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Review Article

Predicting the Effects of Vegetation Management Practices on Hydrologic Processes of Watersheds in the Colorado River Basin

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Abstract

Water shortages are expected throughout the western regions of the United States in the upcoming decades. The impact of these shortages is anticipated to be severe to the increasing numbers of people in the Colorado River Basin where possible climatic changes could cause a 10 to 30 percent reduction in streamflow volumes (Nash and Gleick 1991, Christensen et al. 2004). Implementing vegetation management practices to increase streamflows from upland watersheds is one of the possible solutions to this situation. The best opportunities for increasing streamflows by these management practices are found in high-elevation coniferous forests and low-elevation sclerophyllous shrublands of the basin. Obtaining predictions of responses of hydrologic processes including changes in streamflow volumes to vegetation management practices in these ecosystems is the focus of this paper. A hypothetical scenario illustrating how these predictions are applied in the Colorado River Basin is also presented.

Keywords: *Colorado River Basin, hydrologic processes, prediction, streamflow increases, vegetation management practices, watersheds.*

INTRODUCTION

The Colorado River Basin continues to be the center of a long history of research efforts leading to predictions of how vegetation management practices effects the hydrologic processes of watersheds including streamflow volumes originating on watersheds. The importance of this research has been learning about the possibilities of improving the availability of water resources in the basin by implementing vegetation management practices on watersheds contributing streamflows to the Colorado River and its tributaries. Knowledge of these research results and the increasing ability to reliably predict the effects of these vegetation management practices on hydrologic processes has helped planners, managers, and other decision-makers to select vegetation management practices for this purpose.

Predicting changes in hydrologic processes on watersheds in the Colorado River Basin following modifications of vegetation on the watersheds is the theme of this paper. The cumulative effects of these changes are reflected by changes in streamflow regimes and, more specifically, streamflow volumes. A research program that continues to be a basis to obtain predictions of increases in streamflow volumes; a procedure for extrapolating these predictions to downstream points of water-use; and a hypothetical scenario to illustrate how the predictions of streamflow increases are applied in the Colorado River Basin are presented in this paper. As a background, however, the general characteristics of the basin are considered below.

Colorado River Basin

The Colorado River drains nearly 650,000 km2 of almost all of the state of Arizona and portions of the states of New Mexico, Colorado, Wyoming, Utah, Nevada, and California before it enters the Gulf of California in Mexico. The total drainage area is separated into the Upper and Lower Basins about 15 km south of the Utah-Arizona border. The Upper Basin contains almost 283,000 km2 of land while the Lower Basin is nearly 364,000 km2 in area. In descending order of the annual precipitation gradients of both basins, forests are located at the high end of the gradient, woodland and shrub communities in the middle range, and desert vegetative-types at the low end. The hydrologic and vegetative characteristics of the two basins are presented in the following paragraphs.

Upper Basin

Annual precipitation in the Upper Basin averages 400 mm with most of the precipitation falling on the high-elevation mountains. Approximately 16 percent of this precipitation is converted into streamflow. Annual streamflows from the Upper Basin into the Lower Basin range from 35 to 165 percent of the long-term average of 1.8 million ha-m of water. Much of this streamflow is concentrated in the months when snow that has accumulated in the mountains melts. The water in the Upper Basin serves nearly 5.1 million people with two-thirds of the available water resources consumed in the agricultural sector.

Subalpine forests of species of spruce (Picea spp.), species of fir (Abies spp.), Douglas-fir (Pseudotsuga menziesi), and lodgepole pine (Pinus contorta) trees occupy 27,900 km2 at elevations of 2,100 to 3,500 m. These high-elevation forest ecosystems receive between 500 and 1,400 mm of annual precipitation with the amount of precipitation on a site dependent on the elevational gradient and local topography. Two-thirds of this precipitation is snowfall. Ponderosa pine (Pinus ponderosa) forests are located on 6,050 km2 of landscape at lower elevations between 1,850 and 2,300 m. Annual precipitation in the ponderosa pine forests averages 380 to 635 mm with one-half snow. Intermingling stands of quaking aspen (Populus tremuloides) are found on 12,900 km2 within the subalpine and ponderosa pine forests.

