

Modelling the impact of afforestation on average annual streamflow in the Loess Plateau, China

Xiao Ping Zhang,^{1,2} Lu Zhang,^{3*} Tim R. McVicar,³ Tom G. Van Niel,⁴ Ling Tao Li,³ Rui Li,^{1,2}
QinKe Yang^{1,2} and Liang Wei^{1,2}

¹ Institute of Soil and Water Conservation, Northwest Agriculture and Forest University, 3 Taicheng Road, Yangling, Shaanxi Province, 712100, China

² Institute of Soil and Water Conservation, Chinese Academy of Sciences, 26 Xinong Road, Yangling, Shaanxi Province, 712100, China

³ CSIRO Land and Water, Christian Laboratory, Canberra, ACT, 2601, Australia

⁴ CSIRO Land and Water, Private Bag No. 5, Wembley, 6913, WA, Australia

Abstract:

To prevent severe soil erosion and to ensure sustainable development, the Chinese Central Government mandated in 1999 that forest cover would be significantly increased in the Loess Plateau, China. It is important to assess the subsequent impact on streamflow and its spatial distribution in the region. The water balance model of Zhang *et al.* (2001) was used in this study, and the results showed that the model was able to accurately simulate average annual evapotranspiration (ET), but not average annual streamflow when compared with streamflow measurements from 38 hydrologic stations in the coarse sandy hilly catchments (CSHC) in the Loess Plateau. The model was then calibrated using the measured streamflow, and the index of agreement increased from 0.21 to 0.63, the relative error and root mean square error decreased from 42.7 and 17.2 to 18.0% and 7.9 mm, respectively. Hierarchical cluster analysis and stepwise regression were employed to regionalize the optimized model parameter and relate it to the dryness index and forest cover. Once calibrated, the water balance model was used to assess the impacts of two plantation scenarios on streamflow. The two plantation scenarios assume nearly 5.8 and 10.1% of the study area can be planted with trees. It was predicted that streamflow from the region will decrease by 5.5 and 9.2% under the two plantation scenarios. The rate of streamflow reduction decreased from southeast to northwest mainly due to decreasing precipitation. Copyright © 2007 John Wiley & Sons, Ltd.

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INTRODUCTION

The Loess Plateau ($0.62 \times 10^6 \text{ km}^2$) is located in the middle reaches of the Yellow River basin ($0.75 \times 10^6 \text{ km}^2$) in China (Figure 1(a)). Most areas of the Loess Plateau belong to arid and semi-arid climate with average annual precipitation ranging from 200 mm in the northwest to nearly 750 mm in the southeast. The rainy season from June to September accounts for 60–70% of the total precipitation, most of which is in the form of high-intensity rainstorms. The northwestern Loess Plateau is sandy, while in the southeast a series of complex geomorphic landforms (i.e. plateaux, ridges, mounds and gullies) dominate the area, which is characterized by Loess-paleosol soils with an average depth in excess of 100 m that were deposited during the Quaternary period. Silty clay-loam textures are common with more sandy textures in the northwest and more clay in the southeast (Shi and Shao, 2000). From southeast to northwest, vegetation is distributed as forest, forest-steppe, typical-steppe and desert-steppe zones (Wu and Yang, 1998).

The high-intensity rainstorms, sparse vegetation and long agricultural history have caused severe soil erosion

in this region. The average erosion rate ranges from 5000 to 10 000 tonnes $\text{km}^{-2} \text{ year}^{-1}$, and in some tributaries it is as high as 20 000 to 30 000 tonnes $\text{km}^{-2} \text{ year}^{-1}$ (Shi and Shao, 2000; Xu *et al.*, 2004). To control the severe soil erosion, a number of conservation measures have been implemented in the catchments of the Loess Plateau since the 1950s. Among them, afforestation is considered one of the most effective practices to improve environmental quality. An important part of the Chinese Central Government's environmental policy towards sustainable development in this region is to significantly increase the area of forested land (The State Environmental Protection Administration of China, 2002).

It is believed that forests use more water than grass, and hence, reduce average annual streamflow (Oyebande, 1988; Calder, 1999; Zhang *et al.*, 2001). A number of experiments on plots or small catchments in the Loess Plateau agree in general with this finding (Zhu, 1960; Mi, 1982; Hou and Cao, 1990; Wu *et al.*, 1998; Zhao and Wu, 2001; Huang *et al.*, 2003). Liu and Zhong (1978) pointed out that increasing forest area within a catchment can reduce annual streamflow by altering the partitioning of precipitation into evapotranspiration (ET) and streamflow for catchments in the Loess Plateau; McVicar *et al.*

* Correspondence to: Lu Zhang, CSIRO Land and Water, Christian Laboratory, Canberra, ACT, 2601, Australia. E-mail: lu.zhang@csiro.au

(2007b) provide a summary of previous hydrology-landuse studies conducted on the Loess Plateau.

To understand the hydrologic processes under different land cover in the Loess Plateau, both physically based and conceptual models have been used in recent years (Liu *et al.*, 2001). Some of these models were designed to predict storm hydrographs for flood warning and flood protection purposes. Others were used for water resources planning. However, parameterization of these models in terms of surface conditions such as land cover, limits their application for estimating afforestation impacts on streamflow. Xu *et al.* (2003) used the estimated water yield reduction rate from catchments under different land cover to assess the effects of vegetation cover change on water resource in the Loess Plateau. They predicted that at least 500 million m³ of water will be required for the eco-environmental construction plan in 2050, accounting for about 25% of the annual average streamflow from the region. Zhang *et al.* (2001) proposed a conceptual method for estimating average annual ET for different vegetation covers using data from over 250 catchments worldwide across 29 countries. The model predicts the difference in ET under different vegetation categories along a rainfall gradient. It is simple, effective, requiring minimum inputs, and hence, is very suitable for assessing regional land cover–water resource management issues. The model was tested in Australia and good agreement was shown between the prediction and the local data (Brown *et al.*, 2005).

Ecosystem health and sustainability of social and economic development in arid and semi-arid regions depends on water availability (Wilcox and Newman, 2005). With the development of agriculture and industry, and an increasing urban population, there is an increased demand for water in the Loess Plateau and from other areas that draw on the water resources from the Yellow River. Establishment of afforestation schemes in the region will exert further pressure on the water resources. Understanding the impact of afforestation on streamflow and its distribution will help plan for rational water resources management in the Loess Plateau. The objectives of this study were to test and optimize the water balance model of Zhang *et al.* (2001) for catchments in the Loess Plateau and assess the impact of afforestation on streamflow based on two plantation scenarios.

