Simulation of the Hydrologic Effects of Afforestation in the Tacuarembó River Basin, Uruguay

N. O. von Stackelberg, G. M. Chescheir, R. W. Skaggs, D. M. Amatya

Abstract. *The Soil and Water Assessment Tool (SWAT) was used to simulate the hydrology of two small paired catchments in northern Uruguay. The control and treatment catchments (69 and 108 ha, respectively) were monitored for a three-year pretreatment period during which the land use was grassland with livestock grazing. Subsequently, the treatment catchment was planted (57% afforested) with loblolly pine (*Pinus taeda*). The objectives of the modeling study were to simulate the hydrologic response of the two catchments during the pretreatment period and predict the hydrologic effects of converting the native pasture to pine plantation. SWAT models of the two catchments were calibrated and validated using data measured during the pretreatment period. The model predicted outflows from the catchments reasonably well as compared to observed outflows during the years with above average rainfall (5% to −13% error). Model efficiency (E) for daily outflow volumes was greater than 0.71, indicating a good fit between simulated and observed results. A 33-year continuous simulation was performed on three land uses: grassland with livestock grazing, grassland without grazing, and pine treatment. The conversion of the catchments from the baseline pasture condition with grazing resulted in a predicted reduction in average annual water yield from the catchments of 15% for native grassland without grazing, and 23% for pine trees. A maximum predicted hydrologic effect was estimated by maximizing the model parameter that increases the ability of pine trees to withdraw water from the ground. For this condition, the model predicted a 30% reduction in mean annual water yield from the afforested catchment.*

Keywords. *Afforestation, Hydrologic modeling, Hydrology, Loblolly pine, SWAT, Uruguay.*

Uruguay is a small country in South America that has 85% of its land mass (176,220 km^2) in agriculture, the highest percentage in the world. The predominant physiography of northern Uruguay is gently rolling hills with natural grassland that is typically free of woody plants (trees and shrubs). The grasslands in Uruguay have historically been used for livestock grazing, as they are productive rangelands for forage. In 1989, the Uruguayan government instituted financial incentives for the establishment of tree plantations in an effort to diversify the rural economy. In response, multinational timber corporations have purchased land and planted trees (primarily eucalyptus, loblolly pine, and slash pine) over significant portions of the landscape. Subsequently, local stakeholders have expressed concerns regarding the environmental impact on water resources of converting land from pasture to tree plantations. Of particular concern are the effects of the tree plantations on water yield and downstream water supply, as well as the impact on baseflows in the receiving streams and rivers.

Previous studies on afforestation conducted in Australia, New Zealand, South Africa, and Great Britain employed a paired catchment approach in which the control catchment remained grass and the treatment catchment was planted with trees. Previous reviews of the results of these studies have shown that the establishment of tree plantations on historical grasslands reduces rainwater yield from the landscape, thereby decreasing water flow to tributary streams and rivers (Hibbert, 1967; Bosch and Hewlett, 1982; Sahin and Hall, 1996; Best et al., 2003). The reduction in water yield has been found to be primarily due to the greater evapotranspiration from trees as compared to grass (Holmes and Sinclair, 1986; Zhang et al., 1999, 2001). One of the most extensive experimental data sets on afforestation, both in number of paired catchments and length of observations, is from South Africa (Scott et al., 2000). The catchments in South Africa with mean annual rainfall and potential evapotranspiration most similar to that of Uruguay are located at the Cathedral Peak Forest Influences Research Station, which has one control catchment of grassland and two treatment catchments of *Pinus patula* (75% and 86% afforested). The mean annual total flow reduction 16 to 20 years after planting was 58% and 45%, respectively, while the mean annual low flow reduction was 63% and 46%, respectively. Based on a comparison of previous studies (von Stackelberg, 2005), it was concluded that the effect on water yield due to afforestation is strongly dependent on the climate characteristics (rainfall and potential evapotranspiration) and catchment characteristics (soil and drainage properties) of the research site. No previous studies of afforestation have been conducted in Uruguay.

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In 1999, researchers at North Carolina State University (NCSU), in cooperation with the Agronomy Faculty at the Universidad de la República in Montevideo, initiated a study to evaluate the long-term impacts of land use conversion from grassland to pine plantation on the hydrologic regime. The field study employs a paired catchment approach to evaluate the small watershed-scale effects of afforestation. The catchments were monitored for a three-year pretreatment period during which the land use in both the control and treatment catchments was grassland with livestock grazing. The treatment catchment was subsequently planted with loblolly pine (*Pinus taeda*) in July 2003, and both catchments will be continuously monitored through tree maturation and harvesting.

The objective of the modeling study reported here was to simulate as closely as possible the hydrologic response of the two catchments during the pretreatment period and to predict the hydrologic effects of converting native grassland to pine plantation on the treatment catchment. Supporting objectives of the research included: (1) improving the understanding of the hydrologic processes occurring on the two catchments, and (2) evaluating the effect of weather variability, vegetative rooting depth, soil properties, and groundwater characteristics on water yield from grass and pine trees. The modeling study was intended to complement the objectives of the long-term field research project.

The Soil and Water Assessment Tool (SWAT), developed and maintained by the USDA at the Blacklands Research and Extension Center in Texas (Arnold et al., 1998), was selected as a suitable tool for simulating the hydrologic conditions of the catchments. SWAT (Version 2000) is a continuous, lumped parameter model that uses physically based and empirical relationships to simulate surface and subsurface flows, tree and crop growth, land management practices, and the fate and transport of water quality constituents. SWAT has been widely applied to evaluate the hydrologic and water quality impacts of land management and agricultural practices (Arnold and Fohrer, 2005; Borah and Bera, 2004; USDA, 2006). SWAT has been used to predict the impact of afforestation on streamflow in Europe. These studies used hypothetical watersheds (Eckhardt et al., 2003) or existing watersheds (Heuvelmans et al., 2005; Heuvelmans, 2005) with hypothetical rates and distributions of afforestation. Predicted reductions in streamflow due to afforestation were lower or within the range of reductions observed in the Sahin and Hall (1996) review of field studies. SWAT was applied to a pine treatment catchment and a grassland catchment at the Cathedral Peak Research Station in South Africa (Govender and Everson, 2005). Simulated streamflows were in reasonable agreement with observed streamflows for the grassland catchment, but were greater than observed streamflows for the pine treatment catchment.

Figure 1. Location of the research site in Uruguay.

Methods

SWAT models were developed to simulate the hydrology of the two monitored catchments in Uruguay. The models were calibrated using weather and outflow data measured on the sites from July 2000 to June 2002. The calibrated models were validated using data measured from July 2002 to June 2004. During the calibration and validation study, two scenarios were used to account for higher total outflow and baseflow observed from one of the catchments during the pretreatment period. These scenarios, the reduced evapotranspiration scenario and the added groundwater scenario, will be explained in more detail later in this section.

The calibrated and validated model of the treatment catchment was then used to predict the hydrologic impact of converting the existing grazed grassland to natural grassland (not grazed) and to mature pine plantation. The hydrology of the catchment with each of the three different land uses was simulated using a 33-year (1971 through 2003) historical weather data set for the region. The impacts of each land use conversion were evaluated by comparing average annual outflows and the distribution of daily outflows. Since some uncertainty existed in the depth of tree root penetration and the availability of shallow groundwater to the tree roots, the model parameter affecting groundwater availability (GW_REVAP) was adjusted to evaluate its effect on the catchment hydrology and to present a possible range of water yield values.

Table 1. Summary of catchment characteristics.

Characteristic	Catchment D1	Catchment D2
Area (ha)	69.0	107.7
Elevation (m)	130 - 204	136 - 192
Pretreatment land use	Grassland grazed (97%)	Grassland grazed (97%)
Treatment land use	Grassland grazed (97%)	*Pinus taeda* (57%)
Mean annual rainfall (mm)	1,487	1,487
Mean annual potential ET (mm)	1,215	1,215

Catchment Characterization

The SWAT model has intensive input data requirements, including topography, hydrography, soils, land cover, and weather. The input data for the catchments was compiled and analyzed in GIS.

