Hydrological Impacts of Afforestation: A Case Study Based on Simulation of TOPOG in the Small Watershed of Caogou in Liupan Mountains, China

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Abstract: Forest area in Liupan Mountains is important water conservation area of Loess Plateau. This area experienced large-scale afforestation during the past 3 decades, and the landscape patterns has been changed greatly. These changes have result in consequently changes of characteristics of main hydroecological progress and ecological function. Based on analysis of the dynamic and components characteristics of hydrological process, this paper discussed possible changes of landscape caused by afforestation and their hydroecological impact based on simulation results made by a distributed hydrological model TOPOG, in order to offer a hydroecological view for the undertaking afforestation activity in Liupan Mountains and Loess Plateau. The preliminary scenario simulation and analysis imply that total runoff at catchment outlet will decrease total runoff of catchment if increasing area of Larix principis-uruprechtii woodland through cutting natural broadleaf woodland or reclamation of shrub patches. The decrease of total runoff can reach 28% when the area ratio of Larix principis-uruprechtii patches enlarges from 11.5% to 58%. While reclamation of shrub patches also might reduce availability of water resources because runoff undulating will enlarge.

Key words: afforestation; TOPOG; simulation; runoff discharge; hydrological components

1 Introduction

The large-scale afforestation projects, which were implemented in last decades and will be further continued in future in areas with high ecological significance in China (Liu 2003), will change the landscape pattern greatly and result in changes of ecological function and processes (Forman et al. 1986). Although there have been increasing debates about the ecological effects of afforestation on runoff (Whitehead 1993; Ma 1993; Jackson et al. 2005), it is accepted generally that the change of vegetation and landscape patterns will directly affect the hydrological processes.

The well forested Liupan Mountains is well known as a “green island” on Loess Plateau since more than 60 rivers emanate from here (Fig. 1). As an important head-water area with relatively high biodiversity, long-term afforestation has been carried out in last 4 decades, especially since late 1980s, and the landscape has been changed greatly. The area of natural forest was about 25 000–30 000 ha before the large-scale afforestation started in 1986, and artificial forest was about 3 500 ha (Wang 1988; Li 1999), i.e., a ratio of total forest/woodland area of 8.5%. However, this ratio was increased remarkably to 62.5% (about 50 000 ha) duo to large-scale afforestation and natural forest protection during 1986–1998 (Li 1999).

Taking Caogou Catchment as objective area, which is a drainage basin of a secondary branch of Jinghe River, this paper discussed the hydrological impacts of possible landscape changes based on simulation by a distributed eco-hydrological model of TOPOG, in order to offer an eco-hydrological view for the undertaking afforestation activity.
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2 Methods

2.1 The study area

The small watershed of Caogou with an area of 9.15 km$^2$ is located at the southeastern side of Liupan Mountains, and it is a subbasin of Xiangshuihe River which is a branch of Jinghe River (106°12′–16′ E, 35°27′–33′ N) in the Loess Plateau (Fig. 1). The climate here is semi-humid. Since the wide elevation range of 2200–2930 m, there is a wide variation of meteorological parameters. This can be understand through the data from two weather stations nearby (Fig. 2), of which the Liupan weather station with elevation of 2860 m locates on the mountain top and the Jingyuan station with an elevation of 1960 m is not far away from the outlet of the small watershed. About 70% of the annual precipitation concentrates in the period from June to September, consistent with the growth season. About 70% of the annual potential evaporation concentrates in the period from April to September.

Because of complex landform, forest in this area is maintained quite well compared with the surrounding areas in Loess Plateau. However, little original vegetation is kept, and current vegetation is mainly composed of secondary woodland and artificial forests (Fig. 3a). The main species of artificial forests is *Larix principis-upprechtii* (other species less than 5%), and dominant species of the secondary woodland are *Betula*
populus cathayana and Pinus armandii) (other species such as Quercus liaotungersis less than 2%). Dominant species of shrubs are Corylus heterophylla, Cotoneaster ecutifolius, and Prunus salicina, etc. The dominant species of alpine meadow is Carex spp.