Mountain brush communities dominated by the shrub-form of Gambel oak (Quercus gambelii) are located on 12,900 km2 at elevations of 1,500 to 3,050 m. Erroneously classified as sclerophyllous shrublands on occasion, mountain brush communities are comprised of species that are deciduous rather than persistent (long-lasting leaves) such as the sclerophyllous shrubs. Annual precipitation in the mountain brush communities ranges from 400 to 600 mm with less than one-half snow. Pinyon-juniper woodlands occupy 50,600 km2 of variable topographies between 1,200 and 2,000 m of elevation. Annual precipitation in these coniferous woodlands is 300 to 450 mm with sites at higher elevations often receiving over 500 mm. Big sagebrush (Artemisia tridentata) communities are found on 104,800 km2 of land at elevations up to 3,000 m in both the Upper and Lower Basins of the Colorado River. These communities receive 200 to 500 mm of precipitation annually.

Lower Basin

The Lower Basin receives an average of 350 mmm of annual precipitation. The portion of this precipitation that becomes streamflow is nearly 6 times less than the precipitation that becomes streamflow in the Upper Basin. The Lower Basin is characterized by a recurring climatic cycle of winter rain or snow, a dry spring, summer rainfall, and a dry fall. Almost 20.6 million people benefit from the water in the Lower Basin with three-fourths of this water consumed in agricultural production in the past. However, there currently are increasing allocations of water to the increasing populations of people that are migrating into this basin.

Mixed conifer forests comprised of spruce, true fir, Douglas-fir, and ponderosa pine trees occupy 1,600 km2 of sites at 2,100 to 3,000 m in elevation that are warmer (but not necessarily drier) than the sites of subalpine forests in the Upper Basin. Annual precipitation in these forests ranges from 630 to 760 mm with one- half or more snow. Ponderosa pine forests are found on 24,000 km2 of landscapes at elevations between 1,800 and 2,700 m. From 500 to 650 mm of annual precipitation falls on the ponderosa pine forests with this precipitation almost equally divided into summer rainfall and winter rain and snow.

Pinyon-juniper woodlands occupy 80,900 km2 at elevations that are similar to those of the pinyon-juniper woodlands in the Upper Basin. Summer rains account for more than one-half of the 300 to 450 mm of annual precipitation in these ecosystems with only occasional snowfall. Sclerophyllous shrublands cover 14,200 km2 of the basin. Sonoran scrub oak (Quercus turbinella) represents 90 percent or more of the shrub species on most sites. Sclerophyllous communities are almost exclusively limited to the Lower Basin, are found at elevations of 890 to 2,000 m, and are dominated by shrub species that sprout prolifically after cutting or burning. Annual precipitation in the sclerophyllous shrublands ranges from 380 mm at lower elevations to 650 mm at higher elevations. A total area of nearly 144,900 km2 are ecosystems of either northern desert shrubs dominated by big sagebrush (Artemisia tridentata) at elevations of 750 to 1,500 m or compositions of southern desert shrub species at elevations of 45 to 900 m. Average precipitation in the northern desert shrub ecosystems is 250 mm annually while that in the southern shrub ecosystems averages 150 mm a year.

MATERIAL & METHODES

To obtain reliable predictions of the effects of vegetation management practices on the hydrologic process of watersheds in the Colorado River Basin has required a continuing research program of plot studies, watershed-level investigations, and the development of hydrologic simulators capable of generating these predictions for a wide range of watershed conditions. The results obtained from the plot studies provide a knowledge base relating to the functioning of hydrologic process on small homogeneous sites and the effects of vegetative modifications on these hydrologic processes. These results continue to be combined to form a planning basis for implementing watershed-level investigations. Applications of hydrologic simulators developed for use in the basin are a primary basis for watershed management to predict how hydrologic processes change on a watershed-scale in response to changes in the vegetative structures on watersheds of varying conditions.

Plot Studies

Small plot studies throughout the Colorado River Basin have shown repeatedly that modifications of vegetative structures by cutting, prescribed burning treatments, application of herbicides, or combinations of these treatments change the interception, infiltration, and transpiration processes (Ffolliott and Brooks 1996, Neary and Ffolliott 2005). More specifically, reductions in vegetative covers lead to reductions in interception capacities with more precipitation falling to the soil surface. The amount of this throughfall water that infiltrates into the mineral soil is related to the properties of the soil resource including the depth of the litter layer on the surface and its texture, structure, organic content, and the possible presence of impermeable (hydrophobic) layers. Most of the precipitation falling to the soil but not infiltrating into the soil becomes overland flows of water with much of this water flowing into stream channels on a watershed. Transpiration by the vegetation on a watershed is often the largest loss of incoming precipitation in the water budget for a watershed (Satterlund and Adams 1992, Brooks et al. 2003, Chang 2006). These transpiration losses are also reduced by reductions in vegetative biomass with the magnitude of the losses related to the amount of biomass removed on the plot.

