Mapping Hydrological Ecosystem Services (HESS) in major Vietnamese river basins using remote sensing and hydrological modelling to promote nature-based solutions

Ha, Lan Thanh; Bastiaanssen, W. G.M.; Das, Narendra; Hessels, Tim

DOI
10.1016/j.ejrh.2025.102626

Publication date
2025

Document Version
Final published version

Published in
Journal of Hydrology: Regional Studies

Journal of Hydrology: Regional Studies 61 (2025) 102626

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

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

Mapping Hydrological Ecosystem Services (HESS) in major Vietnamese river basins using remote sensing and hydrological modelling to promote nature-based solutions

Lan Thanh Ha [a,b,*], W.G.M. Bastiaanssen [a,c], Narendra Das [d,e], Tim Hessels [a]

[a] *Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft 2628 CN, the Netherlands*
[b] *Institute of Water Resources Planning, 162A Tran Quang Khai, Hanoi 100000, Vietnam*
[c] *Hydrosat (formerly IrriWatch), Agro Business Park 10, Wageningen 6708 PW, the Netherlands*
[d] *Biosystems and Agricultural Engineering, Michigan State University, MI, USA*
[e] *Civil and Environmental Engineering, Michigan State University, MI, USA*

A R T I C L E I N F O

Keywords:
Hydrological ecosystem services
Ecohydrological modelling
Remote sensing
Natural capital accounting

A B S T R A C T

Study region: This study covers 16 major river basins across Vietnam, encompassing diverse topographies and climatic zones. These basins represent key regions for national water resource planning, agricultural development, and ecosystem conservation.
Study focus: This study presents the quantification results of Hydrological EcoSystem Services (HESS) for 16 major river basins in Vietnam, using integrated earth observation datasets with water and energy balance models such as the Regional Hydrological Extremes for Agriculture System (RHEAS) by NASA-JPL and the Water Productivity (WaPOR) by FAO. Eight HESS indicators, such as total runoff, rootzone water storage, carbon sequestration, and microclimate cooling were evaluated for the hydrological years, representing wet, average, and dry climatic conditions (2005, 2010, 2019 and 2022). A synthesized score was introduced to benchmark sustainability level of these basins throughout the period.
New hydrological insights for the region: The results reveal distinct exhibit a diverse distribution of HESS across basins, interrelationship as well as trade-offs. This study illustrates how remote sensing data and spatial algorithms can be applied to determine various aspects of HESS across different landscapes and ecosystems. Basins in the central regions exhibited stronger ecosystem performance, while those in the more urbanized northern and southern regions showed comparatively lower levels. With quantified HESS and benchmarked sustainability score, the natural capital assets of Vietnam are herewith revealed, and this system can also be applied to other countries. The findings underscore the value of integrating earth observation and ecohydrological modelling to support HESS monitoring, the design of Nature-based Solutions (NbS), and sustainable water resource planning in data-scarce regions.

1. Introduction

To address ongoing challenges posed by climate changes and degrading ecosystems (Malhi et al., 2020; Rama et al., 2022), water

* Corresponding author at: Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft 2628 CN, the Netherlands.
E-mail address: thanhlan.ha@gmail.com (L.T. Ha).

https://doi.org/10.1016/j.ejrh.2025.102626
Received 28 September 2024; Received in revised form 11 July 2025; Accepted 15 July 2025
Available online 19 July 2025

resource planners and environmental advocates are increasingly endorsing ecosystem-based strategies such as Nature-based Solutions (NbS) and green infrastructure (Dunlop et al., 2024; Millennium Ecosystem Assessment, 2005; Xu et al., 2023). These strategies offer multiple benefits for both nature and humans. For example, restoring wetlands can enhance resilience to floods and drought, improve water quality through the removal of organic and non-organic pollutants (Ferreira et al., 2023), and positively improve human well-being (Kolokotsa et al., 2020; Millennium Ecosystem Assessment, 2005). Reforestation in upstream catchments can reduce surface runoff and soil erosion (Fu et al., 2011), enhance groundwater recharge, regulate micro-climate and sequester carbon (Choi et al., 2023). Additionally, restored natural forests can provide livelihoods for communities through the provision of wood and other recreational values (Seddon et al., 2020). These NbS approaches are designed to mitigate further ecosystem degradation while simultaneously meeting the demands of human development and activities (Johnson et al., 2022; UNESCO, 2018).

To enhance the effectiveness of NbS and Integrated Water Resources Management (IWRM) approaches, it is crucial to monitor and assess hydrological ecosystem services (HESS) (Bagstad et al., 2013; Grizzetti et al., 2016). A comprehensive understanding of HESS is essential for developing robust responses to water scarcity (Hoekstra et al., 2012; Liu et al., 2017) and addressing critical challenges in IWRM implementation. Riverine environments and river basins are particularly sensitive, where minor change in upstream areas, such as land-use modifications, agricultural water management, forest protection or damming of river can significantly impact downstream environments and communities (Brauman, 2015; Fu et al., 2017; Pereira, 2020; Poortinga et al., 2019). Enhanced quantification and benchmarking of HESS are crucial for basin planners seeking to optimize basin development objectives, such as increasing biomass production, improving crop yields (Uhlenbrook et al., 2022), or adjusting water management practices to ensure more renewable water for supply during dry seasons, drought periods, or future climate variability scenarios (Apurv and Cai, 2020).

Ha et al. (2023) outlined key indicators related to both consumptive and non-consumptive use within the Hydrological Ecosystem Services framework (HESS17). The HESS17 framework is valuable for implementing water policy frameworks like IWRM and Water Accounting (Ha et al., 2023; Karimi et al., 2013) as well as for Nature-based solutions (NbS) (UNESCO, 2018). NbS have emerged as a central concept in sustainable water management, building on principles of ecological engineering, ecosystem-based adaptation, and green infrastructure (IUCN, International Union for Conservation of Nature, 2020). HESS such as dry season flow support, groundwater recharge, microclimate regulation, and sustaining rainfall provide measurable indicators that are essential for designing and monitoring NbS interventions. Mapping and quantifying HESS at basin scale, therefore, directly supports the implementation and scaling up of NbS in global river basins. HESS mapping can serve as a catalyst for transforming agricultural production systems and achieving multiple SDGs. Specifically, the quantified indicators in this study directly support monitoring progress toward SDG 6 (Clean Water and Sanitation) by assessing water provision and management, SDG 13 (Climate Action) through climate regulation services such as microclimate cooling and carbon sequestration, and SDG 15 (Life on Land) by promoting ecosystem health and sustainable land management.