2.2 Representation of hydrological processes in TOPOG

For the mountainous catchment of Caogou, the hydrological processes are strongly influenced by the complicated distribution of landform, soil and forest/vegetation (Figs. 3 and 4). A right selection of hydrological model will help to understand, separate and evaluate the hydrological effect of forests from the integrated effect of many factors. Comparing with some other models such as SWAT (Arnold et al. 1995; Neitsch, 2000) and SHE (Bathurst et al. 1991), we choose the distributed model of TOPOG developed by CSIRO\(^4\) in Australia (Short et al. 1990; Hatton et al. 1991; Vertessy et al. 1990, 1993, 1996; Silberstein et al. 1999), since it can detailed describe the flow processes in small catchment and has been applied in some researches for varied purposes.

There are two hydrologic modules in TOPOG, i. e. Topog_IRM and Topog_STORM. The Topog_IRM module simulates slowly changing hydrologic states and plant growth over long-term sequences at daily time steps. For each time-step, TOPOG considers each element as a control volume, and calculates the water balance in this element, taking into account its initial state, water coming from the connected upslope elements, rainfall, and evapotranspiration.

Soil evaporation is computed by the method of Choudhury and Monteith (1988). Transpiration is computed using Penman-Monteith equation and the canopy resistance term in the equation is calculated using the stomatal resistance equation of Ball et al. (1987), scaled by the leaf
area index. Water for transpiration can be extracted from the soil depending on vegetation and root characteristics. A plant growth module computes daily rates of carbon assimilation, allocation and respiration. The computations were described by Hatton and Dawes (1991), Vertessy et al. (1996) and Dawes et al. (1997). The infiltration and vertical percolation of water through the unsaturated zone are handled by the Richards’ equation, and TOPOG considers that there is no unsaturated lateral flow. The soil hydraulic model developed by Broadbridge and White (1988) is used to estimate the K-ψ-θ relationship needed to solve the Richards equation. A full description is given by Vertessy et al. (1993).

The lateral water flux between elements in the saturated zone is computed with the Darcy equation. Based on the assumption made by TOPOG of flow tubes, which do not interfere with their neighbours, simulation begins on the highest elements of the catchment, and then goes downward until the outlet is reached. Each element is discretised vertically, so that TOPOG is able to represent layered soils. When there is a saturated layer, lateral subsurface flow is calculated via Darcy’s equation. The piezometric gradient is assumed to be equal to the topographic gradient. As TOPOG allows for several kinds of soils in each element profile, there can be lateral flow in several layers. As deep groundwater does not play an important role in the hydrologic response of the Caogou catchment, we did not use the deep groundwater module, all the subsurface flow is computed via Darcy’s law in the shallow subsurface layers.

The module of Topog_STORM simulates runoff generation processes on each element during a discrete storm event. If the surface is saturated or if rainfall exceeds infiltration capacity, surface runoff can develop; it is calculated according to the kinematic wave equation. Evapotranspiration is neglected during the storm period.

Topog_IRM and Topog_STORM simulate different runoff generation processes, i.e. discharge component of runoff is saturation-excess flow in Topog_IRM, and it is infiltration-excess flow in Topog_STORM. Considering the limitation of observed data, only Topog_IRM was selected to simulate ecohydrological processes in Caogou catchment. However, it will not make considerable simulation error. It was noticed in long term observation that saturation-excess flow is the main component of runoff in Caogou catchment and circumjacent area because of good coverage of vegetation. Surface runoff was rarely observed even in rainstorms, and the flow moves mainly in form of sub-flow before inpouring into riverway. So, Topog_IRM can describe the characteristics of water movement in our study area. Dawes et al. (1997) applied the Topog_IRM model to a cropping rotation catchment over a period of one and a half years and found that simulated evapotranspiration, soil moisture at selected depths and leaf area index agreed with published and field measurements very well.

