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Using remote sensing techniques to evaluate water yield services in Shangri-La, Northwestern Yunnan, China

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Water yield is an ecosystem service that is vital to not only human life, but also sustainable development of the social economy and ecosystem. This study used annual average precipitation, potential evapotranspiration, plant available water content, soil depth, the biophysical table, Zhang parameter, and land use/land cover (LULC) as input data for the Integrated Valuation of Ecosystem Service Tradeoffs (InVEST) model to estimate the water yield of Shangri-La City from 1974 to 2015. The spatiotemporal variations and associated factors (precipitation, evapotranspiration, LULC, and topographic factors) in water yield ecosystem services where then analyzed. The result showed that: (1) The water yield of Shangri-La City decreases from north and south to the center and showed a temporal trend from 1974 to 2015 of an initial decrease followed by an increase. Areas of higher average water yield were mainly in Hutiaoxia Town, Jinjiang Town, and Shangjiang Township. (2) Areas of importance for water yield in the study area which need to be assigned priority protection were mainly concentrated to the west of Jiantang Town, in central Xiaozhongdian Town, in central Gezan Township, in northwestern Dongwang Township, and in Hutiaoxia Town. (3) Water yield was affected by precipitation, evapotranspiration, vegetation type, and topographic factors. Water yield was positively and negatively correlated with precipitation and potential evapotranspiration, respectively. The average water yield of shrubs exceeded that of meadows and forests. Terrain factors indirectly affected the ecosystem service functions of water yield by affecting precipitation and vegetation types. The model used in this study can provide references for relevant research in similar climatic conditions.

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Abstract

Water yield is an ecosystem service that is vital to not only human life, but also sustainable development of the social economy and ecosystem. This study used annual average precipitation, potential evapotranspiration, plant available water content, soil depth, the biophysical table, Zhang parameter, and land use/land cover (LULC) as input data for the Integrated Valuation of Ecosystem Service Tradeoffs (InVEST) model to estimate the water yield of Shangri-La City from 1974 to 2015. The spatiotemporal variations and associated factors (precipitation, evapotranspiration, LULC, and topographic factors) in water yield ecosystem services where then analyzed. The result showed that: (1) The water yield of Shangri-La City decreases from north and south to the center and showed a temporal trend from 1974 to 2015 of an initial decrease followed by an increase. Areas of higher average water yield were mainly in Hutiaoxia Town, Jinjiang Town, and Shangjiang Township. (2) Areas of importance for water yield in the study area which need to be assigned priority protection were mainly concentrated to the west of Jiantang Town, in central Xiaozhongdian Town, in central Gezan Township, in northwestern Dongwang Township, and in Hutiaoxia Town. (3) Water yield was affected by precipitation, evapotranspiration, vegetation type, and topographic factors. Water yield was positively and negatively correlated with precipitation and potential evapotranspiration, respectively. The average water yield of shrubs exceeded that of meadows and forests. Terrain factors indirectly affected the ecosystem service functions of water yield by affecting precipitation and vegetation types. The model used in this study can provide references for relevant research in similar climatic conditions.

34   **Keywords:** Water yield; InVEST model; Ecosystem services; Shangri-La City, Northwest
35   Yunnan, China

Introduction

37   Ecosystem services are direct or indirect benefits provided by nature to mankind (Zhan et al. 2019).
38   Ecosystem serviced generally include exported tangible material products and provided intangible
39   services, which can be further categorized into providing, supporting, regulating, and cultural and
40   entertainment services (Rijal et al. 2021; Sun 2017). The rapid growth of the global population,
41   economic development, improvement of living standards, and increasing human water demand
42   have resulted in the elevation of water shortages as a major threat to the sustainable development
43   of human society (Huang et al. 2021).
44   As an ecosystem service, water yield is not only an important foundation for maintaining
45   regional biodiversity and key ecosystem functions, but also affects the development and
46   distribution of the regional population, society, and economy (Sharafatmandrad & Khosravi
47   Mashizi 2021; Zhao et al. 2019). However, water shortages may lead to a variety of social and
48   environmental problems, including drinking water deficits, reductions to crop yield, and water
49   quality degradation (Huang et al. 2021). Water yield is an important parameter describing regional
50   water resources (Li et al. 2021a) and also plays an indispensable role in other ecological functions,
51   such as the carbon cycle and sediment transport (Ajaz Ahmed et al. 2017; Wang et al. 2020).
52   Therefore, the study of water yield is helpful for understanding the evolution of the water yield
53   ecosystem service function and for exploring the relationship between human beings and water
54   resources, which has great significance for the scientific management and rational utilization of
55   water resources (Lian et al. 2020).
56   There remains no established academic definition of water yield as an ecosystem service. The
57   use of the term 'water yield' mainly relates to the ability of precipitation to directly and effectively
58   replenish surface water and groundwater within a certain period of time, thereby enhancing human
59   well-being (Fan et al. 2018; Li et al. 2021a). However, calculation of the water yield remains a
60   complex process since the water yield is affected not only by rainfall intensity, soil permeability,
61   slope, and vegetation, but also by climate and land use/land cover (LULC) (Wei et al. 2021; Yin
62   et al. 2020). Climate change affects water yield by influencing precipitation and evaporation in the
63   watershed. The LULC can affect the water yield by changing the water cycle of the watershed,
64   thereby affecting evapotranspiration, the infiltration process, and water retention (Song et al.
65   2015). Past attempts to calculate the water yield have utilized measured data such as precipitation
66   storage and soil water storage capacity within water balance methods (Li et al. 2009).
67   The recent rapid development of remote sensing technology and hydrological models has
68   prompted many scholars to quantitatively, visually, and finely analyze and evaluate the water yield

69   function of a regional ecosystem through model simulation. Hydrological models, such as the

70   MIKE System Hydrological European (MIKE SHE) (Refshaard et al. 1995), Soil and Water

71   Assessment Tool (SWAT)(Cong et al. 2020), Water Supply and Stress Index (WaSSI) (Ajaz

72   Ahmed et al. 2017), Variable Infiltration Capacity (VIC) (Srivastava et al. 2020), and Integrated

73   Valuation of Ecosystem Services and Tradeoffs (InVEST) (Yang et al. 2019a) have shown good

74   performance under various geographic conditions. The InVEST mode was developed in 2007

75   through a collaboration between Stanford University, the World Wildlife Fund, the Nature

76   Conservation Society, and other related institutions on the basic of the Budyko curve and annual

77   precipitation (Yang et al. 2019a). The model is relatively simple, suited for applications to

78   catchments lacking observed datasets (Lian et al. 2020; Wei et al. 2021) and provides a reliable

79   method for estimating water yield under different spatiotemporal scales (Yang et al. 2019a; Yin et

80   al. 2020). Furthermore, the InVEST model calculates water yield based on the water balance to

81   fully consider the spatial differences in soil permeability under different LULC and the influencing

82   factors, such as topography and runoff. The model allows the quantitative estimation of the water

83   yield under different landscape types and the results can be reported in the form of shapefiles,

84   tables, and grid maps (Li et al. 2021b).

