Journal of Environmental Management 316 (2022) 115232

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Integrating the Budyko framework with the emerging hot spot analysis in local land use planning for regulating surface evapotranspiration ratio

Ping Yu Fan [a], Kwok Pan Chun [a,b,*], Ana Mijic [c], Mou Leong Tan [d], Omer Yetemen [e]

[a] Department of Geography, Hong Kong Baptist University, Hong Kong S. A. R., China
[b] Department of Geography and Environmental Management, University of the West of England, Bristol, UK
[c] Department of Civil and Environmental Engineering, Imperial College London, London, UK
[d] GeoInformatic Unit, Geography Section, School of Humanities, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia
[e] Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey

ARTICLE INFO

Keywords:
Land use strategies
Spatially-varied
Evapotranspiration ratio
Budyko framework
Dry and wet climates

ABSTRACT

Land use planning regulates surface hydrological processes by adjusting land properties with varied evapotranspiration ratios. However, a dearth of empirical spatial information hampers the regulation of place-specific hydrological processes. Therefore, this study proposed a Local Land Use Planning framework for EvapoTranspiration Ratio regulations (ETR-LLUP), which was tested for the developments of spatially-varied land use strategies in the Dongjiang River Basin (DRB) in Southern China. With the first attempt at integrating the Emerging Hot Spots Analysis (EHSA) with the Budyko framework, the spatiotemporal trends of evapotranspiration ratios based on evaporative index and dryness index, from 1992 to 2018, were illustrated. Then, representative land-cover types in each sub-basin were defined using Geographically Weighted Principal Component Analysis, in two wet years (1998 and 2016) and three dry years (2004, 2009, and 2018), which in turn were identified using the Standard Precipitation Index. Finally, Geographically Weighted Regressions (GWRs) were used to detect spatially-varied relationships between land-cover proportions and evaporative index in both dry and wet climates. Results showed that the DRB was consistently a water-limited region from 1992 to 2018, and the situation was getting worse. We also identified the upper DRB as hotspots for hydrological management. Forests and croplands experienced increasingly water stress compared to other vegetation types. More importantly, the spatial results of GWR models enabled us to adjust basin land use by 1) expanding and contracting a combination of 'mosaic natural vegetation' and 'broadleaved deciduous trees' in the western and eastern parts of the basin, respectively; and 2) increasing 'broadleaved evergreen trees' in the upstream parts of the basin. These spatially-varied land use strategies based on the ETR-LLUP framework allow for place-specific hydrological management during both dry and wet climates.

1. Introduction

Numerous studies have demonstrated the regulations of land use planning on the hydrological cycle, because of the varied evapotranspiration in different land properties (e.g., Liu et al., 2016; Li et al., 2017). Evapotranspiration can indicate the sum of water lost from the earth's surface. The conversions from forests to shrubs and grasslands may cause higher evapotranspiration in the catchment (Sun et al., 2008). An increase in evapotranspiration may also occur when grasslands become croplands (Odongo et al., 2019). As a result, national policies and a series of land use planning guidance include the aim of hydrological management when proposing specific land use strategies. On the other hand, climate condition affects water availability in terms of precipitation as well as energy provision for evapotranspiration, making it a key factor in hydrological cycles (Bierkens et al., 2008). In other words, incorporating the climatic effects, evapotranspiration ratio, instead of evapotranspiration, should be focused on hydrological regulation in land use planning. Evapotranspiration ratio refers to the partitioning of precipitation into evapotranspiration and runoff so that its value has already taken into account the varying climate conditions. Therefore, administering the types and proportions of land covers, according to their effects on evapotranspiration ratios, is needed for sustainable

* Corresponding author. Department of Geography and Environmental Management, University of the West of England, Bristol, UK.
E-mail addresses: 18482392@life.hkbu.edu.hk (P.Y. Fan), kwok.chun@uwe.ac.uk (K.P. Chun), ana.mijic@imperial.ac.uk (A. Mijic), mouleong@usm.my (M.L. Tan), yetemen@itu.edu.tr (O. Yetemen).

https://doi.org/10.1016/j.jenvman.2022.115232
Received 1 February 2022; Received in revised form 7 April 2022; Accepted 2 May 2022
Available online 13 May 2022
0301-4797/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

regional water management.

The varied evapotranspiration ratios based on the interaction of climate and land surface characteristics have been illustrated in the Budyko framework (Budyko & Miller, 1974). The Budyko frame is characterized by two dimensionless indices – evaporative index (EI) and dryness index (DI) (Donohue et al., 2007; Li et al., 2013). EI refers to the proportion of actual evapotranspiration (AET) to precipitation (P). EI values are controlled by the energy used for AET. Before EI values reach 1, the basin is energy-limited with sufficient surface water resources. When all of the available water has been evaporated and transpired, the conversion from energy-limited to water-limited situation occurs, and then the evapotranspiration ratio is measured by DI. DI determines the water limitation by the ratio of potential evapotranspiration (PET) to precipitation (P). The details about the Budyko framework refer to Appendix A in the Supplementary Materials.

Based on the Budyko framework, some studies presented the spatial variations in the evapotranspiration ratio using the long-term mean values of EI and DI (Stisen et al., 2021; Shen et al., 2017) or through modelling the seasonal variations in AET and Q (e.g., Chen et al., 2013). A limitation of these previous studies is that they did not include all evapotranspiration ratios in each time step and each spatial observation. A method to deal with this limitation is using Emerging Hot Spot Analysis (EHSA) (Harris et al., 2017), which is an Arc GIS-based tool to depict the spatiotemporal trends using continuous hydroclimatic data, allowing us to gain insight into historical hydrological conditions. In hydrological studies, EHSA is rarely used. To our knowledge, Fan et al. (2021) used this method to investigate the spatiotemporal changes in hydrological drought risk. This study is the first attempt to integrate the EHSA with the Budyko framework in the land planning field.

In the Budyko framework, studies identified the roles of different vegetation types in evapotranspiration ratio due to their different biological characteristics, such as rooting depth (Zhang et al., 2018; Donohue et al., 2012). Also, vegetation coverage was found as a major factor in the evapotranspiration ratio, with a general positive correlation (Li et al., 2020; Voepel et al., 2011; Yang et al., 2009). Forest lands, for example, had higher evapotranspiration ratios than grassland and croplands (Zhang et al., 2004). Despite the investigations on land use effects on evapotranspiration ratio, Budyko framework has not been fully integrated into the land use planning practices for hydrological management, because existing evidence has been insufficient to inform how and where to adjust the proportions of various land covers. Moreover, the rare study reflected the local influences of land characteristics on the evapotranspiration ratio that vary by location in a basin. Place-specific hydrological management through land use planning is thus constrained.

To capture spatial variations in hydrological responses to diverse land covers, a local model – geographically weighted regression (GWR) – is used in this study. Using EHSA, the Budyko framework, and the GWR models, this study suggests a Local Land Use Planning approach to regulating surface EvapoTranspiration ratio (ETR-LLUP) for hydrological process and water resource management. This approach is tested for the Dongjiang River Basin (DRB) in southern China. The DRB is a crucial water source of several well-developed and densely-populated cities, such as Hong Kong Special Administrative Region, in the Guangdong-Hong Kong-Macau Greater Bay Area (GBA) which is an emergent region for rapid socio-economic growth in China. More than 35 million people in the GBA benefit from the water resource imported from the DRB. Adjusting the evapotranspiration ratio in the DRB by land use planning contributes to optimizing the basin surface hydrological cycle, allowing for continuous water provision and sustainable water resource management. This study is able to achieve four specific objectives by developing the ETR-LLUP framework: 1) to illustrate the spatiotemporal trends of evapotranspiration ratio as hot and cold spots based on the Budyko framework from 1992 to 2018; 2) to differentiate evapotranspiration ratio among land-cover types using the Budyko framework; 3) to describe the heterogeneous impacts of proportions of different land-cover types on the evapotranspiration ratios, at both basin and upper stream levels; and 4) to recommend spatially-varied land use strategies for hydrological management under different climate situations.

