wheat-corn-fallow rotation becomes evapotranspiration and 60% percolates below the bottom of the root zone of crops in the terrace channel for these locations. The fraction of the water retained in the terrace that becomes deep percolation is much smaller for pastureland (about 30%) than for dryland cropping. Therefore, the fraction of retained water used for ET is much higher for pastureland. In drier regions, a greater portion of the retained water becomes evapotranspiration, while a greater portion becomes deep percolation in wetter regions of the Basin. Irrigation of terraced land results in the largest reduction of runoff, most of which goes to deep percolation.

Table 29. Average simulation results at the edge of the field for level terraces with closed ends and median runoff storage capacity at two locations in the Basin for three land uses for a 59-year period.

Location	Annual Precipitation, inches	Acre-Feet per Square Mile of Land Above a Terrace Ridge				
		Non-Terraced Field		Terraced Field Effects		
		Runoff	Percolation	Runoff Reduction	Percolation Increase	ET Increase
Culbertson, NE (flat-channel terrace)	20.94					
Wheat-Corn-Fallow		42.7	3.2	40.5 (95%)	24.0	16.5
Range-Pasture		22.9	0.0	22.4 (98%)	6.4	16.0
Irrigated Corn (net 15.66 inches/yr.)		81.6	14.9	76.3 (94%)	60.3	16.0
Benkelman, NE (broad-base terrace)	18.57					
Wheat-Corn-Fallow		35.2	3.2	29.3 (83%)	18.1	10.7
Range-Pasture		18.7	0.0	16.0 (86%)	4.3	11.7
Irrigated Corn (net 17.44 inches/yr.)		83.2	10.1	59.2 (71%)	49.1	10.1

The runoff reduction listed in Table 29 is at the edge of the terraced field and not at the mouth of a designated drainage subbasin. As with reservoirs, a stream transmission loss needs to be applied to the runoff reduction to estimate the impact of the terraces on the water supply for each of the designated drainage basins and for the full Republican River Basin above Hardy, Nebraska.

Storage terraces have the greatest effect on reducing runoff during periods when runoff from the field is average or less because the sizes of the runoff events are small. They also have the greatest quantity effect in years when runoff is above average. Figure 94 shows a comparison of simulated effects of a broad-base terrace with closed ends and a median storage capacity of 0.57 inches at Oberlin, KS, over a 59-year simulation period. The average runoff for the wheat-corn-fallow rotation on the unterraced field is 53.3 acre-feet per square mile compared to 10.7 acre-feet per square mile for the terraced field above the lowest terrace ridge; an 80% reduction in runoff at the field edge. On average, runoff occurred about nine out of 10 years for the unterraced field while the terraced field produced runoff less than four out of 10 years at Oberlin.

Conservation terraces increase the amount of water that infiltrates into the terrace channel. As shown in Table 29, retained water increases evapotranspiration for crops grown in the channel. Deep percolation occurs when the water content in the crop root zone exceeds the holding capacity of the soil in the terrace channel. Simulation of the impact of a broad-base terrace with closed ends and a median storage capacity of 0.57 inches at Oberlin, KS over a 59-year simulation period showed that deep percolation was less than 50 acre-feet/square mile per year 80% of the time (Figure 95). Percolation occurs much less often than runoff in the basin. These results for Oberlin 1E, KS show that percolation under an unterraced field occurs only on average once every eight years. Further, more than 90% of the total percolation occurred in four years, less than ten percent of the simulation period. Percolation from the unterraced field usually occurs as the result of an extended period of wet conditions rather than from a single large precipitation event. However, runoff flows into the terrace channel nearly every year, which increases infiltration in the terrace channel and enhances deep percolation for the terraced field. Percolation occurs from the terraced field in about seven out of eight years, which is almost as frequent as years with runoff. The average annual percolation from the unterraced field is 11.9 acre-feet per square mile while 42.7 acre-feet per square mile percolates from the terraced field. This represents a four-fold increase in deep percolation from the terraced field. The goal for conservation terraces is usually to reduce erosion and enhance crop yields, yet deep percolation or groundwater recharge is an addition benefit, an unintended consequence.

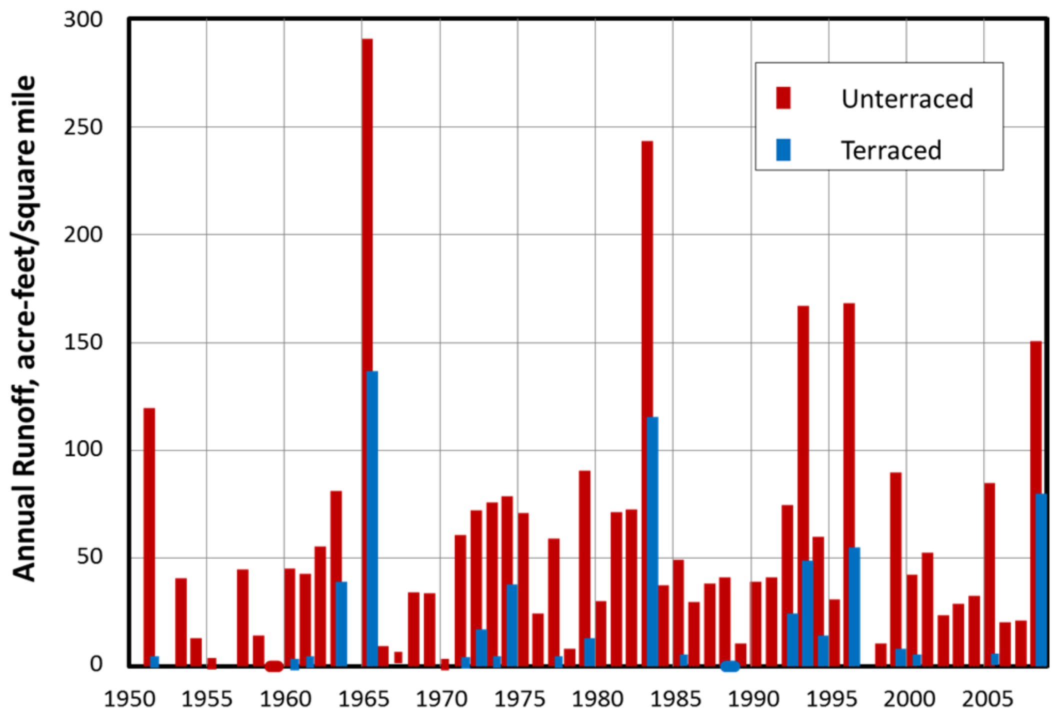


Figure 94. Simulated Runoff from a Wheat-Corn-Fallow Rotation on an Unterraced Field Compared to the Same Field with a Broad-Base, Level, Closed-End Terrace System with Median Storage Capacity of 0.57 inches of Runoff at Oberlin, KS.

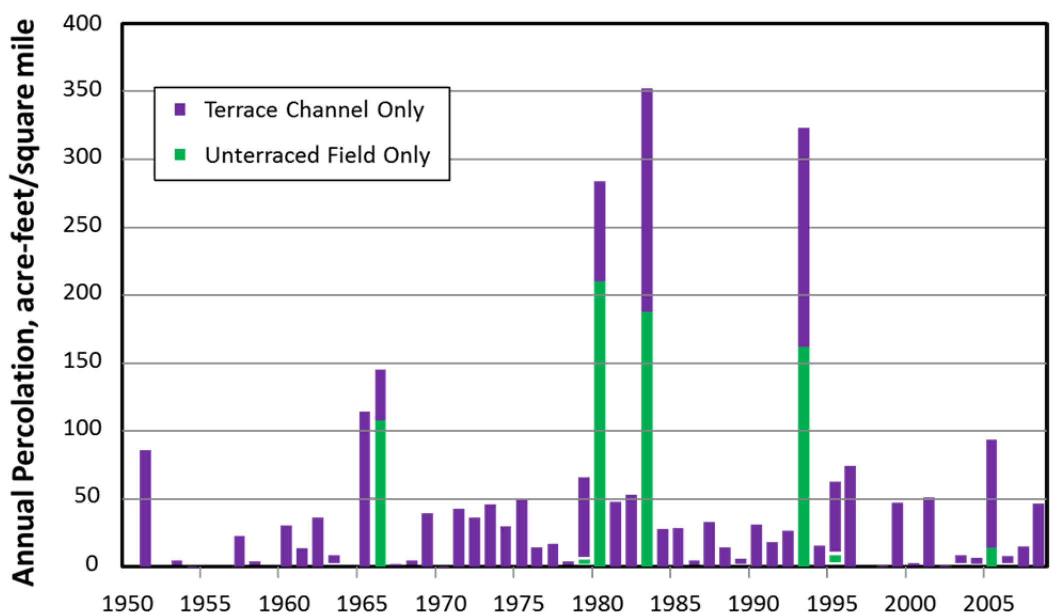


Figure 95. Simulated Percolation from a Wheat-Corn-Fallow Rotation on an Unterraced Field Compared to the Same Field with a Broad-Base, Level, Closed-End Terrace System with Median Storage Capacity of 0.57 inches at Oberlin, KS.

Reservoirs without Land Terracing

The States' inventory of Non-Federal Reservoirs does not contain all of the data required to assess the impacts on streamflow. Information on drainage area, volume, and depth is not available for some reservoirs in the inventory. We used information from reservoirs in the inventory that did have a complete set of descriptive information to develop characteristics of a typical reservoir for each State. The characteristics of the typical reservoir vary across the Basin; therefore, we defined a typical reservoir for weather station locations across the Basin. Table 30 lists the typical reservoir characteristics for reservoirs in Nebraska. The characteristics for a typical reservoir also apply for reservoirs in Colorado and Kansas. The storage capacity of a typical reservoir decreases as one moves east to west across the Republican River Basin. The characteristics of a typical reservoir were a part of the simulation of the water balance at each weather station. We expressed the impacts of the reservoirs in acre-feet per square mile of drainage, which allowed us to apply simulation results directly to the drainage areas for reservoirs in each HUC-12 subbasin.

Table 30. Selected Characteristics of the Typical Reservoir in Nebraska by Location in the Basin.

Range, degrees west	Depth at Principal Spillway, feet	Surface Area, acres	Storage at Principal Spillway Height, acre-feet	Drainage Area, acres
15	12.8	17.5	98	1,550
20	13.0	16.2	90	1,550
25	13.3	15.0	83	1,500
30	13.5	13.9	76	1,500
35	13.8	13.6	68	1,450

Simulation results summarized in Table 31 are for a 59-year period for typical reservoirs at nine locations across the basin. The locations in Table 31 are in order from east to west. Model results indicate that more water flows into reservoirs in the eastern portion of the basin than in the western portion of the basin (reservoirs near Burlington receive about 17% of the inflow near Holdrege). Reservoirs in the eastern portion of the basin overflowed about 50 percent of the years; reservoirs in the center of the basin overflowed about 20 percent of the years, and reservoirs in the west overflowed only about 5 percent of the time or less.

Runoff reduction at a reservoir is retained water that would normally flow downstream. Not all of the runoff reduction would reach the mouth of the subbasin due to transmission losses downstream of the reservoir. Reservoirs in the eastern portion of the basin reduce the annual runoff more than reservoirs in the west (Table 31). For example, runoff for typical reservoirs near Holdrege and Red Cloud decrease runoff by more than 50 acre-feet per square mile of drainage area, which represents about two-thirds of the inflow to the reservoir. Note: 1.00 inches of runoff = 53.3 acre-feet for 1.0 square mile. Reservoirs in the western portion of the Basin capture nearly all of the runoff that enters the reservoir. Because runoff is generally much less in the western portion of the basin, the volume of the runoff reduction is much smaller than in the east.

The runoff reduction listed in Table 31 is at the location of the dam site and not at the mouth of each reservoirs respective designated drainage basin. A stream transmission loss must to be applied to the runoff reduction to estimate the impact of the small Non-Federal Reservoirs on the surface water supply for each of the designated drainage subbasins and for the full Republican River Basin above Hardy, Nebraska.

Table 31. Simulation of Typical Reservoir at Nine Weather Station Locations Across the Basin for a 59-year Period.

		Average Annual Values, acre-feet per square mile of Drainage Area.						
City	State	Inflow	Precipitation onto Water Surface	Evaporation From Water Surface	Gross Seepage	Overflow	Runoff Reduction at Dam Site	Years with Overflow
Holdrege	NE	81.3	5.1	9.3	49.7	27.2	54.1	29
Red Cloud	NE	74.2	4.7	9.2	46.3	23.3	51.0	25
Norton	KS	45.6	3.0	6.9	30.8	10.6	34.9	15
Curtis	NE	43.6	2.7	6.5	28.8	10.9	32.6	13
Imperial	NE	30.4	1.9	4.7	20.7	6.8	23.6	11
Culbertson	NE	30.7	2.2	5.5	23.7	3.6	27.0	11
Colby	KS	33.6	2.1	5.2	22.5	8.0	25.6	11
Yuma	CO	12.3	0.8	2.7	9.6	0.9	11.5	3
Burlington	CO	13.9	1.0	3.0	11.6	0.3	13.6	2

The simulated end-of-month storage shown in Figure 96 illustrates the operation of a typical reservoir near Harlan County Lake, Nebraska. The average end-of-month storage was about 10 percent of full storage content for the 2000-2009 simulation period. This compares to 12.5 percent of full storage content for the entire 59-year simulation period for this typical reservoir. These results are consistent with monitored water levels in reservoirs from the field-monitoring phases of the study.

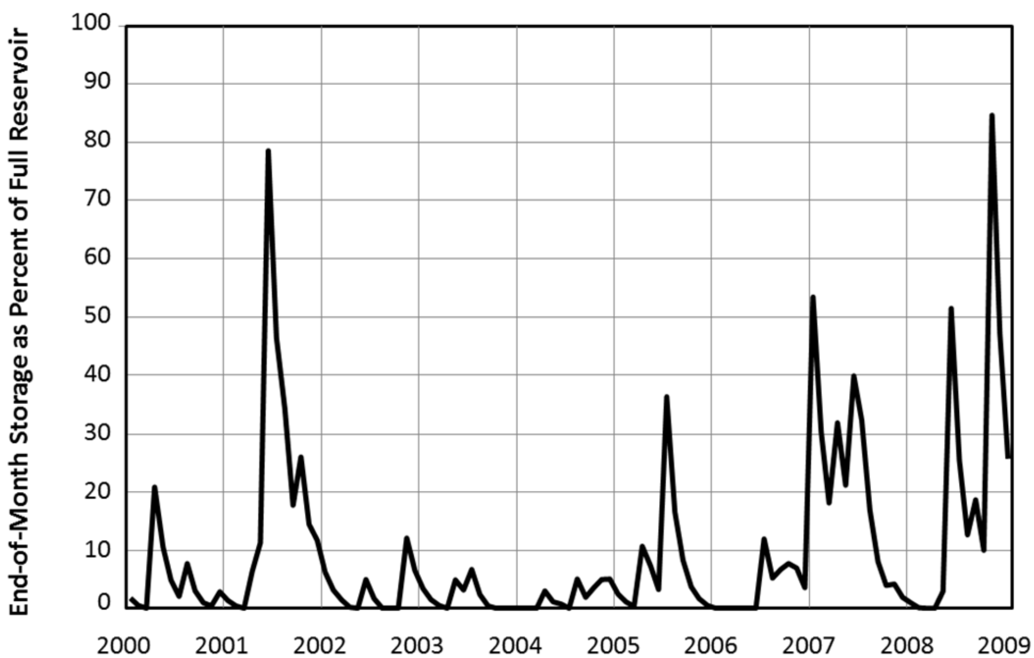


Figure 96. Simulated End-of-Month for a Typical Reservoir near Harlan County Reservoir.

Reservoirs with Land Terracing

Terraces reduce the amount of runoff from areas upstream of reservoirs. Assessing this impact required an additional a step to develop input data for modeling Non-Federal Reservoirs that contain terraces within their contributing drainage area. It was necessary to modify inputs to POTYLDR to account for the effects of the terraced areas on surface runoff into the reservoirs and to conduct a second series of simulations for each of the 32 weather stations and 3 soil types.

We assumed that terraced areas in the reservoir drainage areas had the same effect on groundwater recharge as terraces not above reservoirs. We developed an adjustment factor to account for the reduction in runoff to reservoirs because the terraces. The factor adjusted the runoff curve number for the terraced area. Application of the adjustment factor produced a similar amount of reduction in the long-term average runoff for the terraced areas for the five terrace types. Results of the simulations for the effects of terraces provided reliable information to develop the reduction factors. Average results for four meteorological stations in the most heavily terraced areas in the central part of the Basin gave similar results for each type of terrace. The stations were Colby and Dresden in Kansas and McCook and Cambridge in Nebraska. A similar set of results occurred for graded terraces using four stations in the eastern portion of the Basin. The stations were Superior, Red Cloud, Harlan County Lake, and Holdrege, all in Nebraska. Values in the right-most column of Table 32 show that storage terraces have a smaller adjustment factors than graded terraces. The average value of the runoff curve number for unterraced cropland is about 72. The corresponding value for land with broad-base closed-end terraces is 54, while it is 69 for land with graded terraces.

Table 32. Reduction Factors to Simulate Runoff for Nalysis of Small Reservoirs.

Terrace Type	Storage Capacity, inches	Runoff Reduction, percent			Curve Number Adjustment Factor
		High	Low	Average	
Flat-channel, closed	0.99	90	88	89	0.73
Broad-base, closed	0.48	77	75	76	0.75
Flat-channel, open	0.25	61	58	59	0.88
Broad-base, open	0.20	54	52	53	0.90
Graded	0.05	25	21	23	0.96

As noted previously, some terraces in the basin are located within the drainage area of a reservoir, which reduces inflow into the reservoir. For example, estimated annual inflow to a typical reservoir at Oberlin 1E is 40.6 acre-feet per square mile without terraces, but is it only about 34.8 acre-feet per square mile with terraces in the upstream drainage area of the reservoir (Table 33).

The reduced inflow from upstream terraces translates to an additional reduction in runoff of about 3.9 acre-feet per square mile. This reduction is in additional to the reduction caused by the reservoirs alone. Again, these results are at the dam site without adjustment for stream transmission losses downstream of the reservoir.

The simulated end-of-month storage in Figure 97 illustrates the impact of upstream terraces on runoff for a typical reservoir near Goodland, Kansas. Differences in end-of-month reservoir storage when land is terraced and not terraced are small for this location. Only about eight of the 59 years exhibited a discernible difference. Differences that do occur in the end-of-month reservoir storage do not persist over long periods.

Table 33. Simulation of Typical Reservoirs at Three Locations Across the Republican River Basin When Terraces Are in and Not in the Contributing Area of the Reservoir for a 59-Year Period.

Land Use	Average Annual Values, Acre-Feet per Square Mile of Drainage Area						Years with Overflow
	Inflow	Precipitation on Water Surface	Evaporation from Water Surface	Gross Seepage	Overflow	Runoff Reduction at Dam Site	
Harlan County, Nebraska							
Without Terraces	52.5	4	7.8	35.4	13.1	39.4	21
31% of Cropland Terraced	49.6	3.9	7.5	33.9	11.9	37.7	18
Oberlin, Kansas							
Without Terraces	40.6	2.5	6.3	27.2	9.6	31	13
45% of Cropland Terraced	34.8	2.2	5.6	23.7	7.7	27.1	12
Goodland, Kansas							
Without Terraces	21	1.4	3.6	15.1	3.6	17.4	7
23% of Cropland Terraced	18.5	1.3	3.3	13.5	2.9	15.6	7

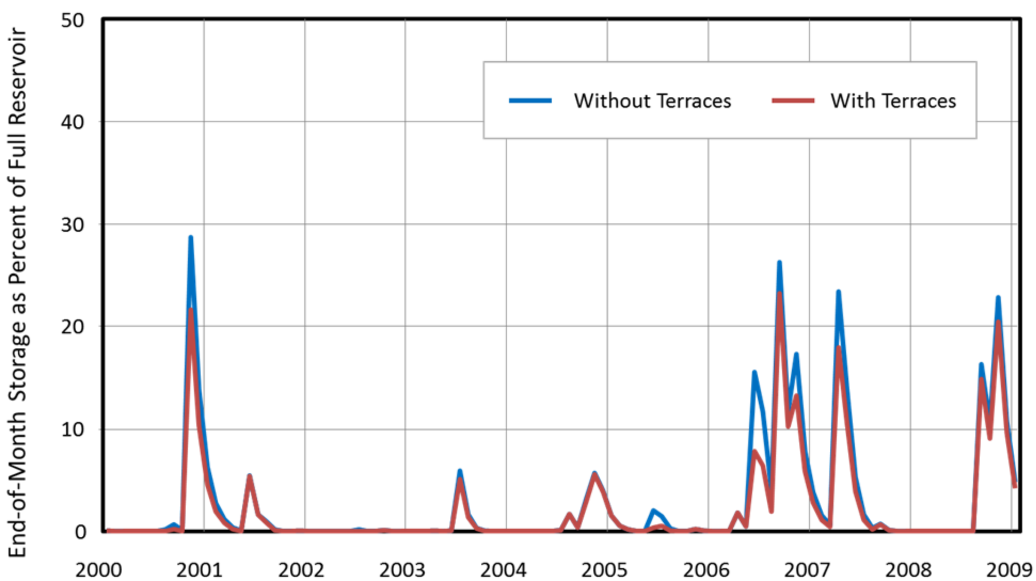


Figure 97. Simulated End-of-Month Storage as a Percent Full Reservoir Storage for a Typical Reservoir with and Without Terraces in the Upstream Drainage Basin near Goodland, KS.