85   The advantages of the InVEST water yield model include strong spatial expression, dynamic

86   evaluation capabilities, simple input data requirements, large output data volume, and strong

87   scalability. Therefore, the model is widely used. Gao et al. (2017) used the InVEST model to

88   evaluate the impact of land use on water-related ecosystem services in the Guishui River Basin in

89   Beijing, China. Xu et al. (2019) used the InVEST model to simulate the water yield ecosystem

90   service function of the Beiyun River Basin in Beijing and explored the impact of urbanization on

91   water yield. Dai & Wang (2020) used the InVEST model to simulate the spatial distribution of

92   water yield in the Hengduan Mountains and quantitatively analyzed the effects of climate,

93   topography, soil, land use types, and other factors on water yield. Nahib et al. (2021) used the

94   InVEST model to estimate the water yield of the Citarum River Basin and explored the sensitivity

95   of water yield to climate factors (precipitation and evapotranspiration) and land use changes. Li et

96   al. (2021b) analyzed the temporal and spatial dynamics of soil and water conservation in China as

97   well as their responses to climate, LULC, and soil changes. The above studies demonstrated that

98   the InVEST water yield model can reliably estimate the water yield ecosystem service in a wide

99   range of catchment types. However, the water yield ecosystem service function varies widely

100   among different regions due to differences in responses to precipitation, evapotranspiration,

101   LULC, and topography (Xie et al. 2017). Few previous studies have attempted to examine the

102   effects of these climatic factors, land use patterns, and topographic factors on water yield in alpine-

103   gorge areas with a complex topography, diverse climate types, and a fragile ecological

104   environment.

105   Shangri-La City, northwestern Yunnan, China, is a typical alpine-gorge area with a complex
106 topography, large extents of sloped cultivated land, and reclamation of steep sloped areas.
107 Therefore, the area is prone to soil erosion, geological disasters, and ecological problems (Sun
108 2017). Improper exploitation of forest resources has resulted in the extinction of a large number of
109 species in some areas of Shangri-La, the decline of soil fertility, and reduction to biodiversity
110 (Yang et al. 2019b). The changes to land use in the region would be bound to affect the water yield
111 by influencing the hydrological cycle. Climate change increases the uncertainty and complexity of
112 the hydrological cycle, thereby changing the water yield service to a certain extent. In addition,
113 Shangri-La City is facing numerous challenges that urgently need to be resolved, including serious
114 water resource shortages, an uneven spatiotemporal distribution of water resources, an
115 unsustainable water supply structure, and extensive exploitation of water resources (Li & Wang
116 2016). Therefore, as a typical alpine-gorge area, there is an urgent need to explore the temporal
117 and spatial differentiation in water yield of in Shangri-La City, northwestern Yunnan.

118   The aims of the present study included: (1) Estimation of the water yield of Shangri-La City,
119 northwestern Yunnan Province from 1974 to 2015; (2) Classification of the importance of water
120 yield ecosystem service functions; (3) Exploration of the responses of water yield to climate
121 factors, LULC, and topographic factors. The results of the present study are expected to provide a
122 reference for the study of water yield, water resources management, and ecological security in
123 Shangri-La City and similar ecosystems.

124 Materials & Methods

125 Study area

126 Shangri-La City is in the northwestern part of Yunnan Province, China, between 26°52′–28°52′ N
127 and 99°20′–100°19′ E and has a total area of 11,600 km^2 (Fig. 1). The city forms a core part of the
128 World Natural Heritage site "Three Parallel Rivers" and falls within a fragile and sensitive area of
129 the ecosystem in the hinterland of the Hengduan Mountains. The city has also been designated a
130 biodiversity hotspot of global significance by the World Wildlife Fund (WWF) (Yang & Wang
131 2015). The climate of Shangri-La City is affected by the monsoon originating from the
132 southwestern Indian Ocean. The wet and dry seasons extend from June to October and November
133 to May, respectively. Shangri-La City has a complex and diverse topography with the local climate
134 characterized by high spatial variability (Liu et al. 2021b). Other climate characteristics of the
135 region include a high atmospheric transparency, increased daytime solar radiation, and rapid
136 increases in temperature, resulting in a large diurnal temperature range. The Jinsha River is the
137 dominant river system in Shangri-La City, with the 13 main tributaries being the Shuoduogang,
138 Dongwang, Gangqu, Jiren, Langdu, Liangmei, Annan, Tangman, Anle, Maidi, Niru, Xinglong,
139 and Baishui rivers. The average surface water and groundwater resources in the study area over

140 many years are 5 billion m³ and 2 billion m³, respectively (Li & Wang 2016). Shangri-La City is

141 rich in soil resources, mainly dark brown soil, brown soil, red soil, alpine shrub meadow soil,

142 brown dark coniferous forest soil, alpine cold desert soil, and alluvial soil (Chen et al. 2019). Most

143 areas of Shangri-La City are subalpine and alpine landforms with elevations exceeding 3,000 m

144 and the region contains 43 species of major forest trees, including 10 species of coniferous forests

145 and 33 species of broadleaf forests (Liu et al. 2018; Yu et al. 2019; Zhang et al. 2020).

146 **The InVEST water yield model**

147 Water yield refers to the amount of water produced per unit area over a given period. The InVEST

148 water yield model runs on a gridded map and is an estimation method based on the Budyko

149 hydrothermal coupling equilibrium hypothesis in which water yield in an area is obtained by

150 subtracting the total actual evapotranspiration per unit area from total precipitation (Budyko 1974).

151 The equations describing the water yield are:

152 $Y(x) = \left(\frac{1 - AET(x)}{P(x)}\right) \times P(x)$ (1)

153   In Eq. (1), $Y(x)$, $AET(x)$, and $P(x)$ are the total annual water yield (mm), the annual actual

154 evapotranspiration (mm), and the average annual precipitation (mm) of grid unit x, respectively.

155 $\frac{AET(x)}{P(x)}$ is the ratio of actual evapotranspiration to average annual precipitation (Zhang et al. 2004)

156 and is calculated as:

157 $\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^w\right]^{1/w}$ (2)

158 $PET(x) = K_c(x) \times ET_0(x)$ (3)

159 $w(x) = \frac{AWC(x) \times Z}{P(x)} + 1.25$ (4)

160 $AWC(x) = min\left(MaxSoilDepth_x, RootDepth_x\right) \times PAWC_x$ (5)

161   In Eq. (2) to Eq. (5), $PET(x)$ is the potential evapotranspiration of grid unit x, $K_c(x)$ is the

162 reference crop evapotranspiration coefficient, $ET_0(x)$ is the reference crop evapotranspiration

163 (mm d⁻¹), $w(x)$ is a nonphysical empirical fitting parameter of natural climate-soil properties,

164 $AWC(x)$ is the available water content of plants and is used to determine the amount of water

165 stored and released by the soil for vegetation growth, calculated as the difference between the field

166 water holding capacity and the wilting point, Z is the $Zhang$ parameter, $MaxSoilDepth_x$ is the

167 maximum soil depth, and $RootDepth_x$ is the root depth.

168 **Data sources and processing**

169 The present study integrated remote sensing, a geographic information system (GIS), and the

170 InVEST model. The data used in the present study included precipitation, potential

171 evapotranspiration, plant available water content, soil depth, land use/land cover (LULC) data, the

172 biophysical table, and the Zhang parameter. In addition, the ENVI 5.3, ArcGIS 10.5, SPSS 22, and

173 InVEST software packages were used in the present study to reprocess and analyze data. The

174 spatial resolution of all input data used in the InVEST model were unified to 30 m × 30 m.

175 *Precipitation (P) and reference evapotranspiration (ET$_0$)*

176 Meteorological data, including precipitation, temperature, and solar radiation, were provided by

177 the Institute of Geographic Sciences and Natural Resources of the Chinese Academy of Sciences,

178 Yunnan Meteorological Services, and the Meteorological Administration of China

179 (https://data.cma.cn/, last accessed March 20, 2021). The meteorological data were obtained from

180 13 meteorological stations distributed across the study area and as well as from the surrounding

181 meteorological stations, Shangri-La, Lijiang, Weixi, Ninglang, Deqin, Gongshan, Fugong,

182 Lanping, Jianchuan, Heqing, Yongsheng, Huaping, and Eryuan. The daily meteorological data

183 were subjected to sorting, interpolation, and clipping preprocessing to obtain annual-scale

184 meteorological data in the standard format of the InVEST model. The kriging interpolation method

185 in ArcGIS 10.5 was used to create a precipitation map of the study area.