2. Data and method

2.1. Study area

The DRB is a tributary of the Pearl River Delta that spans about 35,340 km^2 with a length of 562 km (Yang et al., 2018), most of which is located in Guangdong Province (Fig. 1(a)). The north part of the basin is characterized by natural lands, such as forests and croplands; while more urbanized lands are clustered in the south part (Fig. 1(b1)). A large-scale water reservoir – the Xinfengjiang Water Reservoir – is in the middle part of the basin, to store water resources and regulate hydro-climatic conditions (Fig. 1(b2)). In recent decades, distinct land use changes are observed as an expansion of built-up areas (Gao et al., 2016) and increasing vegetation in the upper DRB (Peng et al., 2014). Ongoing changes in land use affect the evapotranspiration ratio in hydrological cycles. To present the effects of heterogeneous land use on the local evapotranspiration ratio, the DRB is subdivided into 256 sub-basins in this study (Fig. 1(b3)). These sub-basins are the smallest spatial units that collect precipitation to serve as basin water sources with similar land use characteristics. The general increases in EI and DI (Fig. 1(c)) need the hydrological regulations through adjusting land use in the DRB.

2.2. Data sources

Monthly gridded data of AET, PET, and P with a spatial resolution of 0.1° were derived from ERA5 re-analysis datasets (cds.climate.copernicus.eu/) and resampled into annual data for quantifying EI and DI in the DRB from 1992 to 2018. By comparing the runoff data from ERA5 re-analysis datasets to those from DRB observation stations, we validated that ERA5 re-analysis datasets were reliable for quantifying EI in our case based on R^2 values greater than 0.71 (Appendix B, Figure B1). Also, annual precipitation data from ERA5 re-analysis datasets were used to calculate Standard Precipitation Index (SPI) for defining climatic wetness and dryness. When SPI >1, the risk of a flood event increases due to increased precipitation, whereas SPI < -1 indicates a drought risk due to insufficient precipitation (Zhang et al., 2009). From 1992 to 2018, the years 1998 and 2016 showed SPI >1, which were identified as the wet year, while 2004, 2009, and 2018 with SPI < -1 were dry years (Appendix B, Figure B2). Also, the occurred drought and flood events in these selected years can be found in the Bulletins of the Water Resources Department of Guangdong Province (http://slt.gd.gov.cn/) in China. On the other hand, land-cover data with a spatial resolution of 300 m were obtained from the European Space Agency (ESA) Climate Change Initiative (CCI), describing 37 land types, such as rainfed cropland, urban, water, etc., and the details have been shown in Appendix B (Table B1).

2.3. An analytical framework of ETR-LLUP

The aforementioned hydroclimatic and land-cover data were used to develop an approach to Local Land Use Planning for regulating spatially-varied EvapoTranspiration Ratios (ETR-LLUP). This ETR-LLUP framework includes three sections (Fig. 2). Firstly, to illustrate the evapotranspiration ratio in the basin hydrological process, Emerging Hot Spot Analysis (EHSA) was adopted to present the spatiotemporal trends of EI and DI values in the Budyko framework as hot and cold spots. Focusing on two wet and three dry years defined by SPI values, depicting various land-cover types in the Budyko space can help differentiate their effects on hydrological cycles. In both wet and dry years, the land-cover types, which represent the land use patterns in each sub-basin, were identified using Geographically Weighted Principal Component Analysis (GWPCA). Moreover, the GWR model was used to investigate the

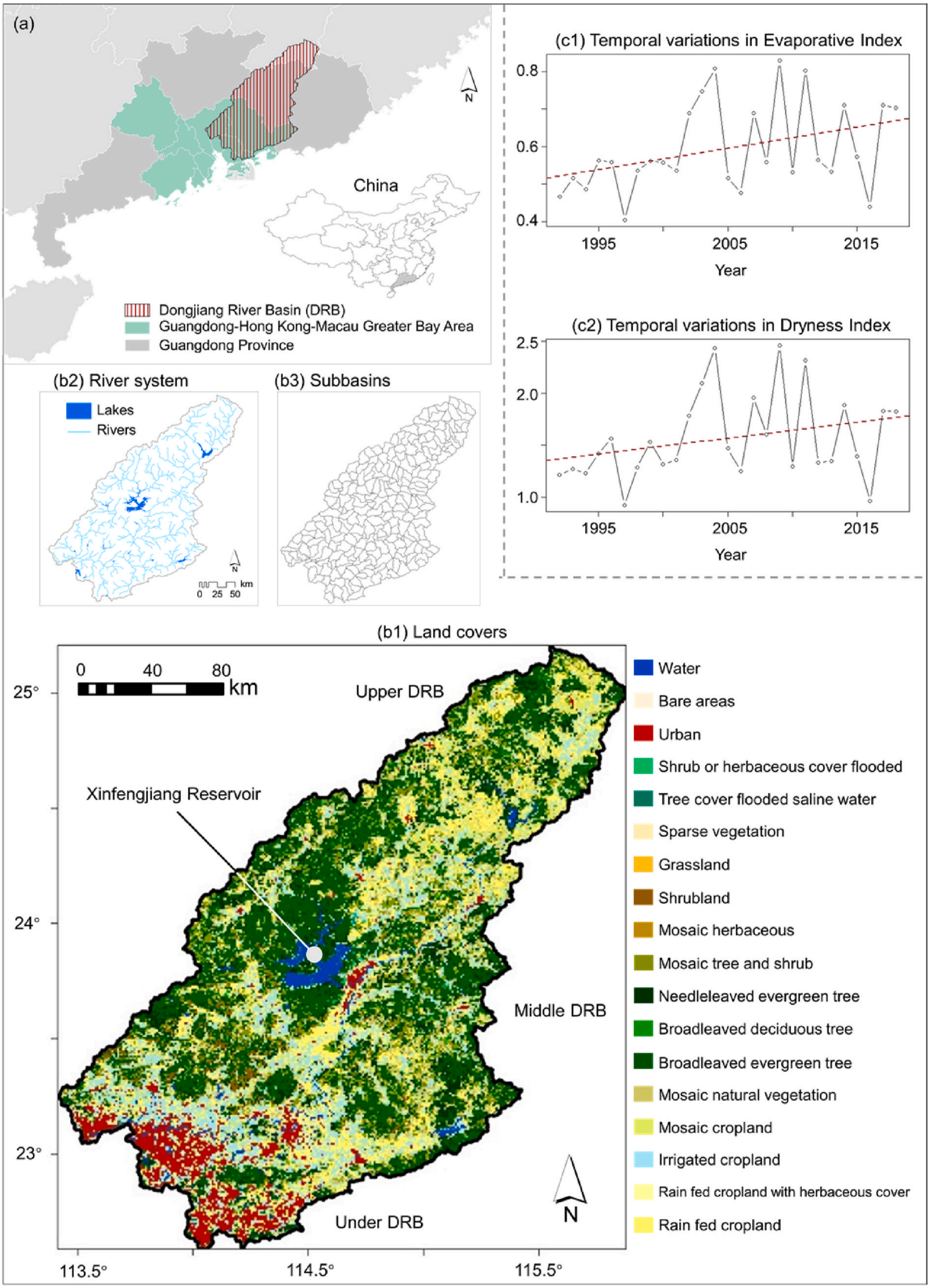

Fig. 1. The location of Dongjiang River Basin (DRB) is shown in (a). The land covers and river systems of DRB are shown in (b1) and (b2), respectively. The DRB is subdivided into 256 sub-basins to present unique hydrological conditions locally (b3). Also, the temporal variations in the evaporative index and dryness index from 1992 to 2018 can be found in (c).