The research site is located within the Tacuarembó River basin in northern Uruguay (fig. 1). Two adjacent catchments (D1 and D2) with similar drainage area, topography, slope, aspect, soils, and vegetation were selected for instrumentation on the La Corona estancia of the El Cerro tract owned and managed by Colonvade, S.A. A summary of catchment characteristics is presented in table 1. Catchment D1 has a drainage area of 69.0 ha, and catchment D2 has an area of 107.7 ha. The aspect of catchment D1 is primarily to the east, while catchment D2 faces south and east.

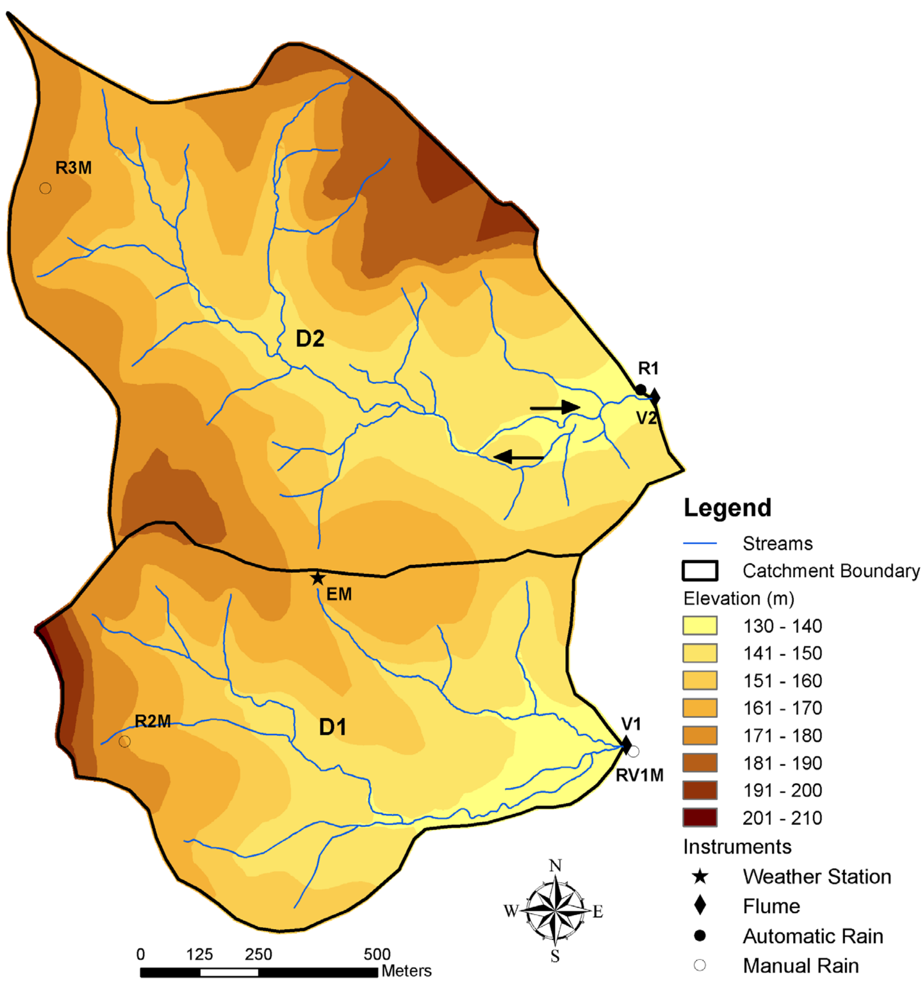

Figure 2. Topography, hydrography, and instrumentation on the research catchments.

Table 2. Soil map unit properties and areal extent.

Soil Map Unit	Layers	SCS Hydrologic Soil Group	Texture	Thickness (cm)	Effective Saturated Hydraulic Conductivity (mm/h)	Catchment D1 (%)	Catchment D2 (%)
A	1	D	Loam	10	20	1	11
B	3	D	Sandy loam/Sandy clay loam	82	14	2	5
C	4	B	Sandy loam/Sandy clay loam	175	92	14	26
D	4	B	Sandy loam/Sandy clay loam	175	33	32	20
DL	3	C	Sandy loam/Sandy clay loam	104	11	6	0
E	1	D	Sandy loam	35	50	7	16
F	3	C	Sandy loam/Sandy clay loam	104	47	25	15
G	3	D	Sandy loam/Sandy clay	110	16	7	2
H	3	D	Sandy loam/Sandy clay	80	16	6	5

The topography of the catchments is characterized by a rolling landscape with protruding rocky hillocks of basalt and sandstone. A comprehensive survey of the catchments in 2000 produced a 1 m contour topographic map. Using GIS software and the 1 m contour map, a digital elevation model (DEM) was developed of the catchments (fig. 2). The elevation of D1 varies from 130 to 204 m, while D2 varies from 136 to 192 m. The topographic relief of the site shows an upper elevation plateau and cliff area in the northern portion of catchment D2 and a similar smaller feature in the western portion of catchment D1. Based on a volumetric analysis of the DEM, catchment D2 has a greater volume of earth on an area-weighted basis above the outlet than catchment D1 (72.9 m to 57.6 m, respectively).

The hydrography of the catchments is characterized by an extensive network of incised channels that convey the surface and subsurface flows from the landscape to the outlets of the catchments. The incision of the stream channels occur–