186   The map of annual reference evapotranspiration was generated based on the extraterrestrial

187 radiation, temperature, and monthly average precipitation. The modified Hargreaves method was

188 used to estimate the ET_0 in areas with a lack of observed data (Droogers & Allen 2002), with

189 estimates shown to be better than those of the Penman-Monteith method (Nahib et al. 2021). The

190 monthly and annual reference evapotranspiration maps were obtained through the ArcMap raster

191 calculator, calculated as follows:

192 $ET_0 = 0.0013 \times 0.408 \times Ra \times (T_{avg} + 17) \times (TD - 0.0123P)^{0.76}$ (6)

193   In Eq. (6), Ra is the   extraterrestrial radiation (MJ m^{-2} d^{-1}), represented in the present study

194 as half of the total solar radiation of the meteorological station, T_{avg} is the mean value of the

195 average highest and average lowest temperatures (° C), TD represents the difference between the

196 average highest temperature and the average lowest temperature (° C), and P is the average

197 monthly precipitation (mm).

198 *Plant available water content (PAWC) and soil data*

199 The plant available water content (PAWC) parameter is used to evaluate the total water stored and

200 released by soil for plants and is determined by the mechanical composition of the soil and the root

201 depth of the vegetation, calculated as per Zhou et al. (Zhou et al. 2005) as:

202 $PAWC = 54.509 - 0.132sand - 0.003(sand)^2 - 0.055(silt)^2 - 0.738clay + 0.007(clay)^2 -$

203 $2.688OM + 0.501(OM)^2$ $\qquad\qquad$ (7)

204 $\qquad$ In Eq. (7), $sand$, $silt$, $clay$, and OM are the contents of sand (%), silt (%), clay (%), and

205 organic matter (%) in the soil, respectively.

206 $\qquad$ The soil data were collected from the field and the data of the second soil survey were provided

207 by the soil and fertilizer station of the Diqing Tibetan Autonomous Prefecture, including soil

208 species, soil-forming parent materials, soil structure, soil depth, soil profile, detailed soil

209 mechanical composition, and soil organic matter content.

210 ***Land use/land cover (LULC)***

211 The present study used LULC data for 1974, 1989, 2003, and 2015, with the data for the first three

212 years obtained from the Nature Conservancy project. The LULC data for 2015 were obtained by

213 visual interpretation and modified based on the classification data in 2003 and the Landsat OLI

214 data in 2015 (downloaded from https://glovis.usgs.gov/, last accessed March 20, 2021). The

215 accuracy of the LULC data were verified through field survey data and was shown to be 94%. The

216 LULC data were classified into 27 classes with a resolution of 30 m.

217 ***Biophysical table***

218 Table 1 shows the biophysical parameters of each LULC class used in the model. The data for root

219 depth were set by reference data from InVEST model documents and with reference to the report:

220 "Crop evapotranspiration: Guidelines for computing crop water requirements", published by the

221 Food and Agriculture Organization of the United Nations (FAO). Different root depths were set

222 for the different land use types. Kc was set according to the reference value of the

223 evapotranspiration coefficient of the FAO.

224 ***The Zhang parameter***

225 The Zhang parameter is an important input parameter used to estimate water yield in the InVEST

226 model and characterizes the seasonal distribution of precipitation within a range of [0, 10]. The

227 Zhang coefficient was set to 3.8 after several test corrections as being closest to the results

228 published in the Shangri-La Water Resources Bulletin.

Results

Analysis of the InVEST model input data

231 The input data of the InVEST water yield model included annual precipitation, potential

232 evapotranspiration (PET), plant available water capacity (PAWC), soil depth, and LULC. The

233 average precipitation values in each region of Shangri-La City in 1974, 1989, 2003, and 2015 were

234 777.52 mm, 865.32 mm, 823.84 mm, and 733.48 mm, respectively, whereas the average PET

235 values were 1,100.80 mm, 973.01 mm, 1,026.06 mm, and 1,024.88 mm, respectively. The input

236   data for 2015 were taken as a case study to analyze the changes in the above parameters (Fig. 2).

237   As shown in Fig. 2a, precipitation in 2015 varied spatially from 598.33 mm to 881.51 mm.

238   Precipitation showed a highly uneven spatial distribution, with high rainfall in the south, low

239   rainfall in the central regions, and slightly higher rainfall in the north. The annual rainfall values

240   in Jinjiang and Hutiaoxia in 2015 were relatively high at 859.63 mm and 832.87 mm, respectively.

241   Fig. 2b shows that annual PET in 2015 ranged from 923.63 mm to 1,194.55 mm across the different

242   regions. The annual PET values of Jinjiang and Hutiaoxia were also relatively high at 1,137.14

243   mm and 1,130.47 mm, respectively. PET decreased gradually from south to north, showing a

244   generally positive relationship to precipitation. Fig. 2c shows that PAWC decreased with

245   decreasing elevation, with high PAWC mainly distributed in areas such as Gezan, Dongwang, and

246   Wujing. Conversely, soil depth decreased with increasing elevation, with low soil depth mainly

247   distributed in areas such as Geza, Jiangtang, and Dongwang (Fig. 2d). The LULC in 2015 mainly

248   comprised mixed forest, coniferous forest, alpine shrub, and alpine meadow, accounting for

249   35.86%, 32.17%, 8.96%, and 8.45% of the total area of the study area, respectively (Fig. 2e).

250   **Characteristics of spatiotemporal variation of water yield**

251   The InVEST water yield model was used to obtain the spatial distribution of water yield in Shangri-

252   La City in 1974, 1989, 2003, and 2015 (Fig. 3). The results showed that water yield was generally

253   higher in the north and south and lower in the central region. The ranking of the different

254   simulation years in terms of spatially averaged annual water yield for all villages and towns was

255   1989 > 2003 > 1974 > 2015, with water yields of 316.05 mm, 266.42 mm, 221.27 mm, and 199.06

256   mm, respectively. Besides for Dongwang Township which showed the largest annual water yield

257   in 2003 of 314.68 mm, the annual water yields of other townships were in general consistent with

258   that of Shangri-La City. The average water yields in Hutiaoxia, Jinjiang, and Shangjiang across

259   the different years were relatively high. Besides for in 1989, the annual water yields of Jiantang

260   Town, Wujing Township, and Luoji Township were relatively low. Taking Gezhan and Dongwang

261   as examples in Fig. 2, the highest water yields were in areas with high PAWC, low soil depth, and

262   alpine meadows.

263   As shown in Fig. 3e, the spatial variation in annual water yield in Shangri-La City from 1974

264   to 2015 was obtained. The changes in water yield were classified as a significant decrease (>−30

265   mm), a decrease (−30–−10 mm), a non-significant change (−10–10 mm), an increase (10–30 mm),

266   and a significant increase (> 30 mm) (Fig. 3). According to the above categorization, the average

267   water yield from 1974 to 2015 from the southeast to the northwest showed significant decreases,

268   decreases, non-significant changes, increases, and significant increases across areas of 3,840 km^2,

269   2,619 km^2, 2,584 km^2, 924 km^2, and 1,646 km^2, accounting for 33.0%, 22.6%, 22.3%, 8.0%, and

270   14.1% of the total area of Shangri-La City, respectively.

271   **Spatial division of water yield importance**

272   The present study determined the grades of importance of the water yield ecosystem service

273   functions in Shangri-La City according to the "China Ecological Protection Red Line – Ecological

274   function Red Line demarcation Technical Guide (trial)": (Grade I) generally important area (< 100

275   mm); (Grade II) moderately important area (100–200 mm); (Grade III) highly important area (200–

276   300 mm) and; (Grade IV) extremely important area (≥300 mm). Taking 2015 as an example (Fig.