MATERIALS AND METHODS

Study area and data

The Coarse Sandy Hilly Catchments (CSHC) are located in the middle of the Loess Plateau covering 0.11 × 10⁶ km² (Figure 1). This region is the most severely eroded area of the Loess Plateau, in that the CSHC 0.04 × 10⁶ km² have soil losses greater than 15 000 tonne km⁻² year⁻¹. The northwest of the CSHC is sandy with low precipitation, and numerous small ponds have developed due to high groundwater levels. The gully

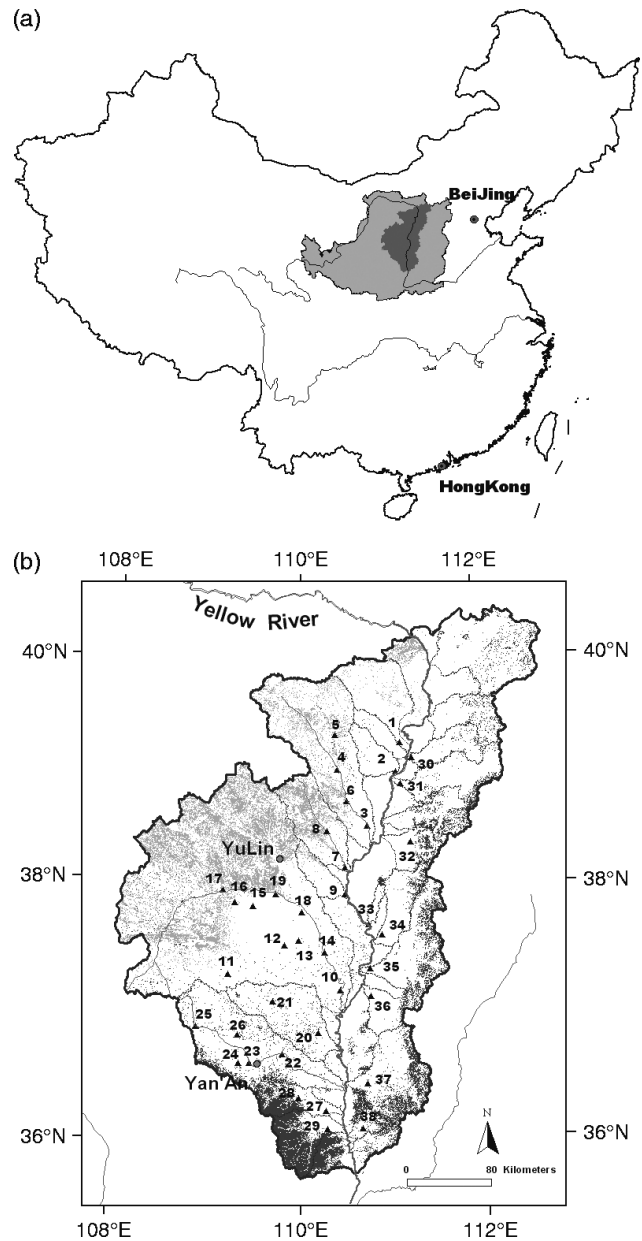


Figure 1. (a) shows the location of the Loess Plateau (light grey shading) and the coarse sandy hilly catchments (CSHC) (dark grey shading) in the middle reaches of the Yellow River basin. (b) shows main catchments in the CSHC and its 38 hydrologic stations (we also call them nested catchments) coded in the plot. In plot (b), the sandy land in the northwestern CSHC is illustrated as grey shading, and forest land is located in the south and east of the CSHC as green shading. In the middle, between them, is hilly–gully landscape

density in the southeast varies from 2 to 8 km⁻² indicating severe soil erosion. The average annual precipitation in the CSHC is 456 mm ranging from 580 mm in the southeast to less than 300 mm in the northwest. The average annual temperature ranges from 6 to 14 °C, and the average annual pan evaporation is 1500 to 2000 mm, which is about 3 to 7 times that of the precipitation (Ran *et al.*, 2000).

Average annual streamflow was averaged from monthly and annual data in 38 nested catchments of the CSHC (Figure 1(b)) from 1980 to 2001. The streamflow data

were provided by the Yellow River Conservancy Commission and quality control was performed (Li *et al.*, 2005). Average annual precipitation and pan evaporation surfaces for the corresponding period in the CSHC were used in this study to generate average annual precipitation and pan evaporation for contributing areas of 38 nested catchments. The surfaces of average annual precipitation and pan evaporation were cumulated from monthly precipitation and pan evaporation surfaces at 58 meteorological stations in and around the CSHC (McVicar *et al.*, 2005a, 2007a). The data came from the State Meteorology Bureau. Major land cover units in the CSHC include grassland (50.3%), agricultural land (28.3%), desert (8.4%), forest land (8.1%), shrub land (4.1%), residential land and water (0.8%) (Zhao *et al.*, 2005). All the spatial inputs were re-sampled to a 100 m grid, corresponding to the resolution of a hydrologically correct digital elevation model (DEM) developed for the CSHC (Yang *et al.*, 2005, 2007).

Average annual water balance model

Following Zhang *et al.* (2001), average annual ET can be estimated by:

$$ET = P \left[\frac{1 + w \frac{E_0}{P}}{1 + w \frac{E_0}{P} + \left(\frac{E_0}{P}\right)^{-1}} \right] \quad (1)$$

where P is precipitation, ET is actual evapotranspiration, E_0 is potential evaporation, w is the plant-available water coefficient. It should be noted that P , ET and E_0 are spatially representative of an entire catchment, and temporally represent average annual fluxes (Donohue *et al.*, 2007). Zhang *et al.* (2001) showed that the model predicts ET from forested catchments when w and E_0 are set to 2 and 1410, and ET from non-forest plants, when w and E_0 are set to 0.5 and 1100 (see Figure 2). These parameter values were obtained by a least squares fit based on the data from over 250 catchments worldwide listed by Zhang *et al.* (1999). The model predicts ET under different vegetation categories along a rainfall gradient. This model is simple, effective, and requires minimum inputs and hence, is well suited for investigating regional land cover-water resource management issues.