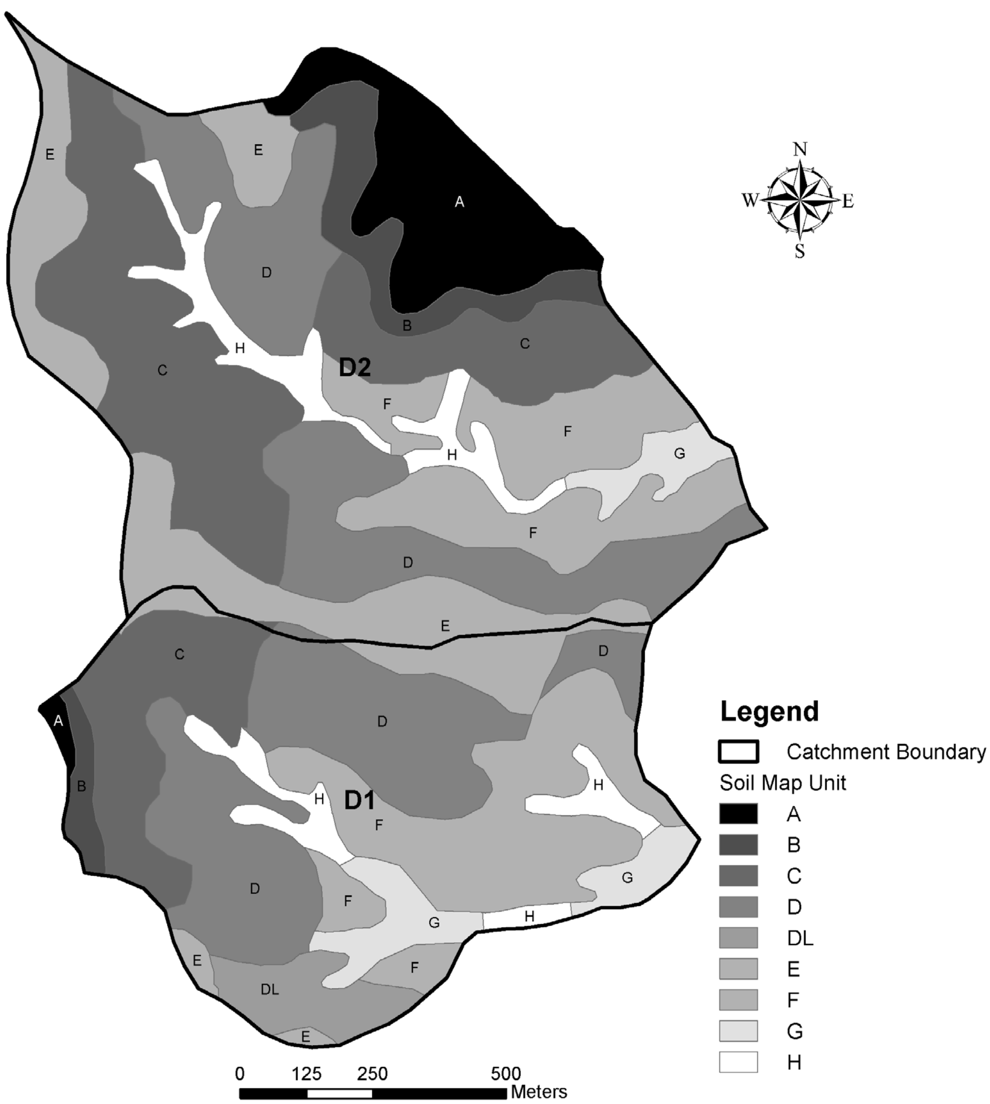

Figure 3. Soil map units on the research catchments.

red through erosive processes over many centuries. The alignment of the stream network was digitized in GIS based on aerial photographs of the site (fig. 2). The average slope of the stream channel ranges between 4% and 10% in the tributaries in the upper elevations of the catchments and between 1% and 1.5% in the main channel in the lower portion. Stream cross-sections were surveyed at selected locations in order to characterize the geometry of the channels for use in the model.

The soils on the catchments in the lower and middle elevations are dominated by sandy loam and sandy clay loam material of varying depth over sandstone. The higher elevations are outcroppings of basalt and sandstone overlain by a shallow topsoil layer. The soils on the site were investigated, classified, and mapped by Molfino (2000). Additional physical and chemical characterization of a subset of the soil map units was conducted by Préchac et al. (2004). The soil map developed by Molfino (2000) was digitized and entered into the GIS database (fig. 3). Soil map unit properties and areas for each catchment are summarized in table 2. Catchment D2 has a higher proportion of the very shallow upper elevation soils (A and E) than D1.

The general vegetation biome of most of Uruguay, including the research site, is grassland (Dasmann, 1984). A vegetation survey was conducted that identified the classification and frequency of the predominant grass species present in each type of soil in the study catchments (Marchesi, 2003). The two catchments were managed as grassland with livestock grazing during a three-year pretreatment period (July 2000 through June 2003). Grazing density for the period was estimated by Colonvade, S.A., field personnel to be 0.9 cattle units per hectare. One cattle unit is defined as the foraging needs of one cow of 380 kg weight with calf. The treatment catchment (D2) was planted with loblolly pine seedlings (*Pinus taeda*) in July 2003, while the control catchment (D1) remained grassland with livestock grazing. Riparian corridors, equipment access lanes, and cliff faces were not planted, resulting in 57% afforestation of catchment D2. The trees were planted in furrows (approx. 10 cm deep and 70 cm wide) and spaced approximately 2.5 m apart. Planting density was 1,000 trees per ha, per the standard planting practices of Colonvade, S.A. The area between furrows was left with grass vegetation, and the furrows were aligned perpendicular to the hillslopes. Cattle and sheep were not allowed to graze on the treatment catchment for approximately three years after tree planting. Livestock will then be allowed to graze on the treatment catchment at reduced grazing densities. The pine trees will be pruned and thinned periodically, per the standard management practices of Colonvade, S.A.

The general climate for most of Uruguay, including the research site, is mid-latitude humid subtropical grassland (Cfa) according to the Köppen climate classification system. The humid subtropical climate has hot, humid summers with frequent thunderstorms and mild winters with precipitation resulting from mid-latitude cyclones. Average annual rainfall measured at a weather station operated and maintained by Instituto Nacional de Investigación Agropecuaria (INIA), an Uruguayan governmental agency, in the town of Tacuarembó (35 km south of the research site) was 1,487 mm for the 26-year period from 1979 through 2004. Rainfall varied from as low as 841 mm in 2004 to as high as 2,797 mm in 2002. The rainfall is fairly uniformly distributed throughout the year, with slightly less rainfall in the months of June, July, and August than in other months. The estimated average annual potential evapotranspiration (PET) from the INIA station was 1,215 mm.

Data Collection

The instrumentation on the project site included a weather station, an automatic rain gauge, four manual rain gauges, and flow stage gauges at two outlet flumes (fig. 2). The weather station measured rainfall, air temperature, relative humidity, wind speed, wind direction, solar radiation, and net radiation on a 30 s interval and averaged or summed the data for recording on a 15 min basis. The additional automatic and manual rain gauges provided backup to the weather station and measurement of rainfall spatial variability across the catchments. Flow rates at the outlet of the two experimental catchments were measured using 1.37 m high HL flumes (Amatya et al., 2001). A calibrated rating curve provided by Bos (1989) was used to estimate flow rates through the flume outlet from measured flow stages. If stage elevations exceeded the 1.37 m maximum height of the stainless steel HL flume, flow rates were calculated assuming a broad crested weir located at the top of the HL flume. The catchments were continuously monitored from the beginning of July 2000 through June 2004, with continued monitoring planned through the growth and harvesting of the pine trees. More detailed information regarding the data collection at the research site can be found in Chescheir et al. (2004).

Model Setup and Parameterization

A hydrologic model of both catchments was created, calibrated, and validated using the SWAT model. SWAT is a semi-physically based, lumped parameter, deterministic, continuous model that relies on detailed soil and plant cover characteristics. GIS data layers were compiled for the AVSWAT2000 (Di Luzio et al., 2002) GIS interface for the SWAT model, including topography, hydrography, soils, and land use, as previously discussed.

The curve number method of estimating surface runoff and infiltration was used in SWAT on a daily time step. The curve number is an empirical index used to relate rainfall to runoff for various types of soil and land cover. Curve numbers for the soils on the watersheds were determined by model calibration. The calibrated curve number values generally correlated with poor to fair hydrologic condition for each hydrologic soil group and land cover, as determined by the Soil Conservation Service (SCS) (Neitsch et al., 2002b). Somewhat higher curve numbers were selected for mixed forest vegetation in the cliff land use to account for the predominant steep and rocky cliffs in these areas and sparse cover of the vegetation.

Initial soil parameters for the model were assigned based on laboratory analysis of on-site soil samples (Molfino, 2000; Préchac et al., 2004). Parameters for soil map units that were not sampled were estimated using the Rosetta computer program (Schaap, 1999). The Rosetta program estimates soil hydraulic properties such as available water capacity and saturated hydraulic conductivity from soil texture data.