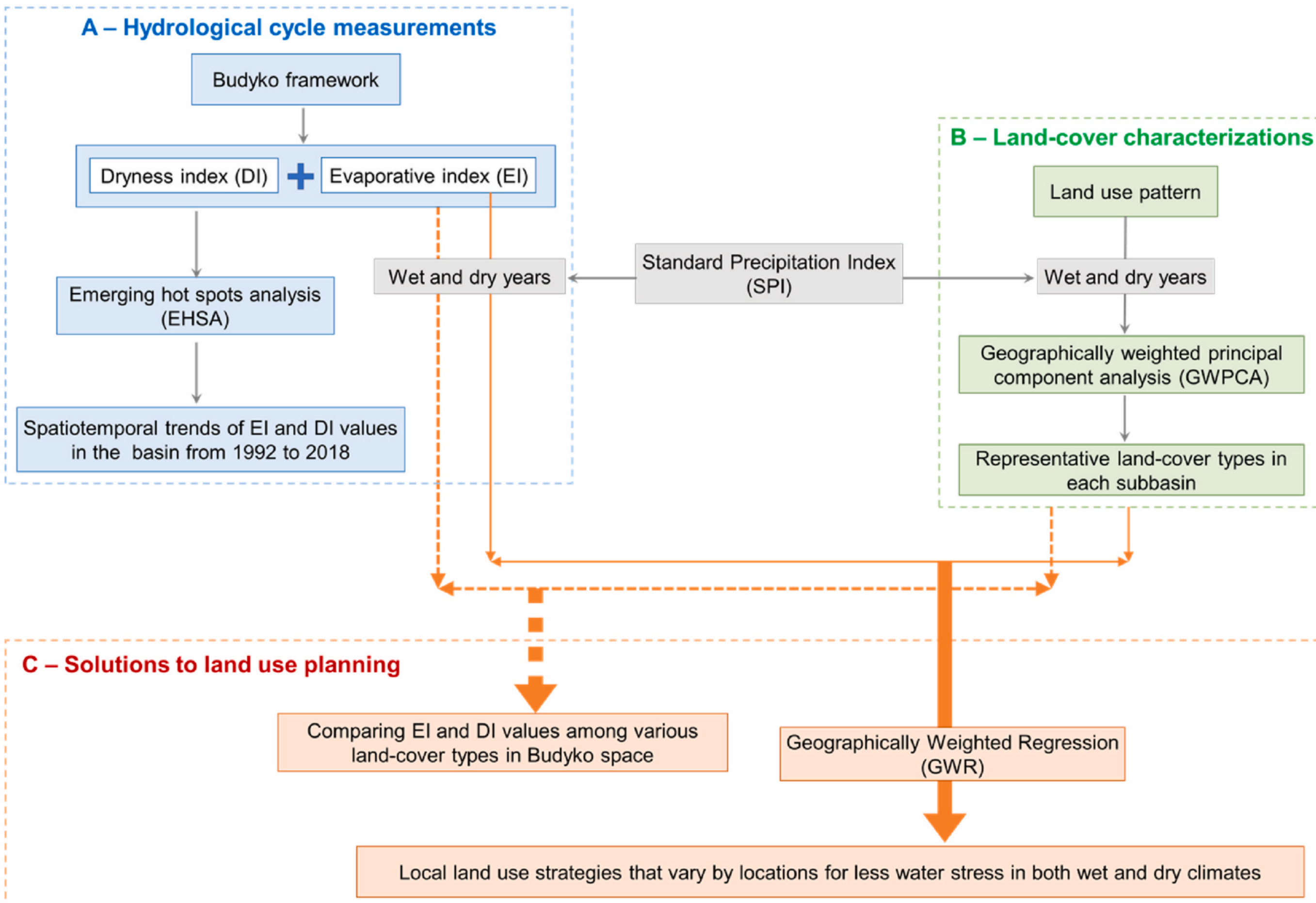

Fig. 2. An Analytical framework for Local Land Use Planning to regulate spatially-varied EvapoTranspiration Ratios (ETR-LLUP).

spatially-varied coefficients between land-cover proportions and EI-based evapotranspiration ratio, for proposing place-specific land use strategies and local evapotranspiration regulation.

2.4. EHSA-based hydrological cycle measurement

Emerging hot spots analysis (EHSA) (Harris et al., 2017) is a geospatial tool to integrate the temporal and spatial information to explore the statistically significant spatiotemporal trends of the Budyko framework-based hydrological process from 1992 to 2018. To perform the EHSA, space-time cubes were created by aggregating our yearly data in each geographical location. These space-time cubes were clustered, based on statistical significance analysis, as hot and cold spots that have statistically significant high and low values of data compared to surroundings (ESRI, 2016). Here, using continuous spatiotemporal data with a yearly temporal resolution and a 0.1-degree spatial resolution, EHSA was mainly used to characterize the historical variations in EI and DI values and to illustrate the hotspots with high water stresses.

2.5. GWPCA-based land-cover characteristics

Principal component analysis (PCA) is commonly used to extract the most important data properties by reducing data dimensions (Demšar et al., 2013). However, the spatially homogenous statistical descriptions derived from PCA cannot interpret the spatial variations in land-cover types (Comber et al., 2016). Therefore, as a localized version of PCA, the GWPCA is used in this study, which reflects spatial effects based on geographical weights (Cartone and Postiglione, 2020; Harris et al., 2015). Using GWPCA, land-cover data was clustered as several uncorrelated geographically weighted principal components (GWPCs). The first GWPC can indicate the most distinct pattern of land use in the basin, followed by the second and third GWPCs. The loading value indicates the importance of each land cover in the overall land use pattern in that GWPC, and the dominant land type should have the highest absolute loading value. Overall, GWPCA characterizes the local land use patterns in our case into some dominant land-cover types as representations, which were then related to the evapotranspiration ratio in the Budyko framework.

Although spatial effects distinguish GWPCA from PCA, Monte Carlo tests (Lu et al., 2014) were also required to support the GWPCA application in this study. With an estimated p-value of 0.01, the results showed that land-cover data were inter-correlated and spatially clustered (Appendix C). In other words, significant spatial heterogeneity in land use necessitated the use of a local model, indicating that GWPCA rather than PCA was required in this study.

2.6. GWR-based local land use solutions

The conventional regression model provides general statistical results of variable relationships based on an assumption that data are space invariant, which thus cannot handle the spatial variations in land-cover and hydrological data. Thus, the GWR model was used here, which can overcome the limitation of the conventional regression model by showing how local relationships vary with spatial changes (Fotheringham et al., 2003; Matthews and Yang, 2012). The GWR equation is as follows (Brunsdon et al., 1996; Fotheringham et al., 2001):

$$y_i = a_{i0} + \sum_{k=1,m} a_{ik} x_{ik} + \varepsilon_i \tag{1}$$

where y_i represents local estimation at location i, a_{i0} and a_{ik} are the intercept value and local coefficient of variable k at location i, respectively. x_{ik} is the observed data of variable k at location i.

Moreover, in the local estimation of the GWR parameter, a spatial weighting of point i is provided based on a spatial distance. Larger spatial weightings are assigned to observations closer to point i. By using spatial weighting to calibrate the GWR model, the spatial effects in measuring the local relationships between land-cover proportions and hydrological conditions are shown.

3. Results

Historical characteristics of hydrological conditions in the DRB were presented by combining the EHSA and the Budyko framework. Focusing on three dry and two wet years, the evapotranspiration ratios in the Budyko framework among land-cover types can be differentiated under wet and dry climates. Furthermore, we captured the spatial variations in the effects of land-cover proportions on EI values, which can provide empirical spatial information for specifying land use strategies and locations for local hydrological management.

3.1. Characteristics of hydrological conditions and land use in ETR-LLUP

3.1.1. Spatiotemporal patterns of EI and DI values in the Budyko framework

Temporal variations in EI and DI values in the DRB based on the Budyko framework were depicted in Fig. 3(a). Throughout the DRB, increased evapotranspiration ratio, decreased surface runoff, and a severer water-limited condition can be observed from 1992 to 2018, because the EI and DI values in the early years (1992–2000) were lower than those in subsequent years (2000–2018) (Fig. 3(a)). The entire basin was always water-limited due to the DI values exceeding 1 consistently. Combined with spatial patterns further, the spatiotemporal trends revealed hotspots of both EI and DI in the north, i.e., the upper DRB, with higher statistically significant values than in the south over the time periods (Fig. 3(b1) (b2)). It means that the upper DRB was more water-limited and drier than other regions, because more precipitation is lost to evapotranspiration and thus less runoff infiltrates into the soil. Therefore, we defined the upper DRB as the hotspots for regulating hydrological cycles by land use planning. In detail, EI hotspots oscillated in the northeast part of the basin in intermittent time periods (Fig. 3 (b3)), similar to the spatiotemporal patterns of EI across 27 years. Moreover, 2002 was the first year when EI hotspots appeared, and till 2018, EI hotspots appeared in 12 years while EI cold spots appeared in only three years. This fact suggested that the DRB began to increase its evapotranspiration ratio in 2002 and maintained a high evapotranspiration ratio from 2002 to 2018.