277   4), the areas of Shangri-La City falling within these different grades in decreasing order were:

278   Grade II (5,053 km²), Grade III (2,427 km²), Grade I (2,349 km²), and Grade IV (1,802 km²),

279   accounting for 43.36%, 20.90%, 20.22%, and 15.52% of the total area, respectively. Areas falling

280   in Grade I were mainly distributed to the east and west of Jiantang, Gezan, and Xiaozhongdian.

281   Those in Grade II were mainly distributed in Naxi, Luoji, the northern part of Sanba, and the

282   western part of Gezan. Those in Grade III were mainly distributed in central Dongwang, Jinjiang,

283   Hutiaoxia, and parts of Sanba and Naxi. Areas falling in Grade IV were mainly distributed to the

284   west of Jiantang, central Xiaozhongdian, central Gezhan, and northwestern Dongwang and

285   Hutiaoxia. Since the areas falling within Grade IV have the highest water yield function value,

286   these areas should be prioritized for protection.

Discussion

Effect of precipitation and evapotranspiration on water yield

289   Changes in climatic factors affect water yield mainly by affecting precipitation and PET (Li et al.

290   2021b). The present study calculated the Pearson correlation coefficient (R) and its significance

291   between water yield and precipitation and between water yield and PET for Shangri-La City from

292   1974 to 2015 at a pixel level (Fig. 5). The correlations between precipitation and water yield were

293   mainly positive, with an average R of 0.83 and with the area with R ≥ 0.8 accounting for ~77.56%

294   of the total study area. In contrast, the correlations between PET and water yield were mainly

295   negative (Fig. 5b), with an average R of −0.52 and the area with R ≤ 0.6 accounting for ~63.61%

296   of the study area. Fig. 5c shows the significance of correlation between water yield and

297   precipitation, with the results indicating that 71.48% of the study area passed the significance test

298   of α ≤ 0.1 (including α = 0.01, α = 0.05 and α = 0.01). Areas showing a highly significant

299   correlation (α = 0.01) accounted for 15.36% of the total area, with these areas mainly distributed

300   in the central areas of Shangri-La City, whereas the areas showing significant correlations of α =

301   0.05 accounted for 44.82% of the total area and were widely distributed. Fig. 5d shows the spatial

302   distribution of the significance of the correlations between water yield and potential

303   evapotranspiration, indicating that only 4.534% of the study area passed the significance test of

304   α ≤ 0.1, with these areas sporadically distributed in each region.

305   The water yield of Shangri-La City generally showed significant changes over time

306   corresponding to changes in precipitation and evapotranspiration, with the effect of precipitation

307   on water yield far exceeding that of PET. Many past studies have similarly shown that a decrease
308   in precipitation results in corresponding decreases in water yield (Lian et al. 2020) and that
309   precipitation is considered to be an important factor affecting changes in yield (Li et al. 2021b;
310   Yang et al. 2021). Evapotranspiration is a key component of the terrestrial water cycle connecting
311   the atmosphere, vegetation, and soil, and represents the sum of vegetation and soil evaporation
312   (Yin et al. 2021). Yang et al. (2021) proved that water production will show an increasing trend
313   with significantly increasing precipitation and decreasing actual evapotranspiration. Li et al.
314   (2021b) found a negative correlation between water yield and evapotranspiration, consistent with
315   the results of the present study.

Effect of LULC on water yield

317   LULC change is an important environmental issue that affects ecosystem services, and particularly
318   water ecosystem services (Liu et al. 2021a). LULC can change the hydrological flux due to
319   changes in the physical properties of the catchment surface, soil, and vegetation, including
320   properties such as surface roughness, albedo, infiltration capacity, root depth, vegetation index,
321   and stomatal conductance (Lian et al. 2020; Wei et al. 2021). The present study used zonal statistics
322   in ArcMap 10.5 to analyze the average water yield under natural / semi-natural vegetation types
323   from 1974 to 2015. The results indicated that the average water yield of shrubs (alpine, subalpine,
324   and valley shrubs) exceeded that of meadows (alpine meadows, subalpine meadows, and valley
325   grassland) and forests (deciduous broad-leaved, evergreen broad-leaf, coniferous, and mixed
326   forests). Subalpine shrubs obtained the highest average water yield over 1974, 1989, 2003, and
327   2015 of 356.70 mm, 525.27 mm, 407.27 mm, and 327.98 mm, respectively (Fig. 6a). Forest land
328   obtained the lowest average water production since the growth of natural forest land requires the
329   consumption of relatively large quantities of water, the evapotranspiration coefficient of natural
330   forest land is relatively large, and the evapotranspiration capacity of forest is relatively strong.
331   Although shrubland requires more water than grassland, the evapotranspiration coefficient of
332   shrubland is lower than that of grassland. Therefore, the average water yield capacity of shrubland
333   exceeded that of grassland. The average water yield under all natural / semi-natural vegetation
334   types over time first increased and then decreased, reaching a peak in 1989.

335   There are differences in evapotranspiration, litter water retention, soil water content, and
336   canopy interception among different vegetation types. Correspondingly, the different vegetation
337   types show obvious differences in water yield capacity (Nahib et al. 2021; Yang et al. 2021). Fig.
338   6b shows the total water production among different vegetation types, indicating that although the
339   average water yield of forests is relatively small, the forest area plays a major role in the water
340   yield ecological service function in Shangri-La City given that forest occupies the largest area. In
341   general, forest land showed the highest total water yield across the four periods of 1974, 1989,
342   2003, and 2015, accounting for approximately 59.69%, 61.80%, 58.21% and 55.75% of the water

343   yield of all vegetation types, respectively. The results of the present study showed that LULC is
344   an important factor regulating changes in the water yield ecosystem service function (Guo et al.
345   2021).

Effect of topographic factors on water yield

347   Elevation significantly affects the distribution of precipitation and vegetation types, thereby
348   indirectly affecting the water yield capacity. Fig. 7 shows the effect of elevation on the water yield
349   ecosystem services in Shangri-La City. The average water yield of each year initially decreased
350   and then increased with increasing elevation. Besides for in 1989, the lowest average water yield
351   occurred at an elevation range of 3,500–4,000 m, whereas the highest average water yield was
352   distributed at an elevation of < 2,000 m and the second highest water yield occurred at an elevation
353   exceeding 4,000 m (Fig. 7a). Over the four periods, the highest water yields were mainly
354   concentrated in areas with elevations exceeding 3,000 m, accounting for > 80% of the total water
355   yield. In contrast, relatively small water yields were evident at elevations < 2,500 m, accounting
356   for ~8.5% of the total water yield (Fig. 7b). There was an increasing trend followed by a decreasing
357   trend in average water yield from 1974 to 2015. The change in average water yield with elevation
358   was greatest in 1989, followed by 2003. Areas of low elevation are mainly distributed in the
359   southern part of the study area characterized by precipitation far exceeding that in the central parts
360   and areas with higher elevation. This results in these areas of low elevation having relatively high
361   average water yield. The proportion of forest area decreased sharply in areas of extremely high
362   elevation, resulting in weakened evapotranspiration and a corresponding increase in the average
363   water yield.

364   Fig. 8a shows the effect of slope on the water yield of Shangri-La City. Water yield initially
365   gradually decreased and then gradually increased with increasing slope, with a minimum water
366   yield in a slope range of 35 ° to 45 °. The total water yield was affected by the area of each slope
367   grade, with the total annual water yield from 1974 to 2015 showing a normal distribution across
368   the different slope grades (Fig. 8b). The majority of water yield was concentrated between slope
369   values of 5 ° to 45 °, accounting for ~85% of the study area, whereas the remaining slope intervals
370   contained a negligible water yield (Fig. 8b). In addition, within each slope grade, water yield
371   initially increased and then gradually decreased over time, with a peak in 1989. In general,
372   topographical factors indirectly affect the water yield ecosystem service function by affecting
373   precipitation and vegetation types (Lian et al. 2020).