Global hydrological models and remote sensing data sets are used to assess HESS at national and regional scales. An example is the global assessment of ecological flow requirements conducted by the International Water Management Institute (IWMI), which was based on river flow statistics generated from the global hydrology model PCR-GlobWB developed by Utrecht University, The Netherlands (Sood et al., 2017). In this process, the incorporation of remote sensing into ecohydrological models overcome the limitations of local and river basin scales by utilizing global remote sensing and publicly available datasets, such as land-use information (Hengl et al., 2014) and Digital Elevation Model (Rau et al., 2024). For water balance analysis, this study utilizes the RHEAS model developed by NASA-JPL. RHEAS is a modular modelling framework that delivers end-to-end results for vertical soil water balance. The model's routine of forcing data is automated, such as precipitation data from Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2014). RHEAS has been rigorously calibrated for the Mekong region, including Vietnam, through NASA-supported SERVIR-Mekong programme and is currently operational in the region under the Mekong Drought and Crop Watch by Asian Disaster Preparedness Center (ADPC) at https://mdcw-servir.adpc.net/.

Another advantageous tool is FAO's Water Productivity model (WaPOR) (WaPOR database methodology, 2020). FAO's WaPOR database provides spatially explicit remote sensing-based estimates of key water, land, and productivity indicators. WaPOR products are derived from remote sensing imagery combined with modelling algorithms and has a global coverage starting from 2020. This study adopts the approach by FAO's WaPOR approach and customizes the code using Python (https://bitbucket.org/cioapps/pywapor/src/master/) to run it for all 16 major river basins in Vietnam. WaPOR is based on the ETLook energy balance model (Bastiaanssen et al., 2012) that processes evaporation and transpiration, along with biomass production such as Net Primary Production (NPP) and Gross Primary Production (GPP). This data was adopted to generate a set of HESS indicators using the approach provided by Ha and Bastiaanssen (2023). In this study, WaPOR and RHEAS was run for entire Vietnam for four years: 2005 (normal year), 2010 (wet year), 2019 (dry year) and 2022 (normal year). Eight HESS indicators were derived, including Total runoff, Natural livestock feed production, Fuelwood from natural forest, Dry season flow, Root zone water storage, Sustaining rainfall, Carbon sequestration and Micro-climate cooling. A synthesized score was introduced based on normalized ranking of sixteen river basins to benchmark the sustainability level of these basins throughout the study period.

The objective of this study is twofold: 1) it describes an operational modelling procedure for the quantification and mapping of HESS for entire Vietnam, taking into account its 16 major river basins and 2) it assesses the country's performance in restoring and maintaining its ecosystem and ecosystem services.

2. Study area

Fig. 1 illustrates the geographical distribution of the 16 major basins across the country, while Table 1 provides a comprehensive list detailing their characteristics. Among these basins, the Red River basin stands out as the largest, covering an area of 88,860 km^2, which constitutes approximately 50 % of its total transboundary basin area of 169,000 km^2 sharing with China and Laos. Following closely, the Mekong basin spans approximately 40,000 km^2 within Vietnam and extends significantly across six countries in the Mekong region, including China, Myanmar, Laos, Thailand, Cambodia and Vietnam, a total area reaching 795,000 km^2. The basin is renowned for its rich biodiversity and resources, and is critically important for regional economic development and people livelihoods (Shrestha et al., 2013).

Locating centrally within Vietnam, smaller basins such as Gianh, Thach Han, Huong, Vu Gia – Thu Bon, Tra Khuc, Kon-Ha Thanh, Ba, South-Eastern River Cluster (SERC) and Dong Nai play essential roles despite their smaller size. They are significant economic and tourism hubs in Vietnam, encompassing cities such as Da Nang, Hue, and Ho Chi Minh City.

3. Research methodologies

3.1. FAO's Water Productivity database (WaPOR)

3.1.1. Actual evapotranspiration

The method to calculate evaporation (E) and transpiration (T) is based on the ETLook model as outlined by (Bastiaanssen et al., 2012). This model is based on the Penman-Monteith (P-M) method with remote sensing as input data. Originally developed by Penman (1948), this approach has been employed by FAO as the standard method for calculating crop reference evapotranspiration (Allen et al., 1998). Eq. 1 illustrates the P-M method.

$$\lambda \boldsymbol{ET} = \frac{\boldsymbol{\Delta}(\boldsymbol{R_n} - \boldsymbol{G}) + \boldsymbol{\rho_a c_p}\frac{(e_s - e_a)}{r_a}}{\Delta + \boldsymbol{\gamma}\left(\mathbf{1} + \frac{r_s}{r_a}\right)} \quad (1)$$

Where λ: latent heat of evaporation [J kg^{-1}]; ET: evapotranspiration [kg m^{-2} s^{-1}]; R_n: net radiation [W m^{-2}]; G: soil heat flux [W m^{-2}]; ρ_a : air density [kg m^{-3}]; c_p: specific heat of dry air [J kg^{-1} K^{-1}]; e_a : actual vapour pressure [Pa]; e_s: saturated vapour pressure [Pa]; Δ : slope of the saturation vapour pressure vs. temperature curve [Pa K^{-1}]; γ : psychrometric constant [Pa K^{-1}]; r_a : aerodynamic resistance [s m^{-1}]; r_s : bulk surface resistance [s m^{-1}].