3.1.2. Spatiotemporal variations in land use

We have defined two wet years (1998 and 2016) and three dry years (2004, 2009, and 2018) according to SPI values from 1992 to 2018. During these five years, the dominant land-cover type in each sub-basin was presented (Fig. 4). Despite the similar land-cover types and distributions, minor land use changes can be observed over five years. In the northern basin, croplands and trees predominated the land use patterns, while water bodies accounted for the most in the middle part of the basin due to Xinfengjiang Reservoir project over there. In the south, grassland was the dominant one in such an urbanized region due to the rapid urban sprawl. Overall, there were eight dominant land-cover types over the whole DRB, namely, 'rain fed cropland', 'rain fed cropland with herbaceous cover', 'mosaic cropland', 'mosaic natural vegetation', 'broadleaved evergreen tree', 'broadleaved deciduous tree', 'grassland', and 'water'. In the upper DRB, three dominant land-cover types were 'rain fed cropland', 'mosaic cropland', and 'broadleaved evergreen tree'.

3.2. Bubyko-based hydrological conditions among land-cover types in ETR-LLUP

To manage hydrological cycles in different land-cover types under wet and dry climates, the Budyko framework illustrated the EI and DI values across the basin in dry and wet years focusing on eight land-cover types derived from GWPCA results (Fig. 5). In wet years (1998 and 2016), the basin had both lower EI and DI values than those in dry years (2004, 2009, and 2018). In wet years, only subtle disparities of EI and DI values between land covers can be observed, implying that, when available water resources are sufficient, evapotranspiration ratios in different land-cover types were very similar. Furthermore, in dry years, croplands and trees had higher water stress due to their higher EI and DI values than other land-cover types. The whole DRB was always water-limited as DI values of all land-cover types kept higher than 1 on average, particularly in dry years.

3.3. Spatially-varied effects of land-cover proportions for local land use planning in ETR-LLUP

Based on the varied hydrological processes among land-cover types, we quantified how the changes in land-cover proportion affect EI-based evapotranspiration ratio, in order to develop spatially-varied land use strategies that differ by locations for managing local evapotranspiration ratios. Firstly, the Pearson correlation analysis was conducted in these selected five years to define the land-cover types having statistical correlations with EI values. The results showed that the proportions of 'mosaic natural vegetation' and 'broadleaved deciduous trees' always had statistically significant correlations with EI values throughout the basin (3×10^4 km^2) in both dry and wet years (Table 1). Moreover, in the upper DRB (about 10^4 km^2), only the proportion of 'broadleaved evergreen tree' was related to EI in five years. By this step, we demonstrated the land-cover types that needed to be adjusted for evapotranspiration ratio management in both wet and dry climates as well as the entire basin and its upper stream.

To identify the potential placements of the above-mentioned land-cover types, the GWR models were developed (Fig. 6). The impacts of land-cover proportions on EI were spatially-varied throughout the DRB (Fig. 6(a–g)). In general, the proportions of 'mosaic cropland', 'mosaic natural vegetation', and 'broadleaved deciduous tree' had negative relationships with EI values in the west part of the DRB. At the same time, the negative relationships between 'broadleaved evergreen tree' proportion and EI values occurred in most of the basin. In the upper DRB, the clear negative relationships between the proportions of 'broadleaved evergreen tree' and EI values can be observed (Fig. 6(i)).

4. Discussion

This study provides EHSA-driven spatiotemporal trends of the evapotranspiration ratio for the development of the ETR-LLUP framework, based on continuous time and space steps. We also discuss the implications of this ETR-LLUP framework for researchers and practitioners in facilitating spatially-varied land use planning taking into account local situations.

4.1. Spatiotemporal trends of evapotranspiration ratio in ETR-LLUP

This study demonstrates the spatiotemporal trends of evapotranspiration ratio over recent decades, by depicting how the overall EI and DI values in the DRB move in the Budyko space from 1992 to 2018 (Fig. 3 (a)) and illustrating EHSA-based spatial disparities between the north and the south (Fig. 3(b1) (b2)). The temporal changes in the evapotranspiration ratio in the DRB show increasingly higher EI values. From a perspective of runoff changes, Niu & Sivakumar (2014) reported that

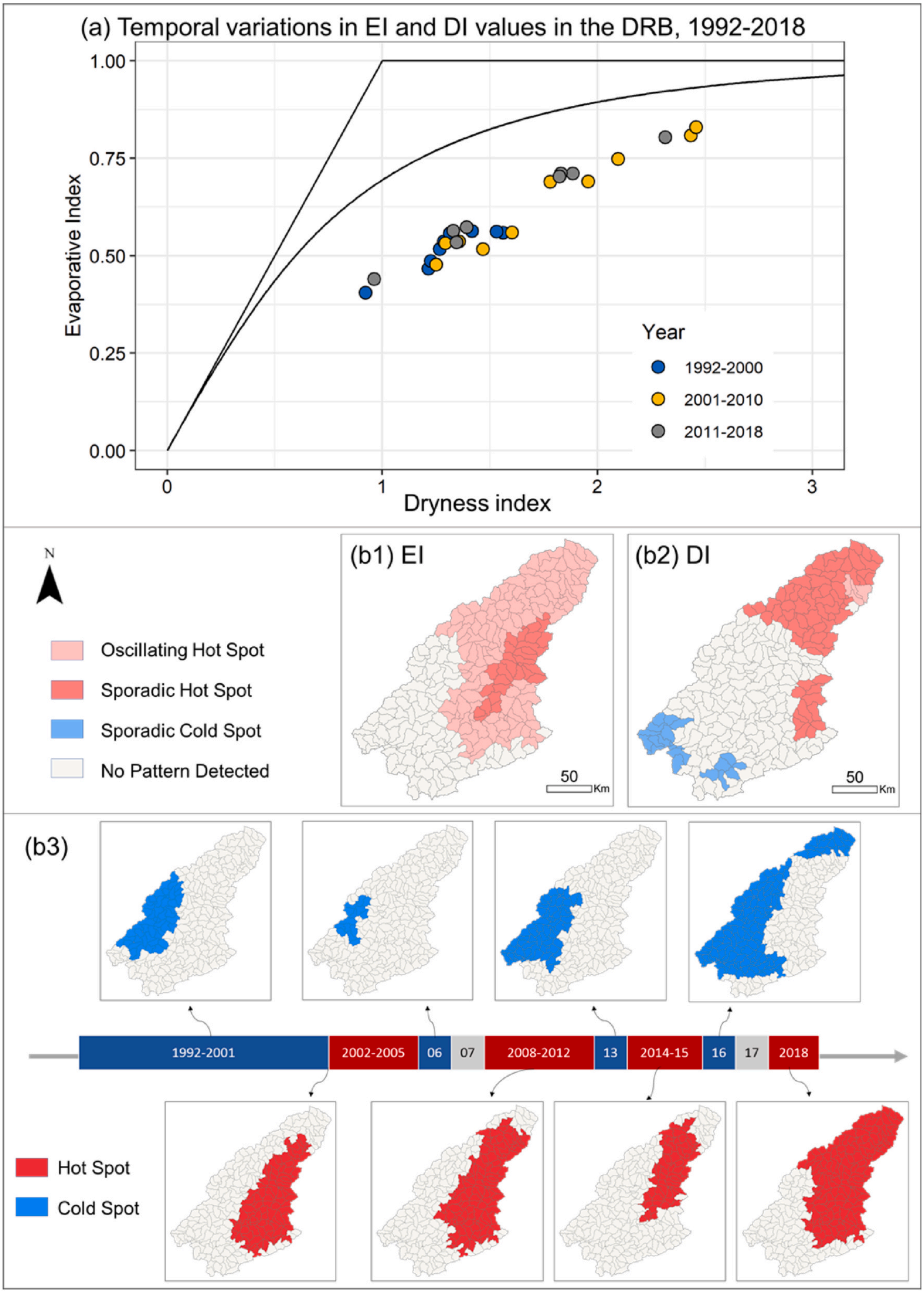

Fig. 3. Spatiotemporal patterns of hydrological conditions based on the Budyko framework in the DRB, from 1992 to 2018. Temporal variations in EI and DI values are shown in (a). Their spatiotemporal patterns are presented as hot and cold spots in (b1) and (b2), respectively. The spatial patterns of EI in individual years are depicted in (b3).