The Overall Water-Budget Modeling Process

The process to simulate the water-budget to estimate the impact of reservoirs and terraces for the different combinations of conservation measures requires three steps: (1) preprocessor, (2) simulation with the POTYLDR model, and (3) post-processing to combine results for the HUC-12s into the results for each subbasin.

Preprocessor

A GIS pre-processor framework provided a means to define geographical area (HUC-12) and to extract needed characteristics of each area from GIS coverages. The information extracted includes:

- The HUC-12 identifier
- Amount of terraced land
- Stream length to the outlet of the subbasin from the centroid of the HUC-12
- Total drainage area of reservoirs
- Percent of three soil types under terraced lands
- Percent of seven land uses in terraced areas
- Percent of five terrace types
- Weighted fraction and identification number for the three nearest meteorological stations
- Estimated transmission loss factor
- The subbasin in which the HUC-12 is located

We extracted the information and entered the data into an Excel spreadsheet with one row for each HUC-12. We copied the data from the spreadsheet into an ASCII file, HUCDAT, that had one row of information for each HUC-12. The file provided input to the POTYLDR model. This dataset was necessary input information for the various conditions simulated.

POTYLDR Simulation

The POTYLDR model and added subprograms as represented in Figure 98 illustrate the basic simulation process. POTYLDR produced the simulated water balances used to develop unit area responses for the water budgets for the 20 HRUs that were necessary to simulate the seven land uses and the operation of Non-Federal Reservoirs near each of the 32 meteorological stations. It required six different simulations at each location; one for each of the three soil types to simulate the effects of no terraces in the drainage area of the Non-Federal Reservoirs and another set of three with terraces in the drainage area of the Non-Federal Reservoir at each of the meteorological stations. Therefore, 192 (32X3X2) runs of the POTYLDR model were required to generate results for the entire basin. All results from the water-balancing modeling simulations are in units of acre-feet/square mile to more easily scale up results for each HUC-12 based on its' specific characteristic (Note: 53.33 acre-feet per square mile is equal to an equivalent depth of 1.0 inch).

The length of the daily record for 31 of the meteorological stations was 59 years, 1950-2008, except for Sedgwick, NE, which had the same information for 1952-2008 (57 years). The input information for each of the 20 HRUs and reservoir appear later. A subprogram, CNSLD, aggregated the output from POTYLDR into a file used in post-processing to organize the results for the entire basin.

Direct results from POTYLDR provided values for long-term average annual amounts of evapotranspiration, runoff, and groundwater recharge from each land use without terraces and long-term average annual amounts of inflow, overflow, net evaporation, and groundwater recharge for the Non-Federal Reservoir with no terraces in its drainage area.

POTYLDR uses daily outputs from the HRUs that were representative of the type and amount of area of the land use conditions in the watershed to compute the inflow to a typical reservoir. The characteristics of the reservoir were represented by a stage-storage-area-discharg**e** relationship, an estimated seepage loss rate under its daily water surface area that was a function of the depth of water in the reservoir, evaporation from the water surface area at the ETo rate, and precipitation onto the water surface. The previous work by Choodegowda (2009) provided a method to determine the seepage rate function. That work determined that about 90% of the seepage from the reservoir would become groundwater recharge and the other 10% was lost as evapotranspiration from the areas of the reservoir that periodically inundated. Additional discussion of reservoir modeling is in the Sensitivity Analyses section of this report.

A spreadsheet procedure provided a means to calculate the extent of each land use practice and terrace type near the meteorological stations. It also calculates the weighted runoff adjustment factor for the terraced land uses in the drainage area of the typical reservoir at each station. We manually entered these values into each of the input files for the POTYLDR model.

Simulations with the POTYLDR model for the scenario that included terraces in the drainage areas of the reservoirs produced the long-term average results for the water budget of the typical reservoir with terraces in its drainage area. Processing these results with the TERRACEPOND and TERRACECHANNEL programs is unnecessary.

After examining the results for reliability, we developed a batch file process to simulate the entire basin and to write the overall results from the water-budget simulations into a master file for post-processing. A simple FORTRAN program, CNSLD, then prepared input for post-processing. The CNSLD program handled each set of two simulations for a single soil type without and with terraces in the drainage area of the reservoir. It read the required output from each of the two simulations and wrote a single row of output to the file, PSR, for subsequent input to the post-processing program. The consolidated file, PSR, had contained 96 rows of information.

The flow chart in Figure 98 illustrates the procedure for simulating the water budget with the POTYLDR model and the ancillary programs.

Post Processing

A post-processing program, POST, combined results from the PSR and HUCDAT files to produce the results for each HUC-12 for the four required scenarios. This program produced the final output for review and production of results.

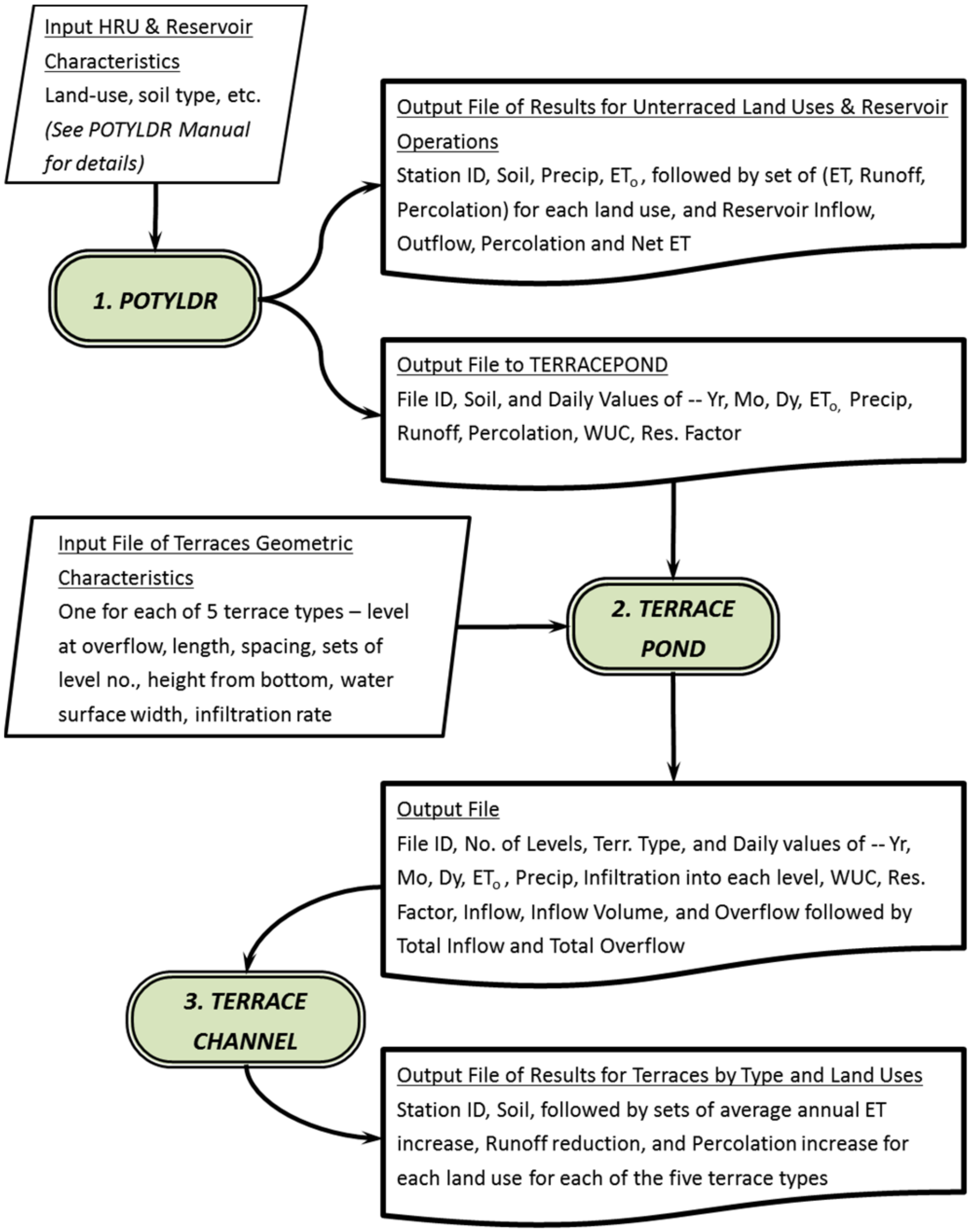


Figure 98. Flowchart of the water Budget Simulation Process for HRUs and Reservoirs.

Geographic Scope

The study area covered the entire basin above Hardy, NE; however, impacts only occur for subbasins that contain terraces or Non-Federal reservoirs. Terraces are most common on deep silt loam soils with slopes that produce enough runoff to collect in terrace channels resulting in less erosion or more crop production. Simulations included these types of lands for terraced and unterraced conditions, as well as the contributing drainage area for Non-Federal Reservoirs. Usually less than about twenty-five percent of the land in the drainage areas of reservoirs is terraced. It is important to realize that areas above reservoirs and terraced land are probably the most productive areas for runoff in the basin. Soils in these areas are less conducive to producing groundwater recharge because of their relatively fine texture. Therefore, an attempt to utilize these results across the entire Republican River Basin is inappropriate. The POTYLDR model with proper input values can simulate runoff and groundwater recharge for the entire Basin; however, substantially more effort would be necessary. Additionally, this analysis compares changes in the hydrologic response when practices are present and when one or more practices are absent. Comparing differences is less prone to error than predicting absolute outcomes.

We totaled model results for the various scenarios in the post-processing procedure for each geographic area defined by a 12-digit hydrologic unit, referred to as HUC-12(s). There are 557 HUC-12s in the study area. Input data for each HUC-12 included the:

- Total subbasin area
- Drainage area of reservoirs
- Area of terraced land
- Percent of three soil types
- Percent of seven land uses in the terraced areas
- Percent of five types of terraces
- Three nearest meteorological stations and the relative weight for each station
- The travel distance from the centroid to the outlet of the subbasin
- The estimated transmission loss factor from the HUC-12 to its subbasin outlet

Results provided an estimate of the additional ET and recharge from the reservoirs and terraces within the HUC-12, the reduction of surface runoff at the subbasin outlet, and the transmission losses from the HUC-12 to the subbasin outlet. The National Hydrologic Dataset shows that 92 of the 557 HUC-12s in the Basin do not have a waterway connection with streams (Figure 1). Impacts of land use changes in these HUC-12s would be through groundwater, *i.e.* baseflow, connections to streams outside of the respective HUC-12.

We used a transmission loss factor to transfer the effects of conservation practices at the edge of the field to the surface water outlet of each HUC-12. The transmission loss factor depends on the distance water must travel in the stream to reach the surface water outlet of the HUC-12 and on the transmission loss per unit of travel expressed as the percent loss per mile of travel. For this study, the travel distance equaled the length of the stream from the centroid to the outlet of the HUC-12. Computing the cumulative effects of HUC-12s in a designated drainage basin used the same transmission loss procedure as for an individual HUC-12. When the designated drainage basin contained a federal reservoir, we accumulated the effects for HUC-12s upstream of the reservoir and the effects of HUC-12s upstream of the outlet of the designated drainage.

The HUC-12s along the North Fork of the Republican River in Nebraska, and the portion of the main stem of the Republican River between the junction of the North Fork and the Arikaree to a point near

Hardy, NE where the river dissects a HUC-12, were split along the river to provide geographic areas on each side of the river. We determined the streamflow length for these geographic areas to estimate the transmission losses for those HUC-12s. The effects of these HUC-12s only transferred to the mainstem of the respective stream and not further downstream along the river. Transmission losses do occur along the mainstem; however, many other unknown factors affect the water balance of these reaches. Determining these factors exceeded the scope of this study.

An average transmission loss of 2 percent per mile applied to transfers of the impact at the land terrace or reservoir location to downstream outlets. We increased the loss to 2.5 percent per mile for the western half of the Basin and decreased the rate to1.5 percent per mile for locations below Harlan County Reservoir. Selection of the transmission loss factors derived from our professional judgment and empirical analysis presented in previous status reports to the RRCA.

POTYLDR Changes

Fieldwork conducted for the study provided information on the water balance for reservoirs and land terraces for conditions in the study area. While it was not possible to make a direct simulation of the field sites with the POTYLDR model, we did use information from the field studies to improve the modeling process. The following summary describes how field results helped amend aspects of the POTYLDR water budget model and subprograms developed to examine the effects of the performance of reservoirs and land terraces.

We examined and adjusted curve numbers to approximate the average annual runoff at the field sites for the ecofallow rotation. The 30-year average curve numbers used to simulate results from the fieldwork for Colby and Norton, Kansas were somewhat higher than used in POTYLD. The POTYLD model separately represents the water balance of the area contributing runoff to the terrace and the terrace channel itself. Separating the land results in less area to provide runoff than simulated in the fieldwork analysis; thus, the total runoff would be less for POTYLD than for fieldwork simulation when using the same curve numbers. Curve numbers used in the water balance models for the fieldwork were similar to those used in the POTYLDR studies that did not separate the field into contributing areas and terrace channels. We also produced monthly values for curve numbers rather than using a constant annual value. The daily curve number values varied based on the amount of available soil moisture in the upper soil zone.

The original version of POTYLDR used a procedure to estimate reference potential evapotranspiration at a location based upon a regression technique of geographical values and the daily minimum and maximum air temperature. Work by the University of Nebraska produced daily values of reference potential evapotranspiration at each study weather station for the period of record. These values represent a grass reference crop as needed for the POTYLDR model.

The factor used in POTYLDR to simulate the effects of residue on evaporation reduction directly from the soil surface was previously constant for the whole year. We changed from an annual value to a monthly value to account for varying amounts of residue on the soil surface throughout the year. Minor changes to the routines to predict water losses from interception better reflected the effects of residue on intercepting rainfall and on sublimation of snow in areas with higher levels of residue.

Previous research on water percolation from terraces showed that the soil below the crop root zone drains more than anticipated when using field capacity values developed for irrigation management. Results show that the water content remaining in the rooting zone after a prolonged period, such as a year, would be only about 70% of the amount expected for the traditional definitions of field capacity.

The POTYLDR model previously used a maximum water content equal to 90% of the reported field capacity for each soil type. We improved the simulation process for deep percolation for this study. We added a factor that allowed the drainage rate to be 0.25 inches per day when the available water content in the Lower Zone exceeded field capacity. The factor decreased to zero when the Lower Zone fell below 70% of its holding capacity. If the soil reached field capacity and no additional water infiltrated, it would require about a year for the Lower Zone to drain to 70% of available soil water content. This change increased the amount of percolation that occurred under the terrace channel, but only slightly affected the contributing slope because the available soil water content in the contributing area seldom exceeds the 70% threshold.

We developed output routines to provide results in forms that could be input directly into subprograms and post-processing routines to enhance interpretation of results. The user's manual prepared for this version of POTYLDR includes the subprograms and the overall simulation process for the Basin.

Modeling Point Locations for Field Results

We used the POTYLDR model to predict the performance of land terraces and typical reservoirs on a daily basis for 1950-2008, a 59-year period. The model simulated the water balance at each of the 32 meteorological stations across the basin for five types of terraces, typical reservoirs and the three major soil types in the basin. We used an inverse distance weighting method to convert results at weather stations to estimates impacts for each HUC-12. Estimates for the HUC-12 depended on the proximity of the centroid of the HUC-12 to nearest three nearest meteorological stations. The average annual precipitation varies across the Basin in an east-to-west fashion. Therefore, we weighted the stations that aligned north to south more favorably than stations that aligned east to west. For the nearest three stations, we used the inverse distance weighting method to provide influence from near stations than more distant stations.

We categorized the soils in the basin into three basic types:

- Deep silt loam with high water holding capacity of 2.25 inches/foot, moderate infiltration, and moderate drainage.
- Deep silt loam with good water holding capacity of 2.00 inches/foot, moderate infiltration, and moderate drainage.
- Deep loamy sand with water holding capacity of 1.25 inches/foot, moderate infiltration, and rapidly permeable subsoil.

We assumed that the maximum root zone depth was six feet for all soils. The simulations included seven land uses:

- Dryland corn - continuous cropping
- Dryland wheat – continuous cropping
- Wheat-corn-fallow rotation -- 3-year rotation
- Wheat-fallow rotation -- 2-year rotation
- Hay and forage – continuous cropping
- Range/Pasture – continuous cropping and
- Irrigated Corn – continuous cropping

Data in Table 27 exemplifies some of the model output for unterraced land in a subbasin of the Prairie Dog Creek. The result for this subbasin uses data from three weather stations in Kansas (Dresden, Norton, and Oberlin 1E) and all three soil types. The output shows the simulated water balance for continuous dryland corn, continuous dryland wheat, and a wheat-corn-fallow rotation. We simulated the other four land uses, but those results are not in this table. For the no terraces conditions, the value of runoff and percolation are of most interest. Runoff is the amount of water that would leave the field edge while percolation is the water that seeps through the root zone when water is not ponded in terrace channels. Most of the water from precipitation goes to ET. These results are of interest individually; however, the purpose of the study was to estimate the difference in performance with and without either land terracing or Non-Federal Reservoirs. The following sections describe the additional analysis required to obtain values for determining data to compute the differences.

Simulation of Impacts for the Basin above Hardy

Assessment of several models indicated that the POTential YieLD Revised model (POTYLDR) provided reliable simulation of the impact of reservoirs and terraced land on surface runoff, evapotranspiration, and deep percolation. The addition of two subprograms enhanced the ability to predict the daily operations of land terraces and reservoir impacts. Choodegowda (2009) focused on the water budget operations of Non-Federal Reservoirs. Information on the water budget led to improvement of POTYLDR to simulate the water budgets of the Non-Federal Reservoirs directly. Adaptation of those procedures to land terraces also provided means to partition water retained by conservation terraces.

Land terraces are located primarily on landscapes in the Basin that produce enough runoff to cause erosion or to recharge the soil profile beneath the terrace channel to enhance rain-fed crop production. Terraces occur extensively on silt loam soils with mild to moderate slopes. These lands produce acceptable yields with reasonable management. Farmers have converted some terraced fields from crop production to various federal conservation programs such as the Conservation Reserve Program. Development of center-pivot irrigation technology has allowed irrigation on some areas originally terraced for rain-fed crop production. Terrace construction expanded rapidly in the 1950s and 60s but has continued at a slower pace until now. Terraces currently protect about 2.15 million acres of land, which represents about 15% of the Basin. About 65% of terraced fields are located above the bottom terrace in the field.

The locations of the small Non-Federal Reservoirs that are included in this study are more diverse in nature. Reservoirs are mainly located in the Basin where sufficient runoff occurs to provide stored water for uses such as livestock watering or for some flood and erosion control. The dominant landscape in the contributing drainage area for the reservoirs consists of silt loam soil with sufficient slope to provide suitable locations for construction of the embankments. Most reservoirs were built as part of federal programs such as the Great Plains Act following the drought of the 1950s or as part of other programs that encouraged water storage and flood control. Landowners have not installed many new reservoirs in recent times. Modern farming practices enhance infiltration and retention of precipitation in the field; thus, runoff is less than for production practices at the time that reservoirs were constructed. The reduction in runoff from other farming practices and fewer incentives has discouraged installation of new reservoirs.