To extend the above method to catchments with varying proportions of forest and agricultural land use, a simple catchment scale model is proposed. Following Eagleson (1982), annual ET from a catchment was assumed to be the sum of the annual ET from forested and non-forested (including herbaceous vegetation and soil evaporation) areas, weighted linearly according to their areas. The general equation can be expressed as

$$ET = f ET_f + (1 - f)ET_{nf} \quad (2)$$

where ET is the total annual ET in mm, f is the fractional forest cover, ET_f is the annual ET from forested areas calculated by Equation (1) with the parameter value set

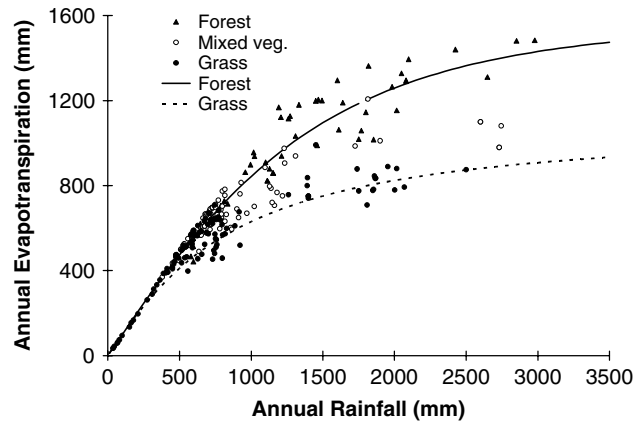


Figure 2. Relationships between mean annual ET and rainfall under different unmanaged vegetation categories in Zhang's water balance model (Zhang *et al.*, 2001)

for forest, and ET_{nf} is the annual ET from non-forested areas calculated by Equation (1) with the parameter value set for non-forest.

Plantation suitability and scenarios

The study area is a transitional zone from semi-humid climate in the southeast to arid climate in the northwest. Vegetation suitability for the region is mainly determined by the combined effects of average annual precipitation on regional scale and the characters of local landform including aspect, slope, and hillslope profile, as they affect soil moisture availability (Wang, 1991; Yang and Shao, 2000). A vegetation suitability map was developed based on the following.

1. Precipitation primarily represents climatic control on vegetation growth. According to Wang (1991), the area with the mean annual precipitation from 550 to 750 mm is the forest zone, and from 450 to 550 mm the forest-steppe zone, from 300 to 450 mm the typical steppe zone, and less than 200 mm the desert-steppe zone. Higher precipitation is more suitable for plantation.
2. The extent of soil moisture availability defined by local factors is dependent upon precipitation. In a forest zone where mean annual precipitation is relatively high, the effect of local factors is minimal in determining vegetation growth. However, in the forest-steppe zone where precipitation is limited, vegetation suitability is, to a large extent, determined by local factors.
3. Aspect was defined with 8 classes, and in the northern hemisphere it was believed that the soil water content decreases in the order of (1) northeast face > (2) north face > (3) northwest face > (4) east face > (5) west face > (6) southeast face > (7) south face > (8) southwest face (Day and Monk, 1974). The hillslope profile could be defined as being concave or convex. The slope gradient is considered to be between 25 and 45° (Tang *et al.*, 1998). Given the relatively low precipitation rates experienced in the CHSC, if more

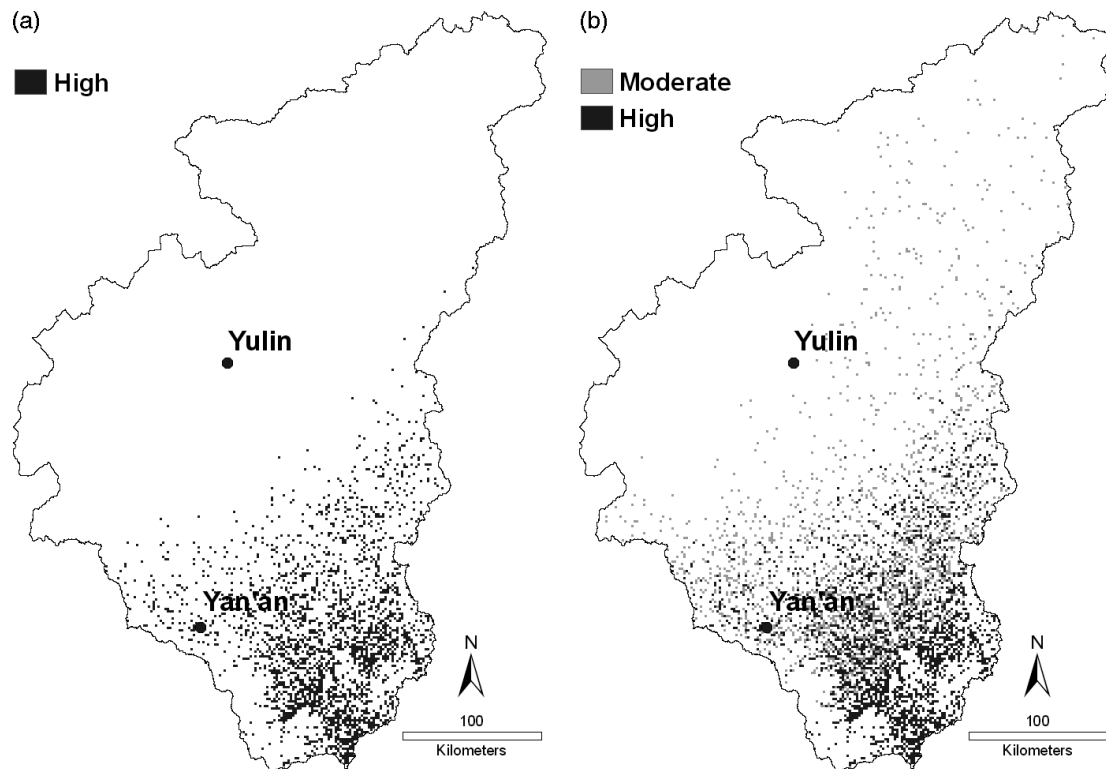


Figure 3. Plantation suitability map in the CSHC determined mainly by the average annual precipitation and local soil water availability in local landform from 100 m resolution DEM (Yang *et al.*, 2007). Plantation scenario 1 is shown in (a) assuming the area with high plantation suitability will be planted; plantation scenario 2 is shown in (b) assuming the area with high and moderate suitability will be planted

water is retained due to local factors (e.g., the influence aspect has on the radiation environment in this extremely gullied landscape (McVicar *et al.*, 2007a)), the more suitable these areas will be for tree growth (Jiang *et al.*, 1987; Yang *et al.*, 1994; Yang and Shao, 2000).

Three vegetation suitability classes were defined: high, moderate and low suitability. The area with mean annual precipitation from 550 to 750 mm was expected to be most or highly suitable for plantation. The places with mean annual precipitation from 450 to 550 mm were also be considered to highly suitable if the combined landform was most suitable for tree planting. The canopy of plantation with high suitability would be expected to be above 90% (Wu *et al.*, 1998).

