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Quantitative estimate of water yield reduction caused by forestation in a water-limited area in northwest China

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[1] The eco-hydrological model SWIM was used to examine the effects of forestation on water yield in a watershed of the Liupan Mountains in northwest China. The results showed that the water yield variation caused by tree species shift among mature forests dominated by larch, poplar and birch was negligible. The vegetation type conversion from grassland to forest strongly reduced water yield. The annual water yield reduction after 10% forestation was 15.8 mm on average with a fluctuation from 3.5 to 19.3 mm. The contribution of site variation to water yield varied from a decrease of 3.5 mm to an increase of 12.3 mm after 10% forestation, which on average was nearly a half of the influence of vegetation conversion between forest and grassland. Site selection for forestation in mountainous areas could be beneficial in alleviating forest-water conflicts and lessening the water yield reduction caused by forestation.

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1. Introduction

[2] Forestation has been greatly encouraged worldwide for soil protection and carbon sequestration. However, forestation usually decreases water yield [*Farley et al.*, 2005; *Wang et al.*, 2008]. Based on data from 504 catchments, mainly from regions with annual precipitation more than 800 mm, *Farley et al.* [2005] concluded that full forestation would reduce water yield by 180 mm/yr on average compared to maintaining grasslands. A potential water yield reduction resulting from 100% forestation was estimated from 50 to 300 mm/yr along the precipitation gradient from 400 to 3,100 mm in China [*Sun et al.*, 2006].

[3] At the margins of Pacific monsoon influences, the eastern part of northwest China is very sensitive to forest-water interaction, and a reduction in water yield through forestation would strongly affect the regional water supply and even human living conditions. For this reason, it is essential to quantify the influence of forestation on water yield. However, previous studies were mostly focused on the long-term averaged influence of forestation on annual water yield considering two extremes, i.e. full forestation or deforestation, not reflecting the dynamics of water yield in the course of forestation [*Sun et al.*, 2006]. Furthermore, a simple simulation of water yield impacts that is only based on a forest area ratio is unable to predict the hydrological effects of forestation since a number of other factors such as climate, soil, landform and tree species also influence water yield [*Farley et al.*, 2005]. Quantification of all factors is an essential precondition for forest-water integrated management and related policy-making in dryland regions.

[4] The Liupan Mountains (104°30′ – 107°10′E, 34°30′ – 37°30′N), located in the eastern part of northwest China, represent an important regional headwater area. In order to understand the hydrological effect of forestation in this region, an eco-hydrological study has been carried out since 2000. The hydrological processes (precipitation, interception, evaporation, transpiration and runoff) and ecological processes (e.g. vegetation dynamics) have been monitored on three scales: single tree, plot and small watershed. Some results at plot scale were reported by *Wang et al.* [2008]. This paper focuses on the water yield reduction and its spatio-temporal variation within a small watershed due to the changes of forest area, tree species and site condition. The study is based on measured data and application of Soil and Water Integrated Model (SWIM).

2. Study Area and Methods

2.1. Site Description

[5] Being an important regional water source, the Liupan Mountains are termed a "wet island". Massive forestation or reforestation has been carried out here for several decades mainly for erosion control and timber production and some negative effects of water yield reduction after forestation have been already observed [*Huang and Liu*, 2002; *Wang et al.*, 2008].

[6] Xiangshuihe (106°15′E, 35°30′N) is a representative small watershed situated in the south-east part of the Liupan Mts., with an area of 43.5 km^2 and an elevation range of 2,070–2,931 m. It is mainly composed of steep slopes with gradients of more than 30 degrees. Haplic luvisol is the only soil type with depth varying from 20 cm on upper slopes to 100 cm on lower slopes. The soil texture is sandy loam with rich stone fragments from 0.05% (vol.) on lower slopes to 30% (vol.) on slope top. Forest soils are porous with a total porosity of more than 60%, and a saturated conductivity of more than 100 mm/h.