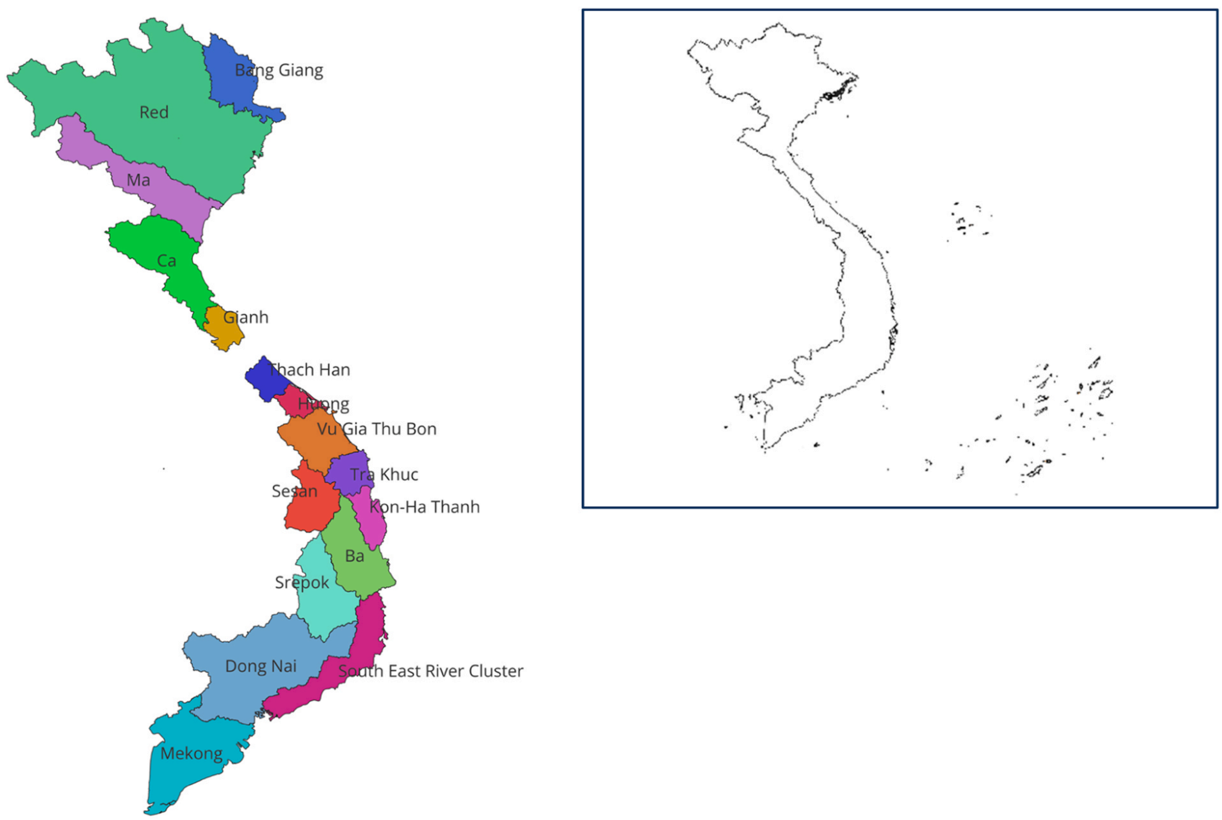


Fig. 1. 16 major basins in Vietnam (Asian Development Bank, 2018).

Table 1
Basin area listing from upstream to downstream.

Basin	Area in Vietnam (km^2)	Total basin area (km^2)
Red	88,860	169,000
Bang Giang Ky Cung	10,847	10,847
Ma	17,653	28,400
Ca	17,900	27,200
Gianh	0406	-
Thach Han	0385	-
Huong	3066	-
Vu Gia – Thu Bon	10,035	-
Tra Khuc	3337	-
Sesan	11,510	-
Srepok	18,230	-
Kon-Ha Thanh	3809	-
Ba	13,417	-
South-Eastern River Cluster (SERC)	6402	-
Dong Nai	36,530	44,100
Mekong	39,945	795,000

3.1.2. Dry matter production

Total biomass production (TBP) [kg m^{-2} or kg ha^{-1}] is defined as the sum of the dry matter produced during the crop growing season or for the annual cycle when pertained to agro-forests or natural vegetation cover. TBP is also a good indicator for crop yield because it integrates three important aspects: the current vegetation status (via Fraction of Photosynthetically Active Radiation absorbed (fPAR)), the meteorological influences (via Photosynthetically Active Radiation (PAR), [MJ m^{-2} day^{-1}]) and the soil moisture conditions of the root zone (via Light Use Efficiency (LUE), [kg DM MJ^{-1}]). The seasonal value represents the total accumulated biomass during one growing season or annual cycle:

$$\boldsymbol{TBPtotal_S} = \sum\nolimits_{end}^{start} (\mathbf{0.864} \quad \boldsymbol{xfPARxPARxLUE}) \tag{2}$$

3.1.3. Soil moisture

Different soil moisture models exist in the international remote sensing society (Das et al., 2018; Singh and Das, 2022), and solutions based on Land Surface Temperature (LST) has a preference because they can look into the subsoil via stomatal responses (Anav et al., 2018). Relative soil moisture content (S_e) and soil moisture stress (S_t) in WaPOR is determined based on the correlation between Land Surface Temperature derived from thermal infrared imagery and vegetation cover derived from the NDVI (Yang et al., 2015). The trapezoidal corners A, B, C and D are estimated for each pixel (Fig. 2). The relative soil moisture content S_e of a specific location (e.g. point E) determined using following equations:

$$\boldsymbol{S_e} = \frac{\boldsymbol{b}}{\boldsymbol{a}+\boldsymbol{b}} \tag{3}$$

In which: $a = LST - T_{\min}$ and $b = (1 - F_c)(LST - T_{s,\max}) + T_{c,\max} - LST$

Where: LST: Land surface temperature [K]; F_c : vegetation cover, $T_{s,\min}$ [K] is estimated as wet-bulb temperature, $T_{c,\min}$ [K] is

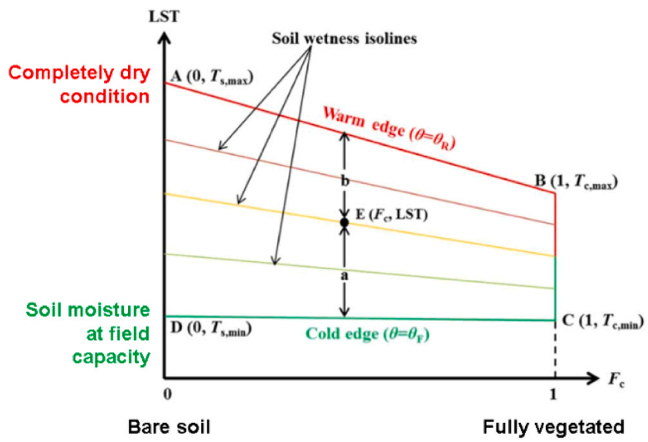


Fig. 2. Trapezoidal method for estimating four extreme conditions (i.e., four corners) representing vegetation coverage/land surface temperature (Fc/LST) space (*WaPOR database methodology*, 2020; Yang et al., 2015).

estimated as air temperature at full vegetation, $T_{s,\max}$ [K] and $T_{c,\max}$ [K] are estimated using modified P-M equation (Yang et al., 2015).

