Available online at www.sciencedirect.com
ScienceDirect

Forest Ecology and Management 251 (2007) 65–81

Forest Ecology and Management

www.elsevier.com/locate/foreco

Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau

Tim R. McVicar[a,*], LingTao Li[a], Tom G. Van Niel[b], Lu Zhang[a], Rui Li[c], QinKe Yang[c], XiaoPing Zhang[c], XingMin Mu[c], ZhongMing Wen[c], WenZhao Liu[c], Yong'An Zhao[c], ZhiHong Liu[c], Peng Gao[c]

[a] *CSIRO Land and Water, GPO Box 1666, Canberra, 2601 ACT, Australia*
[b] *CSIRO Land and Water, Private Bag No. 5, Wembley, 6913 WA, Australia*
[c] *Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, 26 Xinong Road, Yangling, Shaanxi Province, China*

Abstract

China is facing increased environmental pressures as its economy rapidly develops, with shortages of water potentially limiting development—especially in its dryer north and west. The highly erodible Loess Plateau in the Yellow River Basin is the main source of high sediment loads resulting in poor water quality. Engineering and re-vegetation measures have been (and are being) widely implemented to reduce these environmental problems, but it has since been found that re-vegetation activities result in a decrease of streamflow. Given that water resources are currently over allocated in the Yellow River Basin (as seen by the river increasingly not reaching the sea), the external hydrological impacts from current and planned re-vegetation activities need to be taken into account by a wide range of natural resources managers and policy makers. To increase the awareness of the hydrology-landuse change implications in the region, a decision support tool called Re-Vegetation Impacts on Hydrology (ReVegIH) has been developed. To maximize use of the tool, the design of ReVegIH has been participatory with the final design of the functionality actively taking account of user requirements and needs. ReVegIH provides a means for users to: (1) determine where priority (and target) re-vegetation activities should be undertaken; (2) ascertain what species are suitable for a specific location; (3) simulate the related hydrological impact on an average annual basis. The spatial resolution of the first two functions is provided at 100 m, while the third is at the catchment (or county) level for the 113,000 km^2 study site, called the Coarse Sandy Hilly Catchment, which drains the main south flowing branch of the Yellow River. ReVegIH assesses afforestation impacts on average annual streamflow via application of an aerial-weighted evapotranspiration model operating at steady-state forced by long-term (21-year) annual average meteorological data and landuse scenarios. ReVegIH does not consider the changes in annual streamflow following observed 21-year trends of annual precipitation and pan evaporation data, nor as a function of time since afforestation, and the ability to simulate the hydrological impact due to establishing plantations in different areas in the landscape through time is not included.

Keywords: Re-vegetation; Afforestation; Average annual streamflow; Loess Plateau; National Forest Protection Project; Grain for Green; Sloping Land Conversion Program; Water resources; Decision support tool; Precipitation trend; Pan evaporation trend

1. Introduction

In developed countries, foresters, hydrologists, landuse planners and other natural resource managers and policy makers have used computer-based decision support tools (DST) for 20–30 years. In the late 1970s and early 1980s such tools were usually only available in larger offices running microcomputers. Since the late 1980s, these users have had access to increasingly powerful personal computers capable of running sophisticated tools to support their decision making process. Initially DSTs for forestry applications mainly addressed internal operational (or 'on-site') issues (Varma et al., 2000; Lexer and Brooks, 2005, including some papers in their FEM Special Issue), but as DSTs advanced, more examples have focused on external (or 'off-site') issues (Rauscher, 1999; Garcia-Quijano et al., 2005). DSTs most often include some Geographic Information System (GIS) capabilities, which facilitates participation by local stakeholders addressing natural resource management issues (*e.g.*, Gonzalez, 2002).

---

[*] Corresponding author. Tel.: +61 2 6246 5741; fax: +61 2 6246 5800.
E-mail address: tim.mcvicar@csiro.au (T.R. McVicar).

0378-1127/$ – see front matter. Crown Copyright © 2007 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2007.06.025

In contrast, natural resource management (NRM) agencies within countries with developing and non-developed economies have only recently started to build DSTs, some of which are outcomes of international collaborative and aid programs (*e.g.*, Cavric et al., 2003). In such situations there are different (and usually additional) cultural and organisation issues to overcome in order to successfully develop a DST (Kyem, 2004). While a common obstacle in developing and non-developed countries is a technology prejudice, a participatory GIS approach can be a successful tool for resolving conflict associated with forestry management with many and varied stakeholder interests (*e.g.*, southern Ghana, Kyem, 1998). In countries with rapidly developing economies, there are usually complex and rapidly changing organisational and governance arrangements which make the management of natural resources particularly difficult; these issues may be exacerbated in countries with the added pressure of having large populations (*e.g.*, China and India). This means that knowledge of the decision making process within the context of wider cultural and political sensitivities is essential in order to develop a successful DST. Embedding a DST into a wider adaptive management process (Rauscher, 1999) encourages monitoring to assist refinement and evolution of NRM policy and implementation, and offers the additional benefits of: (1) reducing emotional confrontation; (2) focusing on issues and ideas (rather than personalities); (3) encouraging a wide range of views (Ball, 2002). In this paper, we provide an example of a DST developed to support China's re-vegetation program in the Loess Plateau. The following issues are briefly introduced in the remainder of this section: (i) the basis for China's re-vegetation program; (ii) key environmental issues of the Loess Plateau; (iii) a brief review of hydrological-landuse research conducted in the Loess Plateau.

1.1. Basis for China's re-vegetation program

In 1998 the Chinese Central Government established the "National Forest Protection Project (NFPP)" which aims to halt the destruction of natural forests (Ye et al., 2003) thereby reducing environmental degradation. Under the umbrella of this project, the "Grain for Green" (Tui Geng Huan Lin) project was established in 1999 to return cultivated land with slopes of 25° or more to perennial vegetation (*e.g.*, Winkler, 2002; Ye et al., 2003; Wenhua, 2004; Xu et al., 2004; Yang, 2004; Ke and Zhou, 2005). Since 1999 as part of the "Grain for Green" project (or Sloping Land Conversion Program, Xu et al., 2004), over 7 million ha have been re-vegetated, with 5.9 million ha being converted in 2002 and 2003 (Xu et al., 2004). The Chinese Central Government has committed to spend 100 billion Chinese Yuan (approximately $US 12.5 billion) by 2010 on re-vegetation schemes in agricultural land (including subsidies to farmers Yuan, 2002), with their total commitment to the "Grain for Green" project (that will run to 2050) being 337 billion Chinese Yuan (over $US 40 billion, Xu et al., 2004). Implementation of this national re-vegetation project occurs at the provincial, prefecture, county, township, and village levels, in which there exists a great variation in ecohydrological understanding, financial capacity, and management goals (Rozelle et al., 1997; Skinner et al., 2001). To help maximise the financial commitment of the Central Government, these disparate management groups need assistance in designing management plans, while considering specific local issues.

1.2. Key environmental issues of the Loess Plateau

The Loess Plateau is one of the 'hot-spots' of environmental degradation; erosion rates ranging from 20,000 to 30,000 t km^{-2} a^{-1} are commonly reported (*e.g.*, Xiang-zhou et al., 2004) with extremely high rates (59,700 t km^{-2} a^{-1}) also being documented (Shi and Shao, 2000). The average annual precipitation ranges from approximately 250 mm in the north-west to 600 mm in the south-east. The area experiences intense rainfall associated with summer monsoons (accounting for 60–70% of the annual precipitation), and when combined with local soil properties, steep landforms and the low percentage of annual grass cover in late spring, this results in the incredibly high erosion rates described above. Approximately 90% of the sediment delivered to the Yellow River comes from the major south-flowing branch draining the region of the Loess Plateau locally known as the 'sandy coarse-sandy area' (Li, 2003). Our study site is defined by the catchments encompassing this sandy area where the landform is hilly and is thus termed the Coarse Sandy Hilly Catchments (CSHC see Fig. 1). Levees and dykes have been constructed over the past 2000 years on the lower reaches of the Yellow River to contain the river in times of flood (Ren et al., 1985). The high erosion rates from the Loess Plateau combined with continuous presence of levees and dykes means that in the lower reaches of the Yellow River (*i.e.*, on the North China Plain—Fig. 1), the bottom of the river bed is, in places, 20 m above the surrounding land surface (Li, 2003)! About 25% of the sediment load is deposited on the river bed resulting in an increase of river bed height by 8–10 cm annually (Douglas, 1989; Shi and Shao, 2000); annual rates of 10–20 cm were reported between the 1950s and 1970s (Ren

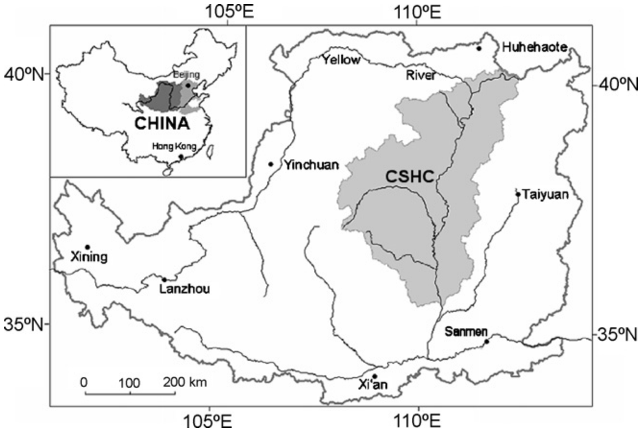


Fig. 1. The inset map shows the location of the 623,586 km^2 Loess Plateau (dark shading) and the North China Plain (lighter shading) on the middle and lower reaches of the Yellow River, respectively. The Loess Plateau supports a population of 82 million people (Xiubin et al., 2003). The main map shows the location of the 112,728 km^2 Coarse Sandy Hilly Catchments (CSHC) where the dark grey line represents the boundary of the Loess Plateau.

et al., 1985). To reduce sediment loads reaching the Yellow River and its main tributaries, two complementary soil conservation management actions are currently used: (1) 're-vegetation schemes', where large areas of pasture and cropping lands are in the process of being re-planted with deeper rooted perennial species (Douglas, 1989; Liang et al., 2003; Ritsema, 2003); (2) 'engineering methods', which involve the construction of terraces on hill slopes and check dams across gullies (Douglas, 1989; Ritsema, 2003; Xiang-zhou et al., 2004). The effectiveness of these two soil conservation measures are critical to the overall management of the Yellow River (Huang, 1988; Douglas, 1989). Note that while the areas used for the engineering measures are known with decadal and catchment-level resolution (Mu et al., 2007), the exact timing and location of their construction is not currently available.

It is generally accepted that these two soil conservation measures also reduce streamflow (*e.g.*, Sun et al., 2006), largely due to increasing rates of evapotranspiration (ET). For example, Xiubin et al. (2003) show that the water yield from the middle reaches of the Yellow River (a mega-scale catchment with an area of 362,000 km^2) decreased by 49.4% from the 1960s to the early 1990s associated with a 26% increase in the area controlled by soil conservation measures. Similar results were found for the Jialu River (a meco-scale catchment of 1121 km^2) and Juyuanguo (a small-scale catchment of 70.7 km^2) catchments (Xiubin et al., 2003). The annual precipitation over the two periods (1959–1969 and 1990–1995) decreased by only 2.9 and 1.7% for mega-scale and small-scale catchments, respectively, and increased by 1.7% for the meso-scale catchment while stream flow decreased on average by half over these two periods (Xiubin et al., 2003). When considering the large areas of the Loess Plateau and the CSHC, there are two primary reasons an increase in ET could have serious repercussions regarding water supply for the vast population reliant on those water resources. Firstly, approximately 43% of the annual runoff to the 752, 444 km^2 Yellow River Basin is generated from the middle reaches of the Yellow River (draining the Loess Plateau from Lanzhou to Sanmen, Fig. 1, Li, 2003; Xiubin et al., 2003). Secondly, water resources are already overcommitted in the Yellow River Basin, due to increasing competition arising from rapid growth of agricultural and industrial activities and rapid urbanisation of the population (*e.g.*, Varis and Vakkilainen, 2001; McVicar et al., 2002b; Xu et al., 2002). These two issues mean that any reduction of streamflow generated from the Loess Plateau is a serious concern for the 107 million people living in the Yellow River Basin and for the 400 million living on the North China Plain partly reliant on its water. With the average annual streamflow decreasing, and demand for water increasing, current water resources will continue to be overcommitted into the future (Wallace, 2000; Xu et al., 2002). Under current conditions, the Yellow River is increasingly failing to reach the Bohai Sea (Li, 2003; Xiubin et al., 2003). This happened for the first time in recorded Chinese history in 1972 (for 15 days) and in 1997 (a 'drought' year) there were 226 zero-flow days; in the late 1990s the average number of zero-flow days per year was approximately 100 (Li, 2003). When zero-flow occurs all sediment is deposited in the river bed and this feedback exacerbates the rate at which the river bed increases its height above the surrounding plain. Consequently, one of the main goals of Yellow River management (the so-called "four nots", Li, 2003, pp. 10) is that 'the channel does not have zero-flow'. Currently, for the entire Yellow River Basin in a typical year, 21 billion m^3 of the 58 billion m^3 of water resources available as streamflow is used for 'scouring sediment and environment protection' (Xu et al., 2002) to minimise river bed aggradation.