### 3 Application of TOPOG

#### 3.1 Parameter calibration

##### 3.1.1 Calibration targets

Like nearly all the so-called physically based models, TOPOG have to be calibrated to fit observed data. In the early exploratory simulations, we simply tried to reach a reasonable hydrological behaviour for our catchment, given the observed runoff volume at catchment outlet as main calibration targets. Soil moisture dynamic and rainfall interception in rainfall events were also used to evaluate calibration result. Transpiration of upper vegetation layer and soil evaporation are considered additionally.

##### 3.1.2 Data and approach

Observed hydrological data and vegetation growth process during growing seasons in 2004 and 2005 are available in our study. We applied the data in 2005 which has a relative longer temporal span of observation to calibrate the parameters, and the data in 2004 for model validation.

##### 3.1.3 Evaluation and results

We evaluate the goodness of simulation by not only the impacts of parameters upon calibration objects (increase or decrease of total quantity), but also the intensity of such impacts (the speed of increase or decrease) and shape of hydrograph. The runoff simulation with calibrated parameters can meet the statistical requirement and $R^2=0.6465$. $R^2$ for soil moisture and interception of upper vegetation layer are 0.8687 and 0.7288 respectively.

#### 3.2 Validation of TOPOG

The simulated hydrograph represents the observed hydrograph quite well (Fig. 5a). With lagged peak discharge during flooding process and flattened, long recession curve, such hydrograph implicates that subsurface flow might be the major form of runoff generation in this catchment. The ratio of surface runoff was only 1.79% in total simulated runoff discharge, just the same with our field observation in this area, implying that infiltration-excess mechanism of runoff generation works restrictedly during rainfall events. Continuous simulation from 2004 to 2005 shows higher simulating
efficiency ($R^2=0.6793$) than that of separate simulation in 2005 (Fig. 5b).

4 Sensitivity and error analysis of parameters

4.1 Sensitivity analysis of parameters

We focus sensitivity analysis on the following 4 parameters: saturated soil conductivity, saturated soil moisture content, depth of soil layer and initial soil moisture content.

When saturated soil conductivity raises from 0.1 to 4 times of actual data (0.36–4.04 m d$^{-1}$) within the reference range of this parameter, the general level of runoff discharge declines, including slowly change and flooding period. However, runoff discharge will increase during the period of low precipitation.

Saturated soil moisture volume content is ranged from 0.6 to 0.8 times of observed data (40%–80%) to be tested, and it makes impact mainly on the fluctuating of discharge curve. Fluctuating of hydrograph is weakened and peak discharge and discharge in declines during the period of low precipitation when saturated soil moisture increases, and soil moisture storage level will rise. In terms of flooding processes, flood recession will be slowed down when saturated soil moisture content increases.

Although soil depth was suggested to be calibrated within a wide range in some work of simulation with distributed hydrological models (Molenat 1999; Carluer et al. 2004), we ranged the soil depth from 0.5 to 2 times of reference value of observed data (60–120cm) in calibration considering that the actual soil depth could not be very large in such a rocky mountainous region like Liupan Mountains. Hydrological processes show high sensitivity to variation of soil depth. The increase of soil depth will delay the peak runoff during storm rainfall events, put down the peak discharge, and increase soil moisture storage as well.

The impact of initial soil moisture content upon hydrological process is comprehensible. Enlarging initial moisture will increase the base flow level and such impact can last during almost the whole growing season. It can also cause higher peak discharge within early simulation period. After calibrating parameter series with observed data during growing season of 2005, we simulated the hydrograph from 2004 to 2005 continuously so we can evaluate the influence of initial moisture setting, since it was the only parameter different between the continuous simulation from 2004 to 2005 and the separate simulation of 2005. The value of initial soil moisture used finally result in a hydrograph that did
not accord with simulation of 2005 perfectly, however, they show very similar runoff level and dynamic characteristics with each other (Fig. 6), implicating that the initial moisture value used in continuous simulation could keep the simulation going on stably. What’s more, the continuous simulation shows higher simulating efficiency than separate simulate on of 2005. Thus we regard the initial soil moisture value as appropriate in principle in terms of data available in this study.