The SWAT model tracks plant growth in order to simulate the hydrology of the landscape. The model requires the designation of land use areas that have similar vegetative cover and management. Land use/land cover GIS coverages were developed for the pretreatment and treatment condition

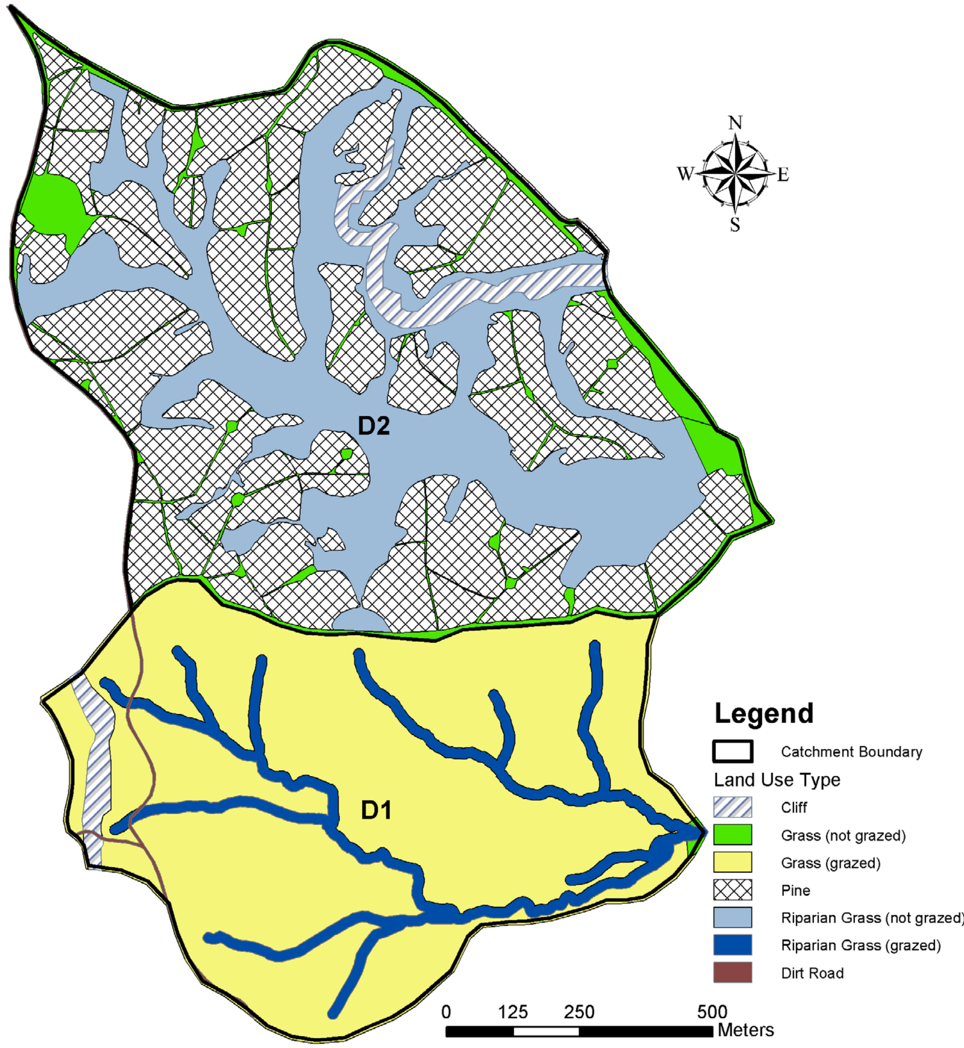

Figure 4. Pretreatment and treatment land use for catchment D1 and treatment land use for catchment D2. Note: the pretreatment land use for catchment D2 was similar to that of catchment D1.

(fig. 4). The land uses/land covers for the pretreatment period were grazed grassland, grazed riparian grassland, cliff face, and gravel road. For the treatment period, coverages representing pine trees, grassland (not grazed), and riparian grassland (not grazed) were added to the D2 watershed. The riparian area in the pretreatment condition was assumed to be a 15.24 m (50 ft) strip along the stream network. For the pine catchment under the treatment condition, the riparian grassland area was assumed to extend to the boundaries of the planted area.

The potential heat units (PHU) parameter specifies how many heat units, or degree days above base temperature, are required for the plant to reach maturity. For tree species, the PHU parameter is an estimate of the growing season, i.e., the amount of time between budding and leaf senescence. Once vegetation reaches maturity in the model, the leaf area index for the plant is set to zero and the vegetation no longer intercepts rainwater nor takes up water from the soil for the purpose of growth. Therefore, after plant maturity, evapotranspiration due to the vegetation does not occur. This modeling approach has a significant effect on soil moisture content and water yield for land covers with vegetation that has reached maturity. Due to the likelihood that plants in these catchments do not stop transpiring and certainly continue to intercept rainwater after maturity, the growing season was extended to delay or prevent the vegetation from reaching maturity. A value of 3,500 PHUs was used for the grassland, riparian grassland, mixed forest, and pine forest, representing the highest allowable value for this parameter in the model.

The SWAT model has an extensive crop growth database with numerous parameters that govern the growth of different types of vegetation. The crop database for range grass was used for the open grassland areas with livestock grazing, range brush for the riparian areas along the stream corridors, and mixed forest for the cliff areas with deciduous and coniferous vegetation. The maximum rooting depth and maximum potential leaf area index for each type of vegetation were selected based on published data (Canadell et al., 1996; Scurlock et al., 2001).

Groundwater “revap” in the SWAT model is defined as the upward movement of water from the shallow aquifer to the overlying soil layers to meet evapotranspirative demand (Neitsch et al., 2002a). Groundwater revap results from capillary action and/or deep-rooted vegetation that removes water directly from the shallow aquifer. The groundwater revap

Table 3. Calibration and validation simulation periods and weather data sources.

Simulation		Period	Weather Data Source
Calibration model warm-up		1 Jan. 1999 - 30 June 2000	INIA Tacuarembó station
Calibration		1 July 2000 - 30 June 2002	Research site station
Validation model warm-up		1 Jan. 1999 - 30 June 2000	INIA Tacuarembó station
		1 July 2000 - 30 June 2002	Research site station
Validation	Control (catchment D1)	1 July 2002 - 30 June 2004	Research site station
	Treatment (catchment D2)	1 July 2002 - 30 June 2003	Research site station

coefficient (GW_REVAP) is the dimensionless fraction of water that moves upward and is assigned by soil type. A value of 0.02 was assigned to the A and B upper elevation soils and 0.20 to the remaining middle and lower elevation soil types, representing the minimum and maximum values, respectively, recommended by the model. The minimum value was selected for the upper elevation soils based on the rationale that the plant roots would have less access to the groundwater due to lesser depth of soil in these areas.

Model Calibration and Validation

The observed data record was divided into two periods for model calibration and validation (table 3). The model calibration period for both catchments was two years, with a 1.5-year model warm-up period. The model validation period was two years for the control catchment, and one year for the treatment catchment due to the tree planting that occurred in July 2003, which modified site conditions. Daily precipitation, temperature, relative humidity, total solar radiation, and wind speed data collected from the meteorological station on the research site were used for the model calibration and validation period. The daily potential evapotranspiration was estimated for a grass reference using the Penman-Monteith method (Allen et al., 1998; Chescheir et al., 2004). Both years in the calibration period were wetter than normal. The validation period had an extremely wet year followed by a dry year.

During the model calibration, model parameters were adjusted so that the outflows from the simulation most closely matched the observed outflows. The parameters that were adjusted during the calibration included curve number, hydraulic saturated conductivity, available water capacity, groundwater delay, baseflow recession, groundwater revap, and deep fraction (defined as the fraction of groundwater that percolates to the deep aquifer and is considered lost to the system). Once it was determined that the calibration was complete, the model was validated. The model validation consisted of assessing the performance of the model by comparing additional predicted versus measured outflows outside of the calibration period. Model parameters were not adjusted for the validation.

Evaluation Criteria

To evaluate the accuracy of the model calibration and validation, a comparison was made between simulated and observed water yield, flow hydrographs, and flow frequency curves. Two statistical measures were conducted to evaluate the "goodness of fit" between the simulated and observed daily flow data: linear regression analysis, and the coefficient of efficiency. Linear regression analysis uses the least squares error method to determine the best-fit line between simulated and observed data. The ideal regression line for the calibration would have a slope of 1.0 and an intercept of 0.0. The coefficient of determination (R^2), a measure of the variance in the simulated data that is attributable to the variance in the observed data, was calculated for each linear regression.

