Integrated Wetland and Landscape Modeling. A Case Study from the Eastern Cape Province, South Africa

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EXTENDED ABSTRACT

Wetlands are very sensitive to ecosystem changes, so integrated analyses and modeling of their process dynamics as well as their interaction with other hydrologic and ecological components provide valuable information for impact assessment. However, since wetland processes are complex, research methods aiming to improve the understanding of wetland dynamics in a landscape perspective must comprise a multidisciplinary and integrated approach. Thus, a project was initiated to model the landscape dynamics of afforestation and their effects on wetlands in the semi-arid Umzimvubu basin, South Africa. The resultant landscape model integrates both the local wetland process dynamics with the larger scale landscape dynamics, while considering the spatial and temporal heterogeneity of these respective scales.

Two catchments (the regional basin of the Mooi river and a small research catchment named Weatherley) in the upper reaches of the Umzimvubu basin have been chosen for detailed analysis of the impacts of afforestation on the water balance and wetland dynamics. Field measurements provided data on vegetation characteristics, soil physics, soil hydrology and hydrological time series for use at each scale. Multi-temporal Remote Sensing (RS) data have been used to delineate land use patterns. A GIS-based digital terrain analysis has been applied to provide a set of geomorphometric and geomorphographic parameters utilizing a Digital Terrain Model (DTM). These data have been integrated into a wetland classification scheme and could therefore be used to differentiate several wetland types according to their specific characteristics and functioning within the landscape.

The analysis of hydrological and bio-ecological time series, soil and terrain analysis as well as physically-based modeling have been combined to identify and simulate dominant processes and dynamics of water flow into and through wetland bodies. This combination of measurements, observations and modeling comprised numerous sub tasks from which process understanding was derived in order to inform a catchment scale model. Firstly, the growth and potential water use of forest plantations has been simulated using the model 3-PG (physiological principles predicting growth). Secondly, detailed observations of surface and subsurface water dynamics combined with local or hillslope scale physically-based model algorithms have been used to describe and simulate streamflow generation mechanisms in the research catchment, Weatherley. This task demonstrated that overland flow, near surface macro-pore flow and groundwater flow are dominant streamflow generation processes on hillslope scale, within the research catchment and similar landforms in the Mooi basin. Finally, appropriate modifications were made to the Precipitation-Runoff Modeling System (PRMS). This catchment scale model was applied to simulate the impacts of various land use scenarios on basin runoff. Since the model's hydrological responses are grouped into Hydrologic Response Units (HRUs), which characterize distributed modeling units with homogeneous hydrological system behavior, impacts of afforestation on different types of wetlands could be identified. The results presented indicate that:

i) Forest plantations will reduce available water significantly as a consequence of higher interception and Evapotranspiration rates. Reduction of water availability ranges from 10.6% up to 21.5% due to afforestation.

ii) The loss of runoff into wetlands due to afforestation with pine and eucalyptus varies between 13.6% and 21.3%.

iii) Hydrological impacts on wetlands are strongly associated with the size and type of the specific wetland. Small Plateau Wetlands (27-48% runoff reduction) are more severely affected due to reduced interflow input from planted surrounding areas than medium-sized Slope Wetlands (11-19% reduction) or Valley Bottom Wetlands (4-9% reduction) which receive water from larger contributing areas.

1. INTRODUCTION

The landscape of the upper reaches of the Umzimvubu river, South Africa has been changed remarkably, since about 60 000 ha have been planted to commercial forestry since 1989. The effects induced by large plantations on landscape dynamics are numerous. They are assumed to cause a variety of changes in the hydrological system behavior (runoff reduction, interception losses and water table fluctuation) as well as ecological changes (drying out of wetlands, biodiversity reduction and destruction of natural habitats). A quantified description of the impacts of the afforestation on wetlands in this region had not been concluded by 1997 (Forsyth *et al* 1997).