The Conservation Committee identified 709 Non-Federal Reservoirs in the study area. The size of the catchment areas for individual reservoirs ranges from less than one-half to several hundred square miles. Most, however, were nearer to two square miles. Representing all reservoirs individually was beyond the scope of this study. Instead, "typical" reservoirs located near appropriate meteorological stations were characterized for conditions in each HUC-12. This approach provided a total treated drainage area for these reservoirs of about 1.2 million acres. This is somewhat less than 10% of the total drainage area of the Basin and about 12.5% of the contributing drainage area for the Basin. We discovered that the predicted catchment area for several Non-Federal Reservoirs in the western portion of the basin were very large for the built storage capacity. In addition, these reservoirs stored much less water than would be expected for large drainage areas. Relative to their size, they had little impact on runoff or recharge. We estimated their storage capacity and used that to estimate how much "effective" drainage area they would have by comparing them to other "typical reservoirs". For instance, we represented the drainage area of the Flagler Reservoir in Colorado as five "typical reservoirs".

We did not simulate every square foot of the Republican River Basin above the Hardy Gage. We divided the watershed into land where runoff drains into Non-Federal Reservoirs and land where runoff does not drain into a Non-Federal Reservoir as shown Figure 99. We also divided the watershed into land protected by terraces and land that is not terraced. The digitization process to determine the amount of terraced land generally resulted in tracing fields and larger land tracts that included terraced land. In such cases, some of the field or land tract is located below the bottom terrace in the field. The land below the bottom terrace of the field does not contribute to runoff retention; however, that land can contribute runoff to the Non-Federal Reservoir if the field is located in the drainage area of a reservoir. We did not simulate areas that do not retain water behind terraces and that do not drain into a Non-Federal Reservoir (crosshatched areas in Figure 99). We used the POTYLDR model to simulate the land conditions represented by the green shaded regions in Figure 99.

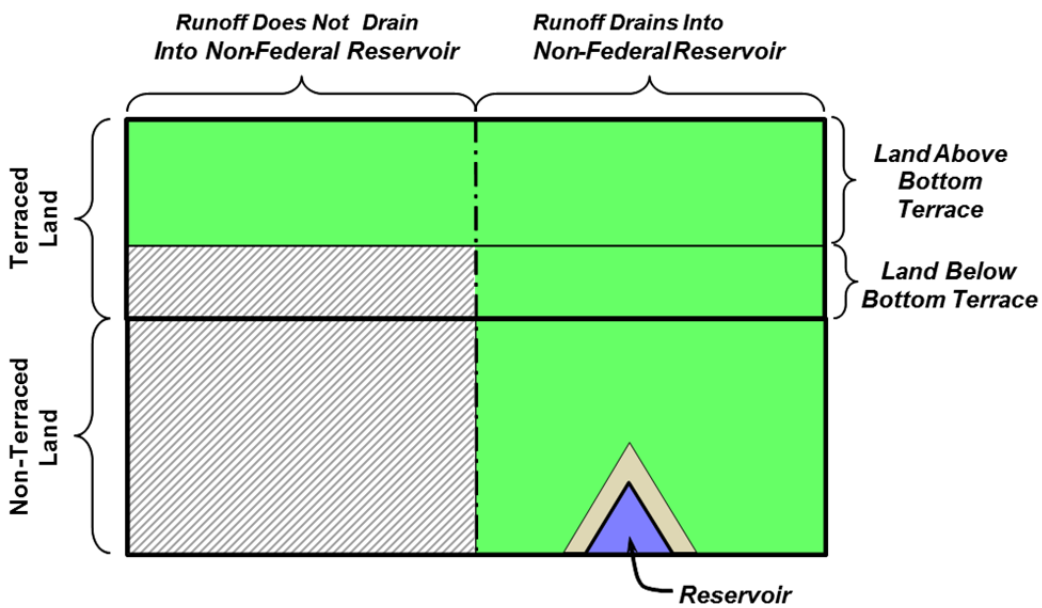


Figure 99. Idealized HUC-12 Showing Regions Represented in the Water-Budget Modeling Process.

Results for the Basin

This study required results for four scenarios to estimate the effects of terraces and small reservoirs on streamflow at each subbasin outlet and the change in groundwater recharge within the subbasin. The scenarios involved simulation when:

1. Neither land terraces nor Non-Federal Reservoirs are present.
2. Only Non-Federal Reservoirs are present.
3. Only land terraces are present.
4. Both Non-Federal Reservoirs and land terraces are present in the catchment area.

Results for scenarios one through three occur directly from simulation; however, scenario 4 required different treatment for terraced land that is in the catchment areas of reservoirs. Terraces in the catchment area reduce reservoir inflow, which in turn reduces reservoir overflow somewhat and reduces groundwater recharge from the reservoir. Thus, terraced land located above reservoirs has less effect on streamflow from the subbasin than terraced land not above reservoirs. This necessitated simulation of an additional condition, (5) reservoirs with terraces in their catchment areas. The location of terraces in the HUC-12 does not affect the amount of groundwater recharge from terraces alone. It does affect the amount of groundwater recharge from reservoirs. Thus, results for scenario (4) were estimated by reducing results from scenario 3 to account for runoff from terraced lands not above a reservoir, and adding that amount to the overflow from reservoirs with terraces in their catchment area. This accounted for the remainder of terraces in the catchment areas of reservoirs to obtain the total runoff within the HUC-12 subbasin. The total groundwater recharge was the sum of the amount from all terraced lands in (2) plus the amount from (4) for the reservoirs with terraces in their drainage area.

This section provides the findings of the study. The effects of the land terraces on the water supply for each of the designated drainage basins and for the full Republican River Basin above Hardy, Nebraska, include:

- The difference in evaporation with and without land terraces, the difference in groundwater recharge with and without land terraces, the difference in ET with and without land terraces, and the total impact on water supply as measured at the gaging station near the bottom of each designated drainage basin.
- The effect of Non-Federal Reservoirs on the water supply in a similar manner to No. 1 above.
- The combined effect of both land terraces and Non-Federal Reservoirs on the water supply in a similar manner to No. 1 above.

These three scenarios define the results required for the Study. A summary of the impacts on streamflow are presented in Table 34. Reservoirs Only without Terraces are results for Non-Federal Reservoirs in the basin. Reservoirs intercept surface runoff and that runoff either overflows the reservoir or remains in the reservoir for a period. Retained runoff is subsequently lost as evaporation from the exposed water surface, some additional evapotranspiration by plants along or in the storage area of the reservoir, or as seepage through the sides and bottom of the reservoir. Water that seeps from the reservoir becomes groundwater recharge under the reservoir. Since retained water does not flow downstream, the reduction is water flow in the stream results in reduced outflow from the subbasin and less water flow along the watercourse to the outlet of the subbasin, which reduces transmission losses. In all cases, the increase in Net ET plus Recharge equals the decrease in Surface Runoff plus decrease in Transmission Loss:

$$ET_n + R_{ch} + Q_l + T_l = 0 \tag{13}$$

where,

ETn = net increase in ET due to water retained in terraces and reservoirs,
Rch= increase in groundwater recharge from terrace channels and reservoirs,
Ql = reduction of streamflow,
Tl = reduction of transmission loss.

The effects are the same for the Terraces Only Scenario as for the Reservoirs Only Without Terraces Scenario. However, for the Terraces Only Scenario more of the retained water is lost as net ET because water is ponded less deeply and the terrace channel generally supports more terrestrial plants that extract more stored water from the soil than the generally less dense plant growth along a reservoir.

Terraces have their full effect for the Terraces Plus Reservoirs Combined Scenario as for the Terraces Only Without Terraces Scenario. The net effect of reservoirs declines somewhat due to terraces in the reservoir catchment areas. Less runoff flows into the reservoirs and subsequently results in less net ET and recharge from the reservoir, and smaller downstream flow and transmission losses as well

Terraces and Non-Federal Reservoirs substantially influence the water resources of the Republican River Basin above Hardy, Nebraska. The impacts when both terraces and Non-Federal Reservoirs are present in the basin are compared to conditions when no terraces or Non-Federal Reservoirs are present (Table 34).

The impact for the whole basin is found by totaling the impact for all subbasins for average annual results, which shows that:

- Net evapotranspiration increased by an average of about 35,900 acre-feet/year.
- Recharge increased about 89,400 acre-feet/year.
- Surface runoff decreased by about 60,500 acre-feet/year.
- Transmission loss decreased by about 64,800 acre-feet/year.

The total drainage area in the Basin is about 22,940 square miles while approximately 3,350 square miles of terraced land existed in the basin in 2006. Field surveys showed that about 65% of the total area for terraced fields, or 2,180 square miles, is above the lowest terrace in the field. Water retained in conservation terraces either goes to evapotranspiration by plants growing in the channel, evaporates from open water standing in the terrace channel, or percolates beyond the root zone of plants along the terrace channel and becomes groundwater recharge eventually. Across the basin, land terracing reduces runoff from the areas above terraces by about 32 acre-feet/year per square mile for an average total retention of about 71,000 acre-feet/year. Evapotranspiration in the terrace channel consumes about 33 percent of the retained runoff (*i.e.* 24,000 acre-feet/year) while the remainder (47,000 acre-feet/year) seeps through crop root zones and eventually recharges groundwater.

The total drainage area for the 709 small, Non-Federal reservoirs is about 5,870 square miles. Of this area, the "effective drainage area" is about 1,750 square miles. A number of these reservoirs are in the western portion of the basin where the soils and drainage network make surface runoff production and transmission very low. The estimated effect of reservoirs only reduces runoff losses by an average of about 33 acre-feet/year per square mile of effective drainage area for an average total of about 58,000 acre-feet/year at the reservoirs. Evaporative processes consume about 20 percent of the runoff retained in the reservoirs (12,000 acre-feet /year) while the remainder of the retention (46,000 acre-feet) eventually seeps from the reservoir and will eventually become groundwater recharge.

Some of the terraced land is in the catchment areas for the reservoirs. The effects of terraces and small reservoirs are not independent. The response of the reservoir depends on the impacts of field terraces. Combining the impacts for the systems and accounting for the overlap gives an average total reduction of runoff of about 125,000 acre-feet/year, about 4,000 acre-feet/year less than for the sum of individual impacts.

Downstream impacts of the reduction in runoff from terraces and reservoirs result in less streamflow and reduced transmission losses along the stream and other watercourses. The sum of the two reductions equals the amount of runoff retained by the reservoirs and terraces. Losses of water from the stream from locations of the reservoirs and the terraced fields decrease the amount of runoff that reaches the outlet of subbasins, or designated drainage basins. The average transmission loss rate in the basin is about two percent of the amount of flow in the stream per mile of flow along the stream. This high loss and the long stream lengths in the subbasins contribute to transmission losses equal to about half of the runoff from fields or overflow from reservoirs that enters the watercourses.

The additional recharge under the reservoirs and the terraced fields may eventually produce additions to surface streamflow or to groundwater for use in the basin. The locations for recharge are further upstream than without the terraces and reservoirs in the basin and on areas where recharge rates are much lower with these conservation practices in place.

Only the additional water lost by evaporation from the reservoirs and additional ET from the terraces channels is a direct loss from the hydrologic cycle in the basin. The additional recharge may still be available depending on many other factors and on the time scale for the accounting used.

Small reservoirs and land terracing are important practices for this basin. Reservoirs store water, provide some potential for a small part of the water use, aid in flood control, grade stabilization in eroding channels, and provide some water-based recreation and wildlife habitat. Terracing reduces soil erosion by water on cropland on sloping lands and increases the available water supply for dryland crops in much of the basin. In addition, these conservation measures provide improved water management close to where runoff occurs.

Distribution of Results

The impact of the simulation scenarios summarized for the HUC-8 subbasins are in Table 34. The results for net evapotranspiration, runoff reduction, recharge, and transmission loss are plotted for HUC-12 subbasins for each scenario in Figures 100 through 107. The results for terraces alone show that the major impact occurs in the central portion of the basin. The impacts are most significant for the lower reaches of Beaver, Sappa, and Prairie Dog Creeks with somewhat smaller impacts at the lower portions of Red Willow and Medicine Creek, and some areas along the mainstem of the Upper and Middle Republican subbasins (Figures 100 and 101). The maps show that the recharge is about twice the net ET for the terraces only scenario. The reductions to stream runoff are about the same scale as the transmission losses.

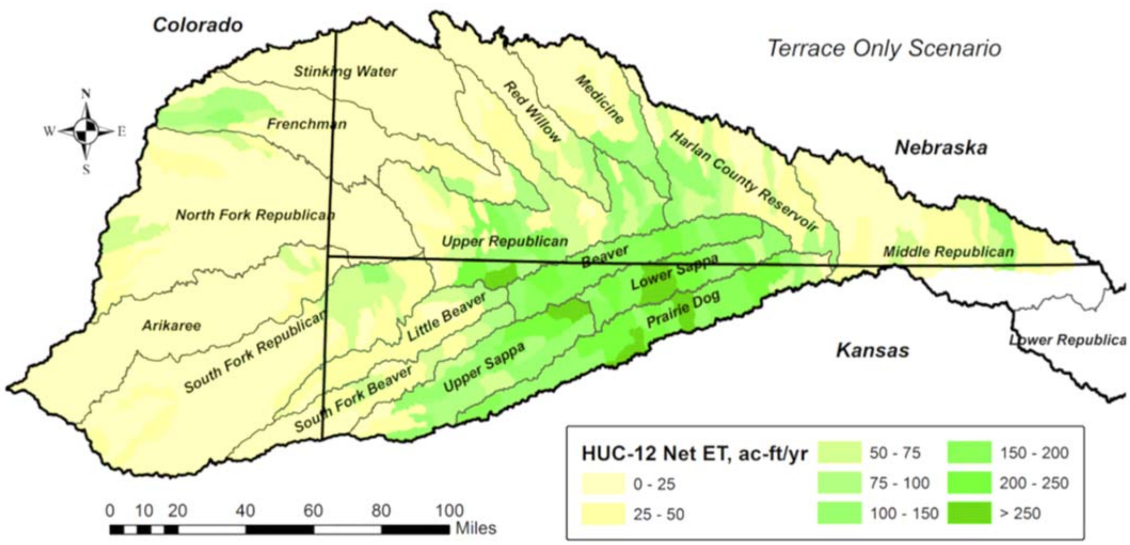
The impact for the Reservoir only scenario appears in Figures 102 and 103. These impacts are much less widely distributed. Some of the most intense effects occur in Medicine Creek, the Upper Republican subbasin, and along the state line in the Middle Republican subbasin. Combining terraces and reservoirs strongly concentrates the impact to the central portion of the Basin with most impact above Harlan County Reservoir (Figure 104 and 105). Simulation of scenario 4 for reservoirs with terraces in the drainage or catchment areas resembles the distribution for reservoirs only (Figure 102 and 103). The distribution of results in Figures 100 through 107 illustrate that the majority of subbasin impacts occur in the lower reaches of the subbasins.

Table 34. Simulation results for HUC-8 subbasins expressed as the average impact in acre-feet/year at the outlet of the subbasin for the 59-year period from 1950 through 2008.

System Simulated →	Terraces Only:	Reservoirs Only:	Terraces and Reservoirs Combined:	Reservoirs With Terraces in Drainage Area:
	Net ET is the increase in the terrace channels Recharge is the increase under the terrace channels Surface Runoff reduction = Runoff reduction at the field edge out of terraces times the Transmission loss percentage based on the distance to sub-basin outlet and the percent/mile loss rate. Transmission Loss Reduction = Runoff reduction at the field edge out of the terrace channels minus the surface runoff reduction	Net ET is the increase in net surface evaporation plus increase in ET from periodically inundated areas within the reservoir storage area Recharge is the net seepage out of the reservoir Surface Runoff reduction is the difference between inflow to the reservoir and outflow from the reservoir times the Transmission loss factor based on the distance to the sub-basin outlet and the percent/mile loss rate. Transmission Loss reduction = The difference between inflow to the reservoir and outflow from the reservoir minus the surface runoff reduction.	Net ET is the sum of Reservoirs With Terraces plus the Net ET for Terraces Only. Recharge is the sum of the Recharge for Reservoirs With Terraces plus the Recharge for Terraces Only. Surface Runoff reduction is the sum for Reservoirs With Terraces plus the surface runoff reduction for Terraces Only.	Effects are the same as for Reservoirs Only except the terraces in the drainage area reduce inflow to the reservoir and results in lower amounts of Net ET, Recharge, Surface Runoff reduction, and Transmission Loss reduction for the reservoirs.
			Some terraces are in the reservoir drainage areas.	Some terraces are in the reservoir drainage areas.
	For ALL Scenarios: Net ET + Recharge = Field or drainage area runoff that does not flow beyond the terrace or reservoir. Downstream this reduction in runoff equals to less surface runoff from the stream plus less Transmission Losses from the stream. In all tables, Surface Runoff and Transmission Losses are shown as negatives to indicate they are reduced.	The effects of transmission losses and recharge on total streamflow and groundwater in each sub-basin is unknown and is beyond the scope of this project.	Results for Reservoirs With Terraces in the drainage area plus Scenario #1 for Terraces Only. Values for Reservoirs With Terraces are shown to the right for clarity only.	

	SCENARIO #1				**SCENARIO #2**				**SCENARIO #3**				**SCENARIO #4**			
	TERRACES ONLY				**RESERVOIRS ONLY WITHOUT TERRACES**				**TERRACES PLUS RESERVOIRS COMBINED**				**RESERVOIRS ONLY WITH TERRACES**			
SUMMARY BY SUB-BASIN	NET ET	SURF RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS
Arikaree	349	-195	364	-518	7	-24	20	-4	355	-213	380	-521	6	-19	16	-3
NFRepublican - Abv CO-NE Stateline	483	-148	368	-704	46	-106	130	-70	530	-253	497	-774	46	-106	130	-70
Republican River	5,207	-14,126	12,537	-3,619	5,785	-22,399	22,551	-5,936	10,585	-34,799	33,301	-9,087	5,378	-20,674	20,764	-5,468
Buffalo Cr	99	-41	125	-183	0	0	0	0	99	-41	125	-183	0	0	0	0
Rock Cr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SFRepublican - Abv Bonny Dam	558	-265	521	-815	177	-97	508	-588	720	-352	979	-1,347	162	-87	458	-532
SFRepublican - BonnyDam to Mouth	894	-931	1,313	-1,275	140	-375	459	-224	1,031	-1,302	1,763	-1,492	137	-370	450	-217
Blackwood Cr	312	-523	804	-592	768	-1,656	2,844	-1,956	1,008	-2,012	3,343	-2,339	697	-1,489	2,539	-1,747
Driftwood Cr	1,165	-1,337	2,303	-2,131	65	-170	234	-130	1,226	-1,494	2,519	-2,250	61	-157	215	-119
Frenchman - abv Enders Dam	680	-163	694	-1,212	120	-276	371	-215	784	-402	1,008	-1,391	104	-239	314	-179
Frenchman - Enders Dam to Mouth	628	-701	1,151	-1,078	271	-606	933	-598	882	-1,268	2,015	-1,628	254	-567	863	-550
Red Willow Cr - Abv Red Willow Dam	326	-677	746	-396	397	-1,027	1,454	-824	693	-1,613	2,063	-1,143	367	-936	1,317	-747
Red Willow Cr - Red Willow Dam to Mouth	189	-489	528	-228	18	-63	68	-23	205	-545	587	-247	16	-55	59	-20
Medicine Cr - Abv Medicine Cr Dam	657	-1,008	1,444	-1,093	1,897	-3,160	6,796	-5,533	2,759	-4,196	8,101	-6,663	2,101	-3,188	6,657	-5,570
Medicine Cr - Medicine Cr Dam to Mouth	136	-291	247	-91	31	-106	109	-33	171	-402	356	-126	36	-110	109	-35
Sappa Cr	5,036	-1,657	9,147	-12,525	1,241	-497	4,397	-5,142	6,192	-2,115	13,197	-17,274	1,157	-458	4,050	-4,749
Beaver Crk	3,757	-1,884	7,004	-8,877	670	-660	2,308	-2,318	4,384	-2,496	9,136	-11,024	627	-612	2,132	-2,147
Prairie Dog - Abv Norton Dam	2,465	-3,438	4,868	-3,895	310	-922	1,138	-527	2,753	-4,286	5,910	-4,376	287	-848	1,042	-481
Prairie Dog - Norton Dam to Mouth	1,157	-1,818	2,764	-2,102	407	-1,024	1,525	-909	1,536	-2,762	4,170	-2,945	380	-944	1,406	-843
Total for Republican River abv Hardy, NE	24,098	-29,692	46,928	-41,334	12,350	-33,166	45,844	-25,029	35,912	-60,550	89,447	-64,810	11,815	-30,857	42,520	-23,476

Note: The transmission loss for the Republican River was calculated from the centroid of each HUC-12 to its junction with the mainstem. Transmission losses were not computed for the mainstem from the junction to Hardy, NE.