4.2 Errors source analysis

The general trend of runoff discharge has been represented quite well in our simulation, however, the detailed characteristics of hydrograph are not described accurately. First of all, simulated peak discharge in early growing season of 2005 is obviously lower than observed ones, and this is a important cause for simulation errors (Fig. 5 b). Additionally, simulated runoff discharge shows higher sensitivity upon rainfall events than actual discharge, and this is mainly related with our setting of soil depth value. Just as what has been mentioned in part 4.1 of this paper, based on consideration for actual soil characteristics in study area and total level trend of discharge, we sacrificed the description accuracy of responding sensitivity of discharge upon rainfall events in a degree.

4.2.1 Errors from meteorological data

Complex landform in mountainous region can often result in spatial variation of meteorological factors, especial precipitation. The data of two weather station located in Xiangshuihe River Basin, including precipitation, were applied to extrapolate weather data within the catchment of Caogou which is a subbasin of Xiangshuihe Basin (with an area of 43.5km²), and both of the spatial distances between Caogou and these two stations are less than 10 km, thus we can assume that the meteorological characteristics represented by the two weather stations should not differ substantially with that in Caogou Catchment. However, the hydrological processe in Caogou Catchment behaves fairly sensitive to variation of such meteorological factors as precipitation because of its quite small area (less than 10 km²). Therefore, the difference between the extrapolated and actual weather data still might result in simulation errors and decline the simulation efficiency.

The simulation during June 2005 is probably influenced by this inaccuracy of precipitation data. LAI (Leaf area index) of vegetation is keeping increase during June, and potential evapotranspiration and interception keep increase consequently. Therefore the runoff discharge should decline gradually if there is no big soil water recharge from rainfall. However, observed runoff discharge increased by about 50% (from 0.208 to 0.294mm) during 527–529 days (Fig. 5a) with no obvious rainfall recorded in weather station at the same time. While at that time the surface snow-melting process had terminated long before, and there is no farmland and reservoir that might make water sluice. So, we believe that in fact there should be a quite significant rainfall event within Caogou catchment at 528 day (June 11, 2005) in spite of the null rainfall record in weather station in Xiangshuihe Basin. Considering the current interception and soil moisture level at that time, this rainfall event should be more than 10 mm or so to cause the increase of 0.086 mm of runoff discharge, whereas both of the two weather stations within Xiangshuihe had no record of this possible rainfall event. One station recorded the precipitation as 0 mm and the other is 0.5mm.

4.2.2 Errors from model construction

As long as our stuffy area is concerned, the absence of representation for snow-melting process in the model could also be a source of simulating errors. An accurate peak discharge for the rainfall event at 587 day (June 30, 2005) is not obtained in our final continuous simulation. According to the comparison between simulated and observed hydrograph after that day and sensitivity analysis of parameters, this inaccuracy is resulted mainly by a lower soil moisture content than actual soil moisture content, while the water recharge of melting snow to soil moisture is somewhat important in this region, especially during early growing season.

5 Scenario simulation and analysis

5.1 Scenario setting

The setting of scenario to be simulated is based on the analysis of historical records of forest cover and the current management strategy of afforestation activities in Liupan Mountains, i.e. transferring natural broadleaf woodland and shrubs into artificial plantation of larch (Larix principris-upprechtii).