China's NFPP and Grain for Green policies were developed for the entire country (a land area of 9.6 million km^2 with wide ranging climatic and landscape conditions) and aims to re-vegetate sloping land. The deep loess soils of the Loess Plateau have the ability to store large water volumes (*e.g.*, Yang, 2001; Messing et al., 2003) and from the perspective of the re-vegetation program, this initially supplements the low precipitation in the area and has encouraged wide-spread afforestation. Initially, following re-vegetation of an area in the Loess Plateau with trees, shrubs, grasses or some mix thereof, there is active growth exploiting the antecedent water stored in the soil matrix (Yang, 2001; Wang et al., 2004b; Yang et al., 2004; Chen et al., 2005; Liu et al., 2005). This active growth usually precludes recharging of soil moisture stores. The result is the development of a dry soil layer (ranging from 3 to 8 m deep Yang et al., 2004) which is usually drier under trees than under shrubs and grasses (Wang et al., 2004b; Yang et al., 2004; Chen et al., 2005). Consequently, when the moisture stores are exhausted, there is not enough available water (due to low precipitation rates in the Loess Plateau and especially in the CSHC) to maintain normal growth rates in the re-vegetated area (Yang et al., 2004). In some cases this has resulted in mortality of the vegetation (*e.g.*, Xiubin et al., 2003; Wang et al., 2004b; Yang et al., 2004), and in other cases while the trees survive, their growth is stunted so that some patches of 30 year old plantation trees are only about 20% of their normal height—colloquially referred to as 'little old man trees' (Yang, 2001; Yang et al., 2004). Localised characteristics are important in determining the amount of sub-optimal growth, as some areas such as gully bottoms or valleys where water accumulates might support normal tree growth, or decrease the extent of the stunting that occurs. Additionally, while the Grain for Green policy aims to re-vegetate all areas with slopes >25°, in the Loess Plateau such steep slopes are usually dry (due to lateral flow and low precipitation) and performing re-vegetation activities there may accelerate erosion due to disturbing the fragile soils (Zhu et al., 2004; Zhang, 2006). Thus, implementing the NFPP policy in the Loess Plateau requires careful consideration of several factors including both the on-site changes to local soil stores and off-site impacts on streamflow associated with implementing the re-vegetation program.

1.3. Brief review of hydrological-landuse research conducted in the Loess Plateau

Large-scale re-vegetation is a widely utilised management option to curb the severe soil erosion from the area, and under the current ''Grain for Green'' policy the rate of re-vegetation has increased; with patterns of re-vegetation activities in the Loess Plateau emulating those observed for all of China (Xu et al., 2004). Positive impacts of such re-vegetation schemes include: (1) stabilising the soil matrix, hence reducing erosion (Xiubin et al., 2003 report reductions of erosion rates ranging from 40 to 90%); (2) reducing peak-flow magnitude after storm events (Huang and Zhang, 2004) thereby reducing the risk of average (not extreme) flooding (Wei et al., 2005); (3) sequestering carbon to offset China's booming economic growth and subsequent energy usage (*e.g.*, Byrne et al., 1996; Foster, 2001); (4) providing habitat and biodiversity security (*e.g.*, Xu et al., 1999; Jiang et al., 2003).

A counter to the positive impacts of re-vegetation is the often observed reduction in annual streamflow, due to increased ET when grasses are replaced with forest as part of the re-vegetation scheme. The reasons forests have relatively higher ET when compared to grass is that many factors governing ET are more favourable for forests than for grass. For example, forests are more aerodynamically efficient; they have more persistent leaf area and greater plant available water capacity compared to grasslands (Calder, 1999; Zhang et al., 2001). Globally, much research has confirmed the decrease in streamflow as a result of increasing forest cover in an area (*e.g.* see Bosch and Hewlett, 1982; Brown et al., 2005, and the references therein); in China Wei et al. (2005) show that 8 of 8 studies report a decrease in peak flow, with 6 of 8 studies showing a decrease in average annual flow. While increasing the forest cover of an area usually results in an associated decrease of streamflow, this is not always the case. For example, Liu and Zhong (1978) for a catchment in the Yangtse River (south China) reported that mean runoff of a non-forested area was roughly 50% that of a forested area. As such there have been conflicting opinions about the impact of implementing the re-vegetation program in the Loess Plateau. Therefore, we have conducted a literature review of landuse-hydrology studies conducted in the Loess Plateau (summarised in Table 1). When data are used at a range of scales taking climate variability into account primarily by a 'paired catchment' experimental design, results overwhelming confirm that on the Loess Plateau, annual streamflow is reduced when associated with afforestation (12 of 13 cases—see Table 1). It is interesting to note that two papers (*e.g.*, Hao et al., 2004; Li et al., 2004) using modelled output contradict the weight of evidence derived from research utilising observed data. Additionally, three 'opinion' papers (*e.g.*, Wu and Zhao, 2001; Zhao et al., 2001; Shi and Li, 2005), based on findings using data, conclude that annual streamflow is reduced when associated with afforestation. Interpretation of results becomes more complex as hydrology-landuse change are analysed at finer temporal resolutions—*i.e.*, from average annual through annual and seasonal to daily (Brown et al., 2005). For example, Huang and Liu (2002) show that streamflow was higher from grasslands than forest from January through September, yet streamflow was marginally higher from forests compared to grasslands from October through December, see Fig. 2(a) and (b). For forested catchments this relative increase of autumn flow (when there is little precipitation) is due to the lag (or buffering) effect that the higher amounts of leaf litter, biological macropores and organic material in the top-soils of forests (the so called 'sponge effect') have on promoting baseflow compared to the more rapid response of infiltration-excess overland flow seen from non-forested catchments (*e.g.*, Huang and Liu, 2002; Bruijnzeel, 2004; van Noordwijk et al., 2004). In addition, to the average monthly results reported by Huang and Liu (2002) discussed here, several of the other studies reviewed here (Huang et al., 2003; Liu and Huang, 2003; Huang and Zhang, 2004; Wang et al., 2004a; Wu and Li, 2005) also report seasonal or monthly averages.

Given that water resource management in the Yellow River Basin is such a complex issue (with many feedbacks, both positive and negative) that partly controls the future development of north China, it is necessary to: (1) better understand regional hydrology-landuse impacts of the Loess Plateau; (2) raise awareness amidst mid to senior users in NRM agencies that influence landuse decisions of the impacts of the re-vegetation program on regional water resources. To address these two aims, a collaborative international project was established (McVicar et al., 2002a). Since it has become increasingly important to ensure that scientific findings are immediately accessible to the relevant users (Argent, 2004) and to address the second aim (above), a goal of this international project was to develop a computer scenario modelling capacity that could easily be used by managers to support their decision making process as they implement the re-vegetation program. The software application is named Re-Vegetation Impacts on Hydrology (ReVegIH); the underpinning hydrology-landuse framework, data sets, and software design (using a participatory approach) of ReVegIH are discussed in Section 2. In Section 3 the main functionality of ReVegIH is described and relevant organisational and cultural issues pertaining to the software design are documented. Additionally, future prospects for addressing a wider range of hydrology issues and broadening the hydrology-landuse tool by integrating other relevant NRM issues in the CSHC (focusing on sediment-landuse within the context of managing water resources the Loess Plateau and the entire Yellow River Basin) are discussed. Finally, in Section 4, conclusions are drawn.

2. Methods

2.1. Hydrology-Landuse model

The algorithm used to simulate the impacts of regional hydrology under changing landuse is based on the framework developed using a global dataset by Zhang et al. (2001); see Eq. (1). This hydrology-landuse framework simulates average annual change in ET as a function of area weighted forest cover for an area (usually a catchment, though administrative areas such as counties can also be used). It does this by assuming that on an average annual time step there are no significant changes of soil moisture stores and that precipitation is either partitioned into ET or runoff. Hence, as a result of increasing

Table 1
Summary of hydrology-landuse research conducted on the Loess Plateau

Citation	Climate variability considered?	Study area(s)	Findings regarding hydrological impacts of increased afforestation	
			Summary of findings	Change in streamflow
Wu et al. (1999)	Yes, paired	4 plots (each 20 m × 5 m)	Mean runoff from Chinese pine forest was 12% of the mean runoff from agricultural land (6 summer seasons from 1988 through 1994, excluding 1989)	↓
Zhao et al. (2002)	Yes, paired	4 plots (each 20 m × 5 m)	Total runoff from *Populus* forest was 13% of the total runoff from agricultural land (6 summer seasons from 1995 through 2000)	↓
Zhao et al. (2003)	Yes, paired	4 plots (each 20 m × 5 m)	Mean runoff from Chinese pine forest was 16% of the mean runoff from agricultural land (6 summer seasons from 1995 through 2000)	↓
Zhao and Wu (2001)	Yes, paired	2 small catchments ($0.10\ km^2$ and $0.301\ km^2$)	Mean streamflow from Chinese pine forest catchment was 48% of the mean streamflow from a bush/grass catchment (3 years from 1996 through 1998)	↓
Wu and Li (2005)	Yes, paired	2 small catchments ($0.10\ km^2$ and $0.301\ km^2$)	Mean streamflow from bush/grass catchment was 25% of the mean streamflow from Chinese pine/*Populus* forest catchment (5 years from 1999 through 2003)	↑
Huang et al. (2003)	Yes, paired	2 small catchments ($0.87\ km^2$ and $1.15\ km^2$)	Total streamflow of forested catchment (planted in 1954) was 68% of the total streamflow from non-forested catchment (25 summer seasons from 1956 through 1980)	↓
Wang et al. (2004a)	Yes, paired	2 small catchments ($0.87\ km^2$ and $1.15\ km^2$)	Total streamflow of forested catchment (planted in 1954) was 63% of the total runoff from non-forested catchment (45 summer seasons from 1956 through 2000)	↓
Wang and Zhang (2001)	Yes, long control period	1 catchment ($435\ km^2$)	Mean streamflow reduced by 58% (20 years from 1960 to 1980) due to afforestation	↓
Huang and Zhang (2004)	Yes, statistically climate adjusted runoff	1 large catchment ($1,117\ km^2$)	Mean streamflow reduced by 32% due to afforestation and other soil conservation practices (32 years from 1958 through 1989)	↓
Liu and Huang (2003)	Yes, paired	2 large catchments ($3,522\ km^2$ and $3,764\ km^2$)	Mean streamflow of forested catchment was 66% of the mean streamflow from non-forested catchment (24 summer seasons from 1964 through 1987)	↓
Huang and Liu (2002)	Yes, paired (2 pairs)	2 large catchments 2 medium catchments ($3,522\ km^2$ and $4,715\ km^2$) ($528\ km^2$ and $807\ km^2$)	Mean streamflow of forested catchments was less than the mean streamflow of non-forested catchments (29 years from 1958 through 1987)	↓
Li et al. (2007)	Yes, statistically climate adjusted runoff	1 (very) large catchment ($30,261\ km^2$)	Mean annual streamflow reduced due to soil conservation practices. Mean annual streamflow from years 1972 through 1997 was 31% of the mean annual streamflow from 1961 through 1971 (37 years from 1961 through 1997)	↓
Liu and Zhong (1978)	No	n/a (stations throughout Loess Plateau)	Mean streamflow of forested area was 73% of non-forested area (13 years from 1951 through 1963) for the Loess Plateau. Additional separate results were also presented for the ChangJiang (or Yangtse) Basin in southern China	↓