The area with mean annual precipitation from 450 to 550 mm was expected to be moderately suitable for plantation. But the places with mean annual precipitation from 300 to 450 mm were also be considered to be moderately suitable if the combined landform was moderately suitable for tree planting. The canopy of plantation with moderate suitability would be expected to be 70–80% (Wu *et al.*, 1998). The residual area was considered to be low suitability.

On the basis of the above concepts, and considering current land cover to exclude current forested land, a vegetation suitability map was developed (Figure 3); detailed Boolean rules are provided in McVicar *et al.* (2005b). From the suitability map, the highly suitable area for plantation covers 6500 km² and the moderately

suitable area covers 4900 km². This represents 5.8 and 4.3% of the total area, respectively. Scenario 1 of the plantation was developed using only the highly suitable area, and scenario 2 comprised both the highly and moderately suitable areas. The areas under scenarios 1 and 2, respectively, represent a 72 and 125% increase in forest area in the CSHC (See Figure 3). On a catchment basis, the plantation area varied from 0 to 45% of the catchments, with the area suitable for plantation becoming increasingly patchy and sparse from south to north.

RESULTS AND DISCUSSION

Testing water balance model

The water balance model of Zhang *et al.* (2001) was used to estimate actual average annual ET for 38 nested catchments in the CSHC. At an average annual time scale, it has been assumed that change in catchment water storage is negligible and actual ET can be calculated as the difference between average annual precipitation and streamflow. Figure 4(a) shows that the actual average annual ET falls within or near the curves representing ET from fully forested and grassy catchments, except for two catchments that plotted far away from the curve for grassy catchments. These two catchments are influenced by high groundwater and possibly groundwater inflow outside of the catchment as suggested by Ran *et al.* (2000) (Figure 4(b)). As a result, these two catchments were excluded from the

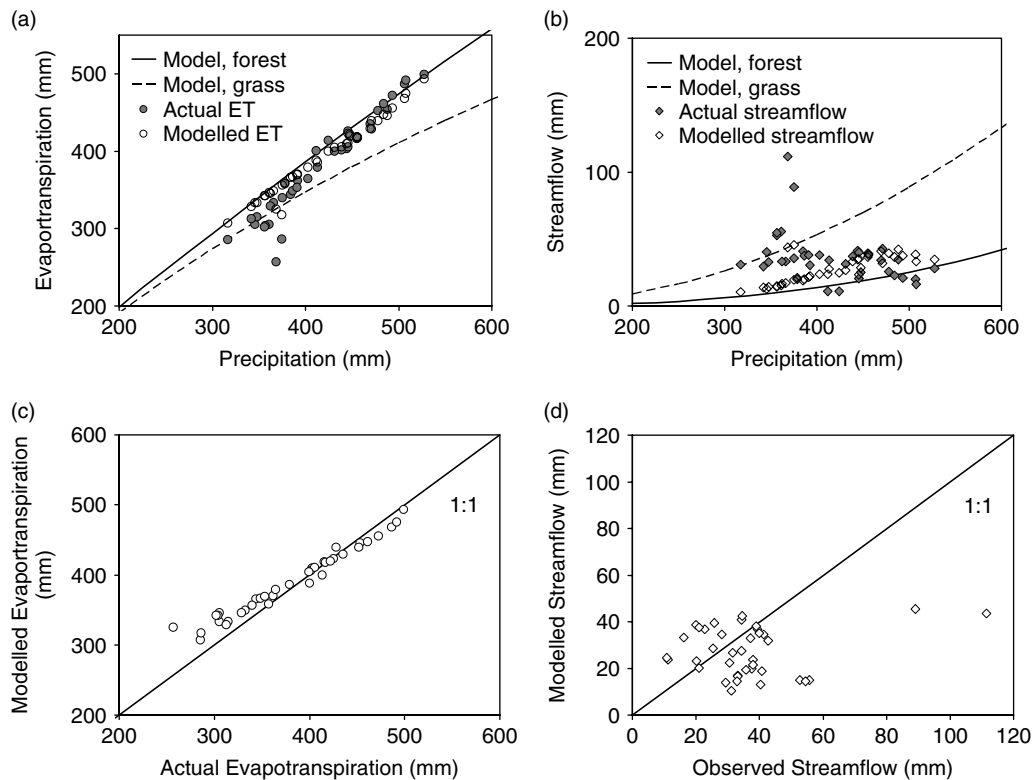


Figure 4. Comparisons of actual and modelled ET (a), (c) and streamflow (b), (d) using the water balance model of Zhang *et al.* (2001) for 38 catchments in the CSHC

analysis. While a good relationship exists for actual and modelled average annual ET (Figure 4(c)), the agreement between the modelled and observed streamflow is not satisfactory (Figure 4(d)). The reason is probably related to the values of the plant-available water coefficient suggested by Zhang *et al.* (2001) that could not fully explain the factors that influence the local water balance, as would be reflected from the following analysis. From the data presented in Figure 4, we can calculate that the percentage of average annual precipitation that becomes average annual streamflow ranges from 15.4 to 2.5% (with a mean of 8.1% and a standard deviation of 3.2%) for the remaining 36 catchments.

Regionalization of the water balance model for the CSHC

It is clear that the water balance model of Zhang *et al.* (2001) is unable to accurately reproduce average annual streamflow for the catchments in the CSHC when using the suggested parameter values. It is, therefore, necessary to calibrate the model using local data. Following Zhang *et al.* (2001), the ratio of average annual ET and precipitation (ET/P) can be plotted against the ratio of potential ET and precipitation (E_{pan}/P) (Figure 5). In the analysis, potential ET was equated to pan evaporation (E_{pan}). It should be noted that potential ET in Equation (1) represents maximum ET that would occur under given climatic conditions, and it can be calculated using different methods. Budyko (1974) argued that on an annual basis the upper limit for ET is equal to net radiation, and hence,

used net radiation to represent the potential evaporation, while Zhang *et al.* (2001) suggested that potential evaporation be calculated using the method of Priestley and Taylor (1972). Systematic differences in the form of potential ET used here will not affect the functional relationships embedded in Equation (1). It can be noted that different w values are required to represent the 38 catchments considered, and inspection of Figure 5 reveals that w should range from 0.1 to 2.0.