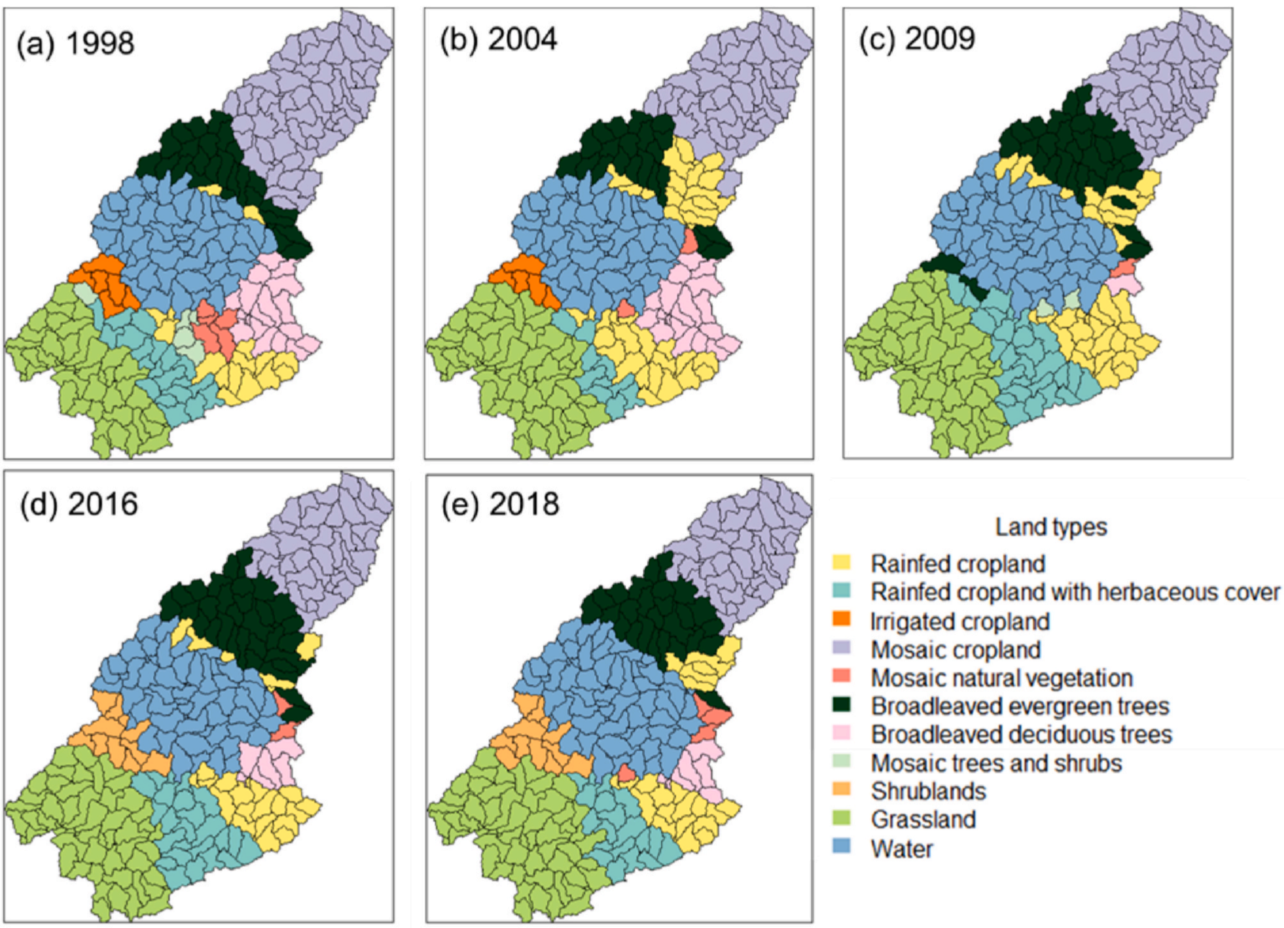

Fig. 4. The dominant land-cover types in five years are shown in (a)~(e). Sub-basins characterized by the same land-cover type are clustered and depicted in the same color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

around 3.5% of annual runoff can be reduced if 25% of grassland was transformed into forestland. A similar claim by Lin et al. (2015) was that the annual runoff in the DRB was predicted to decrease until 2050. It means that, with the current afforestation policy, additional forestland in the DRB causes less precipitation to reach the land surface in the form of runoff. As a result, the partitioning of precipitation to evapotranspiration increases, which can explain the increased EI values in our findings.

The EHSA-based spatial patterns indicate that hotspots in the upper part of the DRB have higher EI values than the south part, because of the faster evapotranspiration ratio of denser vegetated lands in the north (Yang et al., 2009). He et al. (2013) observed the effects of deforestation on increased runoff and thus decreased EI values in the DRB between 1959 and 2008. It suggests that, due to the emergence of environmental awareness, afforestation replacing deforestation can be a factor in the higher EI values in the northern DRB. There has been little research on EI changes based on the Budyko framework, and some existing studies may not reach the same conclusions as ours. For example, Wu and Chen (2013) stated that the EI value in the northern DRB (i.e., the upper DRB) did not have a great difference from that in the south part, using averaged AET and averaged P. Also, Xu et al. (2015) claimed lower EI values in the north than that in the south focusing on the precipitation (P), actual evapotranspiration (AET), and water yield (Q) in only five individual years (1995, 2000, 2005, and 2010). These two studies did not use continuous temporal and spatial data. Thus, with the first use of EHSA in a Budyko framework-based hydrological study, we give more comprehensive features of hydrological cycles by revealing spatiotemporal patterns in each time step and space observation. In this way, the spatially explicit hot and colds of EI values allow for a better understanding of how the Budyko framework-based hydrological conditions changed over time in different geographical locations.

4.2. ETR-LLUP framework implications for local hydrological management

The roles of land-use heterogeneity in hydrological processes have been well investigated. Many studies have described different evapotranspiration ratios and hydrological processes among different land properties (e.g., Alemayehu et al., 2017; Freund and Kirchner, 2017). For example, Kim et al. (2014) used non-spatial statistical models to analyze the long-term evapotranspiration in various land surfaces. Gao et al. (2018) considered land cover as well as topography for developing hydrological models for runoff simulation. Compared to conventional studies, we not only describe the differences in evapotranspiration ratio between vegetation types (Fig. 5), but also reveal that land use is a direct cause of evapotranspiration ratio changes in statistics (Table 1). Our framework also reflects how the Budyko framework-based evapotranspiration ratio responds to the changes in land use patterns by illustrating the positive and negative correlations. Another contribution is that the ETR-LLUP framework emphasizes the specific local situations, such as locally unique land use patterns and the resulting varied surface hydrological processes. To our knowledge, rare studies combined local situations with Budyko framework-based hydrological management. With a spatially-varied insight into local land use practices, this ETR-LLUP framework provides empirical spatial knowledge for implementing context-dependent planning principle. ETR-LLUP-driven land