3.2. Hydrology and water balance using RHEAS

RHEAS is a modular software framework created at NASA's Jet Propulsion Laboratory (JPL) with the aim of simplifying the implementation of water resources simulations and integrating remote sensing observations. At its core, RHEAS features the Variable Infiltration Capacity (VIC) model. The system employs a variety of datasets from diverse sources to either drive or assimilate observations into the hydrologic model. Data assimilation helps constrain hydrologic simulations, thereby enhancing model states and/or parameterizations, and is explicitly integrated into RHEAS (Andreadis et al., 2017). The schematization of RHEAS and the water balance component in VIC is illustrated in Fig. 3, in which:

P: precipitation (mm), E_1: Evaporation from bare soil is extracted only from layer 1 (mm), E_p: potential evaporation (mm), E_c: evaporation from canopy (mm), E_t: transpiration (mm), W_1^c: The maximum soil moisture content of layer 1 (mm), W_2^c: The maximum soil moisture content of layer 2 (mm), Q_d : direct surface runoff (mm), Q_b : baseflow (mm), Q_{12} is the drainage from layer 1 to layer 2; N represents N different types of vegetation; $n = N+1$ represents bare soil.

RHEAS employs VIC for water balance, though other models can also be integrated thanks to the modular framework of RHEAS. RHEAS has a set of datasets that are automated to run VIC simulations at varying spatial resolutions (1°, 1/2°, 1/4° globally). Land cover information is obtained from Moderate resolution Imaging Spectroradiometer (MODIS) global product at a 500 m spatial resolution. Finally, VIC requires information on soil properties which are adapted from global and regional implementations of the VIC model (Andreadis et al., 2017). The VIC model is applied with a spatial resolution of 5 km and the runoff and recharge output data was used in RHEAS to generate daily streamflow.

The reliability of the modeled outputs is supported by prior calibration and validation studies. RHEAS hydrological outputs have been evaluated globally, including the Mekong basin (Chishtie et al., 2019) with validation sites in Vietnam (Ninh Thuan, Vinh Phuc and Binh Dinh). Similarly, WaPOR-based evapotranspiration (ET) and biomass products have been validated across Southeast Asia with satisfactory accuracy. In the context of Vietnam, Ha et al. (2018) successfully applied remote sensing-derived ET and LAI to calibrate SWAT models for the Day Basin, achieving R^2 values above 0.7 and NSE values above 0.65 for streamflow simulations. These independent studies confirm the feasibility of quantifying HESS in data-scarce basins using remote sensing and eco-hydrological models.

3.3. HESS indicators to be included

Based on the established HESS framework (Ha et al., 2023), eight HESS indicators are selected for this analysis (see Table 2). Some HESS indicators were excluded due to their irrelevance for river basin scale. The selected indicators are consistent with those used by Ha and Bastiaanssen (2023). In this manner, a standardized set of HESS indicators can be consistently generated and provided at the river basin scale. Indicators are highly specific and are designed for local geographies, such as leisure and fish stock, and thus were not included in the broader analysis.

3.4. Methodologies

3.4.1. Data flow & sources

Fig. 4 presents the overall flowchart to determine each of the eight HESS indicators. For each HESS indicator, a specific routine is defined, incorporating data from WaPOR and RHEAS model.

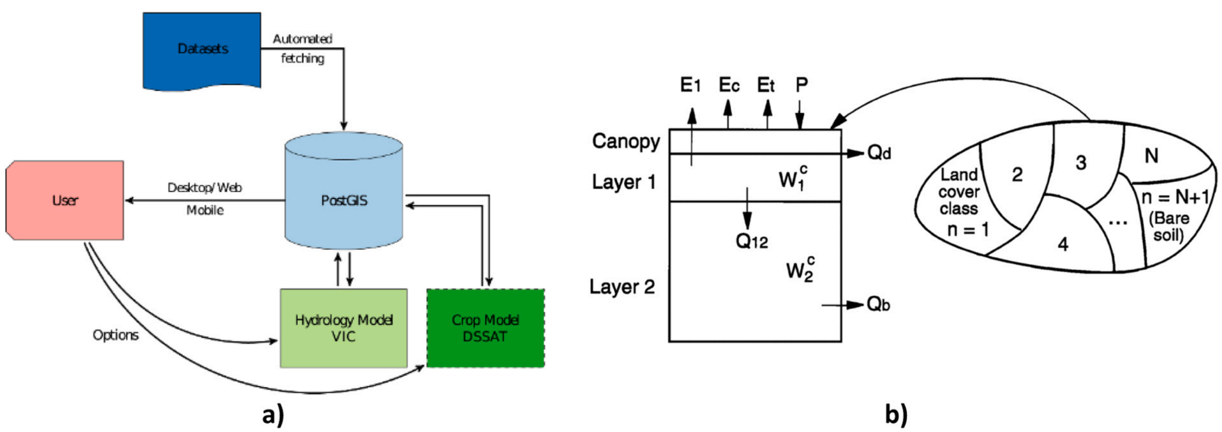


Fig. 3. Schematization of a) RHEAS model (Andreadis et al., 2017) and b) the water balance component using VIC model (Liang et al., 1994).

Table 2
List of HESS to be considered for mapping of Vietnam.