Limitations and uncertainty of the model

375   The InVEST model simplifies the hydrological process in that it does not distinguish between
376   surface and subsurface water. Therefore, many uncertainties persist in the model simulation (Lian
377   et al. 2020; Liu et al. 2021a). The InVEST model requires two main input datasets, namely climate
378   and LULC. These datasets may be prone to errors due to various uncertainties (Hoyer & Chang

379 2014). Classification of landscapes contains subjective elements such as a lack of prior knowledge
380 which may affect classification accuracy. Poor remote sensing image quality may also contribute
381 to poor classification accuracy. These sources of uncertainty affect any ecological assessment (Hou
382 et al. 2013). Precipitation data and evapotranspiration data were obtained through interpolation. In
383 contrast, climate change is complex and difficult to simulate. Therefore, it difficult to obtain
384 accurate meteorological data with high temporal and spatial resolution. Model parameters, such as
385 the evapotranspiration coefficient and maximum root depth, are derived from empirical data.
386 Therefore, the accuracy of these data will affect the accuracy of model simulation to a certain
387 extent, although the basic pattern of water yield should remain unchanged. Furthermore, although
388 water yield is closely related to socioeconomic development and human activities, socioeconomic
389 data and survey data are rarely used as model input data, thereby contributing to a certain degree
390 of uncertainty (Lang et al. 2017). Despite some limitations, the InVEST model is widely regarded
391 as a suitable tool for the evaluation of a variety of ecosystem services within catchments
392 characterized by low data availability (Vigerstol & Aukema 2011). Future research should conduct
393 further field sampling in Shangri-La City to verify the water yield simulated by the InVEST model
394 in the current study. On the other hand, previous studies have shown that the relatively simple
395 InVEST water yield model can provide an accurate estimate of water yield provided that model
396 input data and related parameters can represent the relevant spatiotemporal scales (Redhead et al.
397 2016).

398   Shangri-La City falls within a region containing a fragile and sensitive ecosystem. The region
399 is also a valuable tourist destination in China. However, the development of tourism may result in
400 various negative effects, such as pasture degradation and frequent geological disasters (Yang et al.
401 2019b). In addition, future tourism development will also result in changes to the spatial
402 distribution of land use types. Therefore, assuring sustainable future development of tourism and
403 the economy requires a focus on intensive use of land and reasonable planning. In addition, there
404 should be a move to transformation of traditional tourism to ecotourism to minimize the impact of
405 land development on mountain water yield services.

Conclusions

407 Water yield plays an extremely important role in ecosystem services and is of great significance
408 to regional ecological security and the sustainable development of natural resources. The present
409 study used various datasets as input data for the InVEST water yield model to quantitatively
410 evaluate the water yield ecological service function of Shangri-La City from 1974 to 2015. In
411 addition, the importance of water yield was determined and the responses of water yield to various
412 factors were analyzed. The main conclusions of the present study are outlined below:
413   (1) Annual water yield in Shangri-La City is high in the north and low in the central region.

414 The average water yield of the study area exceeded 100 mm. High water yields were mainly
415 identified in Hutiaoxia, Jinjiang, and Shangjiang. Over the study periods from 1974 to 2015, water
416 yield mainly initially increased and then decreased, with the smallest water yield of 199.06 mm
417 occurring in 2015. The spatial and temporal variability of water yield emphasized the need for
418 additional measures to improve the quality of the ecological environment, thereby strengthening
419 the protection of water resources.

420 (2) The ranking of grades of water yield ecosystem services in Shangri-La City according to
421 the proportion of the study area was Grade II (43.36%) > Grade III (20.90%) > Grade I (20.22%)
422 > Grade IV (15.52%). Areas showing Grade IV water yield were identified to the west of Jiantang,
423 central Xiaozhongdian, central Gezhan, northwestern Dongwang, and the Hutiaoxia. These areas
424 should be given sufficient attention and priority protection.

425 (3) The water yield ecosystem service functions are affected by precipitation,
426 evapotranspiration, vegetation types, and topographic factors. There was a positive correlation
427 between water yield and precipitation, with this relationship shown to be significant in most areas.
428 In contrast, there was a negative correlation between water yield and potential evapotranspiration.
429 The effect of shrubs on water yield exceeded that of meadows and forests under different
430 vegetation types. The average water yields initially decreased and then increased with increasing
431 elevation. Average water yields initially decreased and then gradually increased with increasing
432 slope. In general, the model parameters used in the current study can provide a reference for related
433 research in regions under similar climate conditions.

ADDITIONAL INFORMATION AND DECLARATIONS

448 Program for Innovative Research Team (in Science and Technology) in the University of
449 Yunnan Province, IRTSTYN

Competing Interests

451 The authors have no conflicts of interest to declare that are relevant to the content of this article.

Author Contributions

453 • Yuanhe Yu and Xingqi Sun conceived and designed the experiments, performed the
454   experiments, prepared figures and/or tables, and approved the final draft.
455 • Jinliang Wang conceived and designed the experiments, authored or reviewed drafts of the paper,
456   and approved the final draft.
457 • Jianpeng Zhang analyzed the data, authored or reviewed drafts of the paper, and approved the
458   final draft.

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592

Table 1(on next page)

Biophysical parameters used in the InVEST water yield model applied to Shangri-La City, Yunnan Province, China.

Lucode: LULC code for each type. LULC_desc: description of each type of LULC name. Kc: plant evapotranspiration coefficient for each LULC type. Root_depth: the maximum root depth for each LULC type. LULC_veg: LULC attribute category

| Lucode	LULC_desc	Kc	Root_depth (mm)	LULC_veg
1	Urban land	0.10	10	0
2	Rural residential land	0.30	500	0
3	Highway land	0.20	100	0
4	Airport	0.10	10	0
5	Terrace	0.65	2000	1
6	Flat field land	0.65	2000	1
7	Flat dryland	0.60	1000	1
8	Slope dryland	0.60	1000	1
9	Orchard	0.70	3000	1
10	Deciduous broad-leaved forest	1.00	7000	1
11	Evergreen broad-leaf forest	1.00	7000	1
12	Coniferous forest	1.00	7000	1
13	Mixed forest	1.00	7000	1
14	Alpine shrub	0.50	2000	1
15	Subalpine shrub	0.50	2000	1
16	Valley shrub	0.60	2000	1
17	Alpine meadow	0.65	1700	1
18	Subalpine meadow	0.65	1700	1
19	Valley grassland	0.40	650	1
20	Inland wetland	0.60	1000	1
21	River	0.00	1000	1
22	Lake	0.00	1000	1
23	Reservoir	0.00	1000	0
24	Bare land	0.00	200	1
25	Bare rock	0.00	200	1
26	Flood land	0.00	200	1
27	Permanent snow glacier	0.00	500	1