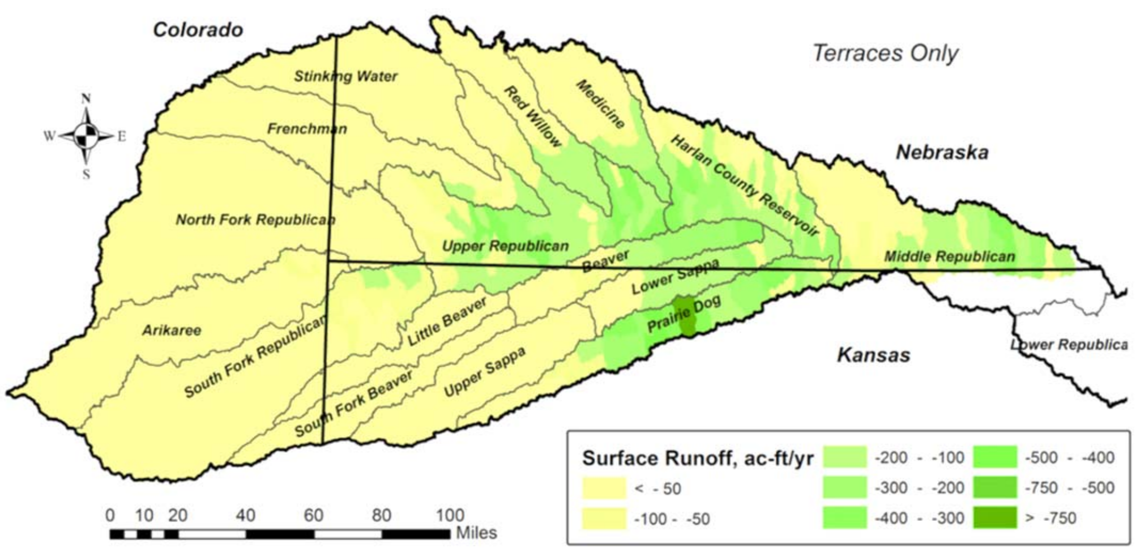
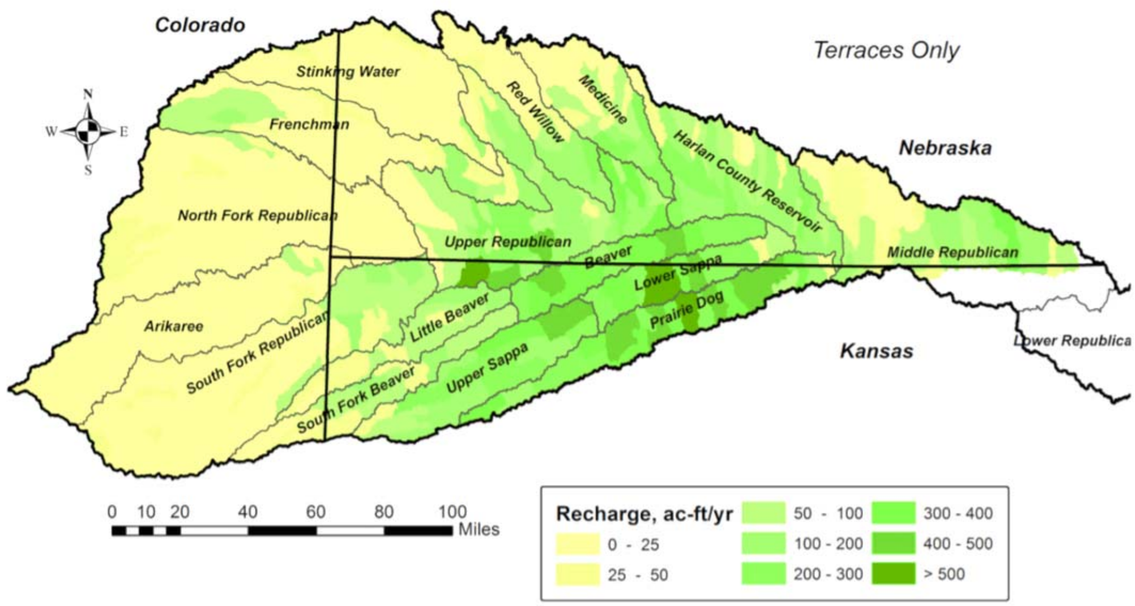


Figure 100. Distribution of Net ET and Surface Runoff in acre-feet/year for the Scenario only Considered Terraced Land



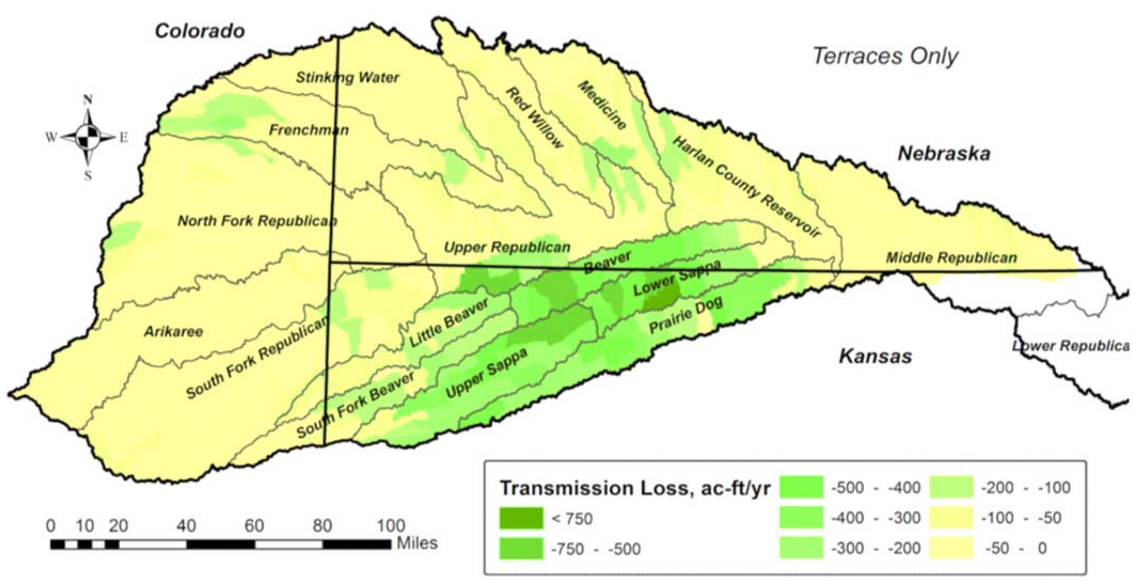
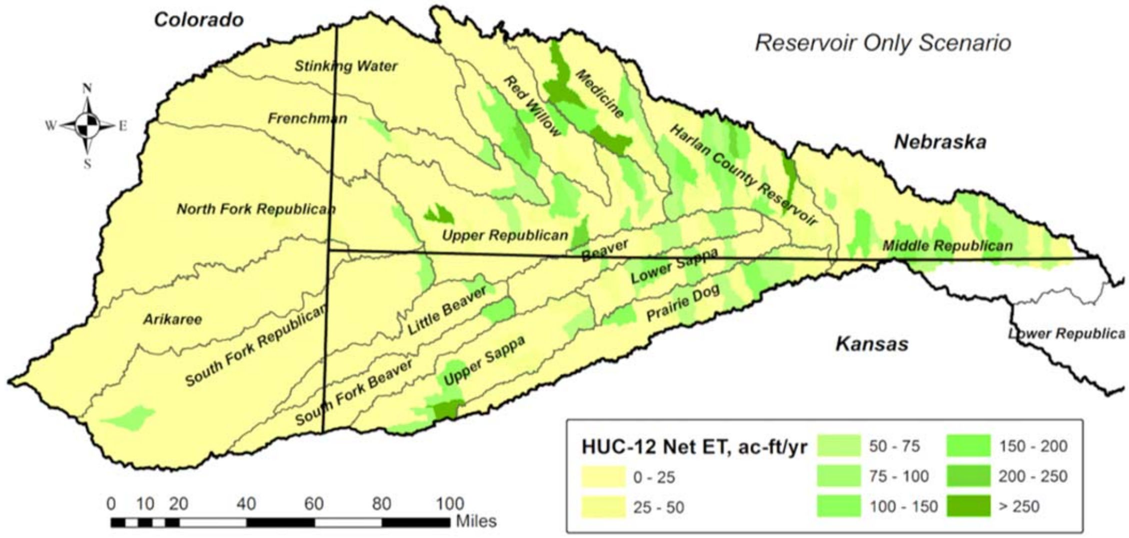


Figure 101. Distribution of Groundwater Recharge and Transmission Losses for the Scenario Considered only the Effect of Terraced Land



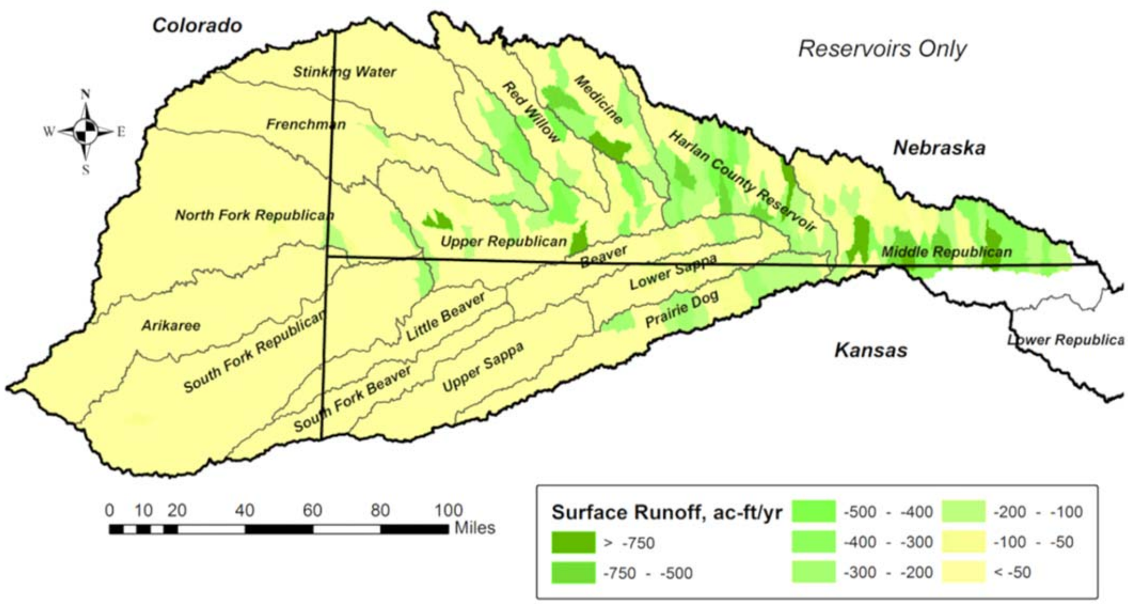
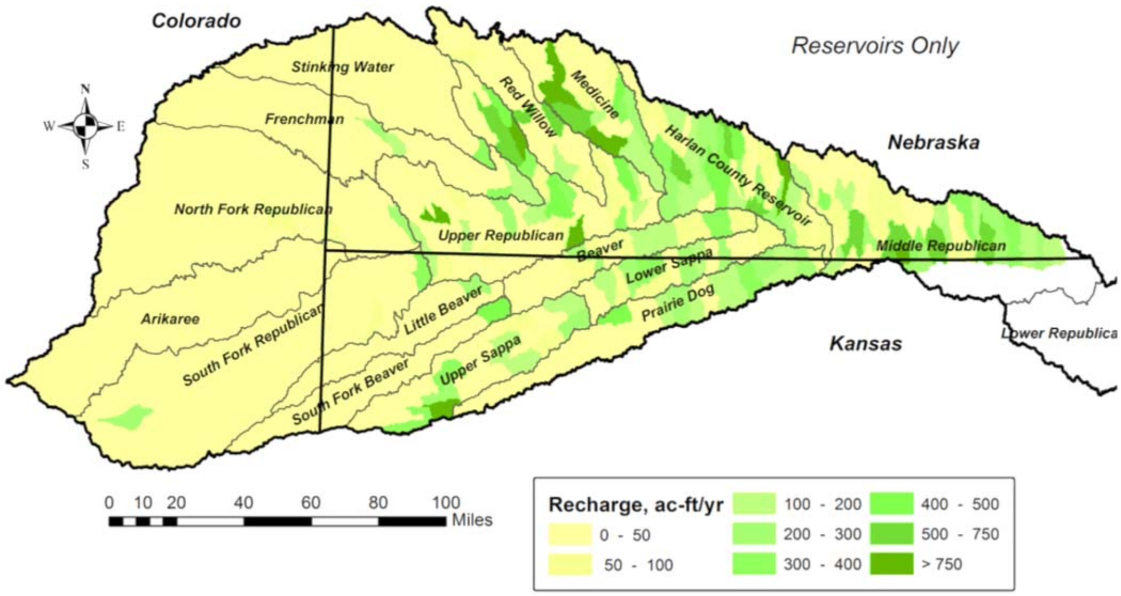


Figure 102. Distribution of Net ET and Surface Runoff in acre-feet/year for the Scenario Only Considered the Effects of Only Reservoirs



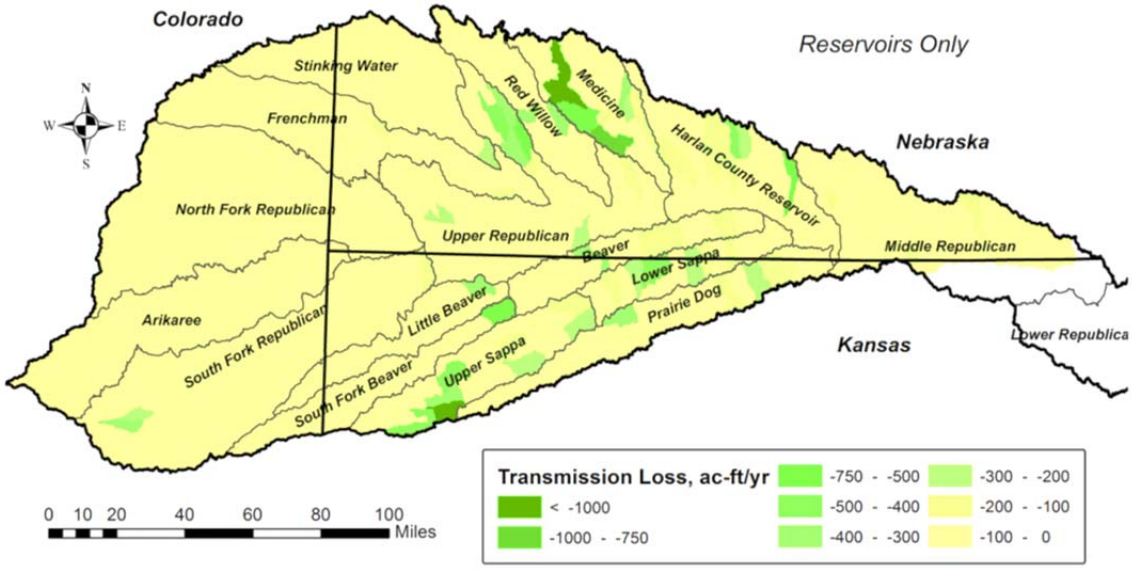
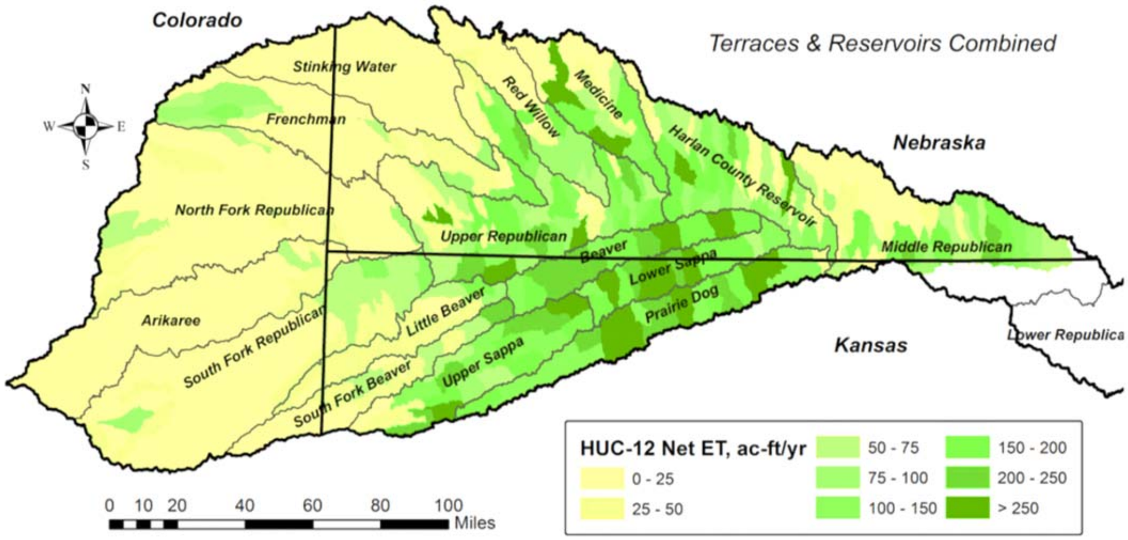


Figure 103. Distribution of Groundwater Recharge and Transmission Losses for the Scenario Considered only the Effect of Reservoirs



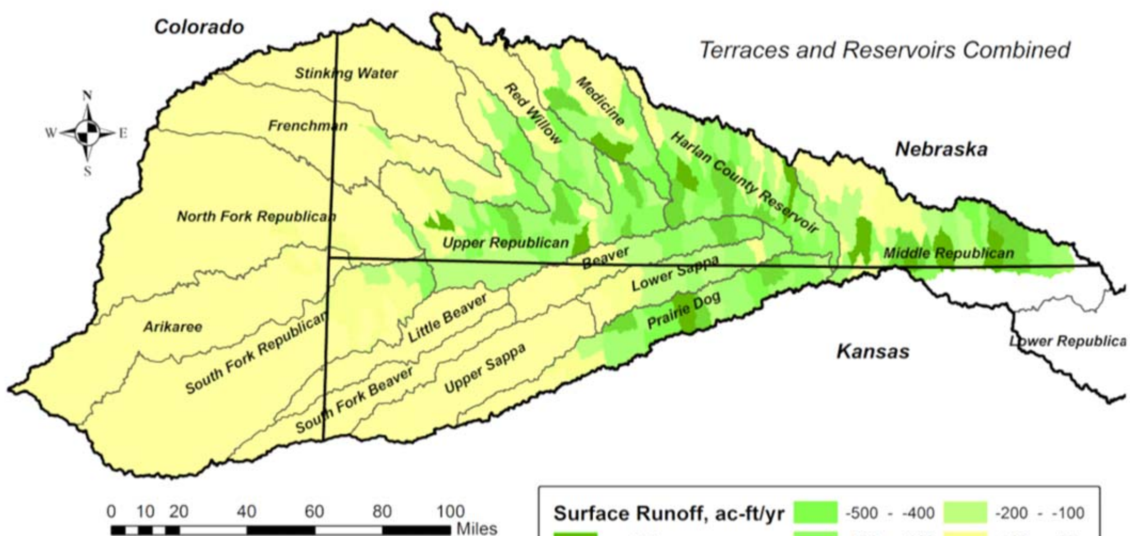
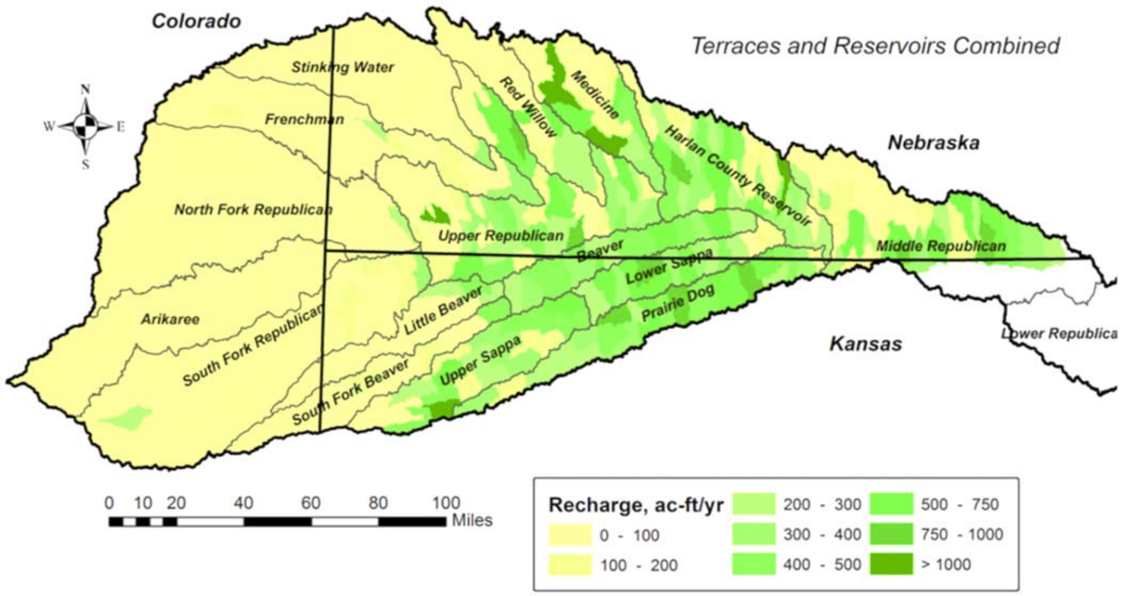