HESS	Ecosystem services/Concept	Unit	Spatial resolution	Temporal resolution	Modelling platform
1	Total runoff	m3/ha	5 km	Daily	RHEAS
3	Natural livestock feed production	kg/ha	250 m	8-day	WaPOR
4	Fuelwood from natural forest	kg/ha	250 m	8-day	WaPOR
5	Dry season flow	m3/ha	5 km	Daily	RHEAS
8	Root zone water storage	m3	250 m	8-day	WaPOR
9	Sustaining rainfall	m3/ha	250 m	8-day	WaPOR
11	Carbon sequestration	kg C/ha	250 m	8-day	WaPOR
13	Micro-climate cooling	℃	250 m	8-day	WaPOR

3.4.2. Calculation of hydrological ecosystem service (HESS)

Total runoff (HESS1) is calculated using the RHEAS model. HESS1 is derived from direct runoff (Q_d) computed for each pixel in the RHEAS model (Andreadis et al., 2017; Liang et al., 1994). The pixel data is aggregated and routed to the nearest stream. **Dry season flow (HESS5)** is also calculated using the RHEAS model. Baseflow (Q_b) can be used to represent drainage from the deep soil layer that contributes to runoff during the dry season.

Natural livestock feed production (HESS3) [kg ha^{-1}] is calculated from biomass production using WaPOR, combined with a land-cover map from GlobCover (Bontemps et al., 2013). Based on GlobCover land-use classification, three land cover classes in 16 river basins are potentially suitable for grazing: consisting of mosaic crop (including vegetation crop) and cropland. As described by Ha and Bastiaanssen (2023), an initial partition is made between above ground and below ground accumulated biomass of the crop organs, characterized by the shoot /root ratio. Additionally, not every above ground biomass would be used for livestock feed, hence a fraction (f_{ABG}) is made for this conversion. The equation is as follows:

$$\textit{Natural livestock feed production} = f_{ABG} \times \alpha_{feed} \times TBP \tag{4}$$

Where $f_{ABG} = 0.65$, and 40 percent of this amount (α_{feed}) is considered natural livestock feed.

Similarly, **fuelwood from natural forest (HESS4)** [kg ha^{-1}] is calculated from WaPOR's biomass production and the GlobCover land-cover map. HESS4 is calculated from broadleaved, deciduous and evergreen land cover classes. Fuelwood is only considered for natural landscapes, for which a conversion coefficient is used to separate above and below ground biomass production as

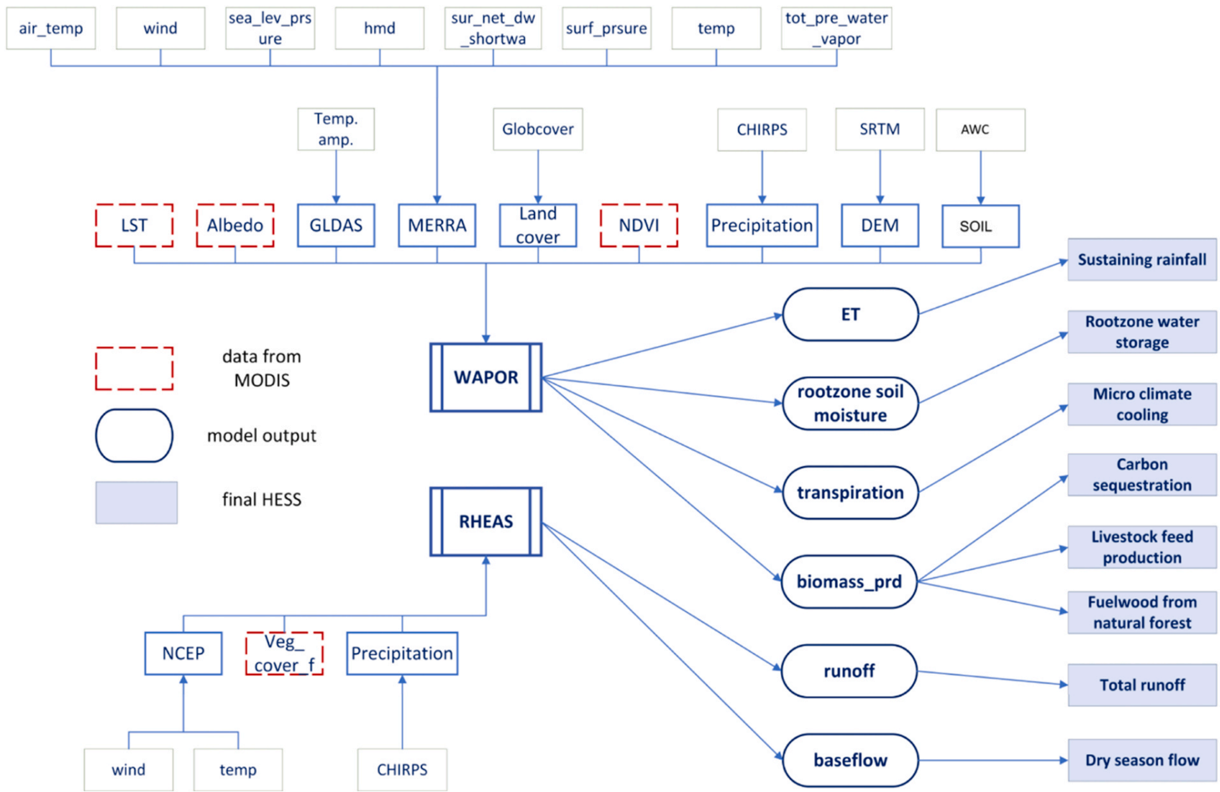


Fig. 4. Hydrological Ecosystem Services (HESS) calculation routine with WaPOR and RHEAS model.

recommended by Ponce-Hernandez et al. (2004). The fraction of above ground biomass production (AGB [kg ha^{-1}]) usable as firewood ($\alpha_{fuelwood}$) is taken as 5 % (e.g., dead wood and debris).

$$\textbf{Fuelwood from natural forest} = \alpha_{fuelwood} \times AGB \tag{5}$$

Carbon sequestration (HESS11) is a fraction of biomass production (CH_2O). One unit of sequestrated carbon C is equivalent to 12/30 (calculated from the molecular weight) or 0.4 unit of biomass, if biomass exists entirely of carbon-hydrates. HESS11 is computed using WaPOR's biomass production results with separated routines for woody vegetation and crops as described in Ha and Bastiaanssen (2023). In this study, the sequestrated carbon fraction is taken as 2 % and 34 % of the total crop biomass production for crops and woody vegetation (e.g., shrubs and trees) respectively. **Root zone water storage (HESS8)** is calculated from WaPOR's relative soil moisture and ISRIC's available water content (AWC), computed for each pixel in millimeters of water depth. **Sustaining rainfall (HESS9)** is computed using WaPOR's simulated evapotranspiration (ET). A fraction is applied to convert ET to HESS9 using the following formula (Ha and Bastiaanssen, 2023):

$$P_{sus} = P - P_{adv} = \alpha ET \tag{6}$$

Where P_{sus} is the sustained rainfall due to local evaporation processes (mm yr^{-1}); P_{adv} is the rainfall originating from external sources (mm yr^{-1}) and α is the evaporation recycling ratio. As demonstrated in (Coerver, 2007), a fraction of 7.5 % can be applied for the climatic conditions encountered in Vietnam.