[7] This watershed has a temperate monsoon climate characterized by a cold-dry winter and warm-wet summer. The mean annual air temperature was 5.9°C and the mean annual precipitation was 641.6 mm with a variation from 323 mm to 966 mm in 1975–2003. More than 80% of annual

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Table 1. Current Distribution of Different Vegetation/Land Use Types in the Xiangshuihe Watershed

	Vegetation/Land Use Type	Origin	Area in Watershed (%)	Maximum LAI[a]	Maximum Depth of Root Zone (cm)
1	Poplar forest	Natural	14.1	2.4	50
2	Birch forest	Natural	27.5	3.9	80
3	Oak forest	Natural	1.3	3.5	80
4	Willow forest	Natural	0.3	3.3	80
5	Pine forest	Natural	14.7	2.9	60
6	Sparse forest	Natural	0.6	2.7	42
7	Shrubland	Natural	12.0	2.6	45
8	Grassland	Natural	4.6	2.0	40
9	Larch plantation	Artificial	23.8	5.5	60
10	Spruce plantation	Artificial	0.7	4.0	60
11	Nursery	Artificial	0.2	2.0	40

[a]LAI: leaf area index.

precipitation was concentrated in the period from June to October.

[8] The primary forests in this watershed have been destroyed. About 58% of the watershed area is now covered mainly by secondary forests with dominant species of Armand pine (*Pinus armandii*), White birch (*Betula platyphylla*), China paper birch (*Betula albo-sinensis*), Himalayan birch (*Betula utilis*), David poplar (*Populus davidiana*) and East-Liaoning oak (*Quercus liaotungensis*). The planted forests of Prince Rupprecht larch (*Larix principis-rupprechtii*) and Thick leaf spruce (*Picea crassifolia*) account for 24.5% of the watershed area. The rest 16.6% is covered by shrubs and grassland (Table 1).

2.2. SWIM Model and Land Use Scenarios

[9] The dynamic eco-hydrological model SWIM integrates hydrological processes, vegetation growth and nutrient cycling at river basin scale by disaggregating the basin into sub-basins and hydrotopes. A hydrotope is a set of elementary units with same land use and soil in a sub-basin. The water fluxes are firstly calculated for every hydrotope, and then the lateral water fluxes to river network are simulated. Soil evaporation and plant transpiration are calculated using the approach of Ritchie, where they are functions of leaf area index (LAI), potential evaporation (PE) and soil moisture. PE is estimated with the method of Priestley-Taylor from solar radiation and air temperature as inputs. A full description of SWIM is given by *Krysanova et al.* [1998, 2005]. SWIM has been applied to predict the hydrological effects of forestation and land use change, particularly in Europe [*Wattenbach et al.*, 2007].

[10] The Xiangshuihe watershed was defined by three raster maps: digital elevation model (DEM), soil, and land use, with a resolution of 10 m × 10 m and divided into 96 hydrotopes belonging to 17 sub-basins. Major soil and vegetation parameters, such as soil texture, porosity, bulk density, and maximum LAI (Table 1), were measured in sample plots with the size of 20 m × 20 m and assigned to hydrotopes according to their vegetation types. Climate data recorded by an automatic weather station (LI-1401) in the watershed were used for model calibration. Daily runoff data measured at the watershed outlet during the growing seasons of 2006 and 2007 were adopted for model calibration and in 2004 and 2005 for model validation. The nondimensional efficiency criterion of Nash and Sutcliffe was used to evaluate the quality of model calibration/validation. Additionally, the comparison between the simulated and measured evapotranspiration (ET) in plots with larch plantation and oak forest was employed to test the model performance.

[11] Poplar and birch forests were the key existing secondary forests. These forests possess lower wood production, and would eventually be naturally replaced as pioneer tree species. Larch as a fast-growing tree species was usually planted in the watershed for economic harvest. In order to evaluate the hydrological effects of changing forested area and tree species, two scenario sets were designed (Table 2). Scenario set I, called Tree-Species, includes two scenarios, in which all the larch plantation in the watershed is replaced by birch and poplar forests, respectively. Scenario set II, named Forest-Area, is composed of eight scenarios, in which the forest coverage varies from 0% to 99.7%, and includes the current situation. The weather data in 1996–2007 from the Jingyuan weather station, located 10 km away from the Xiangshuihe watershed, were used for land use change scenarios.