Plot studies have also provided baseline information on the rates of soil erosion that might be expected with natural conditions and following modifications of vegetative structures. While not considered in this paper, knowledge of hillslope soil erosion is a useful to watershed managers in predicting the magnitude of the sedimentation processes on a watershed.

Watershed-Level Investigations

Watershed-level investigations based largely on results from the plots studies have demonstrated that streamflow volumes from experimental watersheds are often increased by modifications of the vegetation on the treated watersheds (Hibbert 1983, Troendle and Kaufmann 1987, Ffolliott and Brooks 1988, Baker and Ffolliott 2000, Ice and Stednick 2004). Opportunities for increasing streamflows in the Colorado River Basin by these modifications are found mostly in the subalpine, mixed conifer, and ponderosa pine forests at the higher elevations of the basin and the sclerophyllous shrublands at lower elevations.

Vegetation management practices to modify the structure of subalpine, mixed conifer, and ponderosa pine forests are silvicultural treatments that completely or partially clear tree overstories on a watershed to create openings of varying size, shape, and orientation; thinning tree overstories to obtained optimal stocking conditions; or are a combination of clearing and thinning treatments. Implementation of these silvicultural treatments on experimental watersheds in these forests has resulted in streamflow increases of 15 to 55 percent depending on site factors on the watersheds and the long-term management strategies on the watersheds. These streamflow increases are attributed to reductions in interception and transpiration losses, increased overland flows of water, and, at higher elevations, increased accumulations of snow in created opening and a more complete melting of these snowpacks. The increases in streamflow volumes are often sustained at some level for 10 to 25 years after the treatments and then decline to pre-treatment levels.

Vegetation management practices that have increased streamflow volumes from experimental watersheds in the sclerophyllous shrublands are conversions of the vegetation types where the comparatively higher water-consuming shrubs are eliminated on a watershed by applications of chemical herbicides, prescribed burning treatments, or combinations of these conversion methods and replaced with lower water-consuming herbaceous plants. The water savings obtained by these vegetative conversions contribute to the increases in streamflow volumes (Hibbert et al.1974, Hibbert 1983). Opportunities for increasing streamflow volumes in these ecosystems are the greatest on the watersheds where the annual precipitation averages 500 mm or more (Hibbert 1979). Streamflow increases ranging from 20 to 50 percent have been observed on these watersheds. Importantly, sclerophyllous shrubs surviving the initial conversion treatments and shrubs re-sprouting following the conversions must be controlled to maintain the increases in streamflow.

Opportunities to increase streamflow volumes by implementing vegetation management practices are less in the pinyon-juniper woodlands because of the lower precipitation amounts and higher evaporation rates in these coniferous ecosystems. Potentials for increasing streamflow by mechanical methods of clearing the tree overstories are negligible (Ffolliott and Brooks 1988, Baker and Ffolliott 2000). Researchers hypothesize that if an increase in streamflow occurs following a clearing treatment, this increase in streamflow is lost because of the increase in transpiration losses by the increase in herbaceous plants. An aerial application of herbicides on one experimental watershed resulted in a small (but statistically significant) increase in streamflow volume. However, applications of many herbicides are environmentally unacceptable in the Colorado River Basin at this time.

There are few opportunities to increase streamflow volumes from watersheds in the mountain brush communities, big sagebrush communities, and desert shrub-types. The combination of sparse shrub overstories, low precipitation amounts, and high evaporation rates in these ecosystems limits the effectiveness of conversion treatments in increasing streamflow.