The coefficient of efficiency (E) is a calibration statistic used by hydrologists to represent the deviation of the simulated versus observed regression line from the 1:1 line. The modified coefficient of efficiency recommended by Legates and McCabe (1999) was used:

$$E = 1.0 - \frac{\sum_{i=1}^{N} \left| Oi - Pi \right|}{\sum_{i=1}^{N} \left| Oi - \overline{O} \right|} \qquad (1)$$

where O represents observed values, $\overline{O}$ is the mean of observed values, and P represents predicted values. This form of the coefficient of efficiency is considered more conservative than the statistic developed by Nash and Sutcliffe (1970) that uses squared error terms. The coefficient of efficiency varies from minus infinity to 1.0, with a value above 0.7 generally considered a good fit (Legates and McCabe, 1999).

Calibration Scenarios

Comparison of the observed flows during the pretreatment period indicated that outflow from catchment D2 was greater than from D1 on a per unit area basis (Chescheir et al., 2004). Much of this difference was attributed to the continuous baseflow that occurred at D2 and not at D1 (fig. 5). Two hypotheses have been put forth to explain these differences in observed flows. One hypothesis theorizes that evapotranspiration on a per unit area basis is less from catchment D2 than from catchment D1 due to differences in soil properties of the sites. The other hypothesis theorizes that groundwater flows into the D2 catchment from areas outside of the catchment boundary. Two modeling scenarios were therefore developed as potential explanations for the observed discrepancy in baseflows between catchment D1 and D2. These scenarios are referred to as the reduced evapotranspiration scenario (reduced ET) and added groundwater scenario (added GW). The model was calibrated and validated for these two scenarios.

Under the reduced ET scenario, the primary source of baseflow to the catchments was from the higher elevation soils in the upper plateau and cliff areas (soils A and B), as well as along the catchment divide (soil E). Due to the shallow depth of these soils, the soil rooting depth and water storage capacity were assumed to be small, while the infiltration and percolation rate were assumed to be large. As a result of these assumptions, the model simulated lower evapotranspiration from the areas with A, B, and E soils (evapotranspiration approximately 50% of the other soils). Since the treatment catchment (D2) has the greater extent of A, B, and E soils, the simulated baseflows were greater in catchment D2.

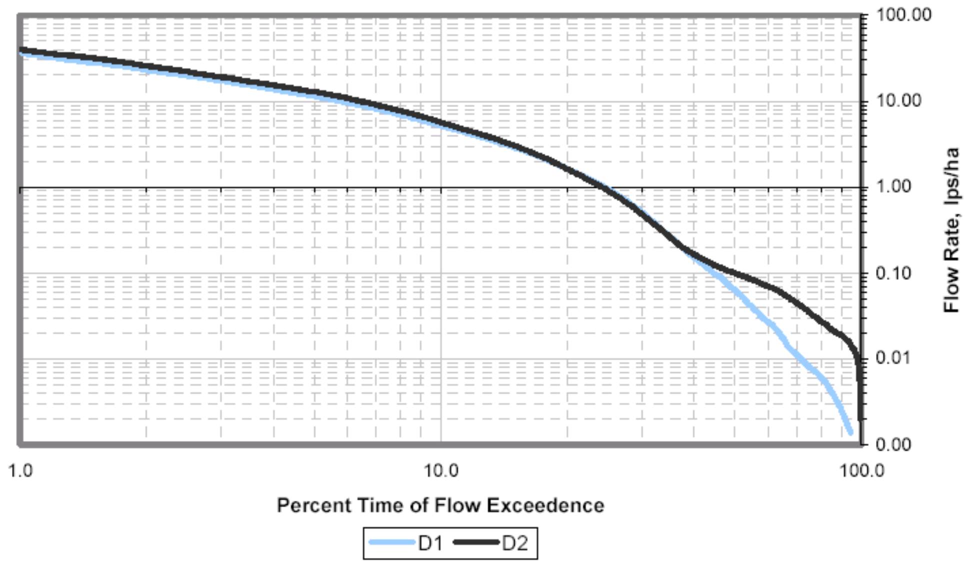

Figure 5. Instantaneous flow frequency curves measured at catchments D1 and D2 flume outlets from July 2000 to June 2003 (Chescheir et al., 2003). These curves show the higher baseflow rates observed from catchment D2.

For the added GW scenario, it was assumed that the greater baseflows in the treatment catchment were due to a source outside of the catchment, either from an additional area in the upper plateau or from a cross-catchment transfer from the control catchment. For the model simulations, the remainder of the area on the upper plateau adjacent to catchment D2 was delineated as the source of the additional baseflow. The groundwater source was 8.1 ha that consisted entirely of grass cover, except for 2% dirt roads, on A soils for the pretreatment condition. Groundwater from the additional area was input into the model as a point source upstream of the catchment outlet. The surface and shallow subsurface lateral flow from the additional area was not included in the model and was assumed to drain away from catchment D2. Under this scenario, the soil rooting depth and water storage capacity of the A, B, and E soils were increased, while the percolation rate was reduced, which resulted in higher evapotranspiration from these soils than under the reduced ET scenario.

Model Application Scenarios

The calibrated hydrologic models were used to perform long-term continuous simulations of selected scenarios using a compiled 33-year weather data set (1971 through 2003). A statistical analysis of the simulation results was conducted to determine the hydrologic characteristics of each scenario and evaluate their hydrologic effects. The first year was used for model warm-up and was not included in the analysis of the simulation results.

Land Use Treatment Scenarios

Three different land cover and management scenarios were simulated for catchment D2 in order to evaluate the hydrologic effect of varying land use treatments:

Grassland with grazing: This scenario was the same as the calibrated model condition of grassland with continuous grazing of sheep and cattle. The same crop parameters for grassland with grazing and riparian grassland with grazing used in the calibrated model were used for the simulation. This scenario was intended to simulate land cover and management practices common in Uruguay.

Grassland without grazing: The land cover for this scenario was grassland without any grazing. The curve numbers used for grassland without grazing were based on SCS published values (Neitsch et al., 2002b). This scenario was intended to simulate a native grassland condition and was used to estimate the hydrologic effects of livestock grazing by comparison to the preceding scenario.

Full-grown pine without grazing: The land covers for this scenario were pine tree and riparian grassland, both without grazing. The curve numbers used for pine trees and riparian grassland without grazing were based on SCS published values (Neitsch et al., 2002b). The default crop parameters for pine trees provided by the model database were used for the simulation of the pine afforestation, with one exception. The base temperature for crop growth was raised from 0°C to 10°C, which was intended to prevent the pine trees from reaching maturity before the start of dormancy (SWAT assigns a leaf area index of zero after plant maturity).

Pine Tree Root Penetration Scenarios

Two scenarios with the pine tree land cover conditions were simulated for catchment D2 that were intended to evaluate the effect of root penetration into the shallow aquifer on water yield and baseflows:

Shallow root penetration: The value of the GW_REVAP parameter for the pine trees was set at 0.2 to simulate shallow penetration of the roots into the shallow aquifer.

Deep root penetration: The value of the GW_REVAP parameter for the pine trees was set at 1.0 to simulate maximum penetration of the roots into the shallow aquifer.

Results and Discussion

Calibration and Validation Performance

A comparison between the observed and simulated daily flow and cumulative flow hydrographs for the reduced ET calibration scenario for the period July 2001 to June 2003 shows good agreement for the storm peaks, hydrograph shape, and baseflows (fig. 6). The flow volumes are presented as flow depths (mm), which is the flow volume averaged over the area of the catchment.