For both, ET/P and the dryness index E_{pan}/P , the data were standardized by subtracting the mean from each instance and dividing the result by the standard deviation for all 36 cases in turn. A hierarchical cluster analysis (Su, 2004; Laaha and Blöschl, 2006; Sanborn and Bledsoe, 2006) was performed on the resulting standardized ratios of ET/P and E_{pan}/P to group the streamflow data. The dendrogram of hierarchical cluster analysis showed that six groups can be identified (Figure 6). For the purpose of model calibration and regionalization the six groups were amalgamated to three based on their positions relative to the various w parameter lines (Figure 5(b)). For example, in Figure 5(b), we see that groups 4 and 5 are close to the line provided when w equals 2.0, likewise groups 1, 2 and 3 are centered on the model with a w equaling 0.1.

Once the catchments were grouped, the water balance model was optimized for each group. In the optimization, we assumed that the model parameter w was equal to 2.0 for forest stand following Zhang *et al.* (2001) and the parameter w for non-forest vegetation was optimized to yield the minimum difference between the modelled and actual average annual ET. Results of the optimization

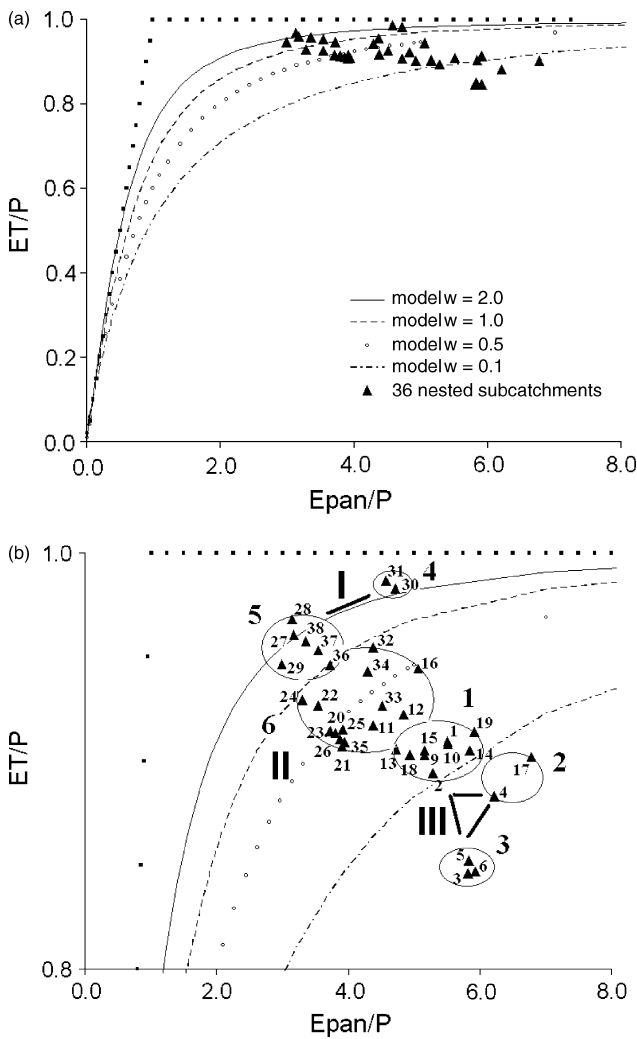


Figure 5. The scatter plot for the data recorded at the 38 hydrologic stations about the relation of (ET/P) and (E_{pan}/P) in the Zhang's model (Zhang *et al.*, 2001). (a) shows the scatter distribution in the scale of ET/P ranging from 0.0 to 1.0, and (b) is an enlarged portion of plot (a). The six numbers in plot (b) shows the groups resulting from the hierarchical cluster analysis (see the middle column of numbers in Figure 6). The three large Roman numerals represent the 3 groups used for model calibration and regionalization, with the thick black lines indicating which of the six groups were merged to produce the final three

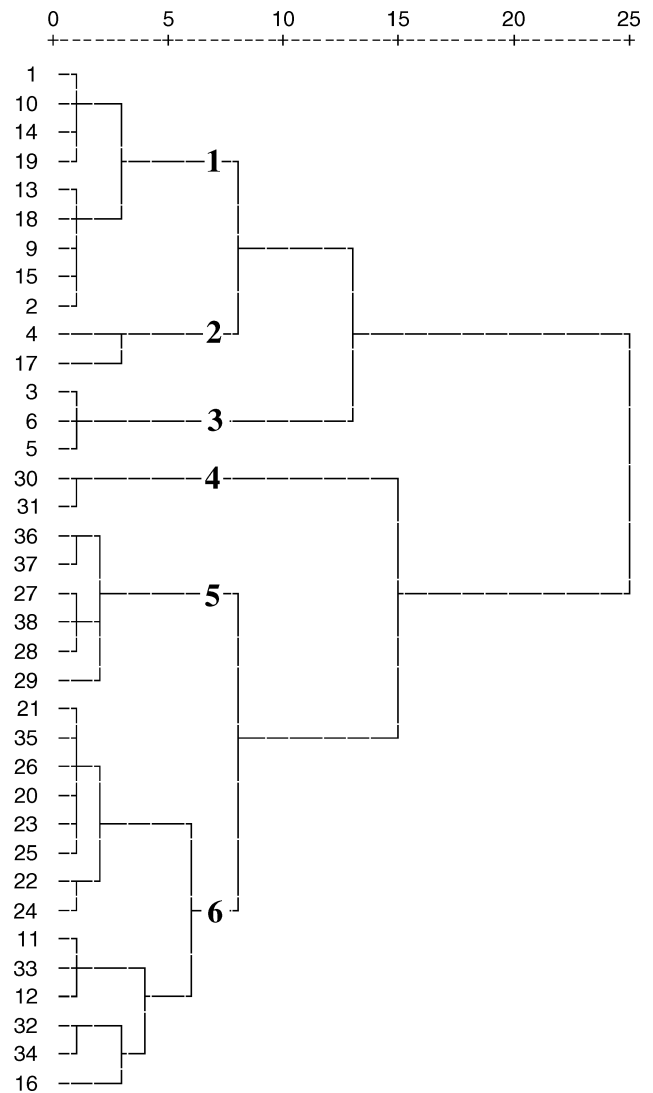


Figure 6. The dendrogram of the hierarchical cluster analysis for 36 hydrologic stations using data from the standardized ratios of ET/P and E_{pan}/P . The between-groups average linkages were used in the process. The upper row of numbers that range from 0 to 25 are the standard distances calculated from squared Euclidean distance. In the left column, the smaller numbers are the hydrological stations codes and the large numbers in the middle column are the six groups defined by the standard distance 7

are shown in Table I. It is clear that the grouping of the catchments and the model optimization significantly increased model accuracy, especially for streamflow as represented by the relative error and root mean square error (RMSE) (Figure 7 and Table II). We also calculated other statistics such as, the modified index of agreement (d_1), the modified coefficient of efficiency (E_1) (see Table II), following recommendations by Legates and McCabe (1999). Both statistics have the advantage of a reduced sensitivity to outliers. The modified index of agreement and the modified coefficient of efficiency for streamflow increased from 0.21 to 0.63 and -0.72 and 0.28, respectively.