Figure 104. Distribution of Net ET and Surface Runoff in acre-feet/year for the Scenario Considered the Combined Effect of Terraced Land and Reservoirs



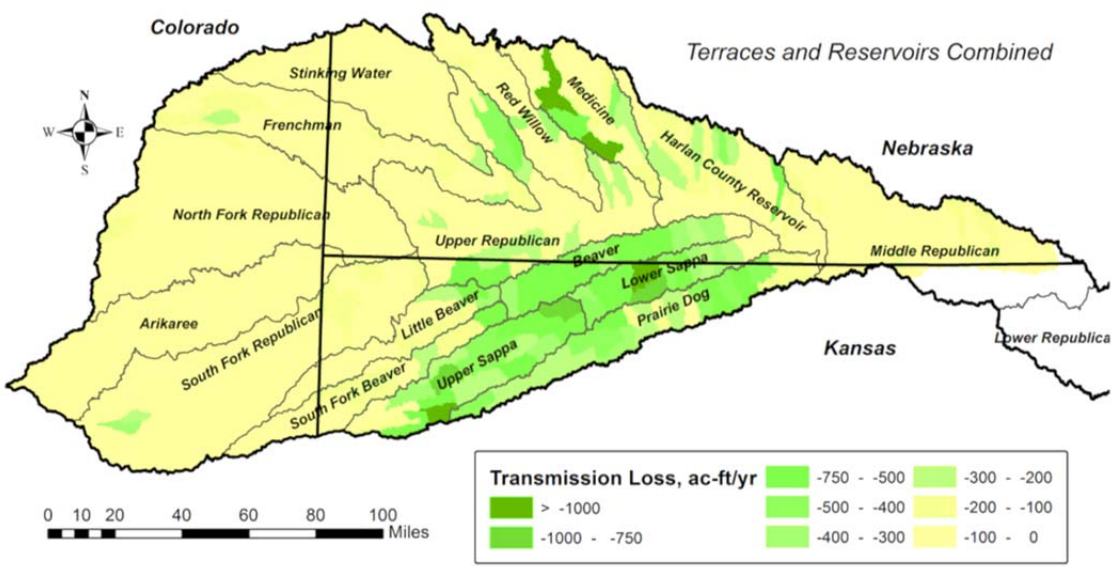
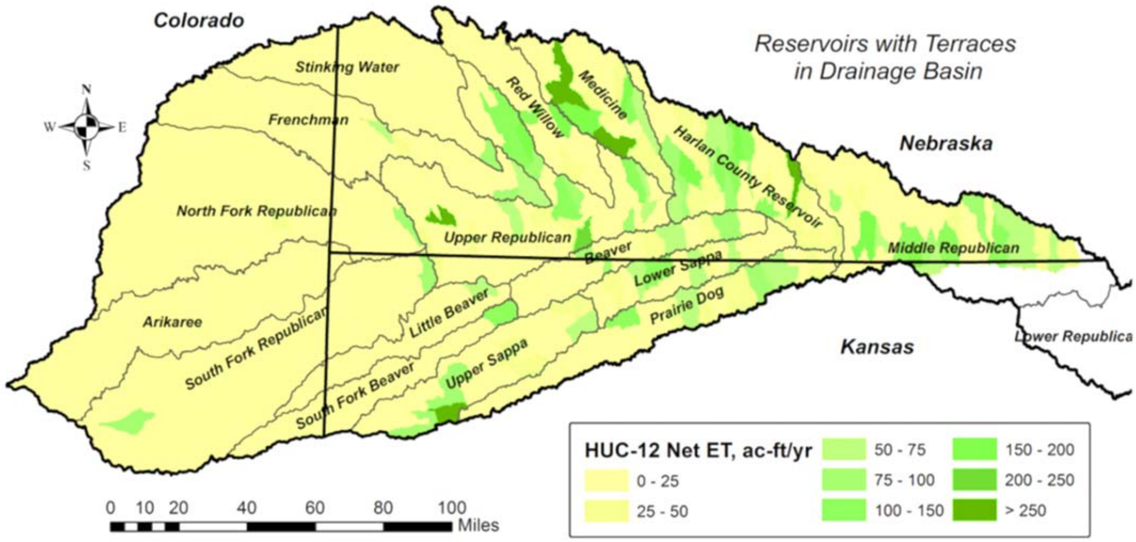


Figure 105. Distribution of Groundwater Recharge and Transmission Losses for the Scenario Considered the Combined Effect of Terraced Land and Reservoirs



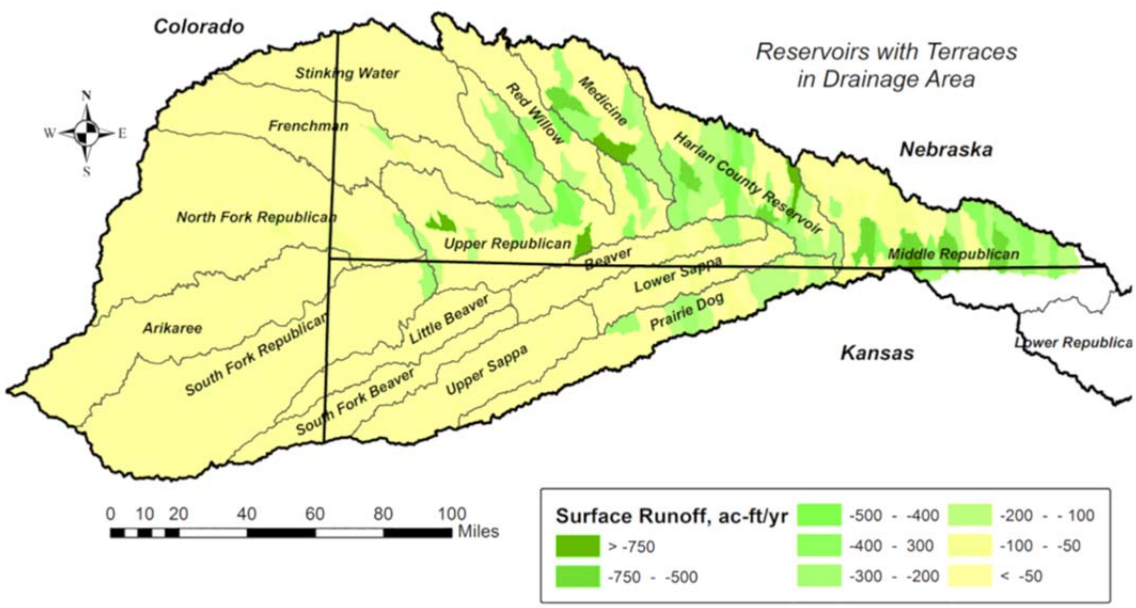
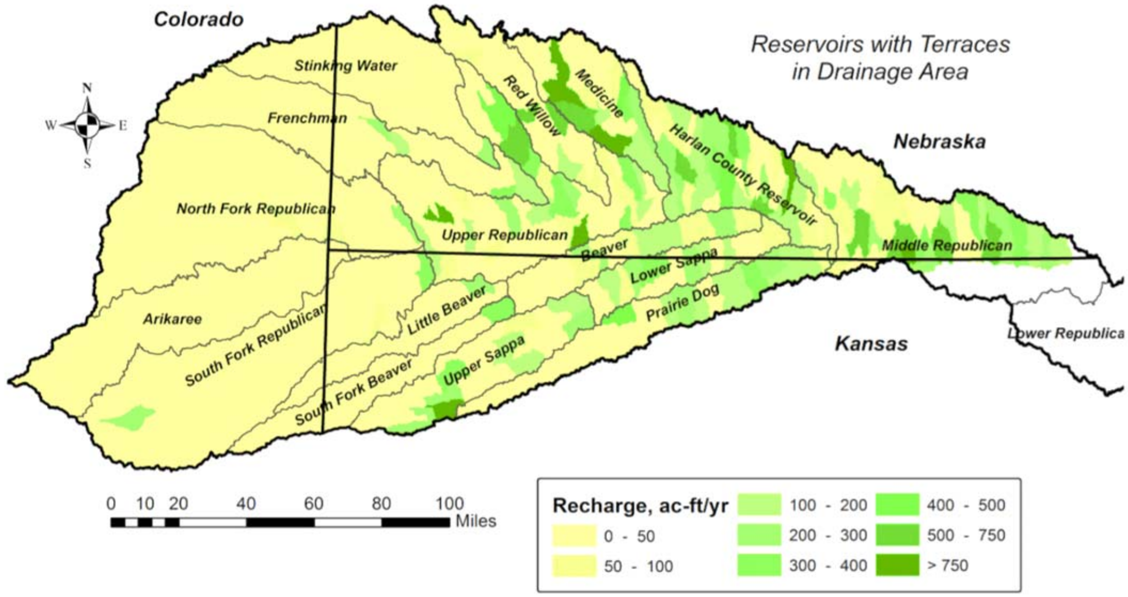


Figure 106. Distribution of Net ET and Surface Runoff in acre-feet/year for the Scenario Considered the Effect of Reservoirs when Terraced Land is in the Drainage Area for the Reservoir



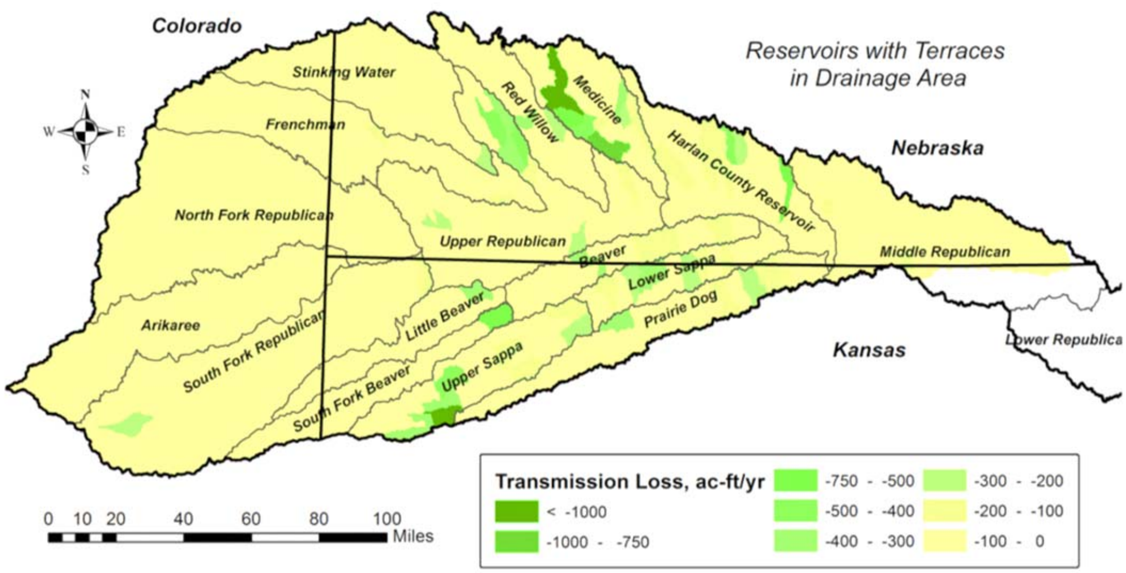


Figure 107. Distribution of Groundwater Recharge and Transmission Losses for the Scenario Considered the Effect of Reservoirs when Terraced Land is in the Drainage Area for the Reservoir

Uncertainty in Transmission Loss

The total water flow that leaves the edge of the fields or that overflows reservoirs results from the performance of terraces and small reservoirs. We estimated the impact of terraces and reservoirs was an upstream reduction of about 126,000 acre-feet per year for the whole Basin. Water that leaves the edge of a field or that overflows a reservoir may be lost in transmission between the field or reservoir and the stream before the water enters the stream. If transmission losses are high, then less of the upstream flow from the fields and reservoirs will reach the stream. Changing the transmission loss rate thus does not alter the total volume of water that leaves fields and reservoirs; it only changes the fraction of the upstream impact that is lost in conveyance and indirectly the flow into streams.

Simulated transmission losses are largest in the western portions of the Basin and lowest in the eastern portion. Periods with wetter conditions likely have lower losses than for dry periods; however, we need better methods and data about transmission loss to improve modeling transmission losses. For now, we can only address the loss with the loss factor. The range of uncertainty for this factor can change estimates of the streamflow impacts by as much as ±25%. We used three sets of transmission losses factors across the Basin to examine the sensitivity of the transmission loss factor. Values for the base loss rate (Table 35) represent our best estimate for average transmission losses in the Republican River Basin. The higher loss rate represents a one percent increase for all HUC-12s, while the lower loss rate reflects a reduction of one percent for all HUC-12s.

The base loss rate resulted in a nearly equal split between transmission loss and streamflow for the 126,000 acre-feet/year impact (Table 35). Raising the loss rate by one percent increased transmission losses by about 13% and deceased streamflow reductions by about 14%. About 55 percent of the upstream impact becomes transmission loss for the high transmission loss. Decreasing the transmission loss rate produced less impact on the transmission losses and enlarged the impact on flows into the stream. Transmission loss for the lower loss rate was about 44% of the total upstream impact. Clearly, the transmission loss factor is an important component for streamflow reduction.

Table 35. Effect of Transmission Loss Factors on the Division of Upstream Impacts for the Basin.

Transmission Loss Rate, % loss / mile		Decrease in Transmission Losses	Decrease in Streamflow	Upstream Impact
3.5 to 2.5	Higher	-70,000	-55,000	-125,000
2.5 to 1.5	Base	-62,000	-64,000	-126,000
1.5 to 0.5	Lower	-43,000	-82,000	-125,000

Note: All Values are Rounded to the Nearest 1,000 acre-feet/year.

Sensitivity Analyses

Many input variable values and assumptions affect the output from computer simulation models. In this project, many values of variables in the computer simulation model along with characteristics of the terraces and small reservoirs, plus the transmission loss factor, affect the streamflow reduction and recharge increase.

Dr. Koelliker has used the POTYLD model for many years. That work has provided him substantial experience with selecting and using reliable values for the situation in this study. Variables affect runoff, soil water storage, percolation, etc. In addition, the amounts of runoff, percolation, etc. in the field have been considered and discussed with Dr. Dean Eisenhauer and Dr. Derrel Martin at the University of Nebraska-Lincoln to ensure that simulation results are realistic. Direct comparison of modeling results to field measurements is not possible for the project; however, the results are consistent with the modeling work by Twombly (2008). In addition, this project focuses on the amount of change in streamflow and recharge only on those areas affected by terraces and a set of small Non-federal reservoirs. Therefore, the process is to predict the change in runoff and recharge rather than the magnitude of streamflow and recharge. The change in streamflow and recharge are the primary focus of the sensitivity analyses.

We examined the sensitivity of the results related to the magnitude of several input values that affect the results for terraces and small federal reservoirs. This section shows how the results of using several different input values for terraces, small Non-Federal Reservoirs, and the transmission loss factor affect the change is streamflow, recharge, net evapotranspiration and the amount of transmission losses in the Basin.

Terrace Input Values

When water is present in terraces there is greater opportunity time for infiltration out of and evaporation from the free-water surface. In addition, if a subsequent event produces runoff before the terrace channel empties there is a greater chance that overflows will occur. Terraces with no retention storage, particularly graded terraces, have less time for additional infiltration and evaporation, but many of these terraces have low areas that can retain small amounts of water and the detention time, too, allows for some infiltration and evaporation to occur. Level terraces with open ends must detain water to create enough depth to allow gravity to cause water to flow to the outlet. Water may stay in the terrace channel for several days during the drain out period allowing additional infiltration and evaporation. Storage-type terraces have level bottoms and even if when breached they have as much effect on runoff as level terraces with open ends. Properly functioning level terraces with closed ends have a large enough retention capacity so that retained water is only lost by infiltration and evaporation from the stored water surface.

We examined the effect of changing the storage capacity of closed-end terraces on the water balance components for the Basin. Raising and lowering the overflow level for both types of storage terraces provided the variation in storage capacity. We analyzed the impact for two larger amounts of terrace storage and two smaller amounts of storage compared to the base amount of storage capacity used for the general simulations. The storage capacity for the base condition came from the field survey. The outlet elevation is an input variable to the TERRACEPOND portion of the model. As discussed previously, the effects of terraces and small reservoirs for the last 10-year period were quite comparable to results for the entire 59-year period; therefore, the sensitivity analysis for storage capacity only covered the last 10-year period only, *i.e.* 1999-2008. The sensitivity analysis results in Table 36 describe the impact for the five levels of storage for the four scenarios used in the study.

Table 36. Results of sensitivity analysis for the impact of changes in terrace storage capacity, the infiltration rate for terraces and the seepage rate from reservoirs on water balance components for the entire Basin.