Thus, a project was initiated to model such landscape dynamics and their temporal and spatial effects on wetland processes introducing an integrated modeling approach. Land use change studies (Helmschrot and Flügel 2002), wetland analysis (Dahlke *et al* 2003) and hillslope process studies (Lorentz *et al* 2004) have been successfully combined with physically-based process models. As a result, the wetland process dynamics and their interrelation with landscape changes have been simulated considering the spatial and temporal heterogeneity of their respective scales.

2. STUDY AREA

The Mooi catchment (307km²) lies in the upper reaches of the Umzimvubu basin (South Africa) and is typical of the southeastern slopes of the Drakensberg escarpment. Altitudes range from about 1 200 m asl. at the Mooi weir in Maclear to 2 700 m asl. in the headwaters. Triassic sediments of the Karoo Sequence formed a scarpland in the catchment, with wide valleys, numerous canyons and a series of sloping plateaus. The soil development depends on the mudstone or sandstone parent material and the hydrological conditions. Climatically, the region lies in a summer rainfall area with a mean annual precipitation of 750 mm/year. The mean annual temperature is 14.1 °C. Temperature and precipitation however show a high temporal and spatial variability. The vegetation is characterized by a grassveld type namely *Highland Sourveld* (Acocks 1987). It is dominated by several sour grass species and traditionally used for rangeland grazing. Different types of wetlands varying in size and functioning occur in the study area. They are controlled by local hydrology, terrain position and geology. Since the establishment of forest industries in 1989 about 19% (58.5 km²) of the Mooi basin have been planted with various pine and eucalyptus species for commercial forestry, while 63 % (193,5 km²) is used as rangeland and 11% (34 km²) is wetland.

Within the Mooi catchment, a small research catchment has been established. Intensive studies have been undertaken in this 1.2 km² research catchment, Weatherley, which is located in the eastern part of the Mooi basin (Figure 1). Altitudes vary smoothly from 1 257 m asl. at the lower weir up to 1 350 m asl. on the divide. In 2001 about 35% of the former grassland which was primarily used for extensive stock-farming was planted with eucalyptus (17 ha) and pine (32 ha). Using soil, vegetation and topographic diagnostic characteristics, some 25% of the catchment has been classified as wetland.

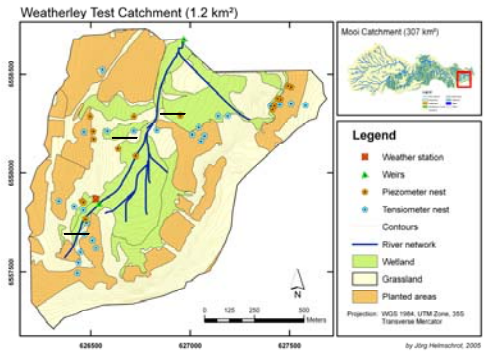

Figure 1. Characteristics and instrumentations of test catchment Weatherley

3. DATA BASE

3.1. Hydro-meteorological Time Series

Long-term daily climate data from several weather stations and runoff data from the weir in Maclear are available for the Mooi basin. The Weatherley catchment has been instrumented systematically since 1995. The soil moisture status was recorded weekly via neutron probe access tubes. These measurements yielded volumetric water content estimates in 29 stations set out in several transects across the catchment. Tensiometers recording soil water potential automatically and groundwater observation wells were installed in 1996 (Lorentz *et al* 2004). In 1997 the instrumentation was completed with two weather stations providing hourly rainfall, wind speed and direction, temperature and radiation data. Two crump weirs measuring depths of flow at breakpoint intervals provided monitoring of basin runoff.