The table is sorted by ascending size of 'study area(s)'. In the column labelled 'Change in streamflow' ↓ means there is a decrease in streamflow associated with increasing forest area, while ↑ means an increase in streamflow associated with increasing forest area. Only papers where results are based on data analysis, as opposed to 'model' or 'opinion' papers are included here. In the column titled 'Climate variability considered?' the term 'paired' means the results are from a paired-catchment (or paired-plot) study, with sites being proximally located so input precipitation is assumed to be identical for the pair.

forest area in a catchment, a modelled increase in ET results in an equal reduction of streamflow on an average annual time step for a given area (catchment). The model is a regional steady state model suitable for broad area scenario simulation. It requires only a limited dataset to parameterise, and was deemed suitable for the purpose of raising the awareness of the impact of land-use change on regional hydrology in the CSHC. It does not dynamically model the growth of forests and does not allow for changes in precipitation and/or evaporative demand due to either climate variability or climate change.

$$\mathrm{ET} = P\left(f\frac{1+w_1E_0/P}{1+w_1E_0/P+P/E_0}+(1-f)\frac{1+w_2E_0/P}{1+w_2E_0/P+P/E_0}\right) \tag{1}$$

where ET is actual evapotranspiration, P is precipitation, f is the fractional forest cover, E_0 is potential evapotranspiration (here we equate this with pan evaporation), with w_1 and w_2 being the

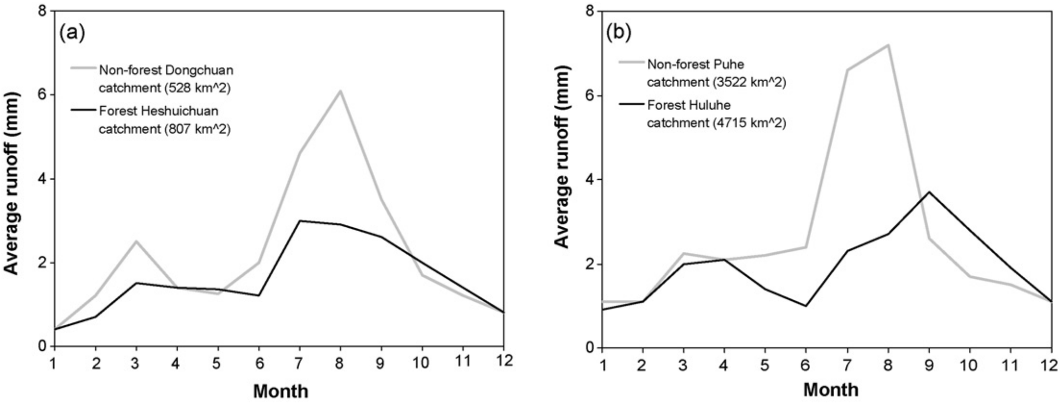


Fig. 2. Results from Huang and Liu (2002) showing the long-term average monthly runoff for the: (a) larger; and (b) smaller forested/non-forested catchment pairs in the Loess Plateau.

plant-available water coefficients for forest and non-forest respectively. In Zhang's et al. (2001) original global model w_1 and w_2 are 2 and 0.5 for forest and non-forest (or herbaceous vegetation), respectively.

In our implementation of Eq. (1) P, ET and E_0 are spatial averages for each area (in our implementation an 'area' is defined as either a catchment or a county) and temporally they represent average annual fluxes (Donohue et al., 2007), while w_1 and w_2 represents the relative difference in the way plants use soil water for transpiration, and is mainly interpreted as the differences in root zone depth (Zhang et al., 2001). Given that the CSHC is located in a semi-arid area, with measured average annual runoff being less than 10% of average annual precipitation (Zhang et al., 2007), and the high density of intensive engineering soil conservation measures, it was appropriate (and necessary—see Fig. 3) to modify w_2 rather than use the global value of w_2 from Zhang et al. (2001) to adequately model average annual streamflow. Zhang et al. (2007) locally calibrated the w_2 parameter to minimise the difference between the average annual modelled (or simulated) runoff and average annual measured (or observed) runoff using the average annual streamflow data derived and quality-controlled by Li et al. (2005a) for 36

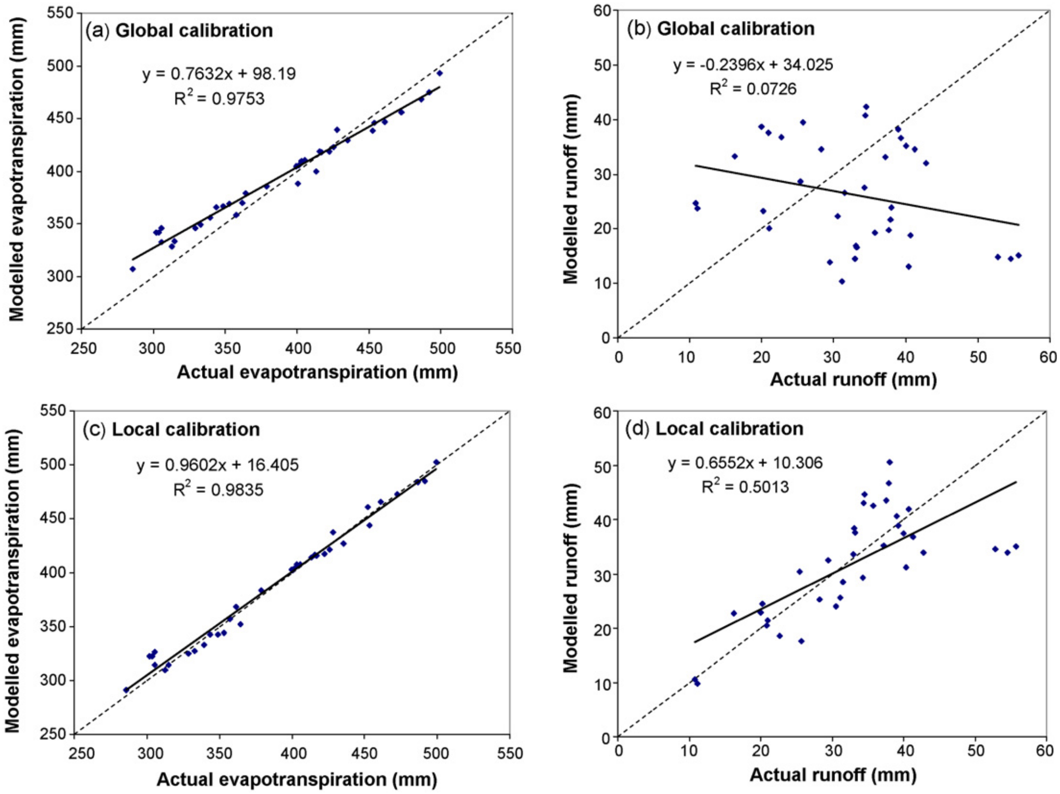


Fig. 3. Crossplots of actual and modelled: (a) average annual actual evapotranspiration (calculated as average annual precipitation minus average annual runoff); and (b) average annual runoff using the global coefficients are shown. After performing the local calibration actual and modelled: (c) average annual evapotranspiration; and (d) average annual runoff are shown. For each sub-plot the dashed line is the 1:1 line. While these data have been presented by Zhang et al. (2007), here the lines of best fit (shown by the solid line in each sub-plot) are not forced to have an intercept of zero.

hydrology stations located in the CSHC from 1980 to 2000. Briefly, Zhang et al. (2007) regionalised the w_2 values using hierarchical cluster analysis of the data space of ET/P and E_0/P to define 3 meta-groups that had w_2 values of 1.61, 0.45 and 0.10; as in the global study the value of 2 was used for w_1 (Zhang et al., 2001). For these 36 hydrology stations results from the global calibration (Fig. 3(a) and (b)) and local calibration (Fig. 3(c) and (d)) are provided. Next to apply the average annual water balance model to the entire CSHC in ReVegIH (not just the contributing areas from the 36 hydrology stations) a modified regression relationship was developed to model w_2 as a function of percent non-forested area and the area averaged dryness index (defined as the ratio of pan evaporation by precipitation—averaged for the 21 years and for each catchment or county). For full details regarding the regionalisation and local calibration of Zhang's et al. (2001) hydrology-landuse framework to CSHC conditions, see Zhang et al. (2007). Others have also locally calibrated Zhang's et al. (2001) framework in south-east USA (Sun et al., 2005) and south-east Australia (Van Dijk et al., 2007).

2.2. Datasets used

The data used in ReVegIH include five raster datasets (landuse/land cover, digital elevation model (DEM), re-vegetation areas, vegetation suitability and precipitation) and two vector datasets (catchment boundaries and county boundaries); they are described below in turn.

2.2.1. Landuse/Land Cover dataset

The source vector database was mapped in 1986 at a scale of 1:500,000 (Shen, 1991), which was converted to raster data with a cell size of 100 m for all the regional hydrological modelling documented here. These data were later over-sampled to 500 m resolution for display purposes only. The percentage woody cover for each area (either a catchment or a county in ReVegIH) and land limits data (highly productive agricultural land, water, urban and forestry), which are used in the re-vegetation scheme, are extracted from these data. Following the hydrology-landuse construct of Zhang et al. (2001) the landuse classes of forest, sparse forest and shrublands have been aggregated to a perennial woody vegetation class (meaning deep-rooted perennial vegetation whose water requirements are different from grasses). The 1986 percentage woody cover for each area defines the 'current conditions' and is the benchmark from which all scenario modelling is compared.

2.2.2. DEM dataset

A 100 m resolution DEM was created using ANUDEM Version 5.1 (Hutchinson, 2004a) from contours, rivers and spot height data (Yang et al., 2005). The resulting DEM is hydrologically correct, in that the river network defined from it is connected without spurious small parallel streams being introduced. The elevations for the CSHC range from 312 to 2760 m above sea level, and slopes can exceed 30° from horizontal in the 100 m resolution model (Yang et al., 2007).

2.2.3. Re-vegetation area dataset

This spatially defines (at 100 m resolution) where the recommended areas are for re-vegetation. It consists of two parts: the target level and the land limit type; see McVicar et al. (2005b) for full details.

2.2.3.1. Target level. The delineation of target levels takes into account land position, slope, aspect and precipitation. Three target levels were defined which correspond to three vegetation growth forms: level 1 is where trees are suitable; level 2 is where shrubs are suitable; and level 3 is where grasses are suitable; see McVicar et al. (2005b) for the definitions of suitability for the three growth forms. It is understood that shrubs and grasses can also grow in areas suitable for trees (*i.e.*, in level 1 areas); likewise, grasses can also grow in areas suitable for shrubs (*i.e.*, in level 2 areas). The term 'target area' in this paper represents the area associated with a specific user-defined target level. Land position (McVicar et al., 2005b), slope and aspect were determined from the 100 m resolution DEM. Slope was calculated using the average maximum (or Horn's) algorithm (Jones, 1998) to fit a plane to the elevations of the immediate 8 neighbouring cells of each cell, with aspect being the direction of the resultant slope plane; these are the default algorithms implemented in ArcGIS. In addition, within the selected target level, users can view priority areas for re-vegetation. Re-vegetation priority areas first rely upon defining steep slopes where soil erosion potential is high and where the slopes are too steep for vegetation to grow well or for effective planting of vegetation using common methods. These steep slope and gully (SSG) areas have slopes $\geq 15^\circ$ from horizontal using the 100 m resolution DEM. Next, re-vegetation priority areas are those cells located in a target area that are both lower in elevation than and adjacent to a SSG boundary cell. Due to the cell size of the datasets, this means that priority areas are 100 m wide zones downhill from the highly erodible SSG areas. In general, re-vegetation of these areas would have the most significant impact on intercepting and utilising soil and water coming from upslope. The anticipated effect of re-planting the priority zones only (compared to re-vegetating the whole target area) will be that the reduction in streamflow will be minimised while the reduction of soil entering the river network will be maximised. If funds are available the entire target area could be re-vegetated, but the ramification of this would be a greater reduction of streamflow. Alternately, if this is not feasible, re-vegetation should be carried out first in the priority zones within these target areas. To avoid encouraging afforestation with trees that may die (or have sub-optimal growth) once the soil moisture store is exhausted, the area deemed suitable for re-vegetation with trees in ReVegIH only occurs in the south, while re-vegetating areas with shrubs is encouraged for the larger (and drier) central and northern portions of the CSHC. This takes into account the gradient of precipitation from south to north, and the local observations that re-vegetating with trees results in a more distinct dry soil layer than re-vegetating with shrubs. Hence, careful selection of species and sites at a local scale is required. We acknowledge that outside of the areas deemed suitable for planting trees, smaller patches of suitable areas would exist (below the resolution of our minimum mapping unit calculated here using 100 m resolution data). To identify these smaller patches, field surveys or spatial analysis using higher resolution data would be needed.