The 8 catchments in Group I (see Figures 5(b)) are located in the southeastern CSHC (Figure 1), except for catchments 30 and 31. This region typically experiences higher rainfall and has a larger percentage of forest cover. The combined effect of forest and soil conservation

Table I. Optimized parameter values for w based on the 3 groups in the CSHC. The Roman numerals are the same as in Figure 5(b)

Group	Optimized w
I (8 hydrologic stations)	1.61
II (14 hydrologic stations)	0.45
III (14 hydrologic stations)	0.10

measures has led to a relatively high ET to precipitation ratio. As a result, these catchments are represented by a relatively higher value of w (the value of 1.61 was used, see Table I). Catchments 30 and 31 are located in the northeastern CSHC. These two catchments are different from the rest of the catchments in Group I in terms of precipitation, percentage forest cover, and geology.

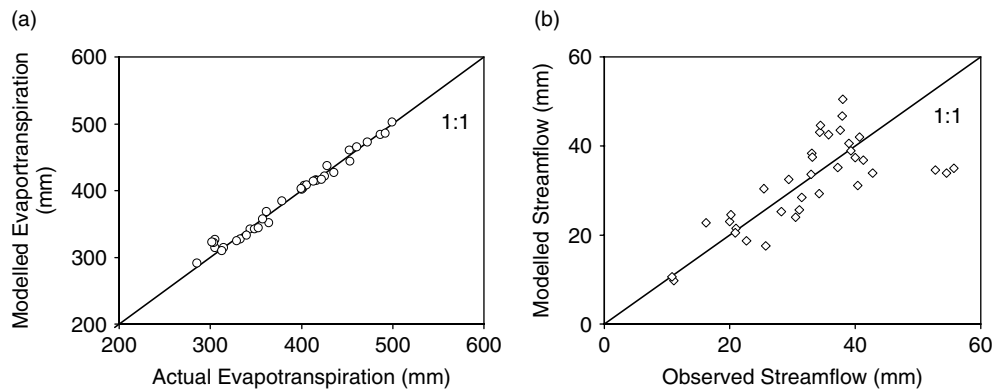


Figure 7. Relationships between modelled and actual average annual ET (a) and streamflow (b) for 36 catchments in CHSC using optimized parameter values for w

Table II. Statistics for both the Zhang model and locally calibrated model outputs compared to the observations at the 36 catchments. The mean and standard deviation for actual ET of the 36 catchments were 387 mm and 61 mm respectively, while for streamflow the same statistics were 33 mm and 11 mm

Statistics	ET (n = 36)		Streamflow (n = 36)	
	Zhang's	Local	Zhang's	Local
d_1	0.85	0.94	0.21	0.63
E_1	0.73	0.89	-0.72	0.28
Slope	1.01	1.00	0.70	0.94
Bias (mm)	6.6	1.0	-6.6	-1.0
Relative error (%)	3.6	1.5	42.7	18.0
RMSE (mm)	17.2	7.9	17.2	7.9

Note: 'n' means number of catchments used in this table; ' d_1 ' is the index of agreement and ' E_1 ' is the coefficient of efficiency (Legates and McCabe, 1999). 'Slope' means slope of the least squares regression, and here the offset was set to 0.

For these two catchments, it has been suggested that the relative magnitude of recharge to regional groundwater systems is high due to their soils predominately having high calcium content (Colman, 1953; Ran *et al.*, 2000).

The 14 catchments in Group II are located in the middle of the CSHC within the hilly-gully landscape, where agricultural land and grassland dominate; the optimized values of w of 0.45 was used (Table I). The catchments in Group III are located in the northwestern CSHC (Figure 1) where sandy soils prevail. Their water balance is greatly influenced by the different geology and soils found in the Ordos tableland contributing to high groundwater levels in this area. The combined effect of these factors means that a high proportion of precipitation becomes streamflow resulting in a comparatively low ET to precipitation ratio. For this group, we used an optimized parameter value of 0.10 for w (Table I). Zhang *et al.* (2001) attributed the difference in ET between forest and grass mainly to their ability to extract soil water as reflected by a larger value of w for forest. Other factors such as soil, geological features, and topographic relief may also affect the parameter w (Fu, 1996).

To facilitate the application of the water balance model to all the catchments in the CSHC, particularly

ungauged catchments, we related the parameter w to the characteristics of the catchments using stepwise regression. The values of w for the 36 catchments were used in the analysis and the following relationship was developed:

$$w_2' = 2.4136 - 1.75685(1 - f) - 0.01659(DI)^2 \quad (3)$$

where f is percentage of forest cover, DI is the dryness index defined as the ratio of average annual E_{pan} and average annual precipitation. The Spearman's correlation coefficient (r^2) is 0.75 for the relationship. An estimate of w from Equation (3) was not directly used to calculate ET , but to identify the catchment in terms of its water balance characteristic, *i.e.* three groups (see Table I). This process ensured that an optimized parameter value was used in the water balance calculation.

Scenario modelling

Average annual streamflow was modelled using the water balance model of Zhang *et al.* (2001), but with optimized parameter values for non-forest vegetation under both current land cover status and future plantation scenarios. Under current land cover status, average annual streamflow in the CSHC was estimated to be 3.81×10^9 m³ or 33.8 mm. If we consider plantation scenario 1, average annual streamflow would reduce by 0.21×10^9 m³ or 1.9 mm, representing a 5.5% reduction in average annual streamflow. The modelled streamflow reduction is 0.35×10^9 m³ or 3.1 mm under the plantation scenario 2 and it represents 9.2% reduction in average annual streamflow.

As expected, the reduction in streamflow is spatially variable (Figure 8). For example, the rate of streamflow reduction varies from 0 to 36%. The minimum reduction occurred in the northwestern CSHC, where there is little area suitable for plantation development. The maximum reduction of 36% occurred in the southeastern CSHC where rainfall is highest.