3.2. Geo-Data

A variety of GIS data were available from previous studies. Multi-scale and multi-temporal land use information has been provided by land use classification from Landsat ETM/TM data and several mapping campaigns (Helmschrot and Flügel 2002). Additionally, data from the forest data base provided by Mondi Forest Ltd. (2004, not publ.) including specific stand information have been used to parameterize the model. A high-resolution, Digital Elevation Models (DEM) has been derived from SRTM data (Mooi, 25 m²) and field-based survey with GPS (Weatherley, 5 m²). These surveys have been used to calculate topographic-related data such as catchment boundaries, river network, slope, exposition and aspect (Dahlke *et al* 2005). A detailed soil map of Weatherley has been provided by the Institute for Soil, Climate and Water (Pretoria), while regional geology was digitized from geological maps (Department of Mines 1977).

3.3. Soil and Vegetation Data

Geochemical and soil physical parameters (type, grain size, pf-curves, field capacity, pH, TOC, N, S, Al, Fe, hydraulic conductivity, bulk density, soil moisture) have been determined by sedimentological analyses of soil cores and samples from several cross-valley and wetland transects in the Mooi catchment (Helmschrot *et al* 2005). Vegetation parameters such as species richness, abundance, Leaf Area Index (LAI), density, rooting depth, height and phenological condition have been measured for grassland and different wetland types along 7 transects in Weatherley. In addition, plant-physiological parameters for forest plantations (heights, Diameter at Breast Height (DBH), LAI, density, stem volume, DBH, basal area stocking rate, etc.) have been measured in selected stands and were extracted from the forest data base.

4. WETLAND ANALYSIS AND DELINEATION APPROACH

A prerequisite for the hydrological modeling of afforestation impacts is the inventory and delineation of different wetlands types. Based on integrated system analysis 3 major wetland types were identified by Dahlke *et al* (2003) within the study area: *i) Valley Bottom Wetlands, ii) Slope wetlands* and *iii) Plateau Wetlands*.

Valley bottom wetlands are developed by the deposition of fine sediment and clays in the valley bottoms. These wetlands are formed in combination with high groundwater fluctuation rates above relatively impermeable layers. These wetlands are mainly controlled by groundwater dynamics with additional water inputs from interflow and rainfall and therefore in most cases permanently saturated. Consequently, they control the base- and stormflow hydrographs of the respective streams. They are characterized by meandering channels, which are often incised and tend to drain the wetlands. Slope wetlands are located at mid- and bottomslopes. They are medium-sized and occur temporarily. Those wetlands are usually controlled by rapid lateral water flow (surface runoff and/or interflow). They are characterized by permeable soil layers with high infiltration capacity and tend to support piping. Plateau wetlands are small wetland patches in plateau situations and are temporary in nature. They are associated with perched groundwater from lateral inflow from the surroundings and/or precipitation input. Each wetland type supports hydrophyte vegetation which is adapted to either permanent or temporary wetland conditions.

Since field-based system analysis indicated a close relationship between wetland hydrodynamics and terrain characteristics, a GIS-based terrain-based analysis system was developed by Dahlke *et al* (2005) to delineate identified wetland types and subtypes in terms of their terrain position, their morphometry as well as their surface/subsurface hydrological regime. Therefore, combinations of specific geomorphometric and geomorphographic parameters derived from a high quality DEM have been used to identify wetland types. As a result a wetland inventory has been done showing that about 15% of the study area is covered by wetlands. Valley bottom wetlands dominate about 57% of the total wetland area, while slope wetlands and plateau wetland cover about 37% and 6%, respectively.

5. INTEGRATED MODEL APPROACH

Physically-based models which simulate hydrological processes at different spatial and temporal scales have been integrated to estimate the hydrological impact of afforestation on the catchment in general and on different wetland types specifically. A plant growth model (Landsberg and Waring 1997) and hillslope models (Simunek *et al* 1999, Hebbert and Smith 1990, Lorentz *et al* 2004) were successfully applied to calibrate and validate the catchment model for scenarios responses to land use changes.