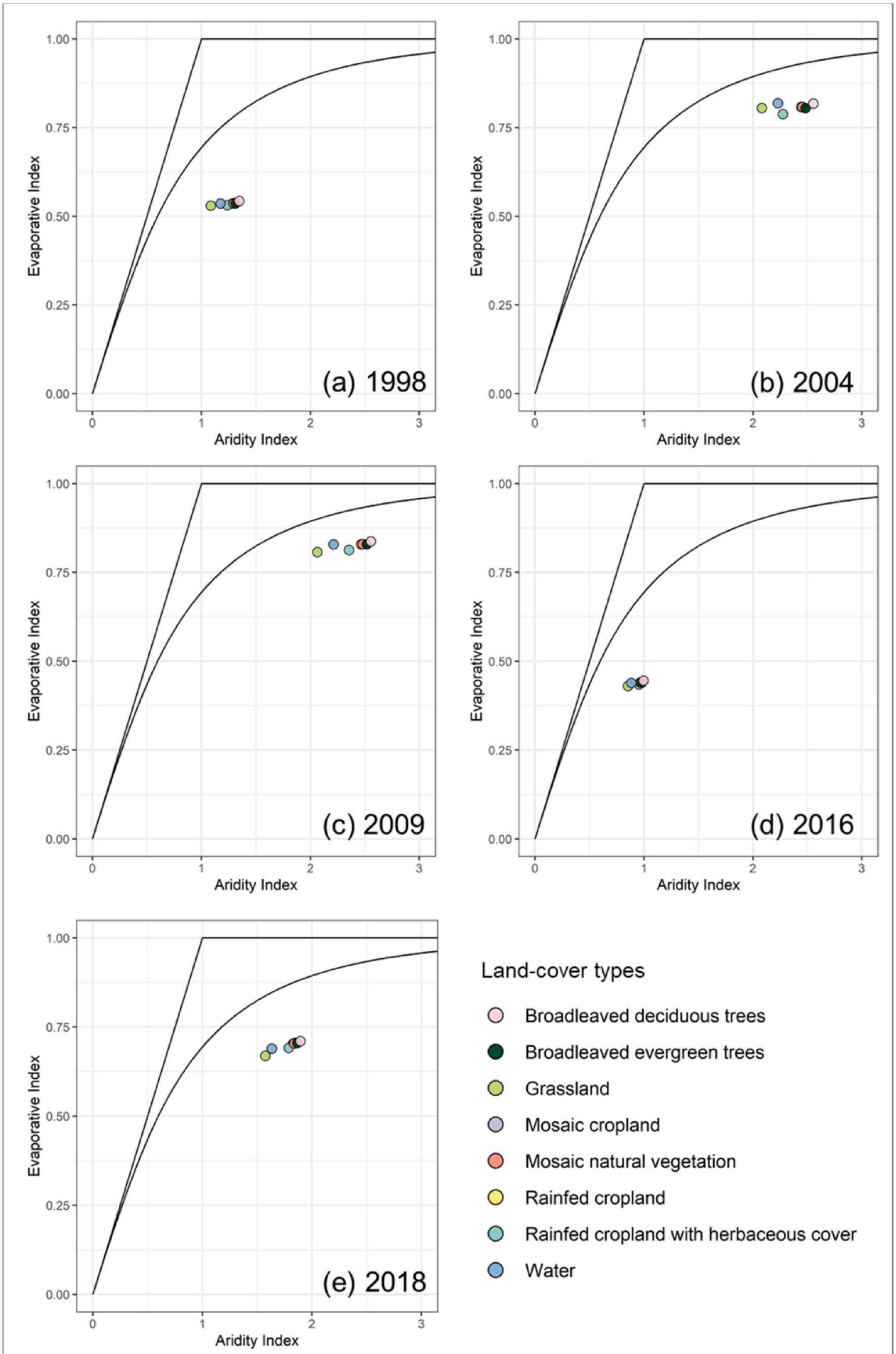

Fig. 5. Hydrological conditions based on the Budyko framework in DRB's eight dominant land-cover types, in 1998, 2004, 2009, 2016, and 2018, respectively.

Table 1
Correlation analysis for land-cover proportions and EI values in five years in the DRB and upper DRB.
Notes: 1998 and 2016 in blue table cells are the wet years and 2004, 2009, and 2018 in red table cells are the dry years. * denotes the land-cover types having statistically significant correlations with EI values (p-value < 0.01).

(a) the DRB

Land types	1998	2004	2009	2016	2018
Rain fed cropland		*			
Rainfed cropland with herbaceous covers					
Irrigated cropland		*			
Mosaic cropland	*		*	*	*
Mosaic natural vegetation	*	*	*	*	*
Broadleaved evergreen trees	*	*	*	*	
Broadleaved deciduous trees	*	*	*	*	*
Mosaic trees and shrubs					
Shrublands				*	*
Grasslands					
Water					

(b) the upper DRB

Land types	1998	2004	2009	2016	2018
Rain fed cropland					
Mosaic cropland	*		*		*
Broadleaved evergreen trees	*	*	*	*	*

use strategies have potentials to deal with local evapotranspiration ratio-based hydrological issues, allowing for social equity in terms of water security.

In practice, the ETR-LLUP framework suggests spatially-varied land use strategies based on the GWR models. We found that the proportions of 'Mosaic natural vegetation' and 'broadleaved deciduous tree' kept statistically significant relationships with EI in dry and wet climates (Fig. 6(d)(f)). These two land-cover types should be prioritized in the land use planning for adjusting hydrological processes. The positive coefficients between land-cover proportions and EI values imply that higher land-cover proportions lead to higher EI values and thereby higher evapotranspiration ratio. Because of the constant water-limited situations throughout the DRB in both dry and wet years (Fig. 5), decreased EI values for lower evapotranspiration ratio should be desirable in land use planning. Therefore, for decreased EI values and attenuated water-limited degrees in both dry and wet years, we recommend increasing the proportions of 'Mosaic natural vegetation' and 'broadleaved deciduous tree' in the west while decreasing them in the east. Furthermore, the land use strategy in the upper DRB is to increase the areas of 'broadleaved evergreen tree' for lower EI values according to their negative correlations (Fig. 6(i)), which has also been supported by Li et al. (2020) who found that, in the upper DRB, additional forest cover can increase surface runoff and mitigate drought in dry season. In summary, we discovered land-cover types that were correlated to EI-based evapotranspiration ratios across the basin as well as its upper stream. Importantly, the locations where the proportions of these land-cover types should be adjusted were also identified. Compared to traditional one-size-fits-all land use patterns, these spatially-varied land use strategies allow for the regulation of local evapotranspiration ratios and the facilitation of place-specific hydrological process management.