Timber obtaining was taken into account in inchoate strategy of afforestation in this region. Since Larix principris-upprechtii has been introduced to this region successfully in 1964 and showed a higher growth speed than local tree species (Li 1999), Larix principris-upprechtii became the major species in afforestation in Liupan Mountains region. The major species still is Larix in actual afforestation activity although afforestation
strategy has been adapted and called for a mixed-species afforestation from 1992. The community of Populus and Betula distribute from elevation 2300 m to 2700 m in this region, almost same with Latrix. Although Populus prefer sunless and semi-sunless slope to sunward slope, while Betula distributes on sunward slope more than sunless slope, both of the two species distribute in habitat of widely ranged environmental characteristics, and their distribution area are appropriate for Latrix in principle. Pinus armandii is not replaced in our scenario because this species brings quite good timber yield, too, agreeing with the current aim of afforestation in this area.

Current actual area ratio of larch plantation in Caogou catchment is 11.5%, lower than the ratio 24.5% in Xiangshuhei River Basin. The ratio of larch plantation in Caogou will be increased to 23.0% when we transfer current Populus secondary forests into larch patches, thus such a transferring was set as scenario I (Fig. 7). Based on this transferring, the area ratio of larch plantation will be increased to 57.8% when Betula patches transferred into larch, too, and this was set as scenario II (Fig. 7). If we transfer shrubs instead of broadleaf woodland patches into larch plantation, the area ratio of larch plantation will be 21.0%, and this is the scenario III (Fig. 7).

5.2 Scenario analysis
In scenario analysis, we mainly discuss the difference of total amount of interception, transpiration, runoff discharge and soil evaporation between scenarios and actual landscape (Table 1). Considering total level of simulation errors, difference within 5 mm will be regarded as indistinctive and not be taken into account.

5.2.1 Scenario for transferring broadleaf woodland into artificial woodland
The trend of hydrograph changes in scenario I and II are quite similar with each other when comparing with actual hydrograph. Nevertheless, the difference between scenario II and actual hydrograph is more obvious than scenario I because of its larger area that has transferred to Latrix. In terms of hydrological components, (i) total evapotranspiration increases prominently: interception increase in a degree and transpiration of upper vegetation layer increase obviously, since average LAI of Latrix (3.58) is higher than Populus (1.83) and Betula (2.15). Total transpiration of under vegetation layer decreases because there usually is poor undergrowth vegetation on the floor of current larch plantation. Soil evaporation shows little difference. (ii) Total runoff discharge

<table>
<thead>
<tr>
<th>Unit: mm</th>
<th>Actual</th>
<th>Scenario I</th>
<th>Scenario II</th>
<th>Scenario III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross rainfall</td>
<td>1409.43</td>
<td>44.62</td>
<td>44.22</td>
<td>33.93</td>
</tr>
<tr>
<td>Delta soil moisture storage</td>
<td>37.81</td>
<td>515.67</td>
<td>529.61</td>
<td>517.89</td>
</tr>
<tr>
<td>Total soil evaporation</td>
<td>76.00</td>
<td>74.46</td>
<td>71.15</td>
<td>75.26</td>
</tr>
<tr>
<td>Total transpiration of upper vegetation layer</td>
<td>385.79</td>
<td>411.19</td>
<td>455.32</td>
<td>384.08</td>
</tr>
<tr>
<td>Total transpiration of under vegetation layer</td>
<td>199.25</td>
<td>163.57</td>
<td>163.51</td>
<td>211.9</td>
</tr>
<tr>
<td>Total ET</td>
<td>1169.38</td>
<td>1187.89</td>
<td>1219.59</td>
<td>1189.13</td>
</tr>
<tr>
<td>Total runoff volume</td>
<td>202.2</td>
<td>176.86</td>
<td>145.57</td>
<td>186.32</td>
</tr>
<tr>
<td>Ratio of surface discharge (%)</td>
<td>1.79</td>
<td>2.14</td>
<td>2.57</td>
<td>1.92</td>
</tr>
<tr>
<td>Peak discharge</td>
<td>4.68</td>
<td>4.36</td>
<td>4.36</td>
<td>4.27</td>
</tr>
</tbody>
</table>
decreases remarkably (Fig. 8a) with the ratio of subsurface flow against total discharge raises in a degree. Total discharge is decreased by 12.35% in scenario I and 28.01% in Scenario II. The increase of total evapotranspiration can account for major part of the decrease of runoff discharge.