5.1. Plant Growth Modeling

The forest growth dynamics and tree water use for *Pinus patula* and *Eucalyptus grandis* stands have been simulated using process-based 3-PG model (Landsberg and Waring 1997). 3-PG requires site and species related parameters as well as basic climate data at a monthly time step. These parameters were provided by field measurements or taken from the forest data base. Additionally parameters were extracted from a similar study presented by Dye (2001). As a result 3-PG simulates stem biomass and volume, average stem diameters, stand basal area and the time course of LAI. Since it includes a simple, single-layer soil-water-balance model, stand water use and available soil water can be estimated at a monthly time step. Monthly evapotranspiration is computed using the Penman-Monteith equation (Monteith and Unsworth 1990), while canopy interception is simulated as a fraction of rainfall and is a function of the canopy LAI. Soil water in excess of the intrinsic soil-water holding capacity for the site is assumed to be lost as runoff and/or deep drainage. Figure 2 shows results representing modeled LAIs for i) *E. grandis,* ii) *P. patula*, and iii) *P. patula* including thinning of the forest stand.

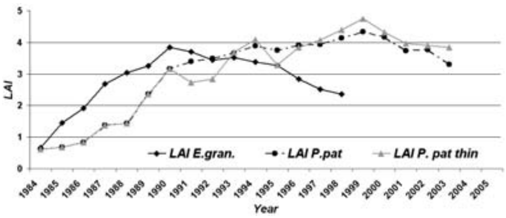

Figure 2. Annual LAI values calculated with 3-PG for forest stands within the study area

5.2. Modeling of Hillslope Hydrology

In the Weatherley research catchment, hillslope hydrological processes have been studied using a variety of observation techniques described in detail by Lorentz *et al.* (2004). Hydrometric monitoring of soil water dynamics has been done analyzing observed water suction and groundwater. These observations are supplemented by periodic water content observations via a network of neutron probe access tubes. Six boreholes allow monitoring of the water table in the fractured sandstone and mudstone rock on the hillslopes and in the wetland. 2D Resistivity surveys have been conducted in transects across the catchment to determine the distribution of hillslope water in the subsurface. Pedological analyses have been used to determine the distribution of hillslope soil water generation. In addition, natural isotopes of oxygen and hydrogen have been sampled in the rainfall and in the surface, soil and ground waters and analyzed to define the sources and pathways of contributions to streamflow. Those observations have been completed by simulating hillslope flow dynamics using HYDRUS 2D (Simunek *et al* 1999) and HILLS9 (Hebbert and Smith 1990).

From this effort, three dominant runoff generation mechanisms (overland flow, near-surface macro-pore flow and groundwater flow) have been identified. These mechanisms were quantified using simple physical-based algorithms applied to measured soil water dynamics and runoff data. In addition, simple unit response functions comprising an advection-dispersion model (ADM) as well as an Overland Flow Model (OFM) were applied to simulate residence times and fluxes of runoff sources. All these techniques have led to a description of streamflow generating mechanisms in the Weatherley catchment as shown in Figure 3 and summarized in Table 1.