Terrace Storage Capacity for Closed-End Types		**SCENARIO #1, ac-ft/yr total**				**SCENARIO #2, ac-ft/yr total**				**SCENARIO #3, ac-ft/yr total**				**SCENARIO #4, ac-ft/yr total**			
Only Changed Storage for Closed-End Terraces		**TERRACES ONLY**				**RESERVOIRS ONLY WITHOUT TERRACES**				**TERRACES PLUS RESERVOIRS COMBINED**				**RESERVOIRS ONLY WITH TERRACES**			
		NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS
Biggest Terrace		27,974	-39,667	58,224	-46,534	12,351	-35,224	47,611	-24,740	39,959	-72,953	103,171	-70,180	11,985	-33,286	44,947	-23,647
Bigger Terrace		26,127	-35,994	52,595	-42,729	12,351	-35,224	47,611	-24,740	38,111	-69,280	97,543	-66,375	11,985	-33,286	44,947	-23,647
SUM FOR ALL 1999-2008 (BASE)		24,986	-32,318	46,122	-38,792	12,351	-35,224	47,611	-24,740	36,970	-65,603	91,070	-62,438	11,985	-33,286	44,947	-23,647
Smaller Terrace		22,648	-28,312	39,947	-34,283	12,351	-35,224	47,611	-24,740	34,632	-61,599	84,893	-57,931	11,985	-33,286	44,947	-23,647
Smallest Terrace		21,937	-27,276	38,319	-32,978	12,351	-35,224	47,611	-24,740	33,920	-60,562	83,266	-56,623	11,985	-33,286	44,947	-23,647
Ac-ft/yr change						Note: Terrace characteristics in the reservoir drainage areas were not changed because of work required and effects are small on overall results.											
Biggest Terrace	BB: 1.29, FC: 1.77 in.	2,988	-7,349	12,102	-7,742												
Bigger Terrace	BB: 0.74, FC: 1.33 in.	1,141	-3,676	6,473	-3,937												
BASE	BB: 0.48, FC: 0.99 in.	0	0	0	0												
Smaller Terrace	BB: 0.32, FC: 0.76 in.	-2,338	4,006	-6,175	4,509												
Smallest Terrace	BB: 0.20, FC: 0.57 in.	-3,049	5,042	-7,803	5,814												
Percent Change																	
Biggest Terrace	Level #, BB: 10, FC: 12	12.0	22.7	26.2	20.0												
Bigger Terrace	Level #, BB: 9, FC: 11	4.6	11.4	14.0	10.1												
BASE	Level #, BB: 8, FC: 10	0.0	0.0	0.0	0.0												
Smaller Terrace	Level #, BB: 7, FC: 9	-9.4	-12.4	-13.4	-11.6												
Smallest Terrace	Level #, BB: 6, FC: 8	-12.2	-15.6	-16.9	-15.0												
Terrace Infiltration Rate for All Types		SCENARIO #1, ac-ft/yr total				SCENARIO #2, ac-ft/yr total				SCENARIO #3, ac-ft/yr total				SCENARIO #4, ac-ft/yr total			
		TERRACES ONLY				RESERVOIRS ONLY WITHOUT TERRACES				TERRACES PLUS RESERVOIRS COMBINED				RESERVOIRS ONLY WITH TERRACES			
		NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS
Lower Rate		25,299	-29,825	41,131	-36,605	12,351	-35,224	47,611	-24,740	37,284	-63,111	86,079	-60,251	11,985	-33,286	44,947	-23,647
SUM FOR ALL 1999-2008 (BASE)		24,986	-32,318	46,122	-38,792	12,351	-35,224	47,611	-24,740	36,970	-65,603	91,070	-62,438	11,985	-33,286	44,947	-23,647
Higher Rate		23,418	-33,527	49,988	-39,880	12,351	-35,224	47,611	-24,740	34,632	-61,599	84,893	-57,931	11,985	-33,286	44,947	-23,647
Ac-ft/yr change						Note: Terrace characteristics in the reservoir drainage areas were not changed because of work required and effects are small on overall results.											
Lower Rate, in./day	0.25 bottom, 0.50 above	313	2,493	-4,991	2,187												
BASE	0.50 bottom,1.00 above	0	0	0	0												
Higher Rate, in./day	1.0 bottom, 2.0 above	-1,568	-1,209	3,866	-1,088												
Percent Change																	
Lower Rate		1.3	-7.7	-10.8	-5.6												
BASE		0.0	0.0	0.0	0.0												
Higher Rate		-6.3	3.7	8.4	2.8												
Reservoir Seepage Rates		SCENARIO #1, ac-ft/yr total				SCENARIO #2, ac-ft/yr total				SCENARIO #3, ac-ft/yr total				SCENARIO #4, ac-ft/yr total			
		TERRACES ONLY				RESERVOIRS ONLY WITHOUT TERRACES				TERRACES PLUS RESERVOIRS COMBINED				RESERVOIRS ONLY WITH TERRACES			
		NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS	NET ET	SURF. RUNOFF	RECHARGE	TRANS. LOSS
Lower Rate		24,986	-32,318	46,122	-38,792	14,851	-31,793	39,713	-22,771	39,448	-62,478	83,597	-60,568	14,463	-30,160	37,474	-21,778
SUM FOR ALL 1999-2008 (BASE)		24,986	-32,318	46,122	-38,792	12,351	-35,224	47,611	-24,740	36,970	-65,603	91,070	-62,438	11,985	-33,286	44,947	-23,647
Higher Rate		24,986	-32,318	46,122	-38,792	10,234	-37,444	53,326	-26,117	34,772	-67,325	95,963	-63,411	9,786	-35,008	49,841	-24,619
Ac-ft/yr change		Note: Terrace characteristics do not affect results.															
Lower Rate, in./day	0.05 linear to 0.60 full					2,500	3,431	-7,898	1,969	2,478	3,125	-7,473	1,870	2,478	3,126	-7,473	1,869
BASE	0.10 linear to 1.2 full					0	0	0	0	0	0	0	0	0	0	0	0
Higher Rate, in./day	0.20 linear to 2.4 full					-2,117	-2,220	5,715	-1,377	-2,198	-1,722	4,893	-973	-2,199	-1,722	4,894	-972
Percent Change																	
Lower Rate						20.2	-9.7	-16.6	-8.0	6.7	-4.8	-8.2	-3.0	20.7	-9.4	-16.6	-7.9
BASE						0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Higher Rate						-17.1	6.3	12.0	5.6	-5.9	2.6	5.4	1.6	-18.3	5.2	10.9	4.1

The results of the sensitivity analysis are generally as expected (Figure 108). Note that the values in Figure 108 represent the percent increase or decrease for each quantity whereas values in Table 36 for streamflow and transmission losses represent the percent changes in the reduction. Larger terrace retention capacities keep more water on the field and therefore increase both net evapotranspiration and recharge while reducing streamflow and transmission losses. Enlarging the storage increased recharge much more than evapotranspiration. Reductions in streamflow and transmission losses are about the same for changes in storage. The range of storage values tested in this analysis is much larger than the expected variation of storage. For example, changes for the bigger and smaller volumes vary from 20% to 50% of the base volume. The range of changes in ET, streamflow, recharge and transmission loss is less than the range of storage changes. We estimated the uncertainty to be about ±5% of the base storage capacity. Therefore, we expect that the effects on streamflow and recharge due to uncertainty of storage will be within the 5% variation of storage.

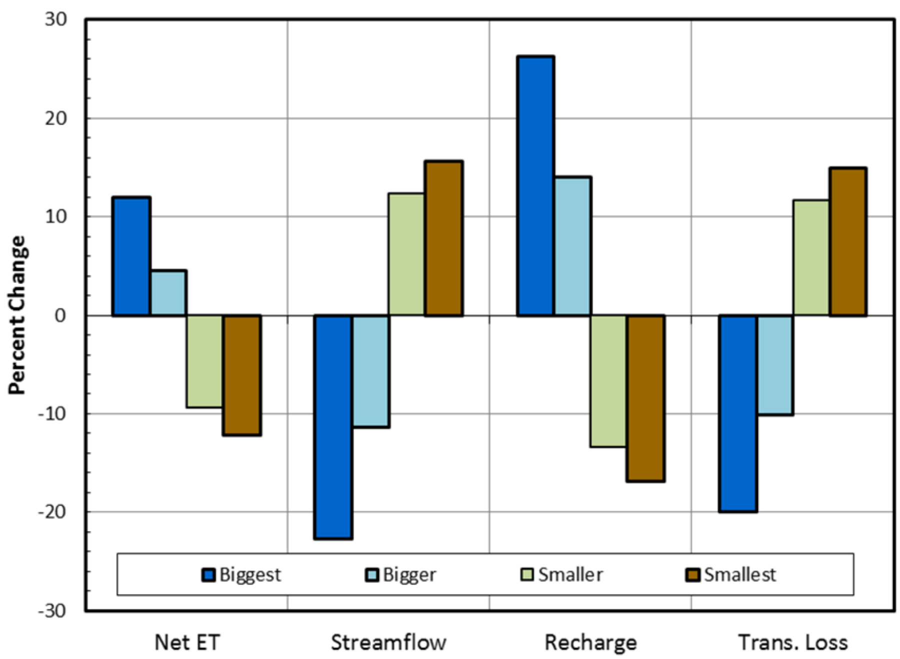


Figure 108. Results of Sensitivity Analysis for Terrace Storage Capacity
(Storage Capacities of Biggest, Bigger, Smaller and Smallest).

Terraces in the drainage areas of the small Non-federal reservoirs have a minor effect on the results for the reservoirs. The amount of land above terraces is only about 10% of the total area in the drainage basin for these reservoirs; therefore, inflow changes to the reservoirs would be only about 1 to 2 percent in most areas. Therefore, the effect of changes in terrace storage capacity on the water balance of reservoirs is small and the difference is less than the variation of results that would occur due to uncertainty of other inputs.

The base rate of infiltration used in the TERRACEPOND program for the overall simulations is 0.5 inches/day for Levels 1 and 2 and 1.0 inches/day is used for all other levels. To examine the sensitivity of the infiltration rate, the infiltration rates were lowered to 0.25 and 0.50 inches/day and the entire basin was simulated for the 10-year period. Subsequently, the rates were increased to

1.0 and 2.0 inches/day and again simulations were conducted for the entire basin. Table 36 shows the results of the runs for the change in infiltration rates in the middle of the table.

The change in infiltration rates had smaller effects than varying terrace storage. Decreasing the infiltration capacity had a larger effect on outcomes than increasing the infiltration rate. Slightly more net evaporation resulted because a larger area was inundated due to slower infiltration. Less recharge occurred with lower infiltration rates. Instead of infiltrating as rapidly, more water remained ponded in the channel and subsequent runoff events, though infrequent, resulted in more overflow from the terrace; therefore, more streamflow and transmission loss occurred. The higher infiltration rates resulted in less net evapotranspiration because more of the water infiltrated over a smaller area. The areas where infiltration did occur lost a greater portion of the water as percolation that became subsequent recharge.

We did not model the effect of infiltration rates for terrace channels in the drainage areas of reservoirs. To simulate changes in terrace infiltration in the POTYLDR portion of the model would have required editing 192 files. However, we can estimate the impact because the change in overflow out of the terraces changes the ratio of the runoff volume to the reservoir volume. The change in infiltration rates would result in less than a one percent change in inflow to the typical reservoir.

When water is present in the bottom of terraces, there is greater opportunity time for seepage and evaporation from the free-water surface. Overflow is more likely if subsequent runoff-producing events occur before the retention has emptied. Terraces with no retention storage, particularly graded terraces, have less time for infiltration and evaporation; however, many terraces have low areas that retain small amounts of water that allows for additional infiltration and evaporation. Level terraces with open ends must detain water to create enough depth to allow gravity to cause water to flow to the outlet. Water may be detained for several days during the drain out period and additional infiltration and evaporation occur during these periods. Storage-type terraces have level bottoms and even if breached, have as much effect on runoff as level terraces with open ends. Properly functioning level terraces with closed ends have adequate retention capacity so that the only loss of water from the terrace is by infiltration and evaporation except for large, very infrequent, events.

Reservoir Analyses

Reservoirs decrease flow from the subbasin, and reduce streamflow and transmission losses. Choodegowda (2009) evaluated the impact of several factors on the amount of overflow, recharge, and net evapotranspiration for small Non-Federal Reservoirs. The analysis showed that the most sensitive factor was the ratio of the annual volume of surface runoff (R) into the reservoir compared to the retention volume of the reservoir (V). Other factors including evaporation rate (E), seepage rate (S), surface are (SA) to volume (V) ratio, and reservoir depth (D) had less effects on the water budget of a reservoir. These results are applicable to the entire basin but testing each subbasin is tedious because of the time and effort needed to change parameters in the 192 separate input files to the POTYLDR model.

Results from Choodegowda for small reservoirs are specific to the location of the reservoir. Factors that affect the water balance from specific reservoirs also apply for the entire basin. This assumes that the effects of transmission losses are unaffected by changes in overflow at the reservoir location.

The comprehensive model was used to examine the sensitivity of the seepage rate on the entire basin by changing the base seepage rate. The base seepage rate in the model that was developed from examining the operation of several of the monitored reservoirs is described by

$$S = 0.10 + \left(1.2 - 0.10\right) \frac{ST}{D} \quad (14)$$

where,

S = seepage rate, inches/day
ST = stage of the reservoir, feet
D = depth of the reservoir at the principal spillway, feet.

The seepage rate is a minimum of 0.10 inches/day at the bottom and increases linearly with the stage or depth of water in the reservoir. The high rate of seepage when the reservoir is nearly full was a consistent characteristic determined from the monitored reservoirs.

The sensitivity analysis involved cutting the range of basic seepage rates in half from 0.05 to 0.60 inches/day, and doubling the range of values from 0.20 to 2.4 inches/day. Changing values entailed a global search and replace in the 192 input files to the POTYLDR portion of the model. Then, the modeling process was run for the last ten years of records. Table 36 shows the results of changing the seepage rate on the impact of reservoirs alone in Scenario #2 for reservoirs only without terraces. The lower seepage rate increases runoff and transmission losses downstream by a combined total of about 5,400 acre-feet/year because more overflow from the reservoirs occurs which is equivalent to an increase of about 9%. More net evapotranspiration occurs from the reservoirs because they hold water more of the time and conversely recharge declined due to less seepage. Net evapotranspiration increased by about 20% while recharge dropped about 17%.

Higher seepage rates decrease runoff and transmission losses downstream because the reservoirs have about 3,600 acre-feet/year, or about 6%, less overflow than for the base case. Less net evapotranspiration occurs because the water seeps out more quickly and the surface area is usually smaller. Higher seepage rates enhanced recharge. Net evapotranspiration is the most sensitive component of the water balance as a percentage, but as a volume, it has a small effect of the overall water balance.

Uncertainty of Assumptions

Simulated transmission losses are larger in the western portions of the basin and lower in the east. Periods with higher precipitation likely have lower transmission losses than during dry periods, because ephemeral waterways are wetter with less bank storage and seepage. Data and processes to more thoroughly simulate transmission losses are lacking. Information on how and when to apply varying loss factors is unavailable. The procedure used to estimate transmission losses in the study relies on a loss factor that has a significant effect in partitioning overflow from terraces and reservoirs. The uncertainty for this factor causes estimates of effects on streamflow to vary by about ±25%. Transmission losses may increase groundwater recharge because much of the loss infiltrates along the ephemeral stream channel and into the alluvial groundwater systems. Transmission losses may also turn into evapotranspiration by plants along the ephemeral waterway. We did not attempt to divide the transmission loss into groundwater recharge or increased evapotranspiration.

This study was intended to evaluate only the impacts of Non-Federal Reservoirs and terraces on water supply of the Republican River Basin above Hardy, Nebraska. It was not intended to evaluate other impacts such as tillage practices, on-farm irrigation practices, or other water conservation practices, or to include other reservoirs that are presumably don't meet the criteria of the Non-Federal

Reservoir. These practices may have an impact on water supply, but the effects were not evaluated. Other small reservoirs in the basin may affect streamflow or ground water recharge by ±15%.

Additional Considerations

There are numerous assumptions and representations needed for simulation of the impact of terraces and reservoirs. This section summarizes some of those considerations.

- All simulations were for the 59-year period of record for the meteorological stations. The overall results are the long-term average for each HUC-12 and for the basin as a whole. While we feel that this is an appropriate climatological record for this analysis, using other climatic data would produce slight differences.
- Computer simulation models of the water balance can produce output on a yearly and monthly basis. This data is available to those familiar with the programs. However, those results are not useful for making conclusions about the overall results.
- Soil types and land uses on terraced fields are not the same as for non-terraced fields. We estimated these differences from the GIS coverages available for the region. We also determined unique properties for the catchment areas above of reservoirs to account for differences in these areas compared to the whole HUC-12.
- The portion of a terraced field above the lowest terrace was set to a constant value of 65%.
- The transmission loss factor is a constant in time and space for each HUC 12.
- The simulated unit values per square mile for the effects of terraces produced by the water balance operations are represented by using the same typical terrace characteristics of each of the five terrace types throughout the basin.
- The characteristics of typical reservoirs were associated with each of the 32 meteorological stations. Output from the simulations at each station for inflow, outflow, percolation, and net ET per square mile of reservoir drainage area were weighted by the distance from the weather station to the centroid of the HUC-12. Values for the three nearest stations to each HUC-12 adequately represent the effects of small Non-federal reservoirs in each HUC 12.
- The terraces surveyed in the basin are representative of the entire population in the Basin.
- Small Non-Federal Reservoirs for which sufficient information was available to describe their characteristics for input to the POTYLDR model were representative of the entire population of those reservoirs included in the study.
- The results of this study cannot be extended to represent all areas within the Basin.
- We did not attempt to compare the results of the simulations with a recorded streamflow record over time from a subbasin.

Based on these considerations and the material in this report we feel that these results are an adequate representation of small reservoirs and terraces on the water balance for the Republican River basin.

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Appendices

Appendix A. Reservoirs with Water-Level Monitoring Equipment

Reservoir Id	Reservoir Name	Location	Storage at Spillway Height m^3	Storage at Spillway Height acre-ft
		COLORADO		
Flagler	Flagler Reservoir	NW1/4SW1/4 Sec. 3, T9S, R50W	3,807,758	3084.7
		KANSAS		
DDC-0057	Shirley Rd. Fill Dam	SE1/4SE1/4 Sec 2 T3S R30W	39,829	32.3
DRA-0001	Atwood Lake	SW1/4SE1/4 Sec 5 T3S R33W	86,344	69.9
DRA-0083	Holste Dam	NE1/4NW1/4 Sec 9 T3S R32W	32,477	26.3
DNT-1AA	Archer Dam	SE1/4SW1/4 Sec 35 T2S R32W	82,470	66.8
DRA-0056	Olson Dam	NW1/4NE1/4 Sec 2 T3S R32W	100,898	81.7
DPL-Hogan	Hogan Dam	SW1/4SW1/4 Sec 25 T1S R20W	5,378	4.4
DPL-Knape	Knape Dam	NW1/4SW1/4 Sec 7 T1S R18W	12,334	10.0
DCN-Zimb	Zimbelman Dam	SW1/4NW1/4 Sec 24 T3S R41W	6,562	5.3
DCN-Otto	Calvin Raile Dam	SW1/4NW1/4 Sec 12 T4S R40W	88,810	71.9
DDC-Moore	L. Moore Dam	SE1/4SW1/4 Sec 3 T3S R29W	45,392	36.8
DNT-Arford	Arford Dam	SW1/4 SW1/4 Sec 6 T2S R22W	84,567	68.5
		NEBRASKA		
NE00244	Schiermeyer Reservoir	SE1/4NE1/4 Sec. 21, T2N, R7W	84,246	68.2
NE00376	Arehart Dam	NE1/4SW1/4 Sec. 36, T6N, R20W	29,603	24.0
NE00406	Sindt Dam	NW1/4NW1/4 Sec. 14 T1N R14W	143,083	115.9
NE00478	Paine Dam	SW1/4SW1/4 Sec. 21 T4N R22W	74,008	60.0
NE00482	Johnson DET Dam 3	E1/2W1/2 Sec. 12 T3N R25W	33,304	27.0
NE00496	Stamford Dam 3-A	S1/2SE1/4 Sec. 8, T2N, R20W	53,040	43.0
NE00557	Dry Creek 3-A	W1/2NE1/4 Sec. 9 T4N R27W	13,568	11.0
NE00559	Dry Creek South 2-A	SW1/4SE1/4 Sec. 18 T2N R29W	75,242	61.0
NE00617	Fredrichs Dam-1	NE1/4NW1/4 Sec. 19, T3N, 15W	61,674	50.0
NE01139	Kilpatrick Dam	NE1/4SE1/4 Sec. 20, T6N, R40W	160,352	129.9
NE01152	Anderson Reservoir	NE1/4SE1/4 Sec. 12, T2N, R37W	10,855	8.8
NE01171	Kugler Dam/Miller Reservoir	S1/2NW1/4 Sec. 32 T3N R31W	88,811	71.9
NE01290	Meents Dam	SE1/4Ne1/4 Sec. 28, T3N, R9W	14,308	11.6
NE01311	Cole Dam	S1/2SE1/4 Sec. 30, T8N, R28W	198,591	160.9
NE01316	Hueftle Reservoir	SE1/4SW1/4 Sec. 19, T8N, R24W	42,678	34.6
NE01337	Ford Reservoir	SW1/4Sw1/4 Sec. 25, T7N, R23W	43,172	35.0
NE01357	Bantam-Coe Reservoir	SE1/4SW1/4 Sec. 23, T1N, R19W	9,868	8.0
NE01468	Felker Dam	SW1/4SW1/4 Sec. 32, T7N, R32W	617	0.5
NE01485	Harms Reservoir	NE1/4SW1/4 Sec. 9, T10N, R35W	1,233	1.0
NE01492	Matheny Reservoir	NW1/4SE1/4 Sec. 26, T1N, R27W	0	0.0

Appendix B. Information Used to Describe the Typical Small Non-Federal Reservoir Characteristics at Each Weather Station.