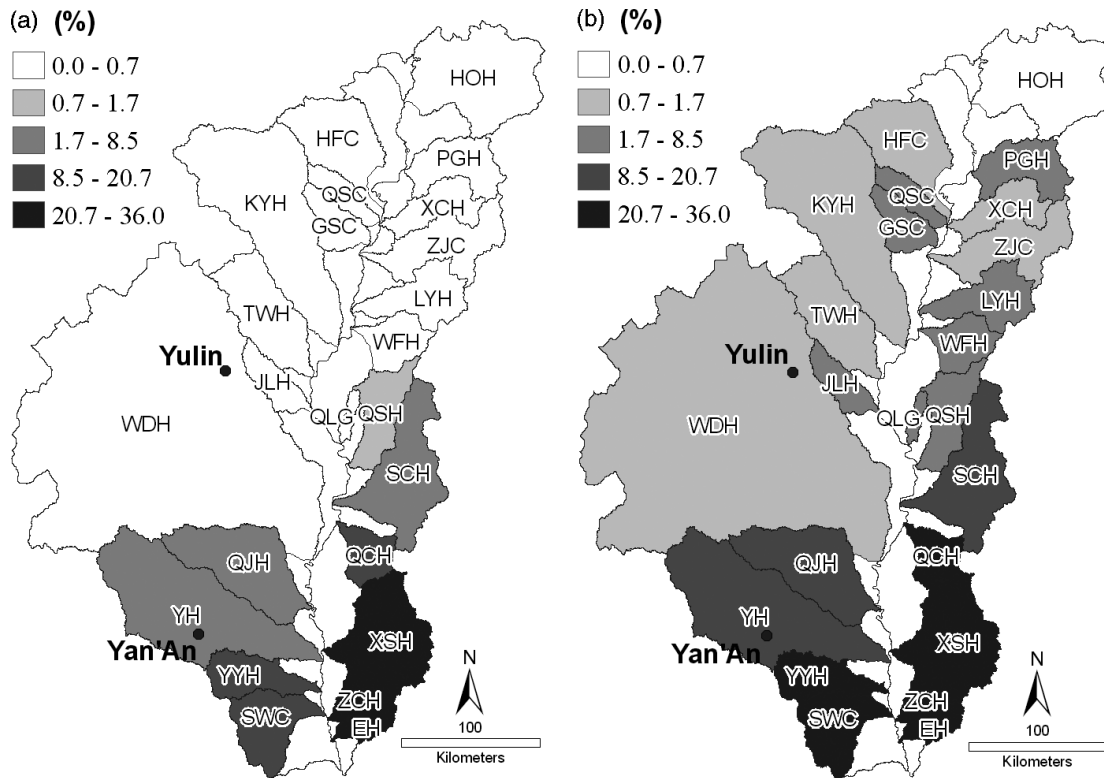


Figure 8. The distribution of streamflow reduction rate by their average annual streamflow in catchments in scenarios 1 (a) and 2 (b)

SUMMARY AND CONCLUSIONS

As one of the most effective measures in preventing soil erosion and improving environmental quality, afforestation is being implemented in the Loess Plateau, China. The water balance model of Zhang *et al.* (2001) was tested using streamflow data from 36 hydrology stations in the CSHC of the Loess Plateau. Although the modelled results were highly accurate for average annual ET, the modelled average annual streamflow was in poor agreement with measurements. The water balance model was then optimized to the local conditions, and it showed that the catchments can be classified into three different groups related to the different regional characteristics. In the southeastern study area, with high precipitation and dense forest cover, the optimized model parameter value was 1.61. Corresponding to the high ground water level in the sandy land of the northwestern study area, the optimized parameter value was 0.1. And for the hilly-gully landscape in the middle of the study area, the optimized parameter value was 0.45. Use of the locally optimized model parameter values in the model of Zhang *et al.* (2001) significantly improved the agreement between modelled and actual average annual streamflow. The index of agreement increased from 0.21 to 0.63, the relative error and RMSE decreased from 42.7 and 17.2 to 18% and 7.9 mm, respectively.

The impact of the two plantation scenarios on average annual streamflow was estimated by using the locally calibrated water balance model. For the entire CSHC, it was predicted that average annual streamflow would reduce by 5.5 and 9.2%, respectively, for the two plantation

scenarios considered. The modelled reduction in average annual streamflow decreases from southeast to northwest, with some areas experiencing up to 36% reduction. In developing and implementing plantation plans, it is important to acknowledge the spatial variability in streamflow reduction to minimize the impacts on water resources in the region (McVicar *et al.*, 2007b).