Micro-climate cooling (HESS13) is calculated from transpiration (T) using WaPOR, with the following formula:

$$\Delta T_{cooling} = \frac{r_{ah}}{\rho_a . C_p} . T \tag{7}$$

With T being transpiration [mm], ρ_a being the density of moist air [kg m^{-3}], C_p is the specific heat at constant pressure for air (1004 J/kg.K), r_{ah} is aerodynamic resistance to heat transfer that we fixed at 70 s m^{-1} following Senay et al. (2013).

4. Results and discussions

4.1. Intermediate results from WaPOR

The 250 m results of ET, soil moisture and biomass production are presented in Fig. 5. Considerable ranges of all these parameters were detected. Areas with a higher soil moisture also have a higher ET and biomass production. The opposite is also true. The large variability of soil moisture is related to land-use influences on infiltration and runoff. Rainfall also impacts soil moisture, but the local patterns are more related to land use, soil type and topography. The power of remote sensing data to encompass local and national scale is clear by studying the results presented in Fig. 6, which presents a detailed view of the same parameters as in Fig. 5 for ET, rootzone soil moisture and biomass production from WaPOR.

Spatial variability is substantial and this creates also questions on whether global scale models can properly assess the effective behaviour of composite landscapes. Validation papers of WaPOR have been published by others (Blatchford et al., 2020; Dhonthi et al., 2024; Marloes and Bastiaanssen, 2019; Weerasinghe et al., 2020) and it is therefore believed these detail results are acceptable for the purpose of HESS mapping.

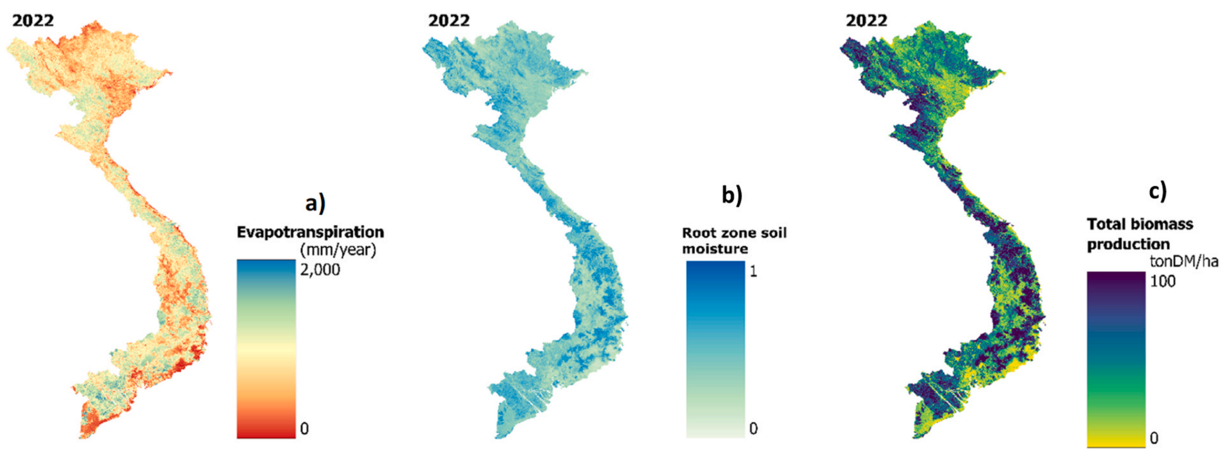


Fig. 5. Intermediate results from WaPOR in 2022 for: a) evapotranspiration (ET); b) Soil moisture; c) Biomass production;.