3. Results and Discussion

3.1. Model Calibration and Validation

[12] Figure 1 shows a good fit between the simulated and measured daily runoff at the outlet of Xiangshuihe, with an efficiency of 0.80 for the calibration and 0.64 for the validation period. The total ET in hydrotopes with larch plantation during the period of June to October, 2005, simulated by the calibrated SWIM is 8.5% lower than that measured in the larch plantation plot in Xiangshuihe (Table 3). The total ET in hydrotopes with oak forest in August to September, 2004 simulated by SWIM is 16.6% higher than the measured value of 88.7 mm from the plot with oak forest located outside of the watershed and 1.2 km away from the outlet of Xiangshuihe [*Xiong et al.*, 2005]. The higher efficiencies in

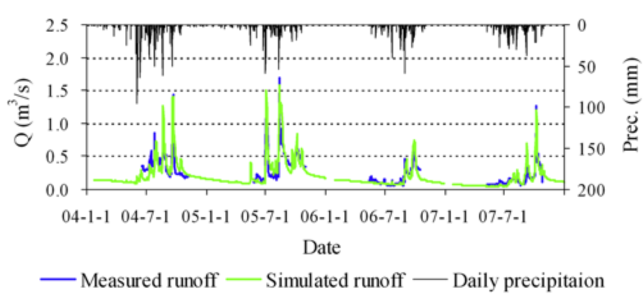

Figure 1. Comparison between the observed and simulated runoff by SWIM at the outlet of Xiangshuihe Watershed.

Table 2. Descriptions of Forestation Scenarios

Scenario	Scenario Definition[a]	Forest Cover Ratio (%)
	Tree-Species	
L to B	All larch plantation changed to birch forest	83.1
L to P	All larch plantation changed to poplar forest	83.1
	Forest-Area	
No forest	All forest converted to grassland	0.0
LBP to G	All larch plantation, birch forest and poplar forest converted to grassland	17.7
LB to G	All larch plantation and birch forest converted to grassland	31.8
LP to G	All larch plantation and poplar forest converted to grassland	45.2
L to G	All larch plantation converted to grassland	59.3
Current	Current situation	83.1
G to L	All grassland converted to larch plantation	87.7
S to L	All shrubland converted to larch plantation	95.1
GS to L	All grass- and shrub-land converted to larch plantation	99.7

[a]Based on the current vegetation of Xiangshuihe watershed.

runoff simulation and low errors in ET simulation indicate that the model is sensitive to runoff and ET and its performance is acceptable.

3.2. Variation of Water Yield

[13] The measured water yield from the watershed during the growing season was 87.6 mm on average for 2004–2007 with a large variation from 55.0 to 125.1 mm. The corresponding runoff coefficient varied from 0.10 to 0.23. This variation results from both the amount and intensity of rainfall. For example, the highest water yield in 2005 was mainly determined by two strong rainfall events with rainfall of 114.2 mm and 55.0 mm, although the total rainfall of 538.0 mm in the growing season was low. In contrast, the highest rainfall depth of 606.5 mm in 2007 produced a low water yield of 60.5 mm since all rainfall events were smaller than 40 mm (Table 3).

[14] A large degree of spatial variation is another feature of the water yield production in this watershed (Figure 2). In 2004–2007, the highest water yield depth from hydrotope was more than 250 mm per growing season; while the lowest one was only 20–40 mm. 36% of the watershed area generated runoff of 40–60 mm, and 28% of the watershed area generated 60–100 mm. The area generating runoff more than 100 mm accounted for 30% of the watershed.