2.2.3.2. Land limit type.

Certain landuses or land cover classes such as water bodies, urban regions, and pre-existing woody areas, by definition, cannot support re-vegetation. Likewise, although possible, it is inadvisable to re-vegetate highly productive agricultural land (*i.e.*, agricultural land that is irrigated or close to a permanent water source Shen, 1991) that is vital for securing food for locals. Therefore, these four landuse types were termed 'land limits', meaning that the land that they cover could not be considered for re-vegetation in ReVegIH. We have defined two land limits: the first consists of water, urban and forest areas (called WUF); the second consists of water, urban, forests and agricultural land (called WUFA). Note for WUF and WUFA the forest class represents perennial woody vegetation comprised of the forest, sparse forest and shrubland classes as introduced in the Landuse/Land Cover dataset above. We maintain calling it 'forest' to better summarise the major historical re-vegetation effort. Throughout the remainder of this paper the term 're-vegetation dataset' is used for brevity referring to the combination of re-vegetation target level/priority area and land limit data.

2.2.4. Vegetation suitability dataset

Is a Boolean (or binary) value for each of 38 species on each 100 m resolution grid cell. Based on a set of criteria for 5 environmental variables using a GIS overlay method (McVicar et al., 2005b), a species is assessed as either suitable, or not, for every grid cell in the CSHC. For the 38 species considered (comprising 24 tree species and 14 shrub species) that were previously selected for the CSHC re-vegetation scheme these datasets were then combined to generate a single suitability dataset by means of binary addition. Each value represented a unique combination of the 38 species' suitability. To reduce the dataset's storage requirement, a look up table for unique numbers of the single dataset was created and is unpacked 'on-the-fly' when users interact with ReVegIH; for full details, see McVicar et al. (2005b).

2.2.5. Precipitation dataset

Monthly precipitation data at 58 meteorological stations in and around the CSHC for the 21-year period from 1980 through 2000 were obtained. These data were then interpolated with ANUSPLIN Version 4.3 (Hutchinson, 2004b) using a bi-variate thin plate spline to produce monthly precipitation surfaces (McVicar et al., 2005a). The precipitation dataset provided in ReVegIH is the annual average of the 21 years; the maximum, mean, minimum and standard deviation of this surface are 557, 413, 276 and 57 mm, respectively. Additionally, pan evaporation surfaces were developed using a quint-variate partial thin plate spline which incorporated a bi-variate thin plate spline function of longitude and latitude with constant linear dependences on vapor pressure deficit, wind, and net radiation (McVicar et al., 2005a, 2007). The pan evaporation dataset used in the regionalisation of the hydrology-landuse framework is the annual average from 1980 through 2000; the maximum, mean, minimum and standard deviation values are 2261, 1875, 1494 and 220 mm, respectively.

2.2.6. Catchment boundaries

These data were extracted from the 100 m resolution DEM introduced previously using the sediment transport and hydrology program called SedNet (Wilkinson et al., 2004). The 42 catchments of the CSHC range from 31,460 to 127 km^2 and are shown in Yang et al. (2005) and listed in Li et al. (2005b).

2.2.7. County boundaries

These were provided at 1:500,000 scale for the 70 counties wholly or partially located in the CSHC. There are 22 counties totally encompassed in the study site and another 14 counties have >90% of their area in the CSHC, with another 10 counties being 30% or more in the study area (Li et al., 2005b). For counties not totally included in the CSHC, both measured data (county area, landuse, land limits, percent woody cover and precipitation) and simulated outputs (ET, woody area, runoff, re-vegetation target levels and priority areas) provided in ReVegIH are only relevant to the part of the county within the CSHC boundary (Li et al., 2005b).

2.3. A participatory approach to software design

The political context of the decision making process needs to be understood when developing a DST. While some western researchers strongly advocate bottom-up participatory stakeholder engagement for all natural resource issues (Ball, 2002; Malczewski, 2004), we have purposefully targeted government users as they have the greatest likelihood of influencing China's current top-down decision-making process. While performing consultation with key government stakeholders, the target audience within the national, provincial, prefecture, county, township, and village hierarchy was identified. Our tool was designed for NRM at the county level (and larger administrative units) for the pragmatic reason that most NRM at the township and village levels in the CSHC did not have access to personal computers at the time of consultation. Providing a tool to the most local level as practical could strengthen local participation in the planning and management process, the lack of which has been highlighted as one major implementation issue of China's re-vegetation program (Yang, 2004).

Several design aspects were clearly identified by county-level stakeholders to maximise the likelihood of use of the DST to support China's re-vegetation program in the CSHC. The essential criteria were:

1. Have a bi-lingual (English and Chinese) interface with all terms defined in both language and cultural contexts (Thomson and Schmoldt, 2001).
2. Be easy to use. Given that the targeted users were likely to have limited computer skills, the software needed to be a straightforward, user-friendly application providing results

in a reasonable time-frame (Argent and Grayson, 2003). A reasonable time-frame in this case had previously been suggested to be ‘less than a few minutes’ during the consultation process.
3. To maximise its accessibility (Malczewski, 2004), it must be standalone and not require other software packages to support its functionality, especially basic GIS functions.
4. A capacity to be distributed on compact disk (CD) due to costly and slow (or non-existent) internet access at the time of consultation for the majority of targeted users in the county and prefecture level offices. The application, including all required datasets and operating frameworks, needed to be distributed on CDs and installed locally (Thomson and Schmoldt, 2001), rather than be a web-based application.
5. An ability to run on a relatively modest personal computer (minimum requirement of a Pentium III 600 CPU with at least 384 MB RAM and at least 300 MB of free hard disk space) thereby maximising access.

ReVegIH provides spatial scenario modelling capabilities and allows stakeholders to determine: (1) where priority (and target) re-vegetation activities should be undertaken; (2) what species are suitable for a specific location; (3) simulate the related steady-state hydrological impact. As a stand-alone application, ReVegIH provides basic GIS functions so users do not need to install expensive proprietary GIS software. ReVegIH is developed in Microsoft’s .NET environment using C# and it calls some TIME (The Invisible Modelling Environment, Rahman et al., 2003, 2004) functions. TIME (also developed in .NET) is a model development environment which supports advanced applications developed using programming languages such as C#, Visual Basic, and C++. Having one set of C# code with both Chinese and English present in the interface helped minimise code development overheads.

3. Results and discussion

Four topics are discussed in this section, they are: (1) scenario hydrology-landuse modeling; (2) species selection using ReVegIH; (3) software design implementation to meet user needs; (4) potential future directions for ReVegIH.

3.1. ReVegIH: software to simulate hydrology–landuse interactions

The two ways to assess the impact of simulated re-vegetation on runoff in ReVegIH are shown in Fig. 4. After first selecting a catchment or county boundary, percent woody cover can be simulated to change in two ways: (1) adjusting percent woody cover using a slide bar; or (2) selecting an appropriate target level/priority area and land limit combination for which the percent woody cover is automatically pre-defined. The hydrology-landuse model then computes the output ET and runoff values. In this way, the user can simulate various management scenarios in order to determine the best option for the situation. Using either method, the simulation of the hydrological impact occurs instantaneously when the percent woody cover value is simulated to change.

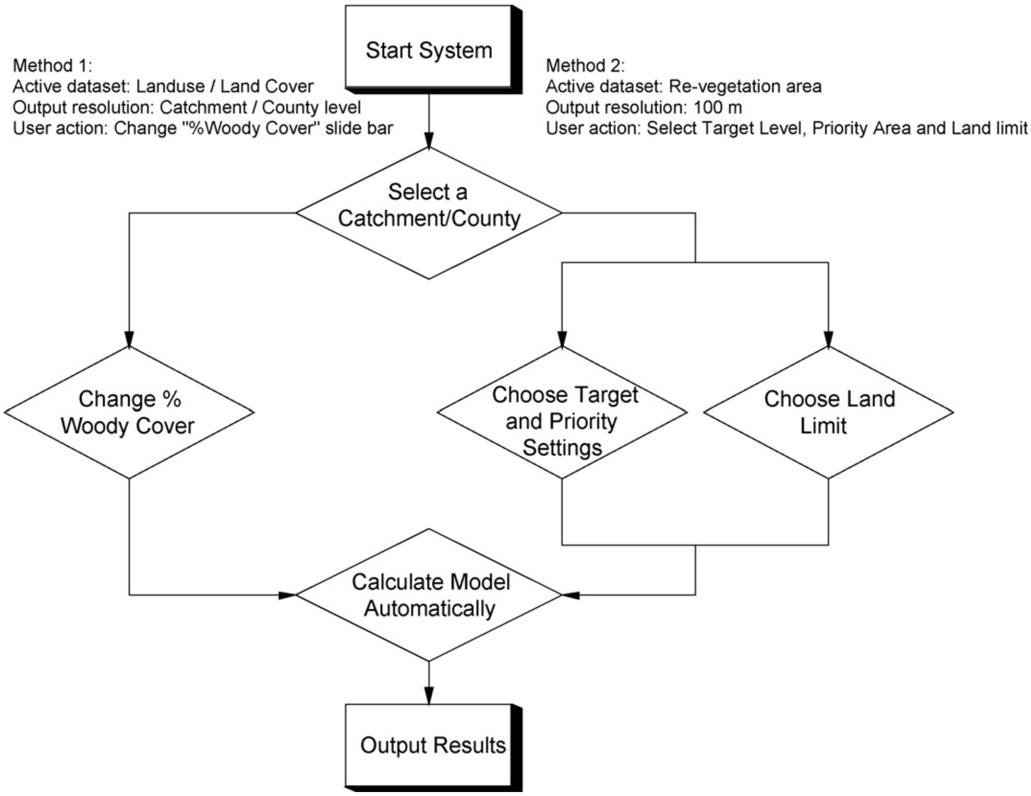
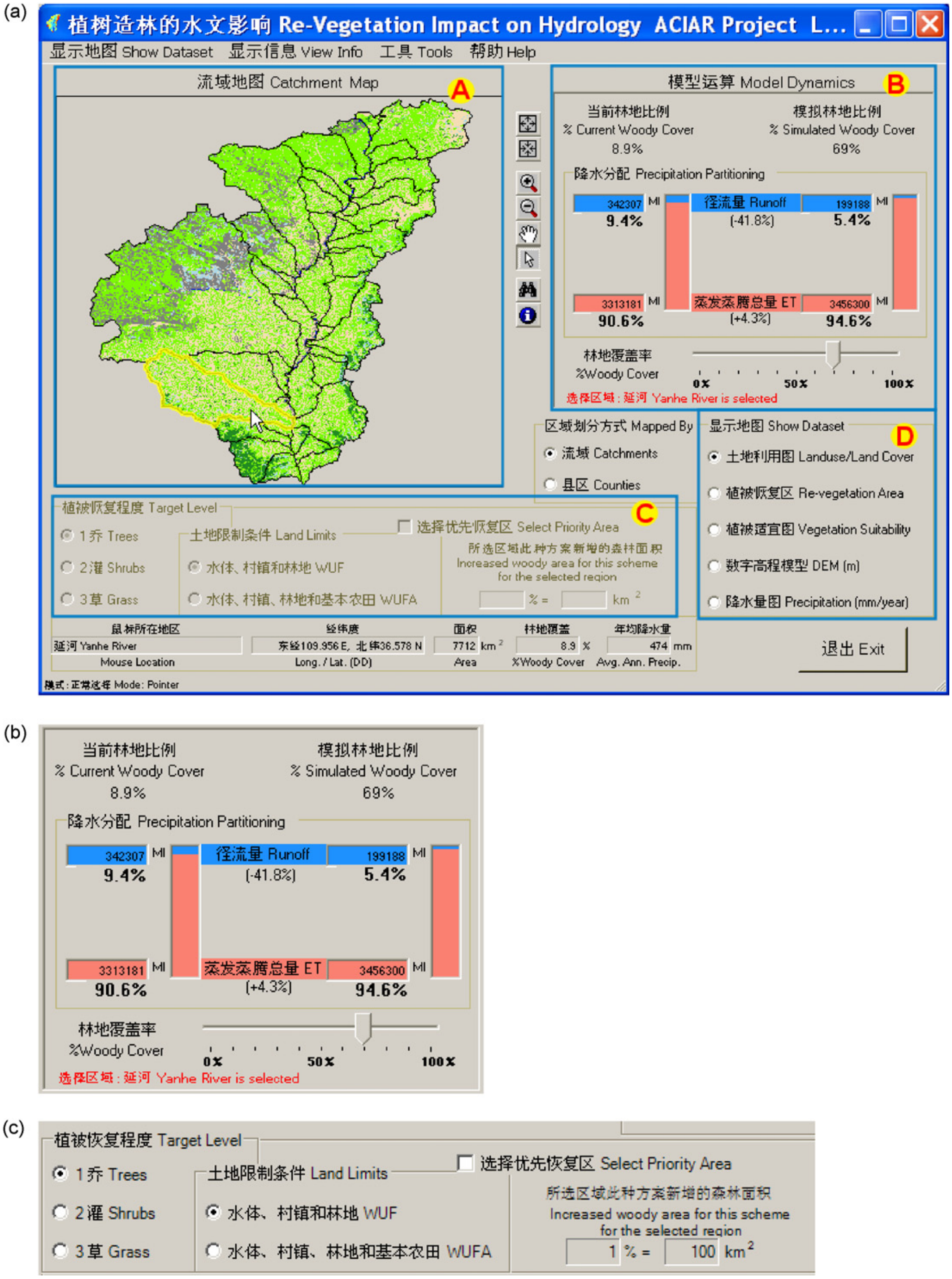


Fig. 4. The ReVegIH system flow chart for ecohydrological assessment is shown.