1

2

Figure 1

The geographical location of Shangri-La City.
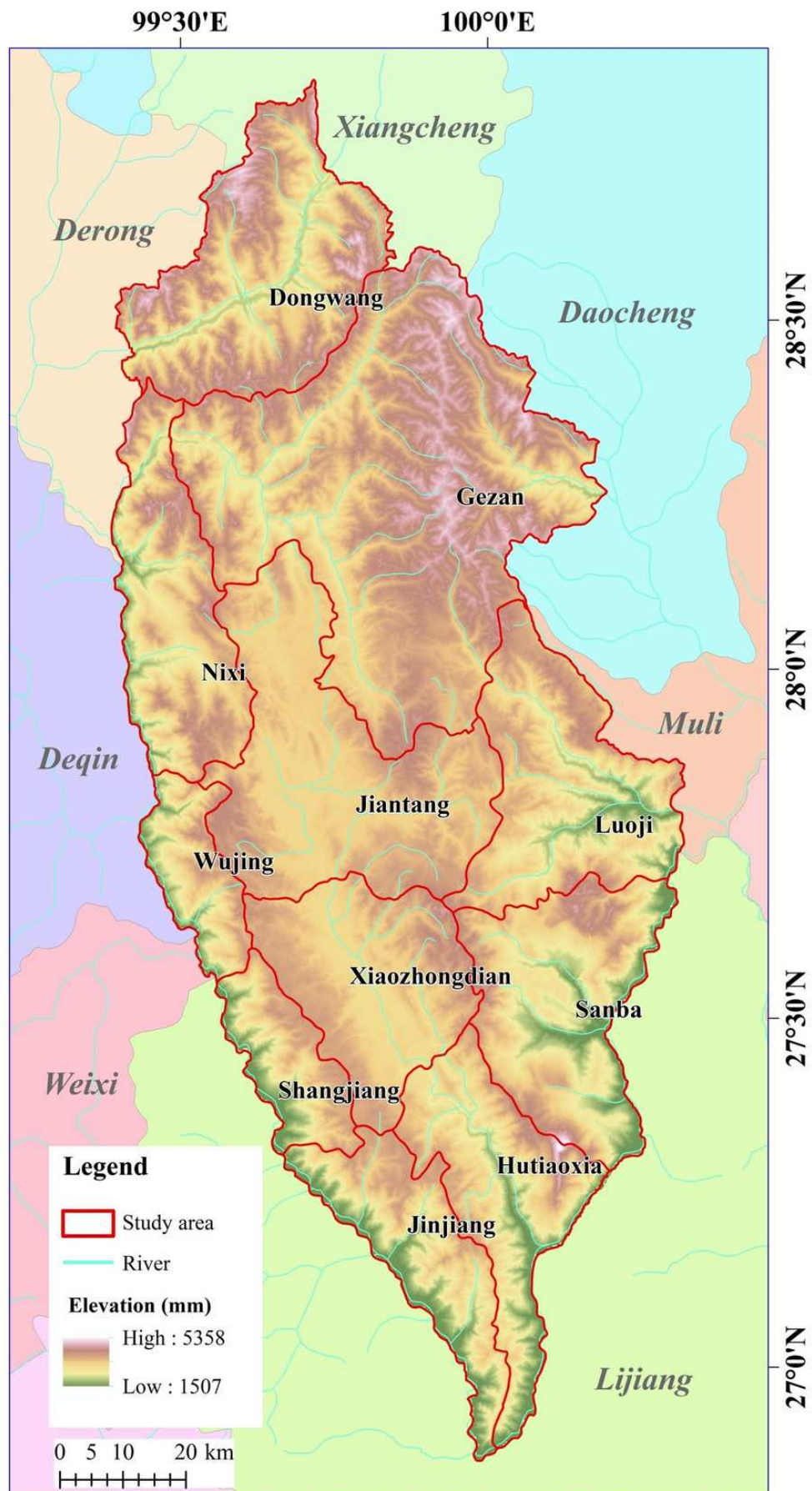
Figure 2

Spatial distributions of the InVEST model input data for 2015 for application to Shangri-La City, Yunnan Province, China.

(a) Annual precipitation (P); (b) Annual potential evapotranspiration (PET); (c) Plant available water content (PAWC); (d) Soil depths; (e) Land use/land cover (LUCC). Abbreviations: LJ: Luoji; DW: Dongwang; NX: Naxi; GZ: Geza; WJ: Wujing; SJ: Shangjiang; JJ: Jinjiang; JT: Jiantang; XZD: Xiaozhongdian; SB: Sanba.
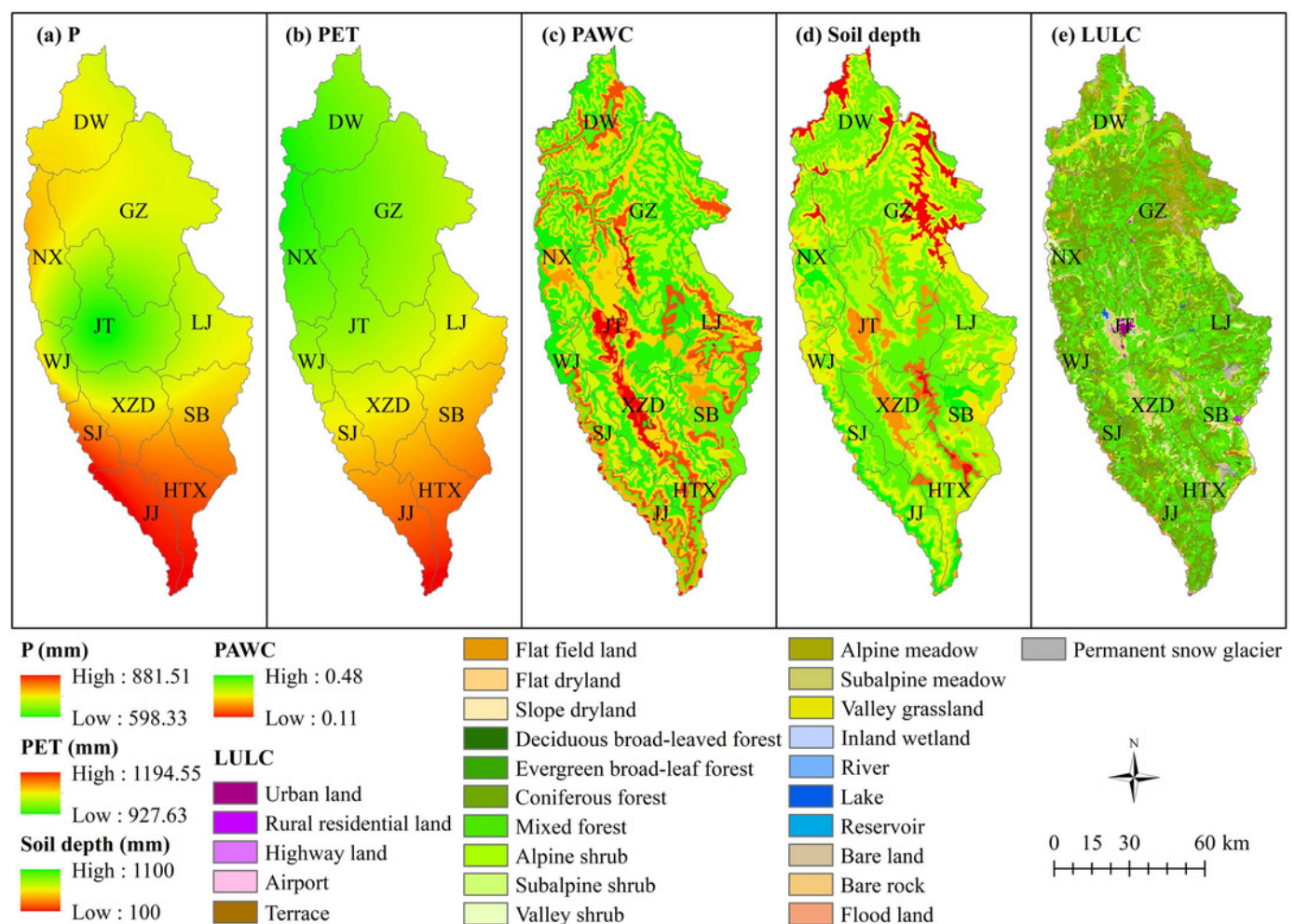
Figure 3

A summary of water yield for Shangri-La City, Yunnan Province, China as simulated by the Integrated Valuation of Ecosystem Service Tradeoffs (InVEST) model.