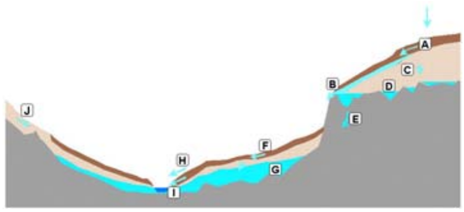

Figure 3. Summary of hillslope processes, Weatherley research catchment

	Description	Occurence
A	Rapid lateral flow near the surface due to macro-pore conductance. Local perched water table of short duration. Matric pressure head discontinuity with deeper perched water table, see D.	In upper slope segments in downstream catchment during high intensity events and some low intensity events with large volumes (>30 mm)
B	Accumulation at the toe of the slope segment with emergence and flow over bedrock.	In upper slope segments in downstream catchment
C	Slow percolation to water tables perched on bedrock.	In all slope segments for most events except low intensity and volume.
D	Water tables perched on bedrock and in bedrock hollows.	Disconnected from soil water in upper slopes of downstream catchment, but connected in lower slopes and in upstream catchment during moderate to intense events.
E	Percolation through bed-rock fractures, re-emergence in hill-slope as well as recharge to local bedrock groundwater.	Assumed to occur in all slope segments.
F	Rapid macro-pore, lateral flow in flatter marsh slopes and infil-tration to marsh groundwater.	Vertical recharge is more rapid than lateral movement in lower slopes of down-stream catchment and in upstream catchment, except when groundwater rises into macro-pore layers.
G	Marsh groundwater level fluctuation.	Rapid for most events in lower downstream catchment. Slower, but connected in upper catchment.
H	Exfiltration, surface runoff and macro-pore discharge to stream	In downstream catchment. Not observed in upstream catchment.
I	Groundwater discharge into stream.	Assumed to occur in up-stream and downstream catchments.
J	Unsaturated redistribution of soil water to bedrock. No groundwater on soil/bedrock interface	In upper parts of western slopes. Generates slowly to soil/bedrock water table downslope.

Table 1. Summary of streamflow generation mechanisms and their occurrence, Weatherley

5.3. Catchment Modeling

i) HRU Delineation and Routing

Since the basin heterogeneity as well as the variety of several wetland types needs to be considered for spatially distributed, physical-based models such as PRMS, the Hydrological Response Units (HRU) approach has been utilized. As defined by Flügel (1995) HRUs are distributed, heterogeneously structured model entities representing specific landscape units of similar response in terms of their hydrological process dynamics. Criteria that are used for definition of the homogeneity are based on the hydrological system analysis of the basin.

Thus, the Mooi and Weatherley catchments have been intensively surveyed during field campaigns. Additionally time series of hydro-meteorological data have been analyzed to identify hydrologically relevant parameters. It was found that land use, soils, geology and topographic features are key parameters influencing streamflow generation, evapotranspiration and storage dynamics. Thus, the HRUs were delineated by GIS overlays for each basin utilizing data layers of land use including different wetland types and forests, slope, aspect, soils and geology as well as a topographic unit. Since land use information was available for different time periods (pre- and post afforestation), scenarios of landscape dynamics were considered in the HRU delineation process. This resulted in 4 HRU data sets being selected for modeling:

i) Mooi before afforestation (70 HRUs),
ii) Mooi after afforestation (67 HRUs),
iii) Weatherley before afforestation (25 HRUs),
iv) Weatherley after afforestation (31 HRUs).

HRUs are topologically linked by applying GIS-based tools to cascade flow components from the upper areas to a lower lying HRU or a river reach. In this study an n-1 relation was applied whereby a percentage of outflow of n HRUs are routed to 1 receiving HRU or connected stream.

ii) Model Concept and Parameterization

The PRMS model is a modular designed, physical-based, distributed parameter model system simulating water fluxes and storages at the catchment scale (Leavesley *et al* 1983). PRMS provides a standard set of process modules, which are used to build the catchment models. Because of its modular structure, new modules can be implemented in PRMS due to the modelers' specific needs.

Minimum climate data requirements are daily total precipitation and daily temperatures. If not available, solar radiation is calculated by the model. The parameterization requires a variety of empirical data for process modules and HRU-related data provided by GIS and remote sensing analysis, other model simulations as well as a field-based system analysis. The model output includes the major hydrological system components, which are predicted separately for each HRU and routed to obtain the total runoff for the watershed. A detailed description of the model is given by Leavesley *et al* (1983).

iii) MMS/PRMS Modeling

Initially, the standard model was calibrated for the Weatherley catchment without considering plantations. First model results indicated that the standard model seemed not appropriate to simulate soil water dynamics within wetlands for two reasons:

- The wetland storage at the beginning of the rainy season was considerably underestimated which resulted in erroneous saturation conditions, and thus surface runoff values when none were observed (see Figure 4).
- Permanent and temporarily saturated wetlands had only limited surface water holding capacity, since standing water was instantaneously removed through surface runoff.