The fluctuating of runoff is weakened in general because of the decline of runoff level (Fig. 8b), and the increase of subsurface flow ratio probably accounts for the flattening of hydrograph in addition. Hydrograph fluctuates more sharply than actual in some part of hydrograph, especially during storm rainfall events.

5.2.2 Scenario for transferring shrubs into artificial woodland
Total evapotranspiration increases while interception, soil evaporation and total transpiration of upper layer vegetation show little difference with actual ones. Transpiration of undergrowth vegetation increases because original shrub patches have no undergrowth vegetation (herbage is neglect in all vegetation types). Total discharge is decreased by 7.85%. The ratio of subsurface flow changes little.

The fluctuating of runoff is magnified in general (Fig. 8b), with peak discharge increasing and base flow level cut down. It is mainly because of the difference of soil characteristics between Latrix and shrub patches. Such changes can be observed mainly in growing season, and runoff fluctuating flatten in a degree during non-growth season.

6 Discussion and conclusions
(1) The simulation efficiency for such main hydrological process as interception, soil moisture and runoff of Caogou catchment are fairly acceptable and can be applied to found the ecohydrological research and landscape management. However, since snow-melting process will change the response mode of soil to precipitation, absence of consideration upon snow-melting may reduce simulate efficiency during non-growth season and early or late growth season. In order to avoid the limitation of TOPOG application in middle and high latitude region, we suggest and will try to take snow-melting process into account in the representation of hydrological processes of TOPOG.

(2) Although initial theta is of high sensitivity, continuous simulation over long periods may avoid substantial uncertainty in estimating this parameter. Its value can be viewed as reasonable and acceptable only when it is proved to be able to simulate flow discharge and soil moisture within a period including two or more growth seasons.

(3) In order to improve the simulation for catchment smaller than 10 km², especially when it is located in mountainous region, accurate meteorologic data is important. Weather station should be located as close as possible to the objective catchment if there is no station within the catchment, and extrapolation of meteorologic data should be avoided if possible.

(4) With good coverage of vegetation and loose forest soil, the main component of total runoff in Caogou catchment is subsurface soil water flow, and the ratio of surface runoff is less than 5%.

(5) The preliminary scenario simulation and analysis imply that total runoff at catchment outlet will decrease total runoff of catchment if increasing area of *Larix principis-upprechii* woodland through cutting natural broadleaf woodland or reclamation of shrub patches. The decrease of total runoff can reach 28% when the area...
ratio of *Larix principis-upprechtii* patches enlarges from 11.5% to 58%. While reclamation of shrub patches also might reduce availability of water resources because runoff undulating will enlarge. Since the forest area in Liupan Mountains and circumjacent region is water resources area for Loess Plateau which is suffering short of water resources severely, landscape management of this region should take the impact of afforestation and other change of vegetation patterns upon runoff generation into account, i.e. optimize the landscape programming by well balancing between soil conservation and maintaining of certain level of total runoff.

References


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造林活动对六盘山小流域水平生态水文过程影响的模拟研究

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摘要: 造林活动对六盘山小流域水平生态水文过程影响的模拟研究。本文选择泾河支流香水河的二级支流草沟小流域为研究对象, 应用 TOPOG 模型对该区域内的造林活动对小流域水平生态水文过程的影响进行模拟预测, 以期为六盘山地区正在进行的退耕还林植被建设提供科学指导。本文选择泾河支流香水河的二级支流草沟小流域为研究对象, 应用 TOPOG 模型对该区域内的造林活动对小流域水平生态水文过程的影响进行模拟预测, 以期为六盘山地区正在进行的退耕还林植被建设提供科学指导。