The spatial distribution of water yield for different years is shown in a, b, c, and d, whereas e shows the spatial distribution of the change in water yield between 1974 and 2015. A statistical summary of average water yield for different areas and different years is shown in f .
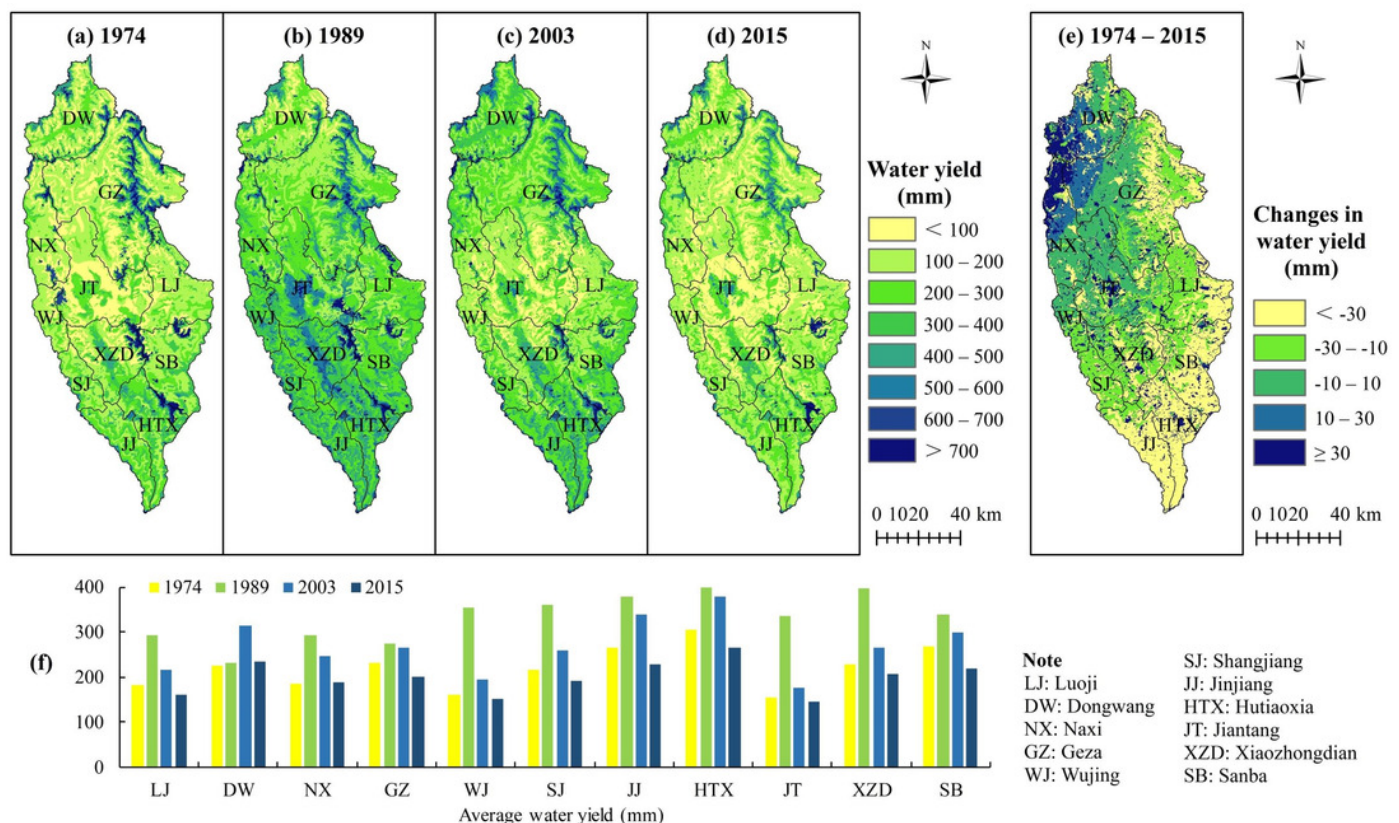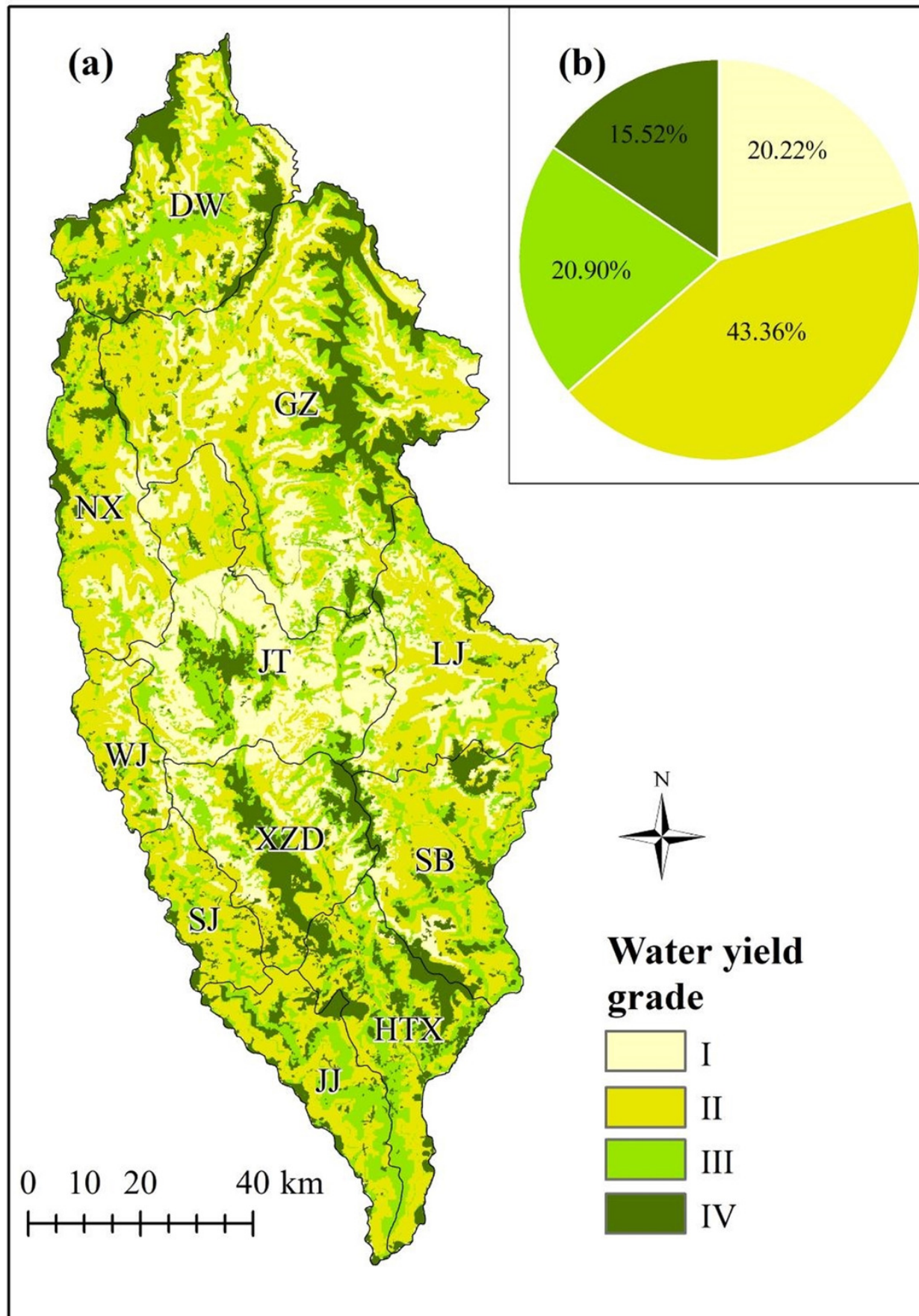
Figure 4

The spatial distribution of water yield in Shangri-La City, Yunnan Province, China as simulated by the Integrated Valuation of Ecosystem Service Tradeoffs (InVEST) model.