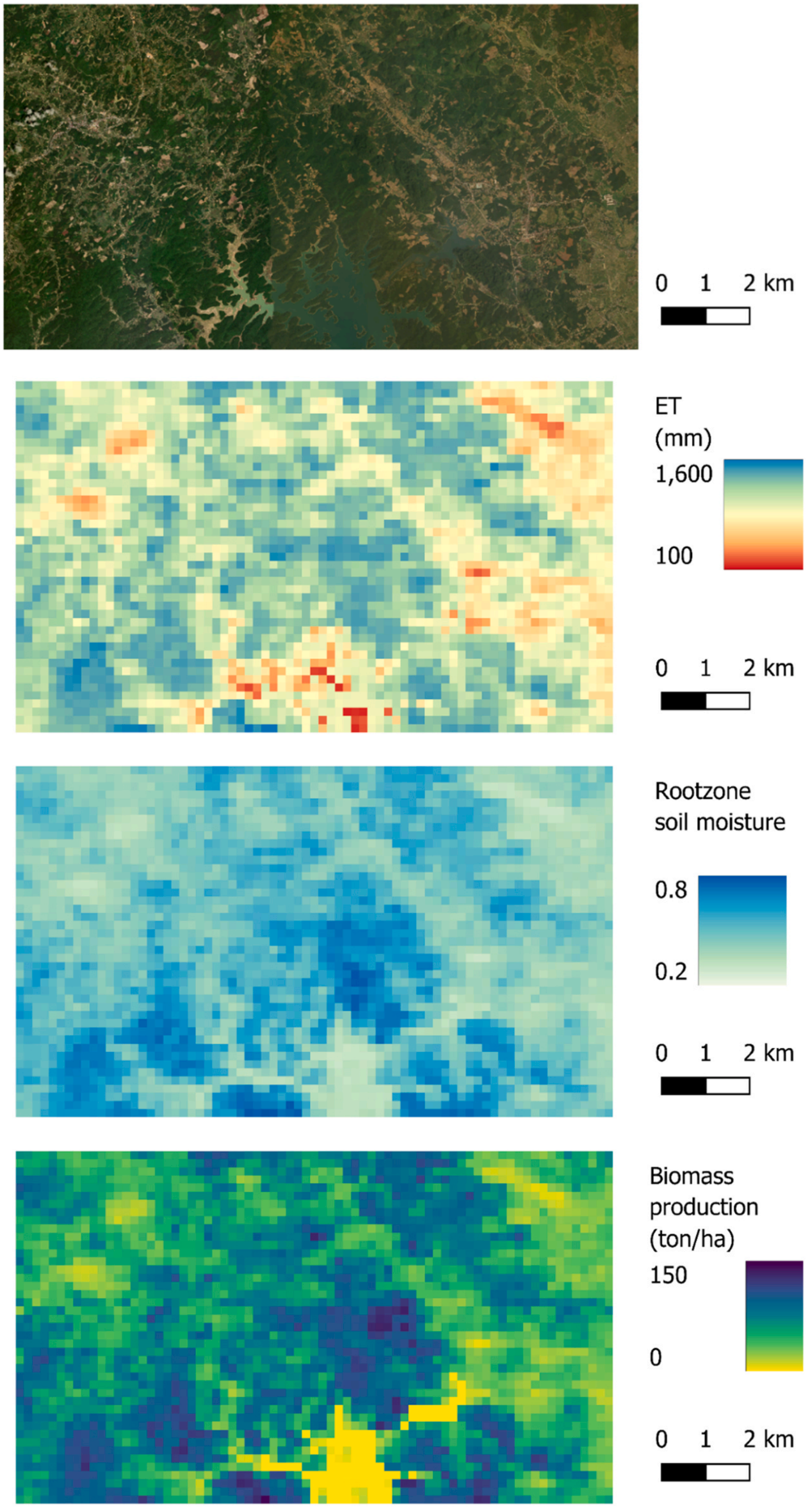


Fig. 6. Zoom in results for 250 m ET, rootzone soil moisture and biomass production in 2022.

4.2. Spatial patterns of HESS

The result for HESS for Vietnam's major river basins for the year 2005 and 2022 is displayed in Fig. 7.

Evidently, total runoff varies significantly across basins. Basins such as Mekong, Tra Khuc, Vu Gia Thu Bon and Kon-Ha Thanh yield higher runoff from overland flow and baseflow with the Mekong achieving the highest average value at 4868 m^3/ha annually. This is a large volume of renewable water resources that can be allocated to multi-purpose water use. Locally, an above average rainfall year will have values up to 10,000 m^3/ha. In contrast, the Bang Giang and Ma basins have lower total runoff, approximately 1700 and

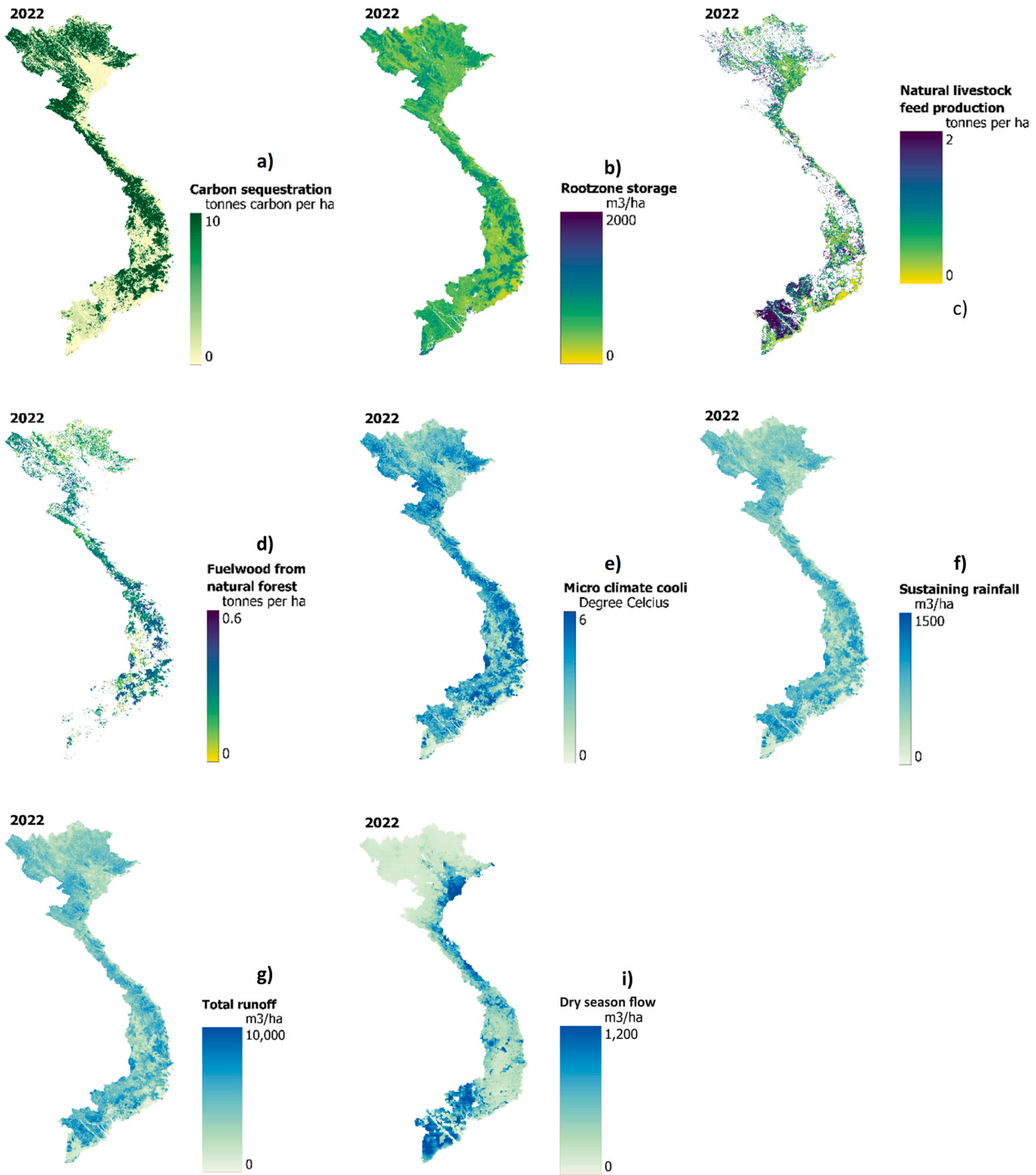


Fig. 7. HESS results for 2022: a) Carbon sequestration; b) Rootzone storage; c) Natural livestock feed production; d) Fuelwood from natural forest; e) Mirco-climate cooling; f) Sustaining rainfall; g) Total runoff; h) Dry season flow.