当前林地比例 % Current Woody Cover 8.9%

模拟林地比例 % Simulated Woody Cover 69%

342307 Ml 9.4% — 径流量 Runoff (-41.8%) — 199188 Ml 5.4%

3313181 Ml 90.6% — 蒸发蒸腾总量 ET (+4.3%) — 3456300 Ml 94.6%

选择区域：延河 Yanhe River is selected

区域划分方式 Mapped By: ● 流域 Catchments ○ 县区 Counties

显示地图 Show Dataset: ● 土地利用图 Landuse/Land Cover ○ 植被恢复区 Re-vegetation Area ○ 植被适宜图 Vegetation Suitability ○ 数字高程模型 DEM (m) ○ 降水量图 Precipitation (mm/year)

植被恢复程度 Target Level: ● 1 乔 Trees ○ 2 灌 Shrubs ○ 3 草 Grass

土地限制条件 Land Limits: ● 水体、村镇和林地 WUF ○ 水体、村镇、林地和基本农田 WUFA

☐ 选择优先恢复区 Select Priority Area

所选区域此种方案新增的森林面积 Increased woody area for this scheme for the selected region: 1 % = 100 km²

鼠标所在地区 Mouse Location: 延河 Yanhe River

经纬度 Long. / Lat. (DD): 东经109.956 E, 北纬36.578 N

面积 Area: 7712 km²

林地覆盖 %Woody Cover: 8.9 %

年均降水量 Avg. Ann. Precip.: 474 mm

模式：正常选择 Mode: Pointer

Fig. 5. The graphical user interface (GUI) of ReVegIH is shown in (a). The areas denoted by the red letters A, B, C and D are referred to in the text where full details are provided. The areas denoted by B and C are shown in detail in parts (b) and (c) of the figure. Note the GUI area C is only active when the ‘Re-vegetation Area’ dataset is selected in D.

The bilingual graphical user interface (GUI) of ReVegIH is shown in Fig. 5a and while its functionality is fully explained by Li et al. (2005b), the four areas most relevant to hydrology-landuse modeling are denoted in red from A to D; their functions are briefly described here for the two methods of simulating landuse change introduced in Fig. 4. In the following use of the letters A, B, C and D refers to those parts of the ReVegIH GUI shown in Fig. 5a.

3.1.1. Method 1

Once a catchment (or county) is selected in A and the ‘Landuse/Land Cover’ dataset is selected in D, then the user can perform catchment (or county) level scenario modeling (Fig. 4). This is achieved by dragging the slide bar in B to simulate landuse change (see the enlargement in Fig. 5b). The model results are shown above the slide bar in B with runoff and ET under the current landuse scheme shown on the left hand side, while runoff and ET under the simulated landuse scheme are shown on the right hand side. The bolded percentages for both the current and simulated woody conditions represent the percentage of average annual precipitation that is partitioned into ET and runoff, whereas the non-bold percentages in parentheses (reported in the middle of the current and simulated woody conditions) are the simulated changes relative to current conditions for ET and runoff, respectively. That is, with a change in percentage woody cover, the value in parentheses reveals the change in runoff and ET relative to current conditions—this is likely to be of most use for water resource managers. It is assumed that re-vegetation activities cannot be performed on water bodies, urban areas and very steep slopes and gullies. Since these landuse classes occupy a certain area in every region, there is a maximum percentage for each region that cannot be exceeded when simulating landuse change. This modeling is only spatially explicit to the catchment (or county) level and only the percentage of the selected area simulated to be covered with woody vegetation is used in the hydrology-landuse calculations.

3.1.2. Method 2

The second approach to simulate landuse change is to access the pre-defined target level/priority area and land limit combinations for any catchment (or county); see Fig. 4. This can only be performed when the ‘‘Re-vegetation Area’’ dataset in D is selected with the modeling being spatially resolved to a 100 m resolution grid cell as introduced above. In C, users can select between the 3 target levels and the 2 land limits (also see the enlargement in Fig. 5(c)) and if the ‘Select Priority Area’ choice is ticked, the re-vegetation scenario will be run using the priority area only. For each combination, the model results are shown in B (and also the enlargement in Fig. 5(b)) and are aggregated to the selected catchment or county. The impacts of selecting various land limit and priority area combinations are shown in more detail in Fig. 6.

Fig. 6 illustrates the effect of switching between the two land limits (WUF or WUFA) and having the priority area selected or not. Definitions of the land limits and priority area are given in the description of the re-vegetation area dataset (Section 2.2). All four examples show the same small part of the 2853 km^2 Ansai County, with the second re-vegetation level (shrubs)

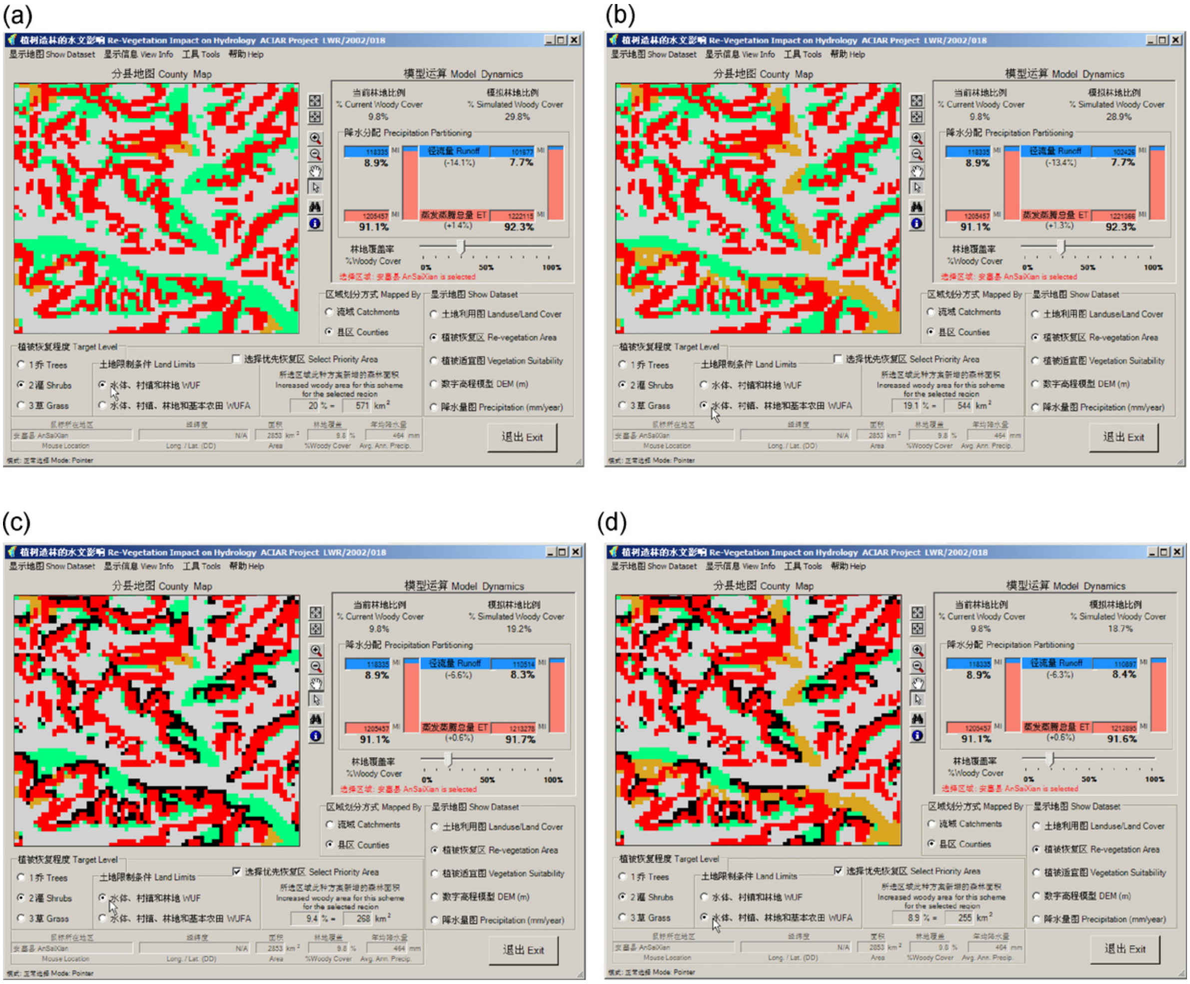


Fig. 6. A comparison of different land limits (either WUF or WUFA) and priority areas for the same small part of Ansai County using re-vegetation target level 2 are shown. In the portion of the GUI displaying the spatial data (A in Fig. 5a), green represents the target areas for re-vegetation at level 2 (*i.e.*, with shrubs), black areas are the priority areas, yellow are the various land-limit areas, red represents steep slopes and gullies that are unsuitable for re-vegetation and grey represents other unsuitable areas: (a) WUF without priority area, (b) WUFA without priority area, (c) WUF with priority area and (d) WUFA with priority area.

Table 2
Detailed results calculated by ReVegIH for the four scenarios shown in Fig. 6

Land limit/priority combination	Area (km^2)	Area (%)	Runoff reduction (Ml)	Runoff reduction (%)
WUF without priority area (a)	571	20.0	16658	14.1
WUFA without priority area (b)	544	19.1	15909	13.4
WUF with priority area (c)	268	9.4	7821	6.6
WUFA with priority area (d)	255	8.9	7438	6.3

In the column labelled ‘Land limit/priority combination’ the letters in brackets refer to the case shown in Fig. 6. Note, results are provided for the entire selected area (catchment or county), not for the small portion of the area that is shown in Fig. 6.

selected. The ‘%Woody Cover’ data shown by the slide bar in B are for the specific combination of the target area and land limit settings. The runoff reduction (both in terms of Ml and %) is calculated relative to that expected for current landuse conditions; see Table 2 for full details.