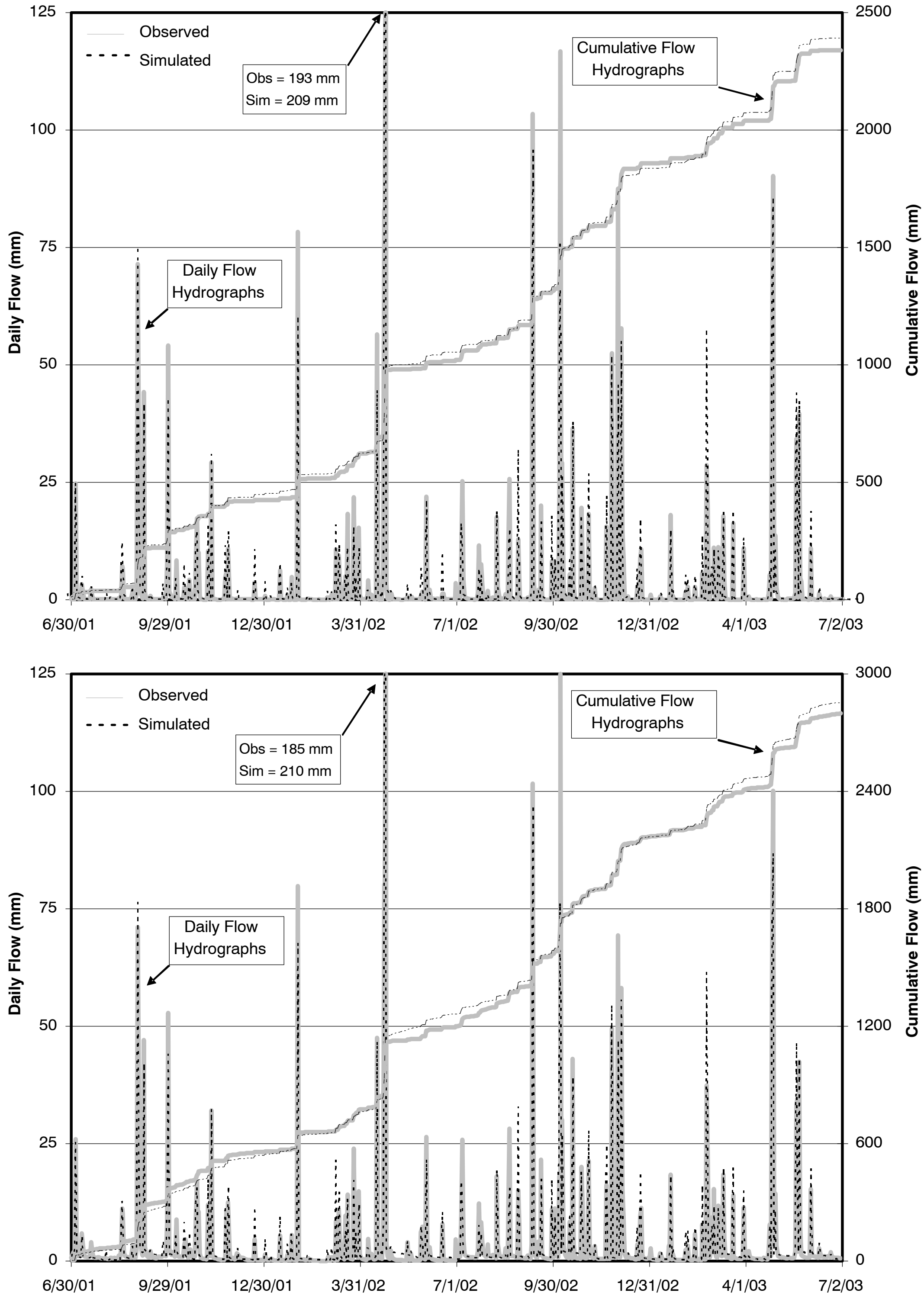

Figure 6. Simulated and observed daily flow and cumulative flow hydrographs for catchments D1 (top) and D2 (bottom) for the reduced ET scenario during one calibration year (2001-2002) and one validation year (2002-2003).

For both calibration scenarios and both catchments, the annual water yields were underpredicted by the model in 2000-2001 (1 July to 30 June, typical) and overpredicted in 2001-2002, although the errors were generally small (table 4). In 2001-2002, most of the error was due to a very large multi-day storm (22-24 April 2002). The accuracy of the observed flow measurements for this storm was questionable, as both outlet flumes were overtopped, requiring flow stages and rates to be estimated (Amatya et al., 2002). The rain gauges also showed inconsistent rainfall amounts during this time period. Hence, simulated and observed water yields (table 4) are shown including and excluding the 22-24 April storm for 2001-2002.

Annual water yields simulated by the SWAT models were within 2.5% of the measured values during the first validation year (2002-2003) for both scenarios and both catchments. The models overpredicted water yield for catchment D1 and underpredicted water yield for catchment D2. The catch–

Table 4. Observed and simulated annual water yield from research catchments for both calibration scenarios during calibration and validation periods.

Year[a]	Rainfall (mm)	Catchment D1 Observed (mm)	Catchment D1 SWAT (mm)	Catchment D1 Error (mm)	Catchment D1 Error (%)	Catchment D2 Observed (mm)	Catchment D2 SWAT (mm)	Catchment D2 Error (mm)	Catchment D2 Error (%)
Reduced ET Scenario									
Calibration									
2000-2001	1808	798	769	−29	−3.7	1068	965	−104	−9.7
2001-2002	2111	1019	1053	34	3.3	1198	1263	65	5.4
(w/o April storm)	(1747)	(734)	(738)	(5)	(0.6)	(920)	(943)	(23)	(2.5)
Validation									
2002-2003	2539	1321	1334	14	1.0	1599	1561	−38	−2.4
2003-2004	1049	150	279	129	86.4	--	--	--	--
Added GW Scenario									
Calibration									
2000-2001	1808	798	753	−45	−5.7	1068	932	−137	−12.8
2001-2002	2111	1019	1040	20	2.0	1198	1233	35	2.9
(w/o April storm)	(1747)	(734)	(725)	(−8)	(−1.2)	(920)	(913)	(−7)	(−0.8)
Validation									
2002-2003	2539	1321	1323	2	0.2	1599	1569	−30	−1.9
2003-2004	1049	150	265	116	77.4	--	--	--	--

[a] Year shown starts on 1 July and ends on 30 June.

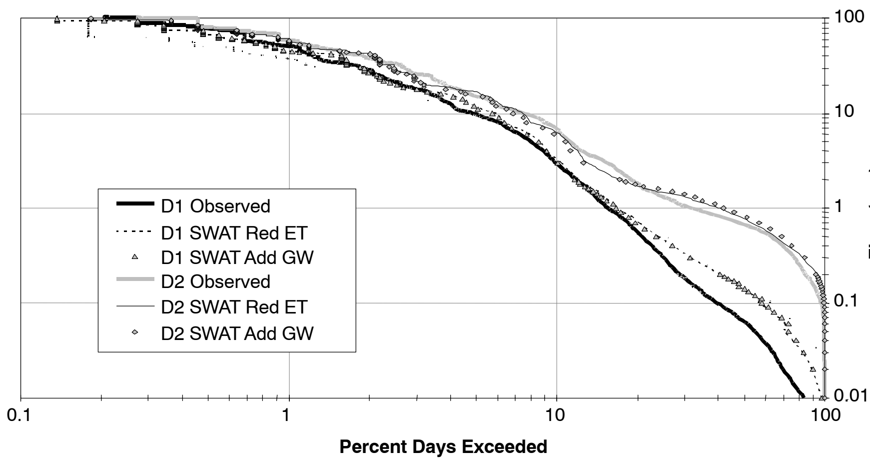

Figure 7. Daily flow frequency curves from research catchments for both calibration scenarios during calibration and validation periods.

ments received considerably less rainfall during the second validation year (2003-2004) than during the other years. The models overpredicted annual water yield for catchment D1 by 129 and 116 mm for the reduced ET and added GW calibration scenarios, respectively. These overpredictions resulted in high percent errors, since the observed water yield was only 150 mm. The errors were primarily attributed to the curve number being too high during dry conditions (antecedent moisture condition I). Such dry conditions did not occur during the calibration period.