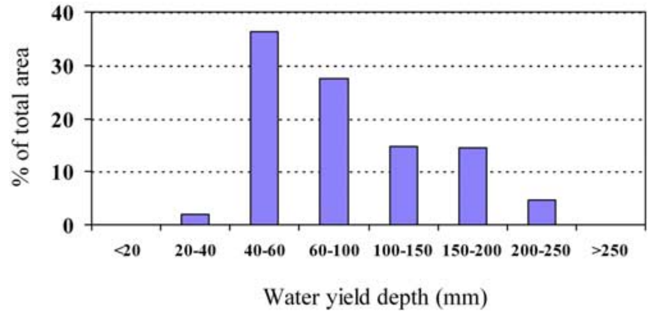

Figure 2. The simulated area distribution of water yield depth of Xiangshuihe with the current vegetation during the growing season of 2005.

3.3. Impacts of Forestation on Annual Water Yield

[15] The absolute and proportional water yield reduction of the watershed were calculated compared with that of the watershed without any forest (87.7% covered by grass and 12% by shrubs) and then used to evaluate the hydrological impacts of forest/vegetation alteration, i.e., tree species shift, vegetation type conversion and site variation.

[16] The tree species shift among larch, poplar and birch in mature forests (maximum LAI 5.5, 2.4, and 3.9, correspondingly) did not significantly affect water yield despite the differences in LAI. When larch plantation, occupying 23.8% of the watershed area, was converted to birch forest, there was almost no change in the average annual water yield. The conversion from larch plantation to poplar forest increased the water yield only by 2.7 mm/yr when 10% of the watershed was converted, which accounted for 5.2% of the water yield under the larch plantation. This can be explained by the fact that ET in the water-limited area is mainly controlled by the available soil water amount rather than by LAI. It was found that ET reaches its maximum level when LAI was 2–3 [*Obrist et al.*, 2003]. As LAI increased beyond this value, the water yield no longer decreased [*Li et al.*, 2005]. The water yield change caused by tree species shift in our study was close to the results of other studies. *Wattenbach et al.* [2007] found that a tree species shift from a Scots pine-dominated forest to a deciduous forest over 10% of the area of a catchment in Germany brought a water yield increase of only 1.1 mm. *Sahin and Hall* [1996] analyzed 145 catchments from different regions of the world and found a water yield difference of 3–6 mm between conifer and deciduous forests.

[17] However, vegetation type conversion strongly affected water yield as indicated by a reduction of mean water yield by 158 mm/yr after full forestation due to the increase of LAI and available soil water as the root zone for forest is thicker than that for grassland. This value is much more than the value of

Table 3. Comparison Between Measured and SWIM-Simulated Evapotranspiration (ET) in Xiangshuihe

Period	Vegetation	Measured ET (mm)	Simulated ET (mm)	Error	
				mm	%
Aug. – Sep., 2004	Oak forest	88.7	103.4	+14.7	+16.6
Jun. – Oct., 2005	Larch Plantation	326.5	298.7	−27.8	−8.5

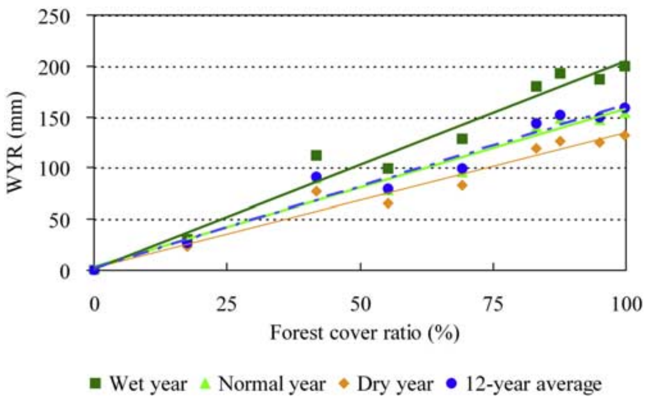

Figure 3. The reduction of annual water yield (WYR) under different forest-cover ratios, which was compared with that of watershed covered by shrub and grassland (Wet year: annual precipitation (AP) > 700 mm; Normal year: 600 mm < AP < 700 mm; Dry year: AP < 600 mm).