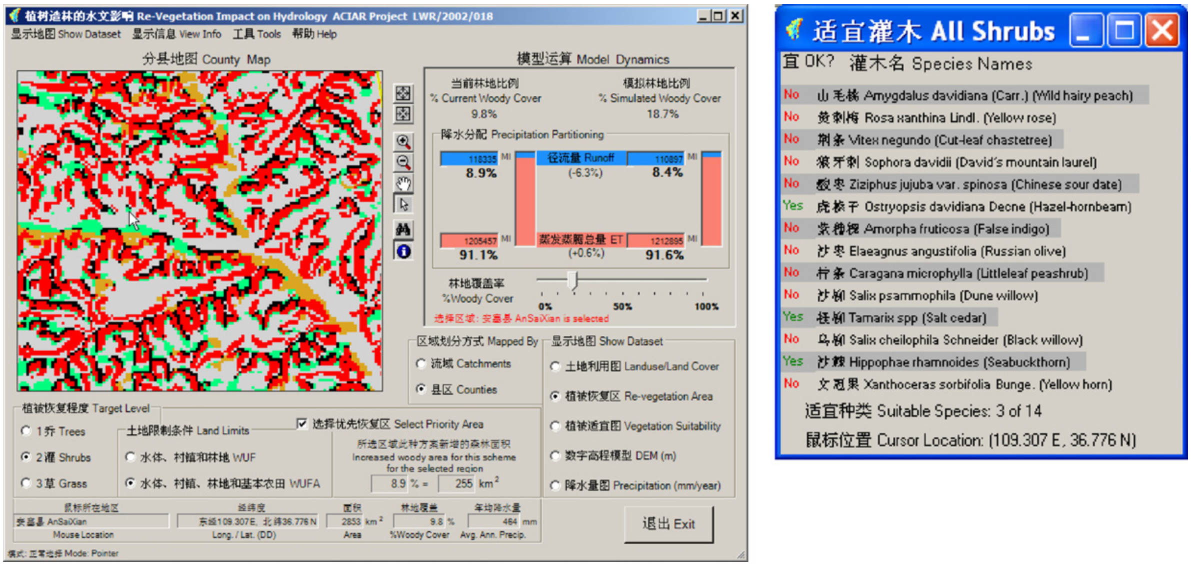
3.2. ReVegIH: software to map species suitability

In addition to modeling hydrology-landuse impacts, ReVegIH can be used to provide detailed (100 m resolution) vegetation suitability information for 38 woody species for the entire CSHC; for full details, see McVicar et al. (2005b). An expected common use of ReVegIH is when users display the re-vegetation dataset as a back drop and query the vegetation suitability database—this is illustrated in Fig. 7. Given that both the re-vegetation and vegetation suitability datasets are provided with a 100 m spatial resolution coupled with the 3 decimal place precision of the decimal degree latitude and longitude data shown in the GUI (Figs. 5a and 7), means that with the aid of a GPS, users can find the same location in the landscape. We recommend that some detailed site assessment be undertaken prior to performing any re-planting as ReVegIH is a regional scale decision support tool, and local factors (near and below the resolution of the data used in the application) may be critical in determining success (or failure) of re-vegetation schemes.

3.3. Software design to meet ReVegIH user requirements

To meet the user requirements introduced in Section 2.3, ReVegIH was implemented with the following four design features:

1. Data auto-load: all data required to simulate change with ReVegIH (outlined above) are loaded automatically while the application starts up, this greatly reduces user activity and possible confusion with data selection.
2. Data pre-processing: one dataset of the CSHC with 100 m resolution has 5310 × 4050 cells so the time spent on cell-by-cell calculation would likely be intolerable for most users (especially considering their modest computing facilities). Wherever possible, pre-processed data were packaged in ReVegIH thus decreasing the time required for landuse simulation modeling.
3. Different data resolution: to reduce ReVegIH's hardware requirements and to ensure that all required components fit onto one CD, two spatial resolutions of data are used: (A) the contextual landuse/land cover, DEM and average annual



当前林地比例 % Current Woody Cover: 9.8%
模拟林地比例 % Simulated Woody Cover: 18.7%
118335 Ml 8.9% — 径流量 Runoff (-6.3%) — 110897 Ml 8.4%
1205457 Ml 91.1% — 蒸发蒸腾总量 ET (+0.6%) — 1212895 Ml 91.6%
选择区域: 安塞县 AnSaiXian is selected

区域划分方式 Mapped By: ○ 流域 Catchments ● 县区 Counties
显示地图 Show Dataset: ○ 土地利用图 Landuse/Land Cover ● 植被恢复区 Re-vegetation Area ○ 植被适宜图 Vegetation Suitability ○ 数字高程模型 DEM (m) ○ 降水量图 Precipitation (mm/year)
植被恢复程度 Target Level: ○ 1乔 Trees ● 2灌 Shrubs ○ 3草 Grass
土地限制条件 Land Limits: ○ 水体、村镇和林地 WUF ● 水体、村镇、林地和基本农田 WUFA
☑ 选择优先恢复区 Select Priority Area
所选区域此种方案新增的森林面积 Increased woody area for this scheme for the selected region: 8.9 % = 255 km^2

鼠标所在地区 Mouse Location	经纬度 Long. / Lat. (DD)	面积 Area	林地覆盖 %Woody Cover	年均降水量 Avg. Ann. Precip.
安塞县 AnSaiXian	东经109.307E, 北纬36.776N	2853 km^2	9.8 %	464 mm

模式: 正常选择 Mode: Pointer

宜 OK?	灌木名 Species Names
No	山毛桃 Amygdalus davidiana (Carr.) (Wild hairy peach)
No	黄刺梅 Rosa xanthina Lindl. (Yellow rose)
No	荆条 Vitex negundo (Cut-leaf chastetree)
No	狼牙刺 Sophora davidii (David's mountain laurel)
No	酸枣 Ziziphus jujuba var. spinosa (Chinese sour date)
Yes	虎榛子 Ostryopsis davidiana Decne (Hazel-hornbeam)
No	紫穗槐 Amorpha fruticosa (False indigo)
No	沙枣 Elaeagnus angustifolia (Russian olive)
No	柠条 Caragana microphylla (Littleleaf peashrub)
No	沙柳 Salix psammophila (Dune willow)
Yes	柽柳 Tamarix spp (Salt cedar)
No	乌柳 Salix cheilophila Schneider (Black willow)
Yes	沙棘 Hippophae rhamnoides (Seabuckthorn)
No	文冠果 Xanthoceras sorbifolia Bunge. (Yellow horn)

适宜种类 Suitable Species: 3 of 14
鼠标位置 Cursor Location: (109.307 E, 36.776 N)

Fig. 7. An example of spatially exploring the re-vegetation dataset (showing the target level/priority area and land limit combination) while dynamically gaining vegetation suitability information for 14 species of shrubs from each 100 m grid cell of the re-vegetation dataset. Vegetation suitability is available for 38 species in total; ‘All Shrubs’ is one of seven predefined subsets the user can select. The meaning of the colors shown in the portion of the GUI displaying the spatial data (A in Fig. 5a) are provided in the caption of Fig. 6.

precipitation dataset are provided at 500 m resolution, for the CSHC they each require roughly 4 MB of RAM; (B) the re-vegetation area and vegetation suitability datasets may attract cell-by-cell analysis, so finer resolution was necessary and these datasets are provided at 100 m resolution (requiring 90 MB of RAM each). Using raster data with two resolutions means only 384 MB of RAM is required to run ReVegIH and only 300 MB of free disk space is required to successfully load the application, so user's computer specifications are greatly relaxed. This allows users with modest computing capacity to successfully install and run ReVegIH.

4. Minimal user input requirements: dataset selection and information can be accessed from a series of drop down menus, from live 'radio-buttons', or from toolbars embedded in the user interface. The use of the radio-buttons and toolbars means that users can circumvent use of the drop down menu system. Selecting the suite of radio buttons and toolbars is performed by clicking the respective active area of the screen with the mouse.

3.4. Future directions of ReVegIH

The current version of ReVegIH is a starting point to provide managers in the region (and other users) with access to regional data sets and environmental models that take into account their requirements. Two improvements to the hydrology-landuse framework would involve being able to better deal with temporal variability. Firstly, the current framework is a steady-state model, it does not consider the changes in streamflow as a function of time since afforestation (Brown et al., 2005), nor the ability to re-vegetate different areas over many years (as in a 25-year rotation). Secondly, the meteorological drivers to ReVegIH are long-term (21 years) averages and hence neither the impacts of climate variability (Wang and Zhao, 1981) nor climate change are captured. In the CSHC the climate is variable; from 1980 through 2000 the spatially averaged maximum, mean, minimum and standard deviation values of annual precipitation are 527, 420, 314 and 60 mm, respectively. The minimum occurred in 1999 and the maximum in 1988, see (Li et al., 2005a). To assess climate change, the annual integrals of precipitation and pan evaporation were used to statistically (at the 95% confidence interval) assess trends; results are shown in Fig. 8(a) and (b) and for full details, see McVicar et al. (2005a). Note, we are assessing the annual (or per annum) change of precipitation and pan evaporation each with units of mm per annum, hence the units of the trend are mm a^{-1} a^{-1} or mm a^{-2}.

Though many stations exhibit a negative trend of annual precipitation (see Fig. 8a), it is only significant at $P = 0.05$ for 9.3% of the stations (or 5 of 54); all are located in the southern portion of the CSHC, where annual precipitation is highest. For these 5 stations, the average annual decrease of precipitation is -8.7 mm a^{-2}, with a standard deviation of 3.4 mm a^{-2}. For pan evaporation, Fig. 8b illustrates that nearly 20% of stations have a significant trend; 9 of the 11 are positive, and these are mainly located in the south of the CSHC. The 9 stations have a mean increase of pan evaporation of 14.4 mm a^{-2} and a standard deviation of 4.3 mm a^{-2}. The results for precipitation and pan evaporation are in agreement with other climate change studies conducted in China (Liu et al., 2004a; Liu et al., 2004b; Wu and Li, 2005); see McVicar et al. (2005a) for full details. Both results show statistically significant trends in the baseline meteorological data in the south-west of the study site that can be described as complimentary (*i.e.*, the drier the region the greater its potential evaporation (equated here to pan evaporation) Hobbins et al., 2001; Lhomme and Guilioni, 2006). The longer-term hydrological impacts of this climate change needs to be understood in context of current, and proposed landuse change. Introducing a temporal component to ReVegIH would allow subtle, yet important, interactions to be seen. For example, if the maximum reduction of streamflow related to landuse change coincides with a period of low precipitation, then the water resources generated from the CSHC to the Yellow River Basin would be less than simulated using the current steady-state average annual hydrology-landuse model within ReVegIH. Obviously to incorporate both temporal issues will result in a more sophisticated DST and would potentially necessitate targeting users with a higher skill level who have a well-founded understanding of a wider range of environmental issues (*e.g.*, Rauscher, 1999; Thomson and Schmoldt, 2001; Kangas and Kangas, 2005).

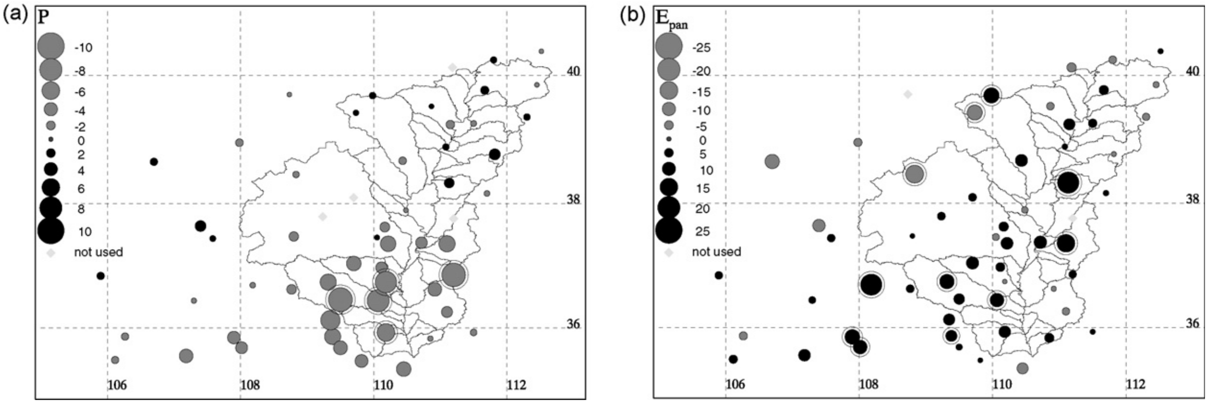


Fig. 8. Annual trends (mm a^{-2}) for the input meteorological data are shown for: (a) precipitation (P); and (b) pan evaporation (Epan). If the trend is significant at the 95% confidence level then a ring is placed around the circle. The 21-year study site average for P and Epan are 420 and 1861 mm a^{-1}, respectively. Stations not used in the analysis (*i.e.*, there was no continuous monthly record for the 252 months) are shown by a small light-grey diamond.