Flow frequency curves (percent of time a flow depth is equaled or exceeded) for simulated and observed daily flow depths were calculated for the combined calibration and validation periods (fig. 7). The SWAT model overpredicted daily flow rates for catchment D1 during low flow periods when observed flow rates were less than 2 mm. Model-predicted flow values were very near observed values for the remainder of the flow regime. For catchment D2, model-predicted flow values were very near observed values over the flow regime, with slight underpredictions when observed flows were between 2 and 10 mm and slight overpredictions when observed flows were less than 2 mm. Simulated flow frequency curves for the added GW calibration scenario were very similar to those for the reduced ET scenario.

The goodness-of-fit statistics calculated for daily flows for the combined calibration and validation period are presented in table 5. The slopes and intercepts approached 1.0 and 0.0, respectively, with coefficients of determination above 0.92. Coefficients of efficiency were greater than 0.71, indicating a good fit between the simulated and observed results. Goodness-of-fit statistics were very similar for the reduced ET and the added GW scenarios.

Table 5. Goodness-of-fit statistics for daily flows from the combined calibration and validation periods.

Statistical Parameter	Reduced ET Scenario D1	Reduced ET Scenario D2	Added GW Scenario D1	Added GW Scenario D2
Regression line				
Slope	0.91	0.94	0.91	0.93
Intercept	0.30	0.17	0.27	0.13
Coeff. of determination (R^2)	0.92	0.93	0.93	0.94
Coeff. of efficiency (*E*)	0.77	0.71	0.78	0.72

Two different hydrologic scenarios for the pretreatment catchment condition (reduced ET and added GW) were successfully calibrated and validated using the SWAT model on a daily time step. These two scenarios were intended to simulate the discrepancy in observed baseflows between catchments D1 and D2. The two modeling scenarios had similar total and storm flow predictions, as well as baseflow predictions for catchment D1, during the pretreatment period. The reduced ET scenario appeared to predict baseflows in catchment D2 slightly better than the added GW scenario; however, the mean absolute difference between the scenarios was smaller than the mean absolute error between the predicted and observed baseflows. Although the model simulations are inconclusive as to which scenario provides a better explanation of the hydrologic processes occurring on the research catchments, they do provide insight as to which watershed characteristics warrant further investigation. One such characteristic to investigate during the continuing field study will be the growth of trees in the shallow soils where ET was theoretically reduced in the reduced ET scenario. If ET is actually reduced, then future growth measurements such as leaf area index and biomass will be lower for trees growing in these shallow soils than for those growing on the deeper soils.

The calibrated models of both scenarios overpredicted outflow volumes from catchment D1 during the dry year (table 3). The overprediction of storm flows was primarily attributable to the model assigning too high a curve number during dry conditions (antecedent moisture condition I). The overprediction of baseflows indicates an underrepresentation of evapotranspiration and/or soil moisture storage. Further information regarding watershed characteristics would be needed in order to conclude what process was being misrepresented in the model. The flow during years with above-average rainfall was better predicted. The consequence of overpredicting outflows during and following dry periods on the model's ability to predict the effect of afforestation was anticipated to be small. However, the effect of the pine plantations on water yield is of greater concern during drought conditions, when water supply is low and baseflows are diminished. Due to the concerns regarding the performance of the model during dry periods, the evaluation of the predicted hydrologic effect was limited to long-term mean annual water yield rather than focusing on the impacts during years with below-average rainfall.

Based on the analysis of the results, the calibration and validation of the models were considered good and appropriate for evaluating the difference in the hydrologic response of the two catchments and for predicting the hydrologic effects of pine afforestation.

Model Application Scenarios

Only the reduced ET calibrated model was used for the model application scenarios, since the results of the reduced ET and added GW models were similar for the calibration and validation simulations.

Land Use Treatment Scenarios

The mean annual components of the water balance were calculated for the various land use treatment scenarios for catchment D2 for the period 1971 through 2003 (fig. 8). The water yield in SWAT is divided into three flow pathways: overland surface runoff, lateral shallow subsurface flow (sometimes referred to as interflow), and groundwater flow from the shallow aquifer. Water is lost from the system through evapotranspiration and percolation to the deep aquifer. The grassland cover without grazing had 15% less mean annual water yield than the grassland with livestock grazing. This was primarily due to the fact that the grassland without grazing had lower curve numbers, resulting in less surface runoff than grassland without grazing. In addition, the grassland without grazing had greater loss resulting from evapotranspiration due to greater leaf area of the grass coverage. For the grassland with grazing, the livestock continuously consumed vegetation, thereby preventing the grass from reaching maturity and resulting in reduced evapotranspiration through the growing season and more runoff.

The pine tree cover had less water yield than the grassland without grazing cover due to the deeper roots and the greater leaf area of the trees during the growing season. The deeper roots of the trees allow greater access to the water in the soil,

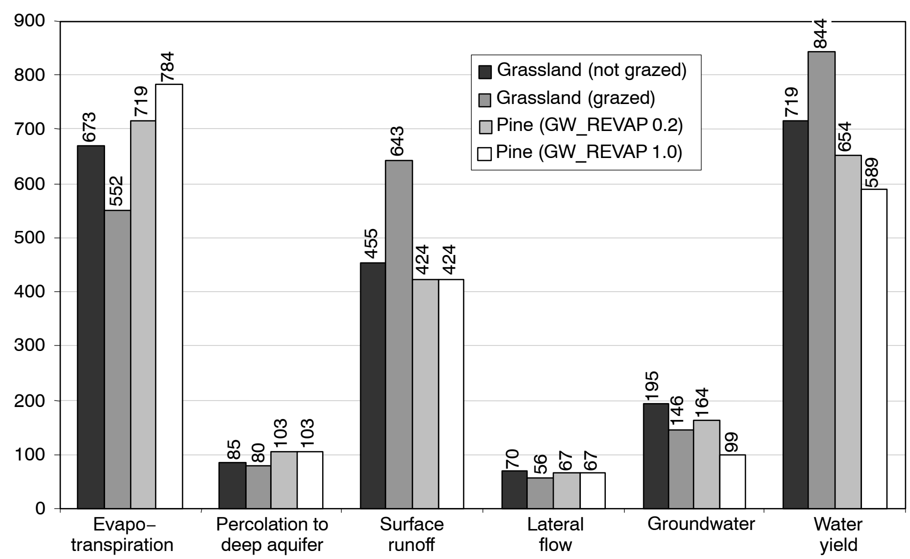

Figure 8. Mean annual water yield and water balance components from catchment D2 for land use treatment and root depth penetration scenarios. (Mean annual precipitation was 1477 mm, and mean annual potential evapotranspiration was 1131 mm).

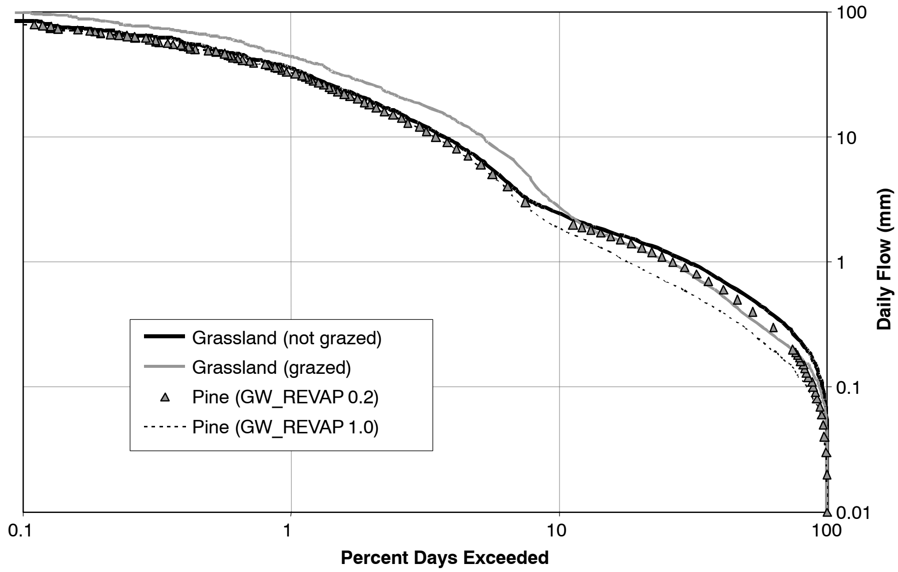

Figure 9. Daily flow frequency curves for catchment D2 for land use treatment and root penetration scenarios.

and the increased leaf coverage results in greater interception of rainfall and evapotranspiration losses. The afforestation of catchment D2 with mature pine trees (57% pine, 40% grasses) resulted in a 23% reduction in mean annual water yield as compared to the pretreatment grassland with grazing condition.