NOAA Weather Stn. ID:	258320		257070		253595		253910		250640		145856		251415	
Station:	Superior, NE		Red Cloud, NE		Harlan Co. Lake, NE		Holdrege, NE		Beaver City, NE		Norton 9 SSE, KS		Cambridge, NE	
Percent of Area Above	11.2		10.9		7.8		7.2		19.8		28.9		21.8	
Terraces, 65% of Total	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of
Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use
	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced
Continuous Rowcrop	31.3	52.9	14.4	52.8	17.4	14.1	21.6	6.5	14.3	18.6	8.0	28.7	13.9	25.8
Continuous Wheat	8.2	13.4	3.3	4.4	3.8	7.2	1.8	4.5	11.5	15.1	12.6	18.2	6.5	12.5
Wheat-Corn-Fallow	2.4	3.9	1.8	2.4	3.3	6.3	1.0	2.4	9.9	13.1	17.2	24.8	8.9	17.0
Wheat-Fallow	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.3	0.4	1.4	2.0	0.7	1.4
Hay & Forage	0.5	0.1	1.7	2.2	0.5	0.4	0.4	0.7	1.2	0.1	0.3	0.1	0.4	0.1
Range/Pasture	52.8	17.3	67.1	21.2	58.0	25.1	43.0	24.8	49.0	23.7	55.9	21.7	58.2	21.2
Irrigated Rowcrop	4.8	12.5	11.7	17.1	16.8	46.7	32.2	61.2	13.8	29.1	4.6	4.6	11.3	22.0
Total	100.001	27.5%	100.001	24.0%	100.001	25.4%	99.999	31.9%	100	21.3%	100	21.2%	100	20.8%
Typical Reservoir														
Drainage Area, Acres	950		950		900		875		875		875		800	
Acres in Drainage Area														
No Terraces														
Continuous Rowcrop	297	0	137	0	156	0	189	0	125	0	70	0	111	0
Continuous Wheat	78	0	31	0	34	0	16	0	100	0	110	0	52	0
Wheat-Corn-Fallow - 1	8	0	6	0	10	0	3	0	29	0	50	0	24	0
Wheat-Corn-Fallow - 2	8	0	6	0	10	0	3	0	29	0	50	0	24	0
Wheat-Corn-Fallow - 3	7	0	5	0	10	0	2	0	29	0	50	0	23	0
Wheat-Fallow - 1	0	0	0	0	0	0	0	0	1	0	6	0	3	0
Wheat-Fallow - 2	0	0	0	0	1	0	0	0	2	0	6	0	3	0
Hay & Forage	5	0	16	0	5	0	3	0	11	0	3	0	3	0
Range/Pasture	501	0	637	0	522	0	376	0	429	0	489	0	466	0
Irrigated Rowcrop	46	0	112	0	151	0	282	0	121	0	41	0	90	0
Total	950	0	950	0	899	0	874	0	876	0	875	0	799	0
Terrace Type, %														
Level, closed, Broad	5.7		38.6		63.5		66.5		72		72.1		73.3	
Level, closed, Flat	0.1		1		3.6		4.3		6.9		7		9.1	
Level, open Broad	1.0		6.7		11		11.5		12.4		12.5		12.7	
Level, open Flat	0.0		0		0.1		0.1		0.2		0.2		0.3	
Graded, Broad	93.3		53.6		21.8		17.6		8.5		8.3		4.6	
Total	100		99.9		100		100		100		100.1		100	
Acres in Drainage Area		Land Above		Land Above		Land Above		Land Above		Land Above		Land Above		Land Abov
With Terraces	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace
Continuous Rowcrop	195	102	90	47	142	14	181	8	110	15	57	13	92	19
Continuous Wheat	71	7	30	1	32	2	16	0	90	10	97	13	48	4
Wheat-Corn-Fallow - 1	8	0	6	0	10	0	3	0	27	2	42	8	21	3
Wheat-Corn-Fallow - 2	8	0	6	0	10	0	3	0	27	2	42	8	21	3
Wheat-Corn-Fallow - 3	7	0	5	0	10	0	2	0	27	2	42	8	20	3
Wheat-Fallow - 1	0	0	0	0	0	0	0	0	1	0	6	0	3	0
Wheat-Fallow - 2	0	0	0	0	1	0	0	0	2	0	6	0	3	0
Hay & Forage	5	0	16	0	5	0	3	0	11	0	3	0	3	0
Range/Pasture	445	56	549	88	437	85	315	61	363	66	420	69	402	64
Irrigated Rowcrop	42	4	100	12	105	46	170	112	98	23	40	1	77	13
Total	781	169	802	148	752	147	693	181	756	120	755	120	690	109
	950	17.8%	950	15.6%	899	16.4%	874	20.7%	876	13.7%	875	13.7%	799	13.6%
Weighted														
POTYLDR Runoff		0.95		0.87		0.81		0.80		0.79		0.79		0.78
Adjustment Factor														
Typical Reservoir														
Characteristics:														
Volume at PS, acre-feet:	60		60		58		56.9		56.7		56.9		53.2	
Depth at PS, feet:	14.8		14.8		14.9		15		15		15		15.2	
Surf. Area at PS, acres:	11.9		11.9		11.3		10.9		11		11		10.1	
Side slope ___:1:	23.6		23.6		22.9		22.2		22.2		22.2		21	
Bottom width, feet:	20		20		20		25		25		25		25	
Bottom length, feet:	20		20		20		25		25		25		25	
Min. seep rate, in./day:	0.1		0.1		0.1		0.1		0.1		0.1		0.1	
Max. seep rate, in./day:	1.2		1.2		1.2		1.2		1.2		1.2		1.2	
	0.76		0.76		0.77		0.78		0.78		0.78		0.80	
Runoff Curve No. Adj.	Runoff Curve Number Comparison Example					Approximate Terrace								
Factor by Terrace type		Unterraced	Terraced			Reduction in Runoff, %								
Level, closed, Broad	0.75	72	54			75								
Level, closed, Flat	0.73	72	53			85								
Level, open Broad	0.90	72	65			50								
Level, open Flat	0.88	72	63			60								
Graded, Broad	0.96	72	69			15								

NOAA Weather Stn. ID:	142213		145906		252100		255310		252065		253690		258628	
Station:	Dresden, KS		Oberlin 1E, KS		Curtis 3 NNE, NE		McCook, NE		Culbertson, NE		Hayes Center, NE		Trenton Dam, NE	
Percent of Area Above	29.8		28.7		8.2		19.7		17.1		6.3		19.0	
Terraces, 65% of Total	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of
Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use
	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced
Continuous Rowcrop	0.0	15.0	4.9	26.2	6.8	21.1	3.9	18.6	5.3	16.2	0.0	6.9	1.7	9.6
Continuous Wheat	13.5	22.7	13.9	22.8	3.4	7.8	14.3	21.2	8.9	19.1	4.4	6.8	11.0	18.9
Wheat-Corn-Fallow	18.3	30.9	19.0	31.0	6.9	16.0	19.5	28.8	12.1	26.1	9.0	13.9	22.5	38.8
Wheat-Fallow	1.5	2.5	1.5	2.5	1.7	4.0	1.6	2.3	1.0	2.1	2.2	3.4	5.6	9.6
Hay & Forage	0.9	0.3	1.2	0.0	0.4	0.3	0.3	0.1	0.6	0.0	0.8	0.1	0.3	0.0
Range/Pasture	60.3	27.4	55.0	16.5	71.0	19.2	54.8	17.3	57.0	15.1	64.9	16.4	51.2	20.0
Irrigated Rowcrop	5.5	1.2	4.3	1.0	9.8	31.7	5.5	11.7	15.0	21.3	18.6	52.4	7.8	3.1
Total	100.001	25.3%	100	19.5%	100	19.6%	99.999	19.5%	100	17.6%	100	22.1%	100	22.0%
Typical Reservoir														
Drainage Area, Acres	800		800		800		775		775		700		725	
Acres in Drainage Area														
No Terraces														
Continuous Rowcrop	0	0	40	0	54	0	30	0	41	0	0	0	12	0
Continuous Wheat	108	0	112	0	27	0	111	0	69	0	31	0	80	0
Wheat-Corn-Fallow - 1	49	0	51	0	18	0	50	0	31	0	21	0	54	0
Wheat-Corn-Fallow - 2	49	0	51	0	18	0	50	0	31	0	21	0	54	0
Wheat-Corn-Fallow - 3	49	0	50	0	19	0	51	0	32	0	21	0	55	0
Wheat-Fallow - 1	6	0	6	0	7	0	6	0	4	0	8	0	20	0
Wheat-Fallow - 2	6	0	6	0	7	0	6	0	4	0	8	0	20	0
Hay & Forage	8	0	10	0	4	0	3	0	5	0	5	0	2	0
Range/Pasture	482	0	440	0	568	0	425	0	442	0	454	0	371	0
Irrigated Rowcrop	44	0	35	0	78	0	43	0	117	0	131	0	56	0
Total	801	0	801	0	800	0	775	0	776	0	700	0	724	0
Terrace Type, %														
Level, closed, Broad	73.3		73.2		73.3		72.9		72.1		71.2		71.1	
Level, closed, Flat	10.8		11.5		11.2		12.2		13.7		15.2		15.4	
Level, open Broad	12.7		12.6		12.7		12.6		12.5		12.3		12.3	
Level, open Flat	0.3		0.4		0.3		0.4		0.4		0.5		0.5	
Graded, Broad	2.9		2.3		2.5		1.9		1.2		0.8		0.7	
Total	100		100		100		100		99.9		100		100	
Acres in Drainage Area		Land Above		Land Above		Land Above		Land Above		Land Above		Land Above		Land Abov
With Terraces	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace
Continuous Rowcrop	0	0	33	7	47	7	26	4	37	4	0	0	11	1
Continuous Wheat	92	16	95	17	26	1	96	15	60	9	30	1	70	10
Wheat-Corn-Fallow - 1	39	10	41	10	16	2	41	9	26	5	19	2	40	14
Wheat-Corn-Fallow - 2	39	10	41	10	16	2	41	9	26	5	19	2	40	14
Wheat-Corn-Fallow - 3	39	10	40	10	17	2	41	10	27	5	19	2	41	14
Wheat-Fallow - 1	6	0	6	0	7	0	6	0	4	0	8	0	19	1
Wheat-Fallow - 2	6	0	6	0	7	0	6	0	4	0	8	0	19	1
Hay & Forage	8	0	10	0	4	0	3	0	5	0	5	0	2	0
Range/Pasture	396	86	393	47	497	71	377	48	399	43	406	48	323	48
Irrigated Rowcrop	44	0	35	0	62	16	40	3	101	16	86	45	55	1
Total	669	132	700	101	699	101	677	98	689	87	600	100	620	104
	801	16.5%	801	12.6%	800	12.6%	775	12.6%	776	11.2%	700	14.3%	724	14.4%
Weighted														
POTYLDR Runoff		0.77		0.77		0.77		0.77		0.77		0.77		0.77
Adjustment Factor														
Typical Reservoir														
Characteristics:														
Volume at PS, acre-feet:	50.4		50.4		47.9		47.9		44.5		44.5		44.5	
Depth at PS, feet:	15.4		15.4		15.5		15.5		15.8		15.8		15.8	
Surf. Area at PS, acres:	9.7		9.7		9.3		9.3		8.5		8.5		8.5	
Side slope ___:1:	20.6		20.6		20.5		20.5		19.2		19.2		19.2	
Bottom width, feet:	10		10		0		0		0		0		0	
Bottom length, feet:	15		15		0		0		0		0		0	
Min. seep rate, in./day:	0.1		0.1		0.1		0.1		0.1		0.1		0.1	
Max. seep rate, in./day:	1.2		1.2		1.2		1.2		1.2		1.2		1.2	
	0.76		0.76		0.72		0.74		0.69		0.76		0.74	

Determination of Land U:	USE SAME AS Trenton Dam													
NOAA Weather Stn. ID:	140439		141699		258920		141029		250760		255090		254110	
Station:	Atwood 2SW, KS		Colby 1SW, KS		Wallace 2W, NE		Brewster 4W, KS		Benkelman, NE		Madrid, NE		Imperial, NE	
Percent of Area Above	23.9		16.9		2.7		13.7		7.5		0.8		1.0	
Terraces, 65% of Total	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of
Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use
	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced
Continuous Rowcrop	1.7	9.6	5.2	20.5	13.9	67.9	0.0	0.1	1.9	9.9	8.9	6.5	0.0	100.0
Continuous Wheat	11.0	18.9	9.3	17.7	2.2	0.6	5.2	6.3	2.3	9.2	12.4	9.6	0.0	0.0
Wheat-Corn-Fallow	22.5	38.8	19.2	36.4	5.9	1.5	14.1	17.0	6.0	24.6	25.5	19.8	0.0	0.0
Wheat-Fallow	5.6	9.6	4.7	9.0	5.9	1.5	14.1	17.1	6.1	24.7	6.3	4.9	0.0	0.0
Hay & Forage	0.3	0.0	0.4	0.1	0.7	0.0	0.8	0.1	0.5	0.0	0.1	0.0	1.2	0.0
Range/Pasture	51.2	20.0	48.0	15.9	62.0	28.5	40.6	18.0	60.5	16.7	23.3	9.8	65.1	0.0
Irrigated Rowcrop	7.8	3.1	13.2	0.4	9.5	0.0	25.2	41.4	22.7	14.8	23.5	49.4	33.7	0.0
Total	100	22.0%	100	17.8%	100.001	27.3%	100.001	22.9%	100	16.9%	100.001	21.0%	100	0.0%
Typical Reservoir														
Drainage Area, Acres	725		725		700		675		675		675		650	
Acres in Drainage Area														
No Terraces														
Continuous Rowcrop	12	0	38	0	97	0	0	0	13	0	60	0	0	0
Continuous Wheat	80	0	68	0	15	0	35	0	15	0	84	0	0	0
Wheat-Corn-Fallow - 1	54	0	46	0	14	0	32	0	14	0	57	0	0	0
Wheat-Corn-Fallow - 2	54	0	46	0	14	0	32	0	14	0	57	0	0	0
Wheat-Corn-Fallow - 3	55	0	47	0	13	0	31	0	13	0	58	0	0	0
Wheat-Fallow - 1	20	0	17	0	21	0	48	0	20	0	21	0	0	0
Wheat-Fallow - 2	20	0	17	0	20	0	47	0	21	0	22	0	0	0
Hay & Forage	2	0	3	0	5	0	5	0	3	0	1	0	8	0
Range/Pasture	371	0	348	0	434	0	274	0	409	0	157	0	423	0
Irrigated Rowcrop	56	0	96	0	66	0	170	0	153	0	158	0	219	0
Total	724	0	726	0	699	0	674	0	675	0	675	0	650	0
Terrace Type, %														
Level, closed, Broad	71		71		70.2		68.6		68		68		67.3	
Level, closed, Flat	15.6		15.6		16.7		18.7		19.4		19.4		20.3	
Level, open Broad	12.3		12.3		12.1		11.9		11.8		11.8		11.6	
Level, open Flat	0.5		0.5		0.5		0.6		0.6		0.6		0.6	
Graded, Broad	0.7		0.7		0.5		0.2		0.2		0.2		0.1	
Total	100.1		100.1		100		100		100		100		99.9	
	USE SAME AS Trenton Dam													
Acres in Drainage Area		Land Above		Land Above		Land Above		Land Above		Land Above		Land Above		Land Abov
With Terraces	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace
Continuous Rowcrop	11	1	33	5	54	43	0	0	12	1	57	3	0	0
Continuous Wheat	70	10	60	8	15	0	34	1	14	1	79	5	0	0
Wheat-Corn-Fallow - 1	40	14	35	11	14	0	28	4	12	2	50	7	0	0
Wheat-Corn-Fallow - 2	40	14	35	11	14	0	28	4	12	2	50	7	0	0
Wheat-Corn-Fallow - 3	41	14	36	11	13	0	28	3	11	2	51	7	0	0
Wheat-Fallow - 1	19	1	16	1	21	0	43	5	17	3	20	1	0	0
Wheat-Fallow - 2	19	1	16	1	20	0	42	5	18	3	21	1	0	0
Hay & Forage	2	0	3	0	5	0	5	0	3	0	1	0	8	0
Range/Pasture	323	48	312	36	353	81	242	32	364	45	147	10	423	0
Irrigated Rowcrop	55	1	96	0	66	0	124	46	138	15	107	51	219	0
Total	620	104	642	84	575	124	574	100	601	74	583	92	650	0
	724	14.4%	726	11.6%	699	17.7%	674	14.8%	675	11.0%	675	13.6%	650	0.0%
Weighted														
POTYLDR Runoff		0.77		0.77		0.77		0.77		0.77		0.77		0.76
Adjustment Factor														
Typical Reservoir														
Characteristics:														
Volume at PS, acre-feet:	44.5		44.5		44.5		42.2		42.2		42.2		40.6	
Depth at PS, feet:	15.8		15.8		15.8		16		16		16		16	
Surf. Area at PS, acres:	8.5		8.5		8.5		7.6		7.6		7.6		7.6	
Side slope ___:1:	19.2		19.2		19.2		17.4		17.4		17.4		18	
Bottom width, feet:	0		0		0		20		20		20		0	
Bottom length, feet:	0		0		0		20		20		20		0	
Min. seep rate, in./day:	0.1		0.1		0.1		0.1		0.1		0.1		0.1	
Max. seep rate, in./day:	1.2		1.2		1.2		1.2		1.2		1.2		1.2	
	0.74		0.74		0.76		0.75		0.75		0.75		0.75	

Determination of Land Use Distribution in Typical Reservoir Drainage Area Without an							Use Wray		Use Wray		Use Flagler		Use Akron	
NOAA Weather Stn. ID:	**143153**		**147093**		**059243**		**054082**		**054242**		**051121**		**057515**	
Station:	Goodland WSO, KS		St. Francis, KS		Wray, CO		Holyoke, CO		Idalia 4NNE, CO		Burlington, CO		Sedgwick 5S, CO	
Percent of Area Above	8.5		9.2		2.9		1.8		3.7		4.7		8.6	
Terraces, 65% of Total	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of
Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use
	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced
Continuous Rowcrop	0.0	6.0	0.0	31.0	0.0	98.9	0.0	98.9	0.0	98.9	0.9	7.0	2.9	0.0
Continuous Wheat	7.4	10.8	2.4	7.0	0.0	0.0	0.0	0.0	0.0	0.0	8.7	40.7	0.5	5.8
Wheat-Corn-Fallow	19.9	29.1	6.3	18.9	0.0	0.0	0.0	0.0	0.0	0.0	17.8	35.3	0.0	15.6
Wheat-Fallow	19.9	29.2	6.3	18.9	0.0	0.0	0.0	0.0	0.0	0.0	4.4	1.0	15.2	15.6
Hay & Forage	0.0	0.0	0.0	0.0	1.1	0.0	1.1	0.0	1.1	0.0	2.2	0.4	0.6	0.4
Range/Pasture	30.7	14.1	71.9	15.0	86.4	1.1	86.4	1.1	86.4	1.1	62.9	13.9	80.2	62.7
Irrigated Rowcrop	22.1	10.8	13.1	9.2	12.4	0.0	12.4	0.0	12.4	0.0	3.1	1.6	0.6	0.0
Total	100.001	19.1%	100	14.5%	99.999	1.0%	99.999	1.0%	99.999	1.0%	100	18.7%	100	52.7%
Typical Reservoir														
Drainage Area, Acres	625		575		500		500		500		500		500	
Acres in Drainage Area														
No Terraces														
Continuous Rowcrop	0	0	0	0	0	0	0	0	0	0	5	0	15	0
Continuous Wheat	46	0	14	0	0	0	0	0	0	0	44	0	3	0
Wheat-Corn-Fallow - 1	41	0	12	0	0	0	0	0	0	0	30	0	0	0
Wheat-Corn-Fallow - 2	41	0	12	0	0	0	0	0	0	0	30	0	0	0
Wheat-Corn-Fallow - 3	42	0	12	0	0	0	0	0	0	0	29	0	0	0
Wheat-Fallow - 1	62	0	18	0	0	0	0	0	0	0	11	0	38	0
Wheat-Fallow - 2	62	0	18	0	0	0	0	0	0	0	11	0	38	0
Hay & Forage	0	0	0	0	6	0	6	0	6	0	11	0	3	0
Range/Pasture	192	0	413	0	432	0	432	0	432	0	315	0	401	0
Irrigated Rowcrop	138	0	75	0	62	0	62	0	62	0	16	0	3	0
Total	624	0	574	0	500	0	500	0	500	0	502	0	501	0
Terrace Type, %														
Level, closed, Broad	66.8		66		62.4		61.8		62.1		62.1		59.9	
Level, closed, Flat	20.9		21.8		25.9		26.6		26.3		26.3		28.9	
Level, open Broad	11.5		11.4		10.8		10.7		10.7		10.7		10.3	
Level, open Flat	0.6		0.7		0.8		0.8		0.8		0.8		0.9	
Graded, Broad	0.1		0.1		0		0		0		0		0	
Total	99.9		100		99.9		99.9		99.9		99.9		100	
Acres in Drainage Area		Land Above		Land Above		Land Above		Land Above		Land Above		Land Above		Land Abov
With Terraces	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace
Continuous Rowcrop	0	0	0	0	0	0	0	0	0	0	5	0	15	0
Continuous Wheat	43	3	13	1	0	0	0	0	0	0	32	12	3	0
Wheat-Corn-Fallow - 1	33	8	11	1	0	0	0	0	0	0	23	7	0	0
Wheat-Corn-Fallow - 2	33	8	11	1	0	0	0	0	0	0	23	7	0	0
Wheat-Corn-Fallow - 3	34	8	11	1	0	0	0	0	0	0	22	7	0	0
Wheat-Fallow - 1	50	12	16	2	0	0	0	0	0	0	11	0	34	4
Wheat-Fallow - 2	50	12	16	2	0	0	0	0	0	0	11	0	34	4
Hay & Forage	0	0	0	0	6	0	6	0	6	0	11	0	3	0
Range/Pasture	174	18	373	40	429	3	429	3	429	3	287	28	238	163
Irrigated Rowcrop	128	10	71	4	62	0	62	0	62	0	16	0	3	0
Total	545	79	522	52	497	3	497	3	497	3	441	61	330	171
	624	12.7%	574	9.1%	500	0.6%	500	0.6%	500	0.6%	502	12.2%	501	34.1%
Weighted														
POTYLDR Runoff		0.76		0.76		0.76		0.76		0.76		0.76		0.76
Adjustment Factor														
Typical Reservoir														
Characteristics:														
Volume at PS, acre-feet:	36.2		36.2		31.7		31.7		31.7		31.7		31.7	
Depth at PS, feet:	16		16		16.2		16.2		16.2		16.2		16.2	
Surf. Area at PS, acres:	6.8		6.8		5.9		5.9		5.9		5.9		5.9	
Side slope ___:1:	17		17		15.6		15.6		15.6		15.6		15.6	
Bottom width, feet:	0		0		0		0		0		0		0	
Bottom length, feet:	0		0		0		0		0		0		0	
Min. seep rate, in./day:	0.1		0.1		0.1		0.1		0.1		0.1		0.1	
Max. seep rate, in./day:	1.2		1.2		1.2		1.2		1.2		1.2		1.2	
	0.70		0.76		0.76		0.76		0.76		0.76		0.76	