Due to the high mortality and sub-optimal growth rates of re-vegetation activities conducted in the Loess Plateau (the ‘little old man trees’) research developing site specific knowledge about vegetation water use and soil storage relationships (*e.g.*, Fu et al., 2003; Huang et al., 2005; Liu et al., 2005) that can be upscaled to the larger region needs to be performed. This research would also need to take planting density and soil properties (*e.g.*, particle size distribution that partly governs soil moisture) that both change as a function of slope and landform into account (Liu et al., 2005). Considering the extreme landscapes of the CSHC (Yang et al., 2005, their Fig. 3) and the 22 common species (16 being trees and 6 shrubs Li et al., 2005b), this is a non-trivial task.

ReVegIH could be extended to simulate the reduction in sediment delivery due to afforestation of selected parts of the landscape. This would require access to a regional-scale sediment-landuse model of complexity suited to available databases (McVicar et al., 2002b) and process understanding. Considering that the dates and location of the engineering soil conservation measures (*i.e.*, check dams and terraces) are not known (Mu et al., 2007), this modelling would be difficult and limited to catchment-scale output; a high resolution process model would be unsuitable. Once established, the two components (hydrology-landuse and sediment-landuse) could be integrated allowing the major biophysical impacts of re-vegetation to be simulated. Integrating these two components and introducing social and economic aspects would allow the so-called ‘triple bottom line’ to be assessed (Argent, 2004), and would provide opportunities to establish multi-criteria assessment of landuse change (*e.g.*, Kangas and Kangas, 2005; Sheppard and Meitner, 2005). To successfully undertake the challenging task of assessing the ‘triple bottom line’ would require both stakeholders and model developers to focus on specific questions (Jakeman et al., 2006).

4. Conclusions

Severe soil erosion from the middle reaches of China’s Loess Plateau into the Yellow River causes widespread management issues for down-stream water users. To minimize these problems, the Chinese Central Government has developed a number of policies aimed at re-vegetating vast tracts of land. While reducing sediment yields, this landuse change also results in less streamflow, as confirmed by many other researchers. In the already over committed Yellow River Basin, any reduction in streamflow results in complex and complicated feedbacks that must be taken into account for basin-scale water resource management. To raise awareness of the reductions in streamflow following re-vegetation, a bilingual decision support tool was developed aimed at county, provincial and national natural resources managers and policy makers. The tool, called ReVegIH, was designed to maximize use by the target audience by minimizing computing hardware and user skill level requirements. The current functionality of ReVegIH means users can determine: (1) where priority (and target) re-vegetation activities should be undertaken; (2) what species are suitable for a specific location; (3) simulate the related hydrological impact. The first two functions are provided at 100 m resolution, while the third is modelled at the catchment (or county) level. Currently, ReVegIH assesses afforestation impacts on average annual streamflow via application of an aerial-weighted evapotranspiration model operating at steady-state. Further improvements to the tool have been suggested if the target audience were to require more sophisticated annual streamflow modelling, including possibly considering more complex interactions of time (since planting different parts of the landscape) and climate (both variability and change). The current version of ReVegIH is aimed at a wide audience and it provides the only comprehensive regional guidance for implementing China’s re-vegetation program in the Loess Plateau.

Acknowledgements

This research was supported by the Australian Centre for International Agricultural Research (ACIAR) project titled ‘Regional impacts of re-vegetation on water resources of the Loess Plateau, China and the Middle and Upper Murrumbidgee Catchment, Australia’ (LWR/2002/018), CSIRO Land and Water, and the Chinese Academy of Sciences and Ministry of Water Resources Institute of Soil and Water Conservation. We would like to thank all stakeholders from China for providing guidance and direction to the development of ReVegIH; for full details, see the acknowledgements in (Li et al., 2005b). Further details about the project can be found at http://www.clw.csiro.au/revegih where the ReVegIH application (including all datasets, all project documentation and the .NET Redistributable framework) is available for free download. Thanks to John Coleman and Paul Rustomji, both from CSIRO Land and Water, for providing helpful comments on an earlier draft of this manuscript. Thanks also to the two anonymous reviewers and special issue editors who all made valuable comments that improved our paper.

References

Argent, R.M., 2004. An overview of model integration for environmental applications-components, frameworks and semantics. Environ. Modell. Softw. 19, 219–234.

Argent, R.M., Grayson, R.B., 2003. A modelling shell for participatory assessment and management of natural resources. Environ. Modell. Softw. 18, 541–551.

Ball, J., 2002. Towards a methodology for mapping ‘regions for sustainability’ using PPGIS. Prog. Plann. 58, 81–140.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55, 3–23.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. J. Hydrol. 310, 28–61.

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agric. Ecosyst. Environ. 104, 185–228.

Byrne, J., Bo, S., Xiuguo, L., 1996. The challenge of sustainability: balancing China’s energy, economic and environmental goals. Energ. Policy 24, 455–462.

Calder, I.R., 1999. The Blue Revolution: Land Use of Integrated Water Resources Management. Earthscan Publications Ltd., London.

Cavric, B.I., Nedovic-Budic, Z., Ikgopoleng, H.G., 2003. Diffusion of GIS technology in Botswana—process and determinants. Int. Dev. Plann. Rev. 25, 195–219.

Chen, H.S., Shao, M.A., Wang, K.L., 2005. Desiccation of Deep soil layer and soil water cycle characteristics on the Loess Plateau. ACTA Ecol. Sin. 25, 2491–2498 (in Chinese with an English abstract).

Donohue, R.J., Roderick, M.L., McVicar, T.R., 2007. On the importance of including vegetation dynamics in Budyko's hydrological model. Hydrol. Earth Syst. Sci. 11, 983–995.

Douglas, I., 1989. Land degradation, soil conservation and the sediment load of the Yellow River, China: review and assessment. Land Degrad. Rehabil. 1, 141–151.

Foster, G.D., 2001. China as great power: from red menace to green giant? Communis. Post-Commun. 34, 157–174.

Fu, B., Wang, J., Chen, L., Qiu, Y., 2003. The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau. Chin. Catena 54, 197–213.

Garcia-Quijano, J.F., Deckmyn, G., Moons, E., Proost, S., Ceulemans, R., Muys, B., 2005. An integrated decision support framework for the prediction and evaluation of efficiency, environmental impact and total social cost of domestic and international forestry projects for greenhouse gas mitigation: description and case studies. For. Ecol. Manage. 207, 245–262.

Gonzalez, R.M., 2002. Joint learning with GIS: multi-actor resource management. Agric. Syst. 73, 99–111.

Hao, F.H., Chen, L.Q., Liu, C.M., Dai, D.K., 2004. Impact of land use change on runoff and sediment yield. J. Soil Water Conserv. 18, 5–8 (in Chinese with an English abstract).

Hobbins, M.T., Ramírez, J.A., Brown, T.C., Claessens, L.H.J.M., 2001. The complementary relationship in estimation of regional evapotranspiration: the complementary relationship aerial evaporation and advection-aridity models. Water Resour. Res. 37, 1367–1387.

Huang, B.W., 1988. River conservancy and agricultural development on the North China Plains and Loess Highlands: strategies and research. Great Plains Quart. 6, 218–224.

Huang, M., Zhang, L., 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrol. Process. 18, 1885–1898.

Huang, M., Zhang, L., Gallichand, J., 2003. Runoff responses to afforestation in a watershed of the Loess Plateau, China. Hydrol. Process. 17, 2599–2609.

Huang, M.B., Liu, X.Z., 2002. Regulation effect of forest vegetation on watershed runoff in the Loss Plateau. Chin. J. Appl. Ecol. 13, 1057–1060 (in Chinese with an English abstract).

Huang, Y.L., Chen, L.D., Fu, B.J., Zhang, L.P., Wang, Y.L., 2005. Evapotranspiration and soil moisture balance for vegetative resortation in a Gully Catchment on the Loess Plateau, China. Pedosphere 15, 509–517.

Hutchinson, M.F., 2004a. ANUDEM Version 5. 1 User Guide. The Australian National University, Centre for Resource and Environmental Studies, Canberra. , http://cres.anu.edu.au/outputs/software.php.

Hutchinson, M.F., 2004b. ANUSPLIN Version 4. 3 User Guide. The Australian National University, Centre for Resource and Environmental Studies, Canberra. , http://cres.anu.edu.au/outputs/software.php.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Modell. Softw. 21, 602–614.

Jiang, Y., Kang, M., Gao, Q., He, L., Xiong, M., Jia, Z., Jin, Z., 2003. Impact of land use on plant biodiversity and measures for biodiversity conservation in the Loess Plateau in China—a case study in a hilly-gully region of the Northern Loess Plateau. Biodivers. Conserv. 12, 2121–2133.

Jones, K.H., 1998. A comparison of algorithms used to compute hill slope as a property of the DEM. Comput. Geosci. 24, 315–323.

Kangas, J., Kangas, A., 2005. Multiple criteria decision support in forest management—the approach, methods applied, and experiences gained. For. Ecol. Manage. 207, 133–143.

Ke, B.S., Zhou, S.Y., 2005. Land acquisition in China: policy development and reform recommendations. In: Sonntag, B.H., Huang, J.K., Rozelle, S., S-kerritt, J.H. (Eds.), China's Agricultural and Rural Development in the Early 21st Century: Challenges, Opportunities and Policy Options. ACIAR Monograph No. 116, Canberra, pp. 469–487.

Kyem, P.A.K., 1998. Promoting local community participation in forest management through the application of a geographic information system: a PPGIS experience from Southern Ghana. In: National Centre for Geographic Information and Analysis (NCGIA) Specialist Meeting on "Empowerment, Marginalization, and Public Participation GIS", Santa Barbara, CA, USA, October 15–17, p. 10., http://www.ncgia.ucsb.edu/varenius/ppgis/papers/kyem/kyem.html.

Kyem, P.A.K., 2004. Of intractable conflicts and participatory GIS applications: the search for consensus amidst competing claims and institutional demands. Ann. Assoc. Am. Geogr. 94, 37–57.

Lexer, M.J., Brooks, R.T., 2005. Decision support for multiple purpose forestry. For. Ecol. Manage. 207, 1–3.

Lhomme, J.P., Guilioni, L., 2006. Comments on some articles about the complementary relationship. J. Hydrol. 323, 1–3.

Li, D.F., Tian, Y., Liu, C.M., Hao, F.H., 2004. Impact of land-cover and climate changes on runoff of the source regions of the Yellow River. J. Geogr. Sci. (English version) 14, 330–338.

Li, G.Y., 2003. Ponderation and Practice of the Yellow River Control. Yellow River Conservancy Press, Zhengzhou.

Li, L.J., Zhang, L., Wang, H., Yang, J.W., Jiang, D.J., Li, J.Y., Qin, D.Y., 2007. Assessing the impact of climate variability and human activities on stream flow from the Wuding River Basin in China. Hydrol. Process., doi:10.1002/hyp.6485.

Li, L.T., McVicar, T.R., Van Niel, T.G., Mu, X.M., Zhang, X.P., Yang, Q.K., Liu, Z.H., 2005a. Quality Control of 21 Years of Monthly Meteorological and Hydrological Data in the Coarse Sandy Hilly Catchments of the Loess Plateau, China. In: CSIRO Land and Water Technical Report 6/05, Canberra, Australia, p. 89 http://www.clw.csiro.au/publications/technical2005/tr6-05.pdf.

Li, L.T., McVicar, T.R., Van Niel, T.G., Zhang, L., Li, R., Yang, Q.K., Zhang, X.P., Mu, X.M., Wen, Z.M., Liu, W.Z., Zhao, Y.A., Liu, Z.H., 2005b. A Bilingual User's Guide for the Decision Support Tool for Managing Re-Vegetation and its Impact on Hydrology (ReVegIH) in the Coarse Sandy Hilly Catchments of the Loess Plateau, China. In: CSIRO Land and Water Technical Report 19/05, Canberra, p. 48 http://www.clw.csiro.au/publications/technical2005/tr19-05.pdf.

Liang, Y.M., Li, R., Cheng, J.M., Liu, G.B., Chen, Y.M., Liu, W.Z., 2003. Vegetation Construction on the Loess Plateau. Yellow River Conservancy Press, Zhengzhou (in Chinese and English).

Liu, B., Xu, M., Henderson, M., Gong, W., 2004a. A spatial analysis of pan evaporation trends in China, 1955–2000. J. Geophys. Res. 109, D15102, doi:10.1029/2004JD004511.

Liu, B.H., Xu, M., Henderson, M., Qi, Y., Li, Y.Q., 2004b. Taking China's temperature: daily range, warming trends, and regional variations, 1955–2000. J. Clim. 17, 4453–4462.