Hence, a new module was implemented to remedy these shortfalls. The module merges the soil zone and the subsurface reservoir into one single physical unit and the storage capacity of the subsurface reservoir was defined as the available storage between field capacity and saturation. When storage in the subsurface reservoir exceeds this capacity, the excess water is routed to surface runoff. The interval 1997-99 was used for calibration of the model and to perform parameter optimization and sensitivity analysis. Thereafter, the model validation has been completed using the entire data set (1997-2002). As shown in Figure 4 model results represent the runoff dynamics in Weatherley (non-forested) and show a slightly better fit between observed (red) and simulated (dark blue) discharge (r=0.88) than using the standard (light blue) model algoritm (r=0.84). While the increase in the measure is relatively small, improvement in timing and magnitude of the first flows of the season are shown in Figure 4. The model, however, tended to underestimate storm hydrographs. A plausible reason might be that measured rainfall data during storm events tend to be inaccurate, i.e. lower than real data due to systematic errors caused by wind drift and splash effects. Rapid regressions of simulated storm hydrographs compared to observations are assumed to be related to an underprediction of infiltration on steep slopes.

The model of the Mooi basin was applied using growth parameters from 3-PG model to parameterize forest dynamics. Thus, time periods before and after afforestation were modeled separately. The post-afforestation model results (Figure 5) reveal that the model was able to capture the overall hydrological dynamics of the basin. In addition high correlation coefficients of r=0.81 (pre-afforestation) and r=0.9 (post-afforestation, Figure 5) proved the reliability of the model parameterized for both conditions.

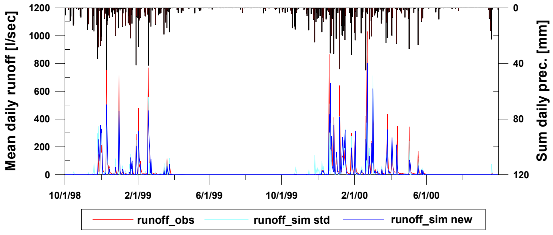

Figure 4. Simulated and observed discharges of the Weatherley Creek (10/1998-09/2000)

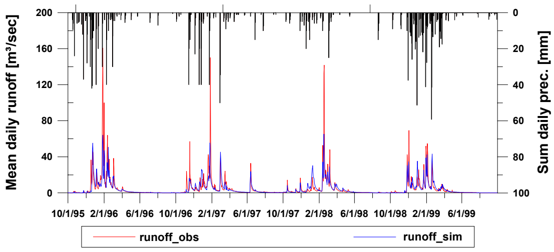

Figure 5. Simulated and observed discharges of the Mooi River considering forest plantations (10/1995-09/1999)

To simulate the impact of forest plantations on water balance and wetland dynamics, an afforestation scenario was performed for Weatherley. For this case, parameters characterizing 15 years old forest stands in best condition were taken from the Mooi model and transposed to the Weatherley model to parameterize those HRUs which were assumed to be planted. Table 2 summarizes annual observed runoff (*OR*) compared to simulated runoff (*SR*) under afforestation. The *Δ-Run* value describes the percentage of annual total water loss as the difference between *OR* and *SR*. The results indicate that available water will be reduced by forest plantations by amounts ranging from 10.6% to 21.5%. This reduction occurs as a result of higher interception and evapotranspiration rates afforded by the afforestation. In addition, flow components were analyzed separately to evaluate impacts on water flow dynamics. Table 2 represents the percentage of annual water loss for each flow component. These results confirm that subsurface flow (*SSF*) will be noticeably more affected then surface (*SF*) and groundwater flow (*GWF*). As an explanation, trees are usually planted on hillslopes and available soil water on the slopes will be taken up by the trees instead of generating interflow. Since surface runoff is mainly generated on bare soil/rock areas and on grassland during intense rainfalls the *SF* is less affected than on afforested grasslands. Results also indicate that this reduction is generally limited to pine plantations.