Determination of Land U	**Use Wray**		**Use Wray**								
NOAA Weather Stn. ID:	**054380**		**059295**		**052932**		**050109**				
Station:	Joes 2SE, CO		Yuma, CO		Flagler 2NW, CO		Akron 4E, CO				
Percent of Area Above	1.7		2.9		5.0		5.4				
Terraces, 65% of Total	Total	Percent of	Total	Percent of	Total	Percent of	Total	Percent of			
Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use	Land Use			
	Percent	Terraced	Percent	Terraced	Percent	Terraced	Percent	Terraced			
Continuous Rowcrop	0.0	98.9	0.0	98.9	0.9	7.0	2.9	0.0			
Continuous Wheat	0.0	0.0	0.0	0.0	8.7	40.7	0.5	5.8			
Wheat-Corn-Fallow	0.0	0.0	0.0	0.0	17.8	35.3	0.0	15.6			
Wheat-Fallow	0.0	0.0	0.0	0.0	4.4	1.0	15.2	15.6			
Hay & Forage	1.1	0.0	1.1	0.0	2.2	0.4	0.6	0.4			
Range/Pasture	86.4	1.1	86.4	1.1	62.9	13.9	80.2	62.7			
Irrigated Rowcrop	12.4	0.0	12.4	0.0	3.1	1.6	0.6	0.0			
Total	99.999	1.0%	99.999	1.0%	100	18.7%	100	52.7%			
Typical Reservoir									Min	Max	Avg
Drainage Area, Acres	500		500		500		500		500	950	691
Acres in Drainage Area											
No Terraces											
Continuous Rowcrop	0	0	0	0	5	0	15	0			
Continuous Wheat	0	0	0	0	44	0	3	0			
Wheat-Corn-Fallow - 1	0	0	0	0	30	0	0	0			
Wheat-Corn-Fallow - 2	0	0	0	0	30	0	0	0			
Wheat-Corn-Fallow - 3	0	0	0	0	29	0	0	0			
Wheat-Fallow - 1	0	0	0	0	11	0	38	0			
Wheat-Fallow - 2	0	0	0	0	11	0	38	0			
Hay & Forage	6	0	6	0	11	0	3	0			
Range/Pasture	432	0	432	0	315	0	401	0			
Irrigated Rowcrop	62	0	62	0	16	0	3	0			
Total	500	0	500	0	502	0	501	0			
Terrace Type, %											
Level, closed, Broad	58.6		57.9		54.4		53.7				
Level, closed, Flat	30.3		31.1		35.1		35.9				
Level, open Broad	10.1		10		9.4		9.3				
Level, open Flat	0.9		1		1.1		1.1				
Graded, Broad	0		0		0		0				
Total	99.9		100		100		100				
Acres in Drainage Area			Land Above		Land Above		Land Above				
With Terraces	Unterrd	Unterrd	Terrace	Unterrd	Terrace	Unterrd	Terrace	Unterrd			
Continuous Rowcrop	0	0	0	0	5	0	15	0			
Continuous Wheat	0	0	0	0	32	12	3	0			
Wheat-Corn-Fallow - 1	0	0	0	0	23	7	0	0			
Wheat-Corn-Fallow - 2	0	0	0	0	23	7	0	0			
Wheat-Corn-Fallow - 3	0	0	0	0	22	7	0	0			
Wheat-Fallow - 1	0	0	0	0	11	0	34	4			
Wheat-Fallow - 2	0	0	0	0	11	0	34	4			
Hay & Forage	6	0	6	0	11	0	3	0			
Range/Pasture	429	3	429	3	287	28	238	163			
Irrigated Rowcrop	62	0	62	0	16	0	3	0			
Total	497	3	497	3	441	61	330	171			
	500	0.6%	500	0.6%	502	12.2%	501	34.1%			
Weighted											
POTYLDR Runoff		0.76		0.76		0.76		0.76			
Adjustment Factor											
Typical Reservoir											
Characteristics:									Min	Max	Avg
Volume at PS, acre-feet:	31.7		31.7		31.7		31.7		32	60	43
Depth at PS, feet:	16.2		16.2		16.2		16.2		15	16	16
Surf. Area at PS, acres:	5.9		5.9		5.9		5.9		6	12	8
Side slope ___:1:	15.6		15.6		15.6		15.6		16	24	19
Bottom width, feet:	0		0		0		0		0	25	8
Bottom length, feet:	0		0		0		0		0	25	8
Min. seep rate, in./day:	0.1		0.1		0.1		0.1		0.10	0.10	0.10
Max. seep rate, in./day:	1.2		1.2		1.2		1.2		1.20	1.20	1.20
	0.76		0.76		0.76		0.76		0.69	0.80	0.75

Appendix C. Summary of Characteristics of the Surveyed Terrace.

Summary of Broad-Base Terraces.

County	Total Field Area (ac)	Number Of Terraces	Average Terrace Area (ac)	Average Internal Terrace Area (ac)	Average Terrace Length (ft)	Field Slope (%)	Average Terrace Spacing (ft)	Average Vertical Interval (ft)	Terrace Type	Terrace Condition	Terrace Id	Maximum Storage Volume (ft^3)	Runoff Needed To Fill Terrace (In)	Maximum Unbreached Terrace Volume (ft^3)	Runoff Needed To Fill Terrace If Unbreached (In)
Cheyenne	15.7	4	3.4	3.52	1100.4	7.25	138.7	9.8	broad-base closed	excellent	2	14887.0	1.11	14887.0	1.11
											4	807.9	0.07	4707.3	0.41
Cheyenne	7.0	78.9	8.0	5.55	1614.4	1.86	272.6	4.1	broad-base partial closure	good	2	16500.9	0.46	16500.9	0.46
											4	11353.7	0.27	11353.7	0.27
Decatur	3.0	45.1	8.6	1.39	1711.2	1.35	280.2	3.0	partical closure	poor	1	17767.4	0.48	34979.2	0.94
Frontier	48.6	10	3.96	4.21	1570.2	3.15	104.4	3.5	broad-base closed	good	3	2050.5	0.28	5167.2	0.71
											6	1782.5	0.26	4432.9	0.65
											9	14151.8	0.95	30727.7	2.06
Frontier	27.1	11	2.20	2.24	1046.4	4.70	93.7	4.3	old broad-base partial closure	non-functional	3	3673.8	0.60	8683.4	1.42
											6	10088.6	1.10	12442.9	1.36
											9	1075.7	0.15	4632.2	0.65
Frontier	22.3	8	2.16	2.29	992.5	4.51	100.7	4.3	broad-base	non-functional	2	0.0	0.00	3293.3	0.31
Frontier	30.5	3	6.44	6.44	1844.3	3.55	205.1	5.4	broad-base partial closure	poor	1	NA	NA	7711.3	0.70
Frontier	52.6	11	3.85	4.14	1307.7	2.96	135.0	3.8	broad-base closed	excellent	3	31342.3	3.32	31342.3	3.32
											6	23806.8	1.44	23806.8	1.44
											9	15985.6	0.91	53258.7	3.04
Furnas	77.6	12	5.80	6.57	1332.7	4.58	147.5	8.7	broad-base	excellent	3	18682.6	1.03	18682.6	1.03

									(except terrace 12 - steep backslope) partial closure		6	19547.3	0.73	30749.7	1.14
											9	5561.5	0.44	17413.5	1.37
Furnas	126.4	13	6.40	6.39	1980.4	3.06	132.8	4.3	broad-base partial closure	poor	3	14136.1	0.67	18082.1	0.86
											6	NA	NA	13725.5	0.38
											9	19889.6	0.54	30322.0	0.82
Furnas	13.9	3	2.35	2.60	1047.5	3.70	102.4	3.6	broad-base closed	excellent	2	13692.1	1.26	15917.8	1.47
Furnas	21.4	2	5.14	4.86	2068.1	2.79	102.3	3.0	broad-base partial closure	poor	2	19738.3	1.00	40091.2	2.04
Furnas	56.6	2	2.39	1.08	691.7	2.04	68.2	3.1	-	-	1	930.3	0.07	6731.3	0.50
Furnas	57.7	9	5.30	5.69	1650.3	2.84	148.3	4.0	broad-base partial closure	poor to non-functional	2	191.9	0.01	3391.4	0.23
											7	2503.3	0.09	13440.0	0.47
Furnas	29.9	10	2.40	2.53	761.3	2.83	145.3	3.9	broad-base partial closure	good	2	1520.2	0.18	1520.2	0.18
											4	740.9	0.06	2340.8	0.18
											6	635.6	0.11	1830.7	0.31
Furnas	1.79	3	0.49	0.61	439.7	11.20	59.9	5.4	broad-base closed	excellent	2	2743.3	1.49	3170.1	1.72
Furnas	5.75	5	0.58	0.69	421.0	11.50	68.8	6.9	broad-base closed	good	2	399.7	0.21	1334.4	0.70
											4	2389.8	0.81	NA	NA
Furnas	15.2	3	3.29	4.12	1078.0	2.58	166.7	3.4	broad-base closed	excellent	2	21935.2	1.48	25353.7	1.71
Furnas	3.87	1	1.50	0.00	628.6	NA	NA	NA	broad-base partial closure	good	1	0.0	0.00	4222.3	0.78
Furnas	116.5	11	9.10	9.64	2125.6	3.58	194.7	6.7	flat channel partial closure	poor (new terraces in good condition)	3	66953.4	1.95	95770.7	2.79
											6	73978.3	1.59	73978.3	1.59
											9	40515.5	1.32	51240.3	1.67

Furnas	8.73	3	1.64	2.06	779.3	4.23	118.0	3.9	broad-base closed	nearly new or excellent	2	20571.4	3.22	20571.4	3.22
Furnas	19.0	9	1.20	1.52	910.8	9.44	67.0	5.6	broad-base closed	good	2	979.2	0.29	3116.5	0.92
											5	2091.3	0.25	9078.6	1.09
Furnas	5.13	9	0.51	0.51	250.8	5.43	84.9	4.8	broad-base partial closure	non-functional	4	165.7	0.06	872.2	0.30
Furnas	5.10	6	0.61	0.56	586.4	8.35	58.4	3.8	broad-base partial closure	good	2	4769.9	1.35	11010.9	3.12
Furnas	4.26	3	1.01	1.27	470.6	4.70	115.8	4.4	broad-base partial closure	good	2	191.8	0.06	1343.1	0.39
Furnas	39.0	8	3.46	3.55	1235.5	3.29	128.8	4.0	broad-base partial closure	poor	2	1793.9	0.09	10298.6	0.51
											5	78.1	0.01	3957.7	0.33
Furnas	8.49	2	3.67	0.00	1361.7	4.65	162.5	5.5	closed	nearly new or excellent	1	14706.3	1.79	14706.3	1.79
Furnas	43.0	13	2.40	2.38	957.7	3.88	113.9	4.2	broad-base partial closure	good	3	2068.6	0.15	4403.0	0.32
											6	298.6	0.04	1987.3	0.26
											9	NA	NA	NA	NA
Harlan	75.8	4	12.28	13.43	1932.8	1.04	427.2	2.9	flat channel partial closure	nearly new or excellent	1	150423.5	4.69	170332.7	5.31
											3	248319.4	5.70	270464.8	6.21
Harlan	25.9	5	4.60	4.81	868.0	1.55	226.8	3.6	broad-base partial closure	poor	2	18186.4	1.69	NA	NA
											4	21311.5	0.82	44065.5	1.69
Harlan	9.30	4	1.40	1.71	884.9	10.60	85.8	7.2	-	-	2	1818.1	0.29	5376.3	0.85
											4	2845.3	0.39	3700.3	0.51
Harlan	13.0	1	9.87	0.00	922.7	NA	NA	NA	broad-base partial closure	good	1	0.0	0.00	NA	NA

Harlan	4.70	3	1.08	1.51	672.6	9.49	93.2	6.6	terrace 1&2 - broad-base terrace 3 - gradient grass waterway	good	3	0.0	0.00	NA	NA
Harlan	56.0	4	3.24	3.60	989.8	2.57	156.6	3.7	-	-	2	17201.4	1.75	32133.8	3.28
											4	0.0	0.00	NA	NA
Harlan	35.3	2	14.50	14.54	1819.7	2.21	359.4	4.0	broad-base partial closure	good	1	0.0	0.00	NA	NA
Hayes	85.6	8	NA	7.83	2326.0	NA	NA	4.1	broad-base partial closure	good	3	NA	NA	NA	NA
											6	7187.4	0.50	7187.4	0.50
Hayes	21.3	5	3.14	3.63	1265.5	5.39	117.4	5.8	broad-base partial closure	excellent to good	2	4732.5	0.50	13482.3	1.42
											4	1414.8	0.09	29532.0	1.77
Red Willow	102.3	9	9.80	9.17	2294.0	1.91	199.9	3.6	broad-base partial closure	good	3	42393.0	1.75	1999.9	2.73
											5	20059.5	0.55	1995.2	0.57
Red Willow	26.6	3	6.22	5.41	1265.7	2.95	237.1	6.3	flat channel closed	excellent	2	34675.8	1.44	59349.4	2.46
Red Willow	60.8	10	2.93	3.11	1179.5	3.41	130.3	3.7	broad-base partial closure	poor	3	482.3	0.05	2744.6	0.26
Red Willow	112.1	23	4.13	4.24	1436.6	2.81	128.3	3.5	broad-base partial closure	good	3	38496.4	2.16	38496.4	2.16
											6	12104.7	1.28	12104.7	1.28
											9	2791.2	0.21	16053.1	1.23
Red Willow	33.8	8	3.51	3.83	1357.6	3.15	132.1	3.5	broad-base partial closure	good	2	6430.1	0.53	8328.1	0.69
											4	3381.6	0.22	8428.9	0.54

Summary of flat-channel terraces.

County	Total Field Area (ac)	Number Of Terraces	Average Terrace Area (ac)	Average Internal Terrace Area (ac)	Average Terrace Length (ft)	Field Slope (%)	Average Terrace Spacing (ft)	Average Vertical Interval (ft)	Terrace Type	Terrace Condition	Terrace Id	Maximum Storage Volume (ft^3)	Runoff Needed To Fill Terrace (In)	Maximum Unbreached Terrace Volume (ft^3)	Runoff Needed To Fill Terrace If Unbreached (In)
Phillips	63.4	5	7.8	7.7	1260	1.61%	351	4.2	flat channel	good	2	49420	1.21	49420	1.21
											4	13619	0.61	13619	0.61
Cheyenne	85.9	4	9.8	13.4	1761	1.42%	249	4.4	flat channel	excellent	1	50137	1.37	50137	1.37
											4	44452	0.95	44452	0.95
Decatur	72.3	5	11.1	11.2	1958	1.94%	274	5.2	flat channel	excellent	2	170766	2.13	170766	2.13
											4	398	0.03	398	0.03
Decatur	51.7	7	4.8	4.8	1198	2.99%	259	5.5	flat channel	good	3	26975	1.42	26975	1.42
											6	79782	2.02	79782	2.02
Decatur	79.4	5	11.9	13.0	1877	1.51%	312	4.2	flat channel	good	2	58226	0.88	58226	0.88
											4	20687	0.63	20687	0.63
Decatur	87.4	9	8.1	8.1	2556	2.37%	136	3.5	flat channel	excellent	2	25321	0.81	25321	0.81
									broad-base		6	23369	0.73	23369	0.73
									broad-base		9	10564	1.10	10564	1.10
Decatur	32.6	5	4.0	4.0	909	2.22%	248	5.2	flat channel	good	2	9549	0.58	9549	0.58
											4	17980	0.91	17980	0.91
Rawlins	48.4	5	6.8	7.2	1412	4.35%	246	9.1	flat channel	excellent	2	28860	1.08	28860	1.08
											4	87279	2.80	99476	3.19
Rawlins	153.0	3	42.6	0.0	2988	0.71%	609	4.4	flat channel	good	2	130058	0.77	130058	0.77
Rawlins	158.3	9	14.1	15.2	2385	1.11%	265	2.5	flat channel	non-functional	6	32519	0.52	32519	0.52
Frontier	27.0	6	3.3	2.8	896	3.03%	191	5.0	flat	good	3	10586	0.62	28684	1.68

									channel		5	32675	2.89	32675	2.89
Frontier	84.1	9	8.1	7.8	1571	1.94%	243	4.4	flat channel	excellent	2	84925	2.24	84925	2.24
											4	63769	2.36	63769	2.36
											8	58299	1.88	58299	1.88
Hayes	69.6	8	6.0	6.5	1388	2.61%	207	5.3	flat channel	good to excellent	3	39305	2.14	39305	2.14
											6	31457	0.87	54501	1.51
Hitchcock	100.9	7	10.5	11.1	2106	2.28%	226	5.1	flat channel	excellent	3	73187	2.01	143523	3.95
											6	173371	3.38	173371	3.38
Hitchcock	24.3	3	3.2	4.1	815	1.37%	209	2.9	flat channel	poor	2	526	0.04	3933	0.32
Hitchcock	96.4	7	12.4	12.0	2121	3.43%	314	7.4	flat channel	excellent	3	136729	2.97	136729	2.97
											6	119063	2.60	119063	2.60
Hitchcock	54.3	7	6.0	6.5	1060	1.11%	261	2.9	flat channel	good	3	14738	0.56	14738	0.56
											6	13827	0.65	13827	0.65
Hitchcock	48.1	4	7.3	5.5	1075	2.79%	324	6.7	flat channel	poor to good	2	57899	1.06	57899	1.06
											4	15477	1.13	15477	1.13
Red Willow	100.7	7	7.9	8.2	1515	2.68%	243	6.1	flat channel	excellent	3	164348	4.73	164348	4.73
											6	75413	2.41	75413	2.41
											8	62415	2.78	62415	2.78
Red Willow	26.6	3	5.8	4.8	1266	3.73%	210	6.3	flat channel	excellent	2	33834	1.58	57571	2.68