(a) according to Grades I–IV indicating the importance of the water yield ecosystem service,

(b) the area proportion of each grade in 2015. The grading classification is shown in Section 3.3.
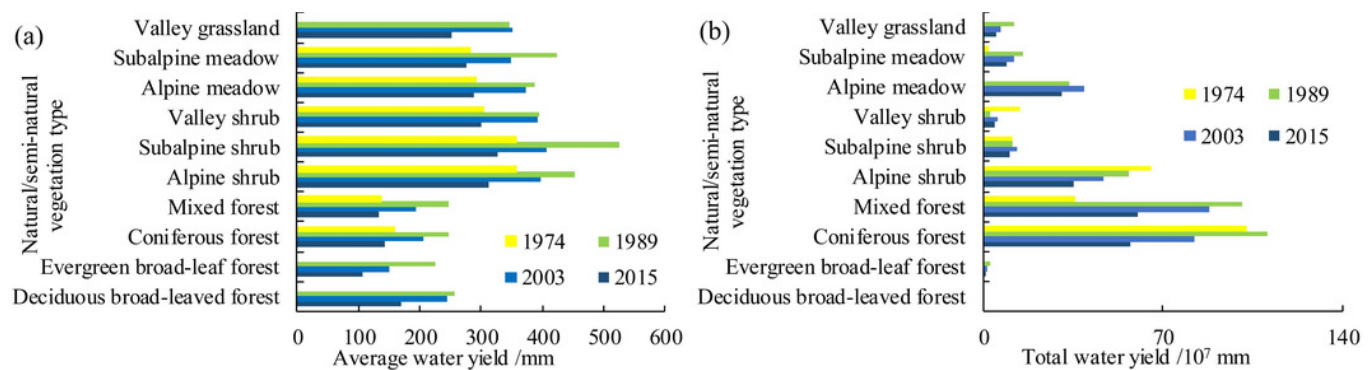
Figure 5

Correlation coefficient (R) and significance test between water yield and precipitation (P), and between water yield and PET from 1974 to 2015 in Shangri-La City, Yunnan Province, China.

(a) The *R* between water yield and P; (b) The *R* between water yield and PET; (c) The significance test of the *R* between water yield and P; (d) The significance test of the *R* between water yield and PET.
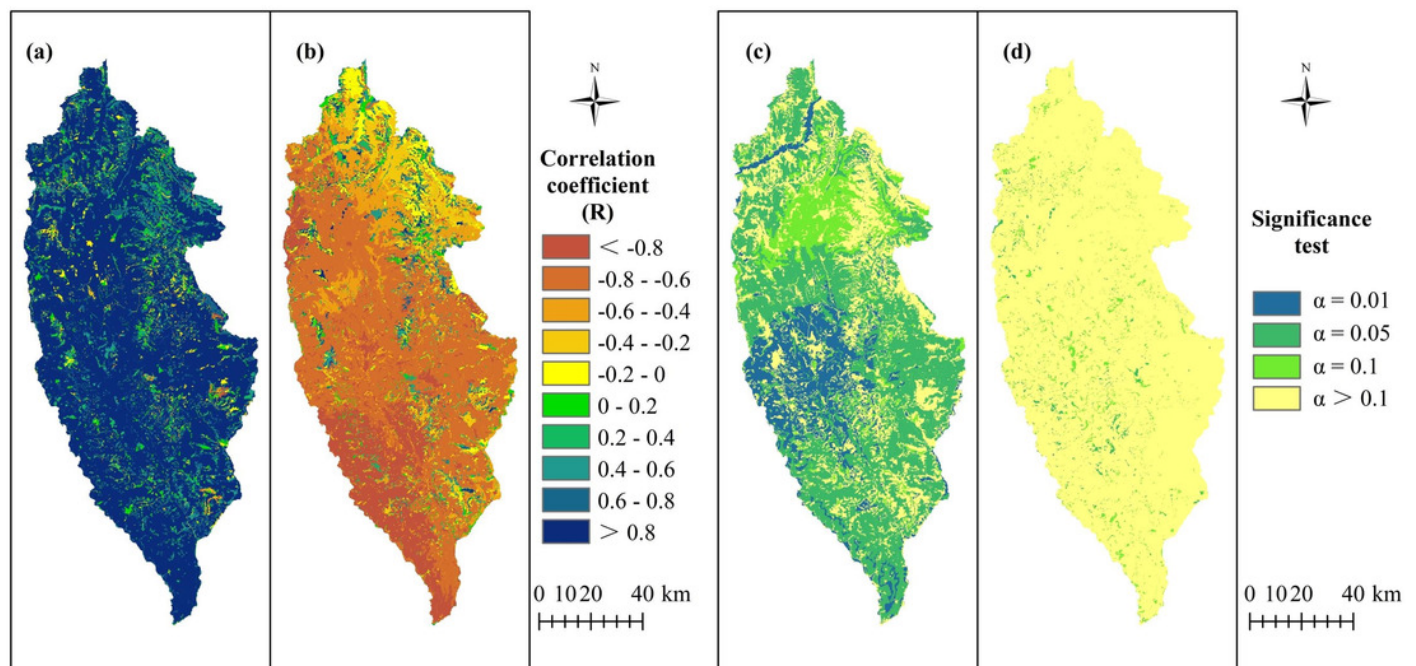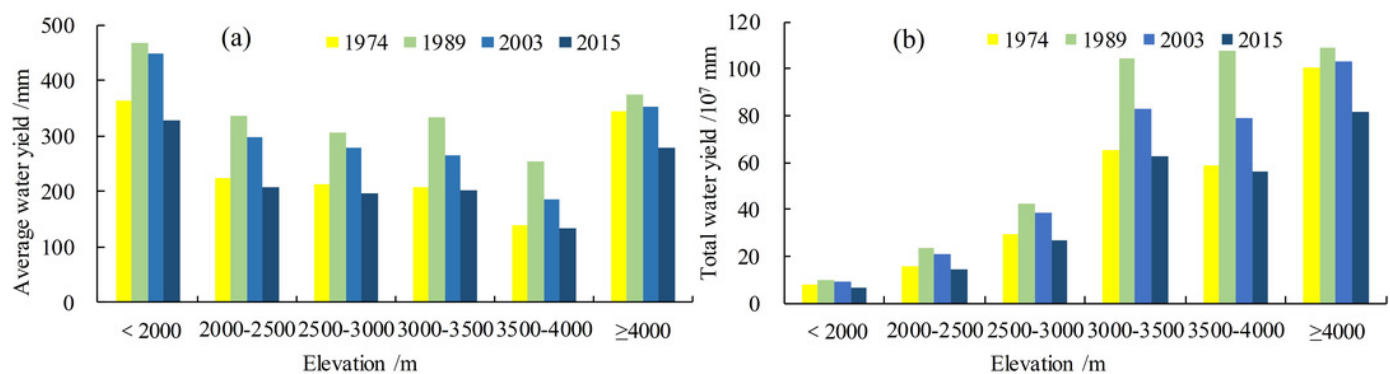
Figure 6

The distribution of water production under natural/semi-natural vegetation types in Shangri-La City from 1974 to 2015.

Figure 7

The distribution of water yield across different elevations in Shangri-La City from 1974 to 2015.

Figure 8

The distribution of water yield at different slope intervals in Shangri-La City, Yunnan Province, China from 1974 to 2015.