Applications of Hydrologic Simulators

The results of the watershed-level investigations represent discrete points on a continuum of possible vegetation management practices for increasing streamflow volumes by changing the structure of vegetation on a watershed. However, information on management practices not included in these watershed-level investigations is often required before selecting the most appropriate vegetation management practice for implementation. Information on the "missing management options" along the continuum of possible management practices is often obtained by applying hydrologic simulators. Applications of the hydrologic simulators generate predictions of increases in streamflow following changes in the structure of vegetation within the confidence limits specified by the simulators. Changes in precipitation and temperature regimes are simulated internally because these changes facilitate predictions of the transpiration losses on the watershed. Changes in interception, infiltration, and overland flows of water are also predicted with the cumulative effects of these changes reflecting the changes in the streamflow regimes of the watershed.

One hydrologic simulator that is applied widely in the Colorado River Basin is the Subalpine Water Balance Model (WATBAL) developed originally by Leaf and Brink (1975) for applications in subalpine forests. WATBAL has also undergone a series of modifications to facilitate its use in other vegetative types and conditions in the basin. Developed largely from the results obtained from plot studies and watershed-level investigations, this hydrologic simulator is capable of predicting the effects of a wide array of vegetation management practices on the hydrologic processes of a watershed including streamflow volumes. Included in these predictions are the responses of streamflow to snowmelt-runoff events, rainfall events, and combinations of these streamflow generators. WATBAL has proven useful in obtaining information on the missing management options along the continuum of possible vegetation management practices for increasing streamflow volumes.

Some of the hydrologic simulators capable of generating reliable predictions of changes in streamflow volumes are quite detailed in their formulation, extensive in their input requirements, and complex in their computing procedure. There are few opportunities for the users of these simulators to modify the operating formats. WATBAL is an example of such a simulator. Other hydrologic simulators are structured with input-output interfaces that allow components representing the hydrologic processes of a watershed to be modified or replaced with other components when updated information on these processes becomes available (Rasmussen and Ffolliott 1981, Ffolliott and Guertin 1988, Ffolliott 1998). Supporting databases containing supplemental input values can be accessed when necessary to complete a simulation exercise. These "user-friendly" operating frameworks provide for maximum flexibility in operating the hydrologic simulators to obtain predictions of the effects of vegetation management practices on streamflow volumes.

To describe the structures, computing capacities, and outputs of the hydrologic simulators available for prediction purposes is beyond the scope of this paper. Therefore, the reader is referred to Hann et al. (1982), Singh (1995), or Dunne (2001) to obtain further information on the formulations, applications, and limitations of these simulators.

Predicting the Effects of a Vegetation Managment Practice on Hydrologic Processes in the Basin

Predicting the effects of a vegetation management practice on hydrologic processes including streamflow volumes from watersheds on the Colorado River Basin and then routing the streamflow to downstream points of water-use requires a sequence of steps (Ffolliott and Fogel 2003, Ffolliott 2007). In the first step, the conditions of the experimental watershed on which the prediction of streamflow increase was obtained in a watershed-level investigation or the conditions of the watershed selected in a simulation of the streamflow increase are characterized in terms of ownership status; climatic, physiographic, and vegetative characteristics; and institutional, social, and economic conditions. The silvicultural prescription of the vegetation management practice proposed for implementation is also specified in reference to the size, shape, and orientation of clearing the tree overstory, the intensity of thinning the tree overstory, or the method of converting the vegetative types on the watershed; the predicted increase in streamflow volumes from the management practice; and the benefits and costs associated with the proposed practice.

Areas within the Colorado River Basin that are not limited by the watershed conditions or the conditions specified by the treatment prescription in implementing the vegetation management practice are identified as "treatable areas" in the second step of the procedure. (The "treatable areas" for the array of vegetation management practices with known potentials for increasing streamflow volumes in the Colorado River Basin are almost 9 million ha or about 15 percent of the total area of the basin). The predicted increase in streamflow volume from the vegetation management practice to be implemented is extrapolated to the total of the "treatable areas" for the vegetation management practice with the summation of the predicted increases in streamflow volumes are routed to downstream points of water-use in the final step of the process.

Stream flow routing is a mathematical-based procedure for determining how the magnitude of streamflow volumes change as the stream flows downstream. There are several mathematical procedures available for routing streamflow from upland watersheds to downstream points. The reader of this paper is referred to Singh (1992), Fread (1993), or Wurbs (1997) for information on the algorithms for these routing procedures.