1220 m^3/ha/yr respectively. Notably, in 2010 – a wet year – total runoff increased exponentially to 8400 m^3/ha in the case of Kon – Ha Thanh (as shown in the Appendix). An opposite trend can be seen in 2019 – a dry year – HESS1 dropped significantly, reaching as low as approximately 1100 m^3/ha in Bang Giang and South-Eastern River Cluster (SERC) basins. These numbers are important for benchmarking basins of the humid tropics. In fact, every Koppen climatic class should get average and target values for each HESS indicator.

HESS3 (Livestock feed production) from leftover post-harvest biomass, demonstrates a consistent trend across most basins, except in SERC. The higher level of industrial development and limited land for agricultural production clearly resulted in low feed production in SERC. While the range of HESS11 for carbon sequestration can be predicted well, the generation of HESS3 in basins like Mekong and SERC requires more field verifications to calibrate certain model coefficients. HESS in the 16 river basins are complex due to various spatial and temporal scales. Trends and growth can be observed within these basins, along with instances of ecosystem services degradation. The performance of these basins can vary significantly, depending on climatic conditions, topographies, land use and landcover, as well as water and land management practices.

Consumptive water use in Vietnam is significant, but it also generates HESS. Areas with high ET will surely sequester more carbon, generate more feed and fuelwood at given land cover classes, induce a stronger local micro climate with lower temperature and lower water demands, and sustains rainfall circulation patterns better. These extra benefits from consumptive use are often ignored by policy makers and water resources planners. Hence a relative high ET can also be interpreted as being beneficial for human services. Addressing soil conservation and sustainable landscape management to improve sequestration of carbon (HESS11) or feed production (HESS3) in these basins necessitates clearer actions, such as altering land management practices (Geneletti, 2013) or introducing reforestation initiatives.

The spider graph (Fig. 8) illustrates the achievement of the eight hydrological ecosystem services. In this visualization, a curve of HESS for a particular year that extends further from the center indicates a more positive performance compared to those curves lying closer to the central point.

The assessment results reveal considerable variability in HESS values across the 16 river basins. Several HESS indicators, such as HESS4: Fuelwood from natural forest and HESS8: Rootzone storage, demonstrate relatively uniform values among the basins. However, several basins stand out with notably higher values. For example, the Kon-Ha Thanh river basin exhibits a significantly high HESS4 of 3.44 ton/ha, while the Srepok river basin shows a HESS8 value of 652 m^3/ha. In terms of carbon sequestration (HESS11), there is substantial disparity observed among the basins. Basins like Vu Gia – Thu Bon and Gianh demonstrate comparatively high values of 24.6 tonC/ha and 23.9 tonC/ha, respectively. In contrast, lower values are observed in basins such as the Mekong (3.9 tonC/ha on average) or SERC and Dong Nai (with averages of 11.9 tonC/ha and 11.3 tonC/ha, respectively).

The spatial patterns of HESS indicators revealed in this study also suggest opportunities for targeted Nature-based Solutions. For instance, basins exhibiting declining microclimate cooling (HESS13) or reduced dry season flow (HESS5) could benefit from forest conservation, riparian buffer establishment, or wetland restoration efforts. High biomass production zones (HESS12) and feed supply areas (HESS10) can also support sustainable agroforestry practices aligned with NbS principles

4.3. Basin ranking and synthesis score

For a quick review of the overall HESS performance, a simple scoring system has been applied. For each HESS, the basin with highest value will score 16 while the lowest scores 1. The detailed and average score of 8 HESS indicators for 2022 is presented (see Table 3).

Fig. 9a described the ranking of the 16 basins for 2022. The Tra Khuc river basin ranks the highest on HESS performance from all 16 river basins. River basins in central Vietnam, such as Vu Gia – Thu Bon (ranked 2nd), Kon-Ha Thanh (ranked 3rd), and Huong (ranked 4th) perform relatively well. Conversely, river basins in the north and south Vietnam where high urbanization rate and population density is observed, exhibit lower rankings. While this could be intuitively expected, it is now based on data facts and quantitative analysis. The Red River basin ranks last among the 16 river basins with a synthesis score of 3, while the SERC basin is ranked 15th. The Mekong River basin, a crucial agricultural production center in Vietnam, only achieves a score of 5.25, placing it 13th out the 16 river basins. While it is excellent for generating total runoff, it falls short in other elements of HESS. Longer term river basin profiles should actually define more precisely the objectives for the future. If for instance baseflow is dropping during dry season, then enhancing surface and soil water storage is key. But if livestock and rural societies are suffering from insufficient feed production, land-use planning is required.

Since result of HESS is available for a dekadal basis, it is possible to generate monthly or seasonal maps of HESS. This information is particularly valuable for decision makers who require insights over shorter term period or wish to examine seasonal variations and perform cross-examinations between wet and dry spells, especially for monsoonal and tropical climates. Differences in seasonal HESS indicators, such as rootzone storage or total runoff, are particularly relevant when addressing water provision needs (related to total runoff or dry season flow) during dry season or when conducting comparative assessment of micro-climate cooling, which is more prone to seasonal climatic variations. Previous studies have also highlighted seasonal changes in HESS over time (Lu et al., 2024; Zhou et al., 2024). Certain variables and trends in seasonal HESS have been linked to climate change, characterized by increasingly extreme and erratic rainfall and temperature patterns. For instance, a study by Shrestha et al. (2021) found that flow rates in Southeast Asia basins have significantly increased, leading to elevated risk of flooding. Land-use change is also associated with rapid changes in ecosystem services, especially those related to food and feed production in Vietnam (Poortinga et al., 2019).

Fig. 9b illustrates the changes in basin rankings over the study period, reflecting the dynamic nature of sustainability score for all basins in 2005, 2010, 2019 and 2022. It is noteworthy that some basins exhibit considerable fluctuations in their overall HESS