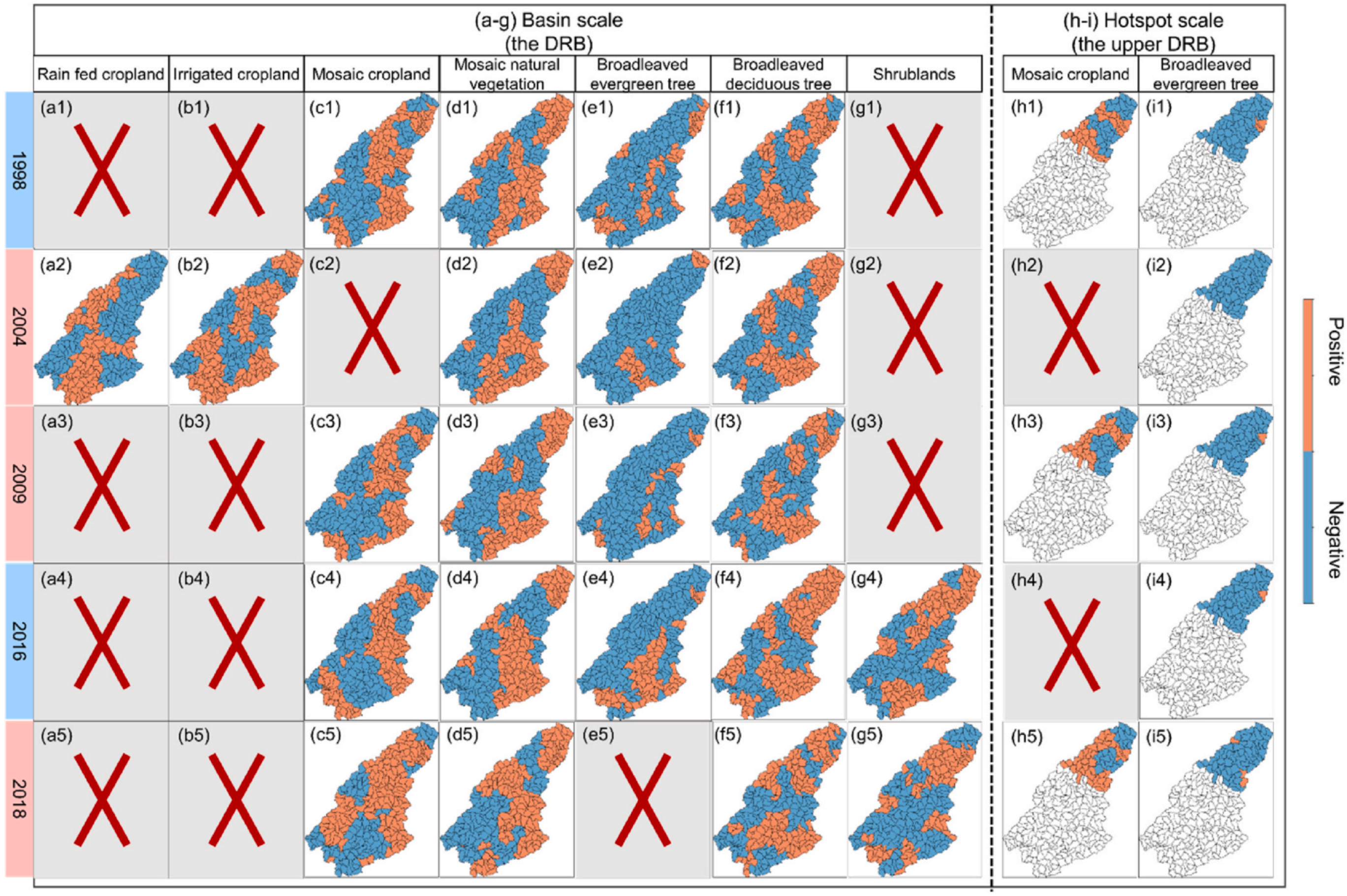

Fig. 6. Spatially-varied correlations between land-cover proportion and EI in five years in the entire basin (a–g) and upper stream (h–i). The red color represents a positive coefficient, and the blue color represents a negative coefficient. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusion

Integrating spatial analysis approaches (i.e., EHSA, GWPCA, and GWR) and the Budyko framework, we have developed a Local Land Use Planning framework for regulating spatially-varied EvapoTranspiration Ratios (ETR-LLUP). This framework provides methods to illustrate the spatiotemporal trends of the Budyko framework-based hydrological conditions in the DRB, and to elucidate the local patterns in terms of the land-cover proportions affecting the EI-based evapotranspiration ratio from 1992 to 2018. In detail, we demonstrate an increase in water-limited trends due to the rising evapotranspiration ratio across the basin in the recent 27 years. The upper DRB, with severer water-limited conditions than the south, is identified as the hotspot for hydrological process regulations. Our findings also indicate that croplands and trees are more water-stressed than other land-cover types in dry years. Moreover, throughout the basin, the proportions of 'mosaic natural vegetation' and 'broadleaved deciduous tree' correlate to the EI-based evapotranspiration ratio significantly in both dry and wet years. The proportions of 'broadleaved evergreen tree' also affect EI values in the upper DRB regardless of dry and wet climates. Importantly, we recommend spatially-varied land use strategies for mitigating water stress in the basin through lowering the evapotranspiration ratio (i.e., EI values). In our case, we suggest 1) increasing the proportions of 'mosaic natural vegetation' and 'broadleaved deciduous trees' in the west while decreasing them in the east; 2) expanding the 'broadleaved evergreen trees' in the upper DRB.

The ETR-LLUP-driven locally-specific land use strategies as well as their appropriate implementation locations are the major research outputs. The proposed ETR-LLUP framework not only theoretically integrates the Budyko framework and the EHSA into the land use planning, but also empirically complements the local land use practices for hydrological processes and water resource management based on spatially-varied land use and hydrological situations.

Credit author statement

Ping Yu Fan: Conceptualization, Methodology, Software, Writing – original draft & Review & Editing. Kwok Pan Chun: Methodology, Writing – review & editing, Supervision. Ana Mijic: Review & Editing. Mou Leong Tan: Review & Editing. Omer Yetemen: Review & Editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was supported by the Hong Kong Baptist University Faculty Research Grant (No. FRG1/17-18/044 and No. FRG1/16–17/034), the Research Impact Fund (No. R2002-20F) from the Hong Kong Research Grant Council (RGC), and the 2232 International Fellowship for Outstanding Researchers Program of the Scientific and Technological Research Council of Turkey (TUBITAK) through grant 118C329. This research was conducted using the resources of the High Performance

Cluster Computing Centre, Hong Kong Baptist University, which receives funding from Research Grant Council, University Grant Committee of the HKSAR and Hong Kong Baptist University. The corresponding author was supported by the New Starter Bundles in the University of the West of England. The Budyko approach in the paper was developed from the PROCORE-France/Hong Kong Joint Research Scheme 2020/21 584 (F-HKBU201/20).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115232.

References

Alemayehu, T., Van Griensven, A., Senay, G.B., Bauwens, W., Srivastava, P.K., Gloaguen, R., Thenkabail, P.S., 2017. Evapotranspiration mapping in a heterogeneous landscape using remote sensing and global weather datasets: application to the mara basin, east Africa. Rem. Sens. 9 (4), 390. https://doi.org/10.3390/RS9040390.

Bierkens, M.F., Dolman, A.J., Troch, P.A., 2008. Climate and the Hydrological Cycle. International Association of Hydrological Sciences.

Brunsdon, C., Fotheringham, A.S., Charlton, M.E., 1996. Geographically weighted regression: a method for exploring spatial nonstationarity. Geogr. Anal. 28 (4), 281–298. https://doi.org/10.1111/j.1538-4632.1996.tb00936.x.

Budyko, M.I., Miller, D.H., 1974. Climate and Life. Academic press.

Cartone, A., Postiglione, P., 2020. Principal component analysis for geographical data: the role of spatial effects in the definition of composite indicators. Spatial Econ. Anal. 1–22 https://doi.org/10.1080/17421772.2020.1775876.

Chen, X., Alimohammadi, N., Wang, D., 2013. Modeling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework. Water Resour. Res. 49 (9), 6067–6078. https://doi.org/10.1002/wrcr.20493.

Comber, A.J., Harris, P., Tsutsumida, N., 2016. Improving land cover classification using input variables derived from a geographically weighted principal components analysis. J. Photogrammetry Remote Sens. 119, 347–360. https://doi.org/10.1016/j.isprsjprs.2016.06.014.

Demšar, U., Harris, P., Brunsdon, C., Fotheringham, A.S., Mcloone, S., 2013. Principal component analysis on spatial data: an overview. Ann. Assoc. Am. Geogr. 103 (1), 106–128. https://doi.org/10.1080/00045608.2012.689236.

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.

Donohue, Randall J., Roderick, M.L., Mcvicar, T.R., 2012. Roots, storms and soil pores: incorporating key ecohydrological processes into Budyko's hydrological model. J. Hydrol. 436 (437), 35–50. https://doi.org/10.1016/j.jhydrol.2012.02.033.

ESRI, 2016. How Emerging Hot Spot Analysis Works. Retrieved. https://desktop.arcgis.com/en/arcmap/10.3/tools/space-time-pattern-mining-toolbox/learnmoreemerging.htm. (Accessed 20 November 2020).

Fan, P.Y., Chun, K.P., Mijic, A., Tan, M.L., He, Q., Yetemen, O., 2021. Quantifying land use heterogeneity on drought conditions for mitigation strategies development in the Dongjiang River Basin, China. Ecol. Indicat. 129, 107945. https://doi.org/10.1016/J.ECOLIND.2021.107945.

Fotheringham, A.S., Charlton, M.E., Brunsdon, C., 2001. Spatial variations in school performance: a local analysis using geographically weighted regression. Geogr. Environ. Model. 5 (1), 43–66. https://doi.org/10.1080/13615930120032617.

Fotheringham, A., Brunsdon, C., Charlton, M., 2003. Geographically Weighted Regression: the Analysis of Spatially Varying Relationships. John Wiley & Sons.