A Prediction Scenario

There are a number of hypothetical scenarios that could be presented to illustrate how the predictions of streamflow increases obtained through modifications of the structures of vegetation on watersheds are applied. That presented by Hibbert (1979) is offered here as one example. Hibbert predicted that streamflow volumes in the Upper Basin of the Colorado River could be increased by 61,650 ha-m or 3.5 percent by treating 20 percent of the vegetative types with known potentials for streamflow increase by implementing vegetation management practices shown to increase the streamflows. One exception to the area to be treated is the aspen forests where 40 percent of the type would be treated. Nearly one-half of the increase in streamflow volumes in the Upper Basin would originate from the high-elevation subalpine forests. More extensive implementations of vegetation management practices would be necessary in the Lower Basin of the Colorado River to obtain an additional 30,825 ha-m or 8 percent increase in streamflow volumes. Almost 90 percent of this predicted increase in streamflow would be obtained by treating one-third of ponderosa pine forests and 20 percent of sclerophyllous shrublands with vegetation management practices shown to increase streamflow.

Not all of the "treatable areas" in either Hibbert's scenario or other scenarios are likely to be homogeneous in their response to a vegetation management practice, and, therefore, the effects of implementing a vegetation management practice on streamflow volumes are not uniform. Watershed managers must also recognize that the predicted streamflow increases are likely to represent the increases obtained with "average precipitation-streamflow regimes" that are not expected to occur every year. Increases in streamflow volumes would be large in some years and small or non-existent in other years depending largely on the variability of annual precipitation. An analysis by Hibbert (1979) indicated that vegetation management practices would increase streamflow volumes to significant levels only on watersheds receiving more than 450 mm of annual precipitation. Residual trees in the overstory and increased presence of herbaceous plants after treatment would consume the precipitation below this amount.

Allowances must also be made for transmission losses in streamflow volumes from the outlet of the watersheds to the downstream points of water-use. Included within these transmission losses are seepage losses of water in the stream channels, evaporation of water from the flowing streams, and consumption of water by the streamside vegetation.

Not all of the "treatable areas" in either Hibbert's scenario or other scenarios could be treated simultaneously because of the large areas that would need to be treated and the operational, economic, and environmental limitations to scheduling large-scale treatments at one time. Therefore, the implementation of the vegetation management practices proposed to increase streamflow volumes from the "treatable areas" must be sequenced in time and space to obtain the most optimal streamflow increases possible. The increases in total streamflow volumes from all of the "treatable areas" would be less (in aggregate) than increases in streamflow from the watersheds as a consequence.

No matter what prediction scenario is considered, the vegetation management practices implemented must be considered within the context of the other ecosystem-based benefits and values on the treated watersheds. Many of the watersheds in the Colorado River Basin are also managed for wood production, livestock grazing, provision of wildlife habitats, and recreational opportunities. Hibbert (1979) also stressed that the costs required to obtain extra water by increasing streamflow volumes from watershed landscapes must be balanced against the costs of alternative approaches to improving the water supply-situation in the basin such as reducing the demands of people for water. Past experience and policy implications indicate that the vegetation management practices implemented for this purpose must also benefit other natural resource values to be economically feasible (Ffolliott and Brooks 1988, Ffolliott et al. 2002, Gregersen et al. 2008). Without these collateral benefits, implementation of vegetation management practices to increase streamflow volumes is likely not to occur.

CONCLUSIONS

A research program of plot studies, watershed-level investigations, and development of hydrologic simulators is the basis to obtain predictions of changes in hydrologic processes following the implementation of vegetation management practices on watersheds in the Colorado River Basin. Of a high priority to watershed managers in the basin is prediction of increases in streamflow volumes. The predicted increase in total streamflow volumes on the "treatable areas" are less than the predicted increases in streamflow from the watersheds, however, because the "treatable areas" are not homogeneous in their responses to a vegetation management practice.

The large areas in the basin to be treated and the operational and economic limitations to scheduling large-scale treatments at one time preclude implementing watershed management practices on all of the "treatable areas" simultaneously. Therefore, it is necessary that the vegetation management practices be sequenced in time and space to obtain the most optimal streamflow increases possible. The increase in total streamflow volumes from all of the "treatable areas" is also less than the increases in streamflow from the watersheds as a consequence. Transmission losses from the "treatable areas" to downstream points also reduce the predicted stream flow increases.

Nevertheless, implementing vegetation management practices on the "treatable areas" within the Colorado River Basins to increase streamflow volumes is one of the solutions to alleviating to some extent the increasing water shortages in the basin.

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