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REFERENCES

- Brown AE, Zhang L, McMahon TM, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**: 28–61.
- Budyko MI. 1974. *Climate and Life*. Academic: San Diego; 508.
- Calder IR. 1999. *The Blue Revolution—Land Use and Integrated Water Resources Management*. Earthscan publications: London.
- Colman EA. 1953. *Vegetation and Watershed Management*. The Ronald press company: New York.
- Day FP, Monk CD. 1974. Vegetation pattern on a southern application watershed. *Ecology* **55**: 1064–1074.
- Donohue RJ, Roderick ML, McVicar TR. 2007. On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrology and Earth System Sciences* **11**: 983–995.
- Eagleson PS. 1982. Ecological optimality in water-limited natural soil-vegetation systems, 1. Theory and hypothesis. *Water Resources Research* **18**: 325–340.
- Fu BP. 1996. On the calculation of evaporation from land surface in mountainous areas. *Scientia Meteorologica Sinica (In Chinese)* **16**: 328–335.
- Hou XL, Cao QY. 1990. Study on benefits of vegetation reducing sediment in the Loess hilly gully region, north of Shaanxi province, China. *Bulletin of Soil and Water Conservation (In Chinese)* **10**: 3–40.
- Huang MB, Zhang L, Gallichand J. 2003. Streamflow responses to afforestation in a watershed of the Loess plateau, China. *Hydrological Processes* **17**: 2599–2609.
- Jiang DS, Liu MM, Huang GJ. 1987. An initial approach to the redistribution laws of precipitation on convex and concave hill slopes. *Bulletin of Soil and Water Conservation (In Chinese)* **1**: 45–50.
- Laaha G, Blöschl G. 2006. A comparison of low flow regionalization methods—catchment grouping. *Journal of Hydrology* **323**: 193–214.
- Legates DR, McCabe GJ Jr. 1999. Evaluating the use of "Goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research* **35**: 233–241.
- Li LT, McVicar TR, Van Niel TG, Mu XM, Zhang XP, Yang QK, Liu ZH. 2005. *Quality Control of 21 Years of Monthly Meteorological and Hydrological Data in the Coarse Sandy Hilly Catchments (CSHC) of the Loess Plateau, China*, CSIRO Land and Water Technical Report, 6/05, Canberra, Australia, 89, <http://www.clw.csiro.au/publications/technical2005/tr6-05.pdf>.
- Liu CM, Zhong JR. 1978. The effect of forest on stream flow in the Loess plateau. *Acta Geographical Sinica (In Chinese)* **33**: 112–126.
- Liu SX, Zhang SF, Liu CM. 2001. Advances on the research into the mechanism of hydrological cycle in Yellow river catchment. *Geographical Research (In Chinese)* **3**: 257–285.
- McVicar TR, Li LT, Van Niel TG, Hutchinson MF, Mu XM, Liu ZH. 2005a. *Spatially Distributing 21 Years of Monthly Hydrometeorological Data in China: Spatio-Temporal Analysis of FAO-56 Crop Reference Evapotranspiration and Pan Evaporation in the Context of Climate Change*, CSIRO Land and Water Technical Report 8/05, Canberra, Australia, 316, <http://www.clw.csiro.au/publications/technical2005/tr8-05.pdf>.
- McVicar TR, Wen ZM, Van Niel TG, Li LT, Yang QK, Li R, Jiao F. 2005b. *Mapping Perennial Vegetation Suitability and Identifying Target and Priority Areas for Implementing the Re-Vegetation Program in the Coarse Sandy Hilly Catchments of the Loess Plateau, China*, CSIRO Land and Water Technical Report, 18/05, Canberra, Australia, 67, <http://www.clw.csiro.au/publications/technical2005/tr18-05.pdf>.
- McVicar TR, Van Niel TG, Li LT, Hutchinson MF, Mu XM, Liu ZH. 2007a. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *Journal of Hydrology* **338**: 196–220.
- McVicar TR, Li LT, Van Niel TG, Zhang L, Li R, Yang QK, Zhang XP, Mu XM, Wen ZM, Liu WZ, Zhao YA, Liu ZH, Gao P. 2007b. Developing a decision support tool for China's re-vegetation program: simulating regional impacts of afforestation on average annual streamflow in the Loess plateau. *Forest Ecology and Management* (in press). DOI 10.1016/j.foreco.2007.06.025.
- Mi DS. 1982. Damage status of Ziwuling mountain forest and its influence in recent years. *Bulletin of Soil and Water Conservation (In Chinese)* **5**: 49–50.
- Oyebande L. 1988. Effects of tropical forests on water yield. In *Forests, Climate, and Hydrology—Regional Impacts*, Reynolds ERC, Thompson FB (eds). Kefford Press: Singapore.
- Priestley CHB, Taylor RJ. 1972. On the assessment of the surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* **100**: 81–92.
- Ran DC, Liu LW, Zhao LY, Bai ZG, Liu B, Wang H (eds). 2000. *The Change of Soil and Water Conservation, Streamflow and Sediment in Hekou-Longmen Region in Middle Reaches of Yellow River*. Yellow River Water Resources Press: Zhengzhou, China.
- Sanborn SC, Bledsoe BP. 2006. Predicting streamflow regime metrics for ungauged streams in Colorado, Washington, and Oregon. *Journal of Hydrology* **325**: 241–261.
- Shi H, Shao M. 2000. Soil and water loss from the Loess Plateau in China. *Journal of Arid Environments* **45**: 9–20.
- Su JM (eds). 2004. *The Guide of Application and Development for SPSS12.0 for Windows*. Publishing House of Electronics Industry: Beijing, China.
- Tang KL, Zhang KL, Lei AL. 1998. The study and demonstration for the threshold slope degree of converting slope farming land in Loess hilly gully region, China. *Chinese Science Bulletin (In Chinese)* **43**: 200–203.
- The State Environmental Protection Administration of China. 2002. *Eco-environmental construction plan in China*, <http://www.zhb.gov.cn/eic/650771267141500928/20021129/1036175.shtml> (Date last accessed 4 May 2006).
- Wang YF. 1991. *The Vegetation Resources and their Rational Usage on the Loess Plateau, China*. Chinese Science and Technology Press: Beijing, China.
- Wilcox BP, Newman BD. 2005. Ecohydrology of semiarid landscape. *Ecology* **86**: 275–276.
- Wu QX, Yang WZ. 1998. *Vegetation Construction and its Sustainable Development in Loess Plateau*. Science Press: Beijing, China.
- Wu QX, Zhao HY, Wang YK. 1998. Flow production and sediment production and their processes in Chinese pine woodlands in the Loess Plateau. *Acta Ecologica Sinica (In Chinese)* **18**: 151–157.
- Xu JH, Wang L, Wang J. 2003. Water quantity analysis of vegetation restoration on the Loess plateau. *Yellow River (In Chinese)* **25**: 13–15.
- Xu XZ, Zhang HW, Zhang OY. 2004. Development of check-dam systems in gullies on the Loess plateau, China. *Environmental Science and Policy* **7**: 79–86.
- Yang WZ, Shao M. 2000. *Soil Water Study on the Loess Plateau*. Science Press: Beijing, China.
- Yang WZ, Ma YX, Han SF. 1994. Soil water ecological regionalization of afforestation in Loess plateau. *Journal of Soil and Water Conservation (In Chinese)* **8**: 1–9.
- Yang QK, Van Niel TG, McVicar TR, Hutchinson MF, Li LT. 2005. *Developing a Digital Elevation Model Using ANUDEM for the Coarse Sandy Hilly Catchments of the Loess Plateau, China*, CSIRO Land and Water Technical Report 7/05, Canberra, Australia, 74, <http://www.clw.csiro.au/publications/technical2005/tr7-05.pdf>.
- Yang QK, McVicar TR, Van Niel TG, Hutchinson MF, Li LT, Zhang XP. 2007. Improving a digital elevation model by reducing source data errors and optimising interpolation algorithm parameters: an example in the Loess plateau, China. *International Journal of Applied Earth Observation and Geoinformation* **9**: 235–246.
- Zhang L, Dawes WR, Walker GR. 1999. *Predicting the Effect of Vegetation Changes on Catchment Average Water Balance*, Technical Report 99/12, Cooperative Research Centre for Catchment Hydrology: Canberra, ACT.
- Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**: 701–708.
- Zhao HY, Wu QX. 2001. Studies on streamflow and sediment yield in small catchment covered artificial Chinese pine stand in Loess Plateau. *Progress in Natural Science (In Chinese)* **11**: 829–834.
- Zhao MJ, Yang QK, Liang W. 2005. Land use and cover change of coarse sand area in middle reaches of Yellow river. *Bulletin of Soil and Water Conservation (In Chinese)* **25**: 41–43.
- Zhu XM. 1960. The influence of vegetation on soil and water loss in loess region. *Acta Pedologica Sinica (In Chinese)* **8**: 110–120.