Freund, E.R., Kirchner, J.W., 2017. A Budyko framework for estimating how spatial heterogeneity and lateral moisture redistribution affect average evapotranspiration rates as seen from the atmosphere. Hydrol. Earth Syst. Sci. 21 (1), 217–233. https://doi.org/10.5194/hess-21-217-2017.

Gao, C., Zhou, P., Jia, P., Liu, Z., Wei, L., Tian, H., 2016. Spatial driving forces of dominant land use/land cover transformations in the Dongjiang River watershed, Southern China. Environ. Monit. Assess. 188 (2), 84. https://doi.org/10.1007/s10661-015-5088-z.

Gao, H., Sabo, J.L., Chen, X., Liu, Z., 2018. Landscape heterogeneity and hydrological processes: a review of landscape-based hydrological models. Landsc. Ecol. 33 (9), 1461–1480. https://doi.org/10.1007/s10980-018-0690-4.

Harris, P., Clarke, A., Juggins, S., Brunsdon, C., Charlton, M., 2015. Enhancements to a geographically weighted principal component analysis in the context of an application to an environmental data set. Geogr. Anal. 47 (2), 146–172. https://doi.org/10.1111/gean.12048.

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Ansari, S., Potapov, P., 2017. Using spatial statistics to identify emerging hot spots of forest loss. Environ. Res. Lett. 12 (2), 024012 https://doi.org/10.1088/1748-9326/aa5a2f.

He, Y., Lin, K., Chen, X., 2013. Effect of land use and climate change on runoff in the Dongjiang basin of south China. Math. Probl Eng. https://doi.org/10.1155/2013/471429.

Kim, W., Komori, D., Cho, J., Kanae, S., Oki, T., 2014. Long-term analysis of evapotranspiration over a diverse land use area in northern Thailand. Hydrol. Res. Lett. 8 (1), 45–50. https://doi.org/10.3178/HRL.8.45.

Li, D., Pan, M., Cong, Z., Zhang, L., Wood, E., 2013. Vegetation control on water and energy balance within the Budyko framework. Water Resour. Res. 49 (2), 969–976. https://doi.org/10.1002/wrcr.20107.

Li, G., Zhang, F., Jing, Y., Liu, Y., Sun, G., 2017. Response of evapotranspiration to changes in land use and land cover and climate in China during 2001-2013. Sci. Total Environ. 596, 256–265. https://doi.org/10.1016/j.scitotenv.2017.04.080.

Li, T., Xia, J., She, D., Cheng, L., Zou, L., Liu, B., 2020. Quantifying the impacts of climate change and vegetation variation on actual evapotranspiration based on the Budyko hypothesis in north and south Panjiang basin, China. Water 12 (2), 508. https://doi.org/10.3390/w12020508.

Li, Z., Zhou, P., Shi, X., Li, Y., 2020. Forest effects on runoff under climate change in the Upper Dongjiang River Basin: insights from annual to intra-annual scales. Environ. Res. Lett. 16 (1), 014032 https://doi.org/10.1088/1748-9326/abd066.

Lin, K., Zhai, W., Huang, S., Liu, Z., 2015. An evaluation of the effect of future climate on runoff in the Dongjiang River basin, South China. Proc. Int. Assoc. Hydrol. Sci. 368, 257–262. https://doi.org/10.5194/piahs-368-257-2015.

Liu, Y., Xiao, J., Ju, W., Xu, K., Zhou, Y., Zhao, Y., 2016. Recent trends in vegetation greenness in China significantly altered annual evapotranspiration and water yield. Environ. Res. Lett. 11 (9) https://doi.org/10.1088/1748-9326/11/9/094010.

Lu, B., Harris, P., Charlton, M., Brunsdon, C., 2014. The GWmodel R package: further topics for exploring spatial heterogeneity using geographically weighted models. Geo Spatial Inf. Sci. 17 (2), 85–101. https://doi.org/10.1080/10095020.2014.917453.

Matthews, S.A., Yang, T.C., 2012. Mapping the results of local statistics: using geographically weighted regression. Demogr. Res. 26, 151–166. https://doi.org/10.4054/DemRes.2012.26.6.

Niu, J., Sivakumar, B., 2014. Study of runoff response to land use change in the East River basin in South China. Stoch. Environ. Res. Risk Assess. 28 (4), 857–865. https://doi.org/10.1007/s00477-013-0690-5.

Odongo, V.O., van Oel, P.R., van der Tol, C., Su, Z., 2019. Impact of land use and land cover transitions and climate on evapotranspiration in the Lake Naivasha Basin, Kenya. Sci. Total Environ. 682, 19–30. https://doi.org/10.1016/j.scitotenv.2019.04.062.

Peng, Z., Gu, C., Liu, Z., Lin, W., Zhou, P., 2014. Impact of land use change during 1989-2009 on eco-capacity in Dongjiang watershed. Chin. J. Plant Ecol. 38 (7), 675. https://doi.org/10.3724/SP.J.1258.2014.00063.

Shen, Q., Cong, Z., Lei, H., 2017. Evaluating the impact of climate and underlying surface change on runoff within the Budyko framework: a study across 224 catchments in China. J. Hydrol. 554, 251–262. https://doi.org/10.1016/j.jhydrol.2017.09.023.

Stisen, S., Soltani, M., Mendiguren, G., Langkilde, H., Garcia, M., Koch, J., 2021. Spatial patterns in actual evapotranspiration climatologies for Europe. Rem. Sens. 13 (12), 2410. https://doi.org/10.3390/rs13122410.

Sun, G., Zuo, C., Liu, S., Liu, M., Mcnulty, S.G., Vose, J.M., Mcnulty, J.M., 2008. Watershed evapotranspiration increased due to changes in vegetation composition and structure under a subtropical climate. Jawra J. Am. Water Resour. Assoc. 44 (5), 1164–1175 https://doi.org/10.1111.

Voepel, H., Ruddell, B.L., Troch, P.A., Ruddell, B., Schumer, R., Brooks, P.D., Sivapalan, M., 2011. Quantifying the role of climate and landscape characteristics on hydrologic partitioning and vegetation response. Water Resour. Res. 47 (10), W00J09. https://doi.org/10.1029/2010WR009944.

Wu, Y., Chen, J., 2013. Analyzing the water budget and hydrological characteristics and responses to land use in a monsoonal climate River Basin in south China. Environ. Manag. 51 (6), 1174–1186. https://doi.org/10.1007/s00267-013-0045-5.

Xu, J., Xiao, Y., Li, N., Wang, H., 2015. Spatial and temporal patterns of supply and demand balance of water supply services in the Dongjiang lake basin and its beneficiary areas. J. Resour. Ecol. 6 (6), 386–396. https://doi.org/10.5814/J.ISSN.1674-764X.2015.06.006.

Yang, D., Shao, W., Yeh, P.J.-F., Yang, H., Kanae, S., Oki, T., 2009. Impact of vegetation coverage on regional water balance in the nonhumid regions of China. Water Resour. Res. 45 (7), 1–13. https://doi.org/10.1029/2008WR006948.

Yang, L.E., Chan, F.K.S., Scheffran, J., 2018. Climate change, water management and stakeholder analysis in the Dongjiang River basin in South China. Int. J. Water Resour. Dev. 34 (2), 166–191. https://doi.org/10.1080/07900627.2016.1264294.

Zhang, L., Hickel, K., Dawes, W.R., Chiew, F.H.S., Western, A.W., Briggs, P.R., 2004. A rational function approach for estimating mean annual evapotranspiration. Water Resour. Res. 40 (2), W02502. https://doi.org/10.1029/2003WR002710.

Zhang, Q., Xu, C.-Y., Zhang, Z., 2009. Observed changes of drought/wetness episodes in the Pearl River basin, China, using the standardized precipitation index and aridity index. Theor. Appl. Climatol. 98 (1–2), 89–99. https://doi.org/10.1007/s00704-008-0095-4.

Zhang, S., Yang, Y., McVicar, T.R., Yang, D., 2018. An analytical solution for the impact of vegetation changes on hydrological partitioning within the Budyko framework. Water Resour. Res. 54 (1), 519–537. https://doi.org/10.1002/2017WR022028.