Liu, C.M., Zhong, J.X., 1978. Analysis of impacts of forest on annual runoff in Loess Plateau. J. Geogr. Sci. 33, 112–126 (in Chinese).

Liu, W.Z., Hu, M.J., Li, F.M., Zhang, X.C., 2005. Ecological characteristics of soil water and its relation to land and vegetation in a small semiarid watershed in a loess hilly area of China. Int. J. Sust. Dev. World 12, 326–333.

Liu, X.Z., Huang, M.B., 2003. Hydrologic behaviour and effect of forest on regulation of river runoff in Loess Hilly and Gully Region. Agric. Res. Arid Areas 21, 72–76 (in Chinese with an English abstract).

Malczewski, J., 2004. GIS-based land-use suitability analysis: a critical overview. Prog. Plann. 62, 3–65.

McVicar, T.R., Li, L.T., Van Niel, T.G., Hutchinson, M.F., Mu, X.M., Liu, Z.H., 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. In: CSIRO Land and Water Technical Report, 8/05, Canberra, Australia, p. 316 http://www.clw.csiro.au/publications/technical2005/tr8-05.pdf.

McVicar, T.R., Van Niel, T.G., Li, L.T., Hutchinson, M.F., Mu, X.M., Liu, Z.H., 2007. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. J. Hydrol. 338, 196–220.

McVicar, T.R., Van Niel, T.G., Zhang, L., Rui, L., Yang, Q.K., Zhang, X.P., 2002a. ACIAR Project LWR/2002/018 Proposal, CSIRO Land and Water. http://www.clw.csiro.au/ReVegIH/.

McVicar, T.R., Wen, Z.M., Van Niel, T.G., Li, L.T., Yang, Q.K., 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, p. 68 http://www.clw.csiro.au/publications/technical2005/tr18-05.pdf.

McVicar, T.R., Zhang, G., Bradford, A.S., Wang, H., Dawes, W.R., Zhang, L., Lingtao, L., 2002b. Monitoring regional agricultural water use efficiency for Hebei Province on the North China Plain. Aust. J. Agric. Res. 53, 55–76.

Messing, I., Chen, L., Hessel, R., 2003. Soil conditions in a small catchment on the Loess Plateau in China. Catena 54, 45–58.

Mu, X.M., Zhang, L., McVicar, T.R., Chille, B.S., Gao, P., 2007. Estimating the impact of conservation measures on stream-flow regime in catchments of the Loess Plateau, China. Hydrol. Process. 21, 2124–2134.

Rahman, J.M., Seaton, S.P., Cuddy, S.M., 2004. Making frameworks more useable: using model introspection and metadata to develop model processing tools. Environ. Modell. Softw. 19, 275–284.

Rahman, J.M., Seaton, S.P., Perraud, J.-M., Hotham, H., Verrelli, D.I., Coleman, J.R., 2003. It's TIME for a new environmental modelling framework. In: MODSIM 2004 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand Inc, Townsville, Australia, pp. 1727–1732.

Rauscher, H.M., 1999. Ecosystem management decision support for federal forests in the United States: a review. For. Ecol. Manage. 114, 173–197.

Ren, M.E., Yang, R.Z., Bao, H.S., 1985. An Outline of China's Physical Geography. Foreign Language Press, Beijing.

Ritsema, C.J., 2003. Introduction: soil erosion and participatory land use planning on the Loess Plateau in China. Catena 54, 1–5.

Rozelle, S., Huang, J., Zhang, L., 1997. Poverty, population and environmental degradation in China. Food Policy 22, 229–251.

Shen, H.Q., 1991. China Loess Plateau 1:500 000 Land-Use Map (part of the Loess Plateau Resources and Environmental Remote Sensing Series). Xi'an Atlas Press, Xi'an.

Sheppard, S.R.J., Meitner, M., 2005. Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups. For. Ecol. Manage. 207, 171–187.

Shi, H., Shao, M., 2000. Soil and water loss from the Loess Plateau in China. J. Arid Environ. 45, 9–20.

Shi, P.L., Li, W.H., 2005. Impact of forest vegetation changes on hydrologic process and runoff. In: China Ecology Network http://www.51st.cn/Webs/News/Show_News.asp?ID=3653.

Skinner, M.W., Kuhn, R.G., Joseph, A.E., 2001. Agricultural land protection in China: a case study of local governance in Zhejiang Province. Land Use Policy 18, 329–340.

Sun, G., McNulty, S.G., Lu, J., Amatya, D.M., Liang, Y., Kolka, R.K., 2005. Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States. J. Hydrol. 308, 258–268.

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S.G., Vose, J.M., 2006. Potential water yield reduction due to forestation across China. J. Hydrol. 328, 548–558.

Thomson, A.J., Schmoldt, D.L., 2001. Ethics in computer software design and development. Comput. Electron. Agric. 30, 85–102.

Van Dijk, A.I.J.M., Hairsine, P.B., Arancibia, J.P., Dowling, T.I., 2007. Reforestation, water availability and stream salinity: A multi-scale analysis in the Murray-Darling Basin. Australia. For. Ecol. Manage. 251, 94–109.

van Noordwijk, M., Poulsen, J.G., Ericksen, P.J., 2004. Quantifying off-site effects of land use change: filters, flows and fallacies. Agric. Ecosyst. Environ. 104, 19–34.

Varis, O., Vakkilainen, P., 2001. China's 8 challenges to water resources management in the first quarter of the 21st Century. Geomorphology 41, 93–104.

Varma, V.K., Ferguson, I., Wild, I., 2000. Decision support system for the sustainable forest management. For. Ecol. Manage. 128, 49–55.

Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. Agric. Ecosyst. Environ. 82, 105–119.

Wang, H.S., Huang, M.B., Zhang, L., 2004a. Impacts of re-vegetation on water cycle in a small watershed of the Loess Plateau. J. Nat. Resour. 19, 344–350 (in Chinese with an English abstract).

Wang, L., Shao, M.A., Wang, Q.J., Jia, Z.K., Li, J., 2004b. Review of research on soil desiccation in the Loess Plateau. Trans. Chin. Soc. Agric. Eng. 20, 27–31 (in Chinese with an English abstract).

Wang, L.X., Zhang, Z.Q., 2001. Impact of forest on river streamflow in arid areas. J. Nat. Resour. 16, 439–444 (in Chinese with an English abstract).

Wang, S.W., Zhao, Z.C., 1981. Droughts and floods in China, 1470–1979. In: Wigley, T.M.L., Ingrasham, M.J., Farmer, G. (Eds.), Climate and History: Studies in Past Climates and Their Impact on Man. Cambridge University Press, Cambridge, pp. 271–288.

Wei, X., Liu, S., Zhou, G., Wang, C., 2005. Hydrological processes in major types of Chinese forest. Hydrol. Process. 19, 63–75.

Wenhua, L., 2004. Degradation and restoration of forest ecosystems in China. For. Ecol. Manage. 201, 33–41.

Wilkinson, S., Henderson, A., Chen, Y., 2004. SedNet User Guide. Client Report for the Cooperative Research Centre for Catchment Hydrology. CSIRO Land and Water, Canberra, Australia, p. 98.

Winkler, D., 2002. Participation in forestry in Tibetan Southwest China: a strategy to resolve resource use conflicts. Mt. Res. Dev. 22, 397–399.

Wu, Q.X., Li, Y.Y., 2005. Yield process and its characteristics in different kind of small watersheds in Huanglong Mountainous area. Sci. Soil Water Conserv. 3, 10–15 (in Chinese with an English abstract).

Wu, Q.X., Zhao, H.Y., 2001. Basic laws of soil and water conservation by vegetation and its summation. J. Soil Water Conserv. 15, 140–144 (in Chinese with an English abstract).

Wu, Q.X., Zhao, H.Y., Wang, Y.K., 1999. Flow production and sediment production and their processes in Chinese Pine Woodlands in the Loess Plateau. Acta Ecol. Sin. 18, 151–157 (in Chinese with an English abstract).

Xiang-zhou, X., Hong-wu, Z., Ouyang, Z., 2004. Development of check-dam systems in gullies on the Loess Plateau, China. Environ. Sci. Pol. 7, 79–86.

Xiubin, H., Zhanbin, L., Mingde, H., Keli, T., Fengli, Z., 2003. Down-scale analysis for water scarcity in response to soil-water conservation on Loess Plateau of China. Agric. Ecosyst. Environ. 94, 355–361.

Xu, H., Wang, S., Xue, D., 1999. Biodiversity conservation in China: legislation, plans and measures. Biodivers. Conserv. 8, 819–837.

Xu, Z.G., Bennett, M.T., Tao, R., Xu, J.T., 2004. China's sloping land conversion programme four year on: current situation and pending issues. Int. For. Rev. 6, 317–326.

Xu, Z.X., Takeuchi, K., Ishidaira, H., Zhang, X.W., 2002. Sustainability analysis for Yellow River water resources using the system dynamics approach. Water Resour. Manage. 16, 239–261.

Yang, H., 2004. Land conservation campaign in China: integrated management, local participation and food supply option. Geoforum 35, 507–518.

Yang, Q.K., McVicar, T.R., Van Niel, T.G., Hutchinson, M.F., Li, L.T., Zhang, X.P., 2007. Improving a digital elevation model by reducing source data errors and optimising interpolation algorithm parameters: an example in the Loess Plateau. Chin. Int. J. Appl. Earth Obs. Geoinf. 9, 235–246.

Yang, Q.K., Van Niel, T.G., McVicar, T.R., Hutchinson, M.F., Li, L.T., 2005. Developing a digital elevation model using ANUDEM for the Coarse Sandy Hilly Catchments of the Loess Plateau, China. In. CSIRO Land and Water Technical Report 7/05, Canberra, Australia, p. 74 http://www.clw.csiro.au/publications/technical2005/tr7-05.

Yang, R.J., Fu, B.J., Liu, G.H., Ma, K.M., 2004. Research on the relationship between water and eco-environment construction in Loess Hilly and Gully Region. Environ. Sci. 25, 37–42 (in Chinese with an English abstract).

Yang, W.Z., 2001. Soil water resources and afforestation in Loess Plateau. J. Nat. Resour. 16, 433–438 (in Chinese with an English abstract).

Ye, Y.Q., Chen, G.J., Fan, H., 2003. Impacts of the ''Grain for Green'' Project on Rural Communities in the Upper Min River Basin, Sichuan. China. Mt. Res. Dev. 23, 345–352.

Yuan, H., 2002. China's Re-Vegetation Program Initiated: Announcement of Details from the Chinese Central Government. People's Daily Overseas Edition, Beijing, p. 1.

Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37, 701–708.

Zhang, X.P., Zhang, L., McVicar, T.R., Van Niel, T.G., Li, L.T., Li, R., Yang, Q.K., Liang, W., 2007. Modeling the impact of afforestation on mean annual streamflow in the Loess Plateau, China. Hydrol. Process., doi:10.1002/hyp.6784.

Zhang, Z.F., 2006. Formation and prevention of soil and water loss in the southern mountains of Ningxia Province, China. In: Hydraulic Engineering Network (In Chinese) http://www.shuigong.com/papers/zhili/20060403/paper19216.shtml.

Zhao, H.Y., Wu, Q.X., 2001. Study on runoff and sediment yield of a small Chinese Pine catchment in Loess Plateau. Prog. Nat. Sci. 11, 829–834 (in Chinese with an English abstract).

Zhao, H.Y., Wu, Q.X., Liu, G.B., 2001. Mechanism on soil and water conservation of forest vegetation on the Loess Plateau. Sci. Silvae Sin. 37, 140–144 (in Chinese with an English abstract).

Zhao, H.Y., Wu, Q.X., Liu, G.B., 2002. Studies on hydro-ecological effects of *Populus* Davidiana stand. Acta Phytoecol. Sin. 26, 497–500 (in Chinese with an English abstract).

Zhao, H.Y., Wu, Q.X., Liu, G.B., 2003. Studies on hydro-ecological effects of artificial Chinese Pine stand in Loess Plateau. Acta Ecol. Sin. 23, 376–379 (in Chinese with an English abstract).

Zhu, J.Z., Zhou, X.C., Hu, J.Z., 2004. On the objectives of plantation establishment on Loess Plateau. Chin. Water Resour. 16, 28–30 (in Chinese).