50–100 mm/yr measured at Diediegou located in the northern end of the Liupan Mts., most likely because the mean annual precipitation in our research site is 199 mm more than that in Diediegou [*Wang et al.*, 2008]. It was also about 50 mm/yr higher than the potential water yield reduction calculated through an empirical formula based on mean annual precipitation and air temperature in the region [*Sun et al.*, 2006]. The amount of water yield reduction mounts up with larger rates in wet years with more annual precipitation when the forest cover ratio increases (Figure 3). For example, the water yield reduction after full forestation varied from 93 mm to 213 mm when the annual precipitation fluctuated in the range of 372–966 mm. In contrast, the proportional reduction of annual water yield was higher in dry years e.g. 86% for precipitation of 327 mm and 38% for precipitation of 966 mm after full forestation. The average of proportional reduction over 12 years was 59.3% after full forestation, which is in agreement with the conclusion of *Farley et al.* [2005] about a water yield reduction of 50% or more in a region with a runoff coefficient of 0.3. These results showed that full forestation would not result in a complete loss of water-yield in our watershed under current climatic condition.

[18] The spatial heterogeneity of watershed made an uneven water yield reduction after forestation. For example, water yield reduction varies from 3.5 mm/yr to 19.3 mm/yr per 10% forestation (Table 4). This indicates that water yield is strongly influenced by non-vegetation site conditions such as slope, aspect, soil depth, soil porosity, and soil water conductivity, through affecting the variation of soil water availability. The mean water yield reduction in the watershed was 15.8 mm/yr for 10% forestation. Thus the deviation of water yield reduction in each site from this value should be viewed as the contribution from site conditions. This contribution varied from a water yield decrease of 3.5 mm/yr to an increase of 12.3 mm/yr per 10% forestation, whose average amounted to nearly half of the influence of vegetation conversion between forest and grassland. *Wattenbach et al.* [2007] found similar results for Brandenburg in Germany.

[19] Utilizing this heterogeneity it would be possible to lessen the negative effect of forestation on water yield. In order to keep a relative high water yield, the sites with lower water yield reduction after forestation such as type No. 3 and No. 4 in Table 4, which have steep slopes and a high percentage of rich stone fragments, should be forested prior to other sites.

4. Conclusions

[20] The simulation with SWIM showed that tree species shifts among larch, birch and poplar in mature forests only slightly affect the annual water yield, but the vegetation type conversion (forestation) has a strong influence. The integrated impact of both vegetation type conversion and site features produced an annual water yield reduction varying from 3.5 mm/yr to 19.3 mm/yr per 10% forestation of watershed, with an average of 15.8 mm/yr.

[21] The spatial heterogeneity of site conditions also plays an important role in water yield change. In mountainous watersheds, selecting forestation sites with lower water yield reduction can be helpful to alleviate the water yield reduction due to forest area increase. A basic suggestion from this study is that preferential forestation on the steep slope sites with rocky soil would be beneficial for maintaining water yield in regions with similar physical conditions. However, further studies on integrated forest-water management in headwater catchments are needed.

Table 4. Comparison of Water Yield Reductions Due to Forestation on Different Sites and Their Site Features in Xiangshuihe Watershed

	Site Type				
	1	2	3	4	5
Slope gradient (degree)	25	20	40	35	15
Slope aspect	Sunny	Shady	Shady	Sunny and shady	Sunny
Slope location	lower	bottom	middle	lower	top
Soil thickness (cm)	100	100	100	42	100
Total porosity (%)	48.8	56.2	53.4	53.0	64.0
Field capacity (vol.%)	32.1	40.6	38.8	25.2	56.4
Stone fragment content (vol.%)	21.0	11.1	24.5	33.0	0.24
Saturated conductivity (mm/h)	162.8	20	84.9	307.1	36.2
Current vegetation	Larch plantation	Poplar forest	Birch forest	Shrubland	Grassland
Area ratio in watershed (%)	23.8	14.1	27.5	12.0	4.6
Water yield reduction per 10% watershed forestation (mm/yr)	−18.5	−15.3	−3.5	−5.5	−19.3
Contribution to water yield by site features (mm/yr)[a]	−2.7	+0.5	+12.3	+10.3	−3.5

[a]Deviation of water yield reduction in each site type from watershed average of 16.5 mm/yr for 10% forestation.

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