The water yield from the pine treatment was less than that from the grassland without grazing, which was less than that from grassland with grazing. The pine treatment of catchment D2 involved two land cover and management conversions; approximately 57% of the catchment was afforested with pine trees, while livestock grazing was discontinued on the remainder of the catchment that remained grassland. Both these land use changes would decrease the water yield; however, since the water yield from the pine treatment was less than that from the grassland without grazing, the hydrologic effect due to afforestation of the catchment was greater than that due to removal of livestock grazing (fig. 8).

An analysis of the flow regime of the predicted outflow from catchment D2 for each land use showed lower storm flows and higher baseflows from the grassland without grazing than from the grassland with grazing (fig. 9). The reduced storm flows from the grassland without grazing was due to the lower curve numbers selected to account for the greater vegetative cover; consequently, more rainfall infiltrated and was available for groundwater flow.

The hydrologic effect of mature growth with full development of the canopy was simulated by maximizing the growing season by setting the potential heat units parameter to 3,500. The SWAT model determines the period of dormancy by calculating threshold daylength for crop growth, which is a function of the location of the watershed on the globe. For the research site, dormancy was set from 12 May to 3 August each year. The SWAT model sets leaf area index during dormancy at 0.75 for perennial vegetation and trees, which is considered to be low for coniferous trees that do not lose their needles during dormancy. The model did not allow adjustment of this parameter without modification of the source code. Therefore, the model may be underpredicting the hydrologic effect during the winter months. Since PET is small during the winter months, this error is anticipated to be small relative to the overall hydrologic effect of the trees and overall model uncertainty.

Pine Tree Root Penetration Scenarios

Two values for the GW_REVAP parameter for the pine trees were selected for comparison to evaluate the effects of root penetration: 0.2, the value generally used for vegetation in the model calibration, and 1.0, representing the maximum possible removal of water from the shallow aquifer by deep roots and capillary action. The higher groundwater revap fraction (1.0) resulted in a mean annual reduction in water yield from catchment D2 of 65 mm, or 30%, as compared to the grassland with grazing pretreatment condition (fig. 8).

Both pine treatments had lower storm flows than the grassland with grazing. The pine treatment with a groundwater revap coefficient of 0.2 had baseflows similar to those of the grassland with grazing, while the pine treatment with a coefficient of 1.0 had lower baseflows (fig. 9). The lower baseflows for the pine land cover with groundwater revap coefficient of 1.0 is an indication of the greater utilization of the water in the soil through evapotranspiration by the pine trees. For the pine tree land use scenario where groundwater revap was 0.2, there was very little change in baseflow, as the increase in baseflow due to greater infiltration was offset by a decrease due to greater evapotranspiration.

An analysis was conducted to evaluate the effect of the pine treatment on baseflows. Since traditional baseflow separation techniques apply to larger catchments, a methodology was developed to separate the baseflow from the storm flow for the research catchments. For the analysis, flow in a given day was considered entirely baseflow if no rain occurred on that day or the previous day, which was considered valid since the travel time of surface runoff in the catchments was less than one day. This method does not capture all of the baseflows, but instead attempts to isolate that portion of the daily flow record that is clearly baseflow and present it as a mean daily flow rate. The pine treatment with a groundwater revap coefficient of 0.2 resulted in a 14% increase in mean daily baseflows as compared to the pretreatment grassland with grazing condition (table 6). The increase in baseflows is attributable to the greater infiltration of precipitation under

Table 6. Mean daily baseflow for grassland with grazing land use and effect of pine treatment root penetration for catchment D2.

	Mean Daily Baseflow (mm)		
Season	Grassland with Grazing	Treatment (GW_REVAP 0.2)	Treatment (GW_REVAP 1.0)
Annual	0.47	0.53	0.35
Summer	0.33	0.46	0.29
Autumn	0.62	0.62	0.42
Winter	0.52	0.67	0.44
Spring	0.35	0.32	0.22

the treatment vegetation and the relative lack of access of the pine trees to the groundwater. The pine treatment with GW_REVAP of 1.0 resulted in a reduction in mean daily baseflows of 24% (table 6) due to the greater access of the pine trees to the groundwater. There was a large seasonal variation effect on mean daily baseflows, with the greatest reductions occurring during the summer season (22 December to 21 March). The summer season had the lowest baseflows, primarily due to a lower water surplus (precipitation minus PET).

Selection of the groundwater revap parameter is significant due to its effect on baseflows. The value of 1.0 for the groundwater revap fraction represents the greatest reduction in water yield resulting from the afforestation of catchment D2 (fig. 8). The actual value of the groundwater revap fraction is likely somewhere between 0.2 and 1.0. Further monitoring of the catchments as the pine trees mature and further refinement of the model for the treatment condition will be required to select the appropriate value for the groundwater revap parameter.

Conclusions

Based on the modeling results, pine afforestation of catchment D2 was predicted to reduce mean annual water yield from the landscape by 23% as compared to the grassland with grazing pretreatment condition. The difference in flow volumes was predicted to occur primarily during the less frequent storm flows, with a minor increase in baseflows predicted (14%). Therefore, at the treatment rate of catchment D2 (approx. 60% pine and 40% grass), the afforestation was not predicted to have detrimental effect on baseflows. The level of effect observed in the field will depend on the pathway of subsurface flow and the access of the tree roots to water in the ground.

Simulation of grassland without livestock grazing resulted in decreased water yield as compared to the pretreatment condition of grassland with grazing. This difference was primarily due to the lower curve numbers associated with undisturbed grass as compared to grazed grass. The lower curve numbers for the ungrazed grass resulted in less runoff, more infiltration, and greater evapotranspiration. Previous studies have shown that infiltration is reduced (Gifford and Hawkins, 1978; Branson et al., 1981) and runoff is increased when grasses are subjected to grazing (Holechek et al., 2004). Further investigation is recommended to determine if the increase in water yield due to grazing predicted by the model is observed. The removal of livestock is an important consideration when quantifying the hydrologic effects of afforestation, as the pine treatment of catchment D2 has nearly 40% grassland cover in protected riparian areas and between planting zones.

An important consideration in the evaluation of the hydrologic effects of afforestation is the ability of deep-rooted trees to remove groundwater from lower portions of the soil profile and shallow aquifer. The soil profiles of the map units on the catchments were typically shallow, ranging from 10 to 175 cm. The calibrated model had a maximum rooting depth of 1.5 m for the grass vegetation, which is consistent with the literature and resulted in good prediction of outflows from the catchments during the model calibration period. The grass vegetation had access to water throughout the soil profile due to the shallow soils, thereby reducing the effect of introducing deeper-rooted trees. There is the potential for the tree roots to extract water from the rocky parent material underlying the soils. The groundwater revap (GW_REVAP) parameter for the pine trees was set to its maximum of 1.0 to simulate this phenomenon. Incorporating the maximum groundwater revap parameter, the mean annual water yield was reduced by 30% due to the conversion from grassland with grazing to pine trees. The additional reduction in water yield was entirely from the more frequent baseflows, which were reduced by 24%.

The actual effect on water yield of the afforestation is likely to fall somewhere within the range predicted by the various land use treatment and root penetration scenarios simulated in this study (23% to 30% reduction). This prediction could be improved through increased understanding of the subsurface hydrologic processes and groundwater conditions in the catchments.

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