The impact of afforestation on wetland dynamics has been analyzed separating flow components for each wetland type specifically for the Weatherley catchment. Changes are summarized as percentages based on the non-afforested model results in Table 3. The following conclusions can be drawn from the modeled results: ***i)*** wetlands total runoff losses (*Δ-Total)* vary between 13.6% and 21.3%; ***ii)*** the total runoff loss of plateau wetlands (*Plt*), which are small in size, range from 26.6% to 47.8%. In these wetlands, water input is limited to rainfall, since water of planted surroundings is taken up in plant growth; ***iii)*** medium-sized Slope wetlands (*Slp*) runoff loss varies between 11.1% and 19.9% and is mainly caused by reduced surface and subsurface inflows from upslope areas; and ***iv)*** Valley bottom wetlands (*Val*) are less affected (3.9-8.7% water loss), since those wetlands are mainly controlled by groundwater dynamics and modeled as saturated areas connected to the stream.

Year	P [in]	OR [in]	SR [in]	Δ-Run [%]	Δ-SF [%]	Δ-SSF [%]	Δ-GWF [%]
1998	26.7	6.6	5.9	-10.6	-4.1	-18.1	-3.1
1999	40.5	19.0	15.7	-17.4	-7.0	-18.3	-4.4
2000	55.0	33.3	28.8	-13.5	-6.3	-15.9	-1.0
2001	38.9	17.2	13.5	-21.5	-8.9	-11.1	-1.7

Table 2. Annual rainfall (*P*), observed (*OR*) and simulated (*SR*) runoff (in inch) and predicted changes of major flow components (in percent) on basin scale, Weatherley

Year	W-Type	ΔS Flow [%]	ΔSS Flow [%]	ΔGW Flow [%]	ΔSum [%]	ΔTotal [%]
1998	Plt	- 64.3	- 27.1	-11.6	**-36.0**	
	Slp	- 33.8	- 23.0	- 4.8	**-17.4**	
	Val	- 7.8	- 16.4	- 4.2	**- 4.3**	**- 14.8**
1999	Plt	- 77.7	- 59.8	- 8.9	**- 27.4**	
	Slp	- 23.1	- 23.4	- 3.1	**- 13.6**	
	Val	- 8.7	- 10.3	- 3.0	**- 8.1**	**- 21.3**
2000	Plt	- 83.0	- 64.0	- 4.4	**- 26.6**	
	Slp	- 4.0	- 13.0	- 2.0	**- 11.1**	
	Val	- 6.2	- 2.9	+ 1.2	**- 3.9**	**- 17.0**
2001	Plt	- 90.1	- 43.6	- 17.4	**- 47.8**	
	Slp	- 16.4	- 22.1	- 3.8	**- 19.9**	
	Val	- 1.4	-8.4	+ 1.7	**- 8.7**	**- 13.6**

Plt - plateau wetland; Slp - slope wetland; Val - valley bottom wetland

Table 3. Annual changes of flow dynamics in Weatherley compared to non-afforested model results (in percent), 10/1998-09/2001

6. CONCLUSIONS

This study has shown that an integrated modeling approach was successfully applied to simulate the impacts of afforestation on basin and wetland dynamics. The approach presented here, demonstrated that ***i)*** time series and system analysis, GIS/RS analysis and physically-based process modeling has a unique value in providing information for simulating the landscape dynamics at different scales; ***ii)*** model simulations carried out for 2 basins considering pre- and post-afforestation conditions have demonstrated that afforestation influences the basin water balance significantly, primarily in subsurface water availability; and ***iii)*** influences of forest activities on wetland water balance and process dynamics are strongly associated with the size and type of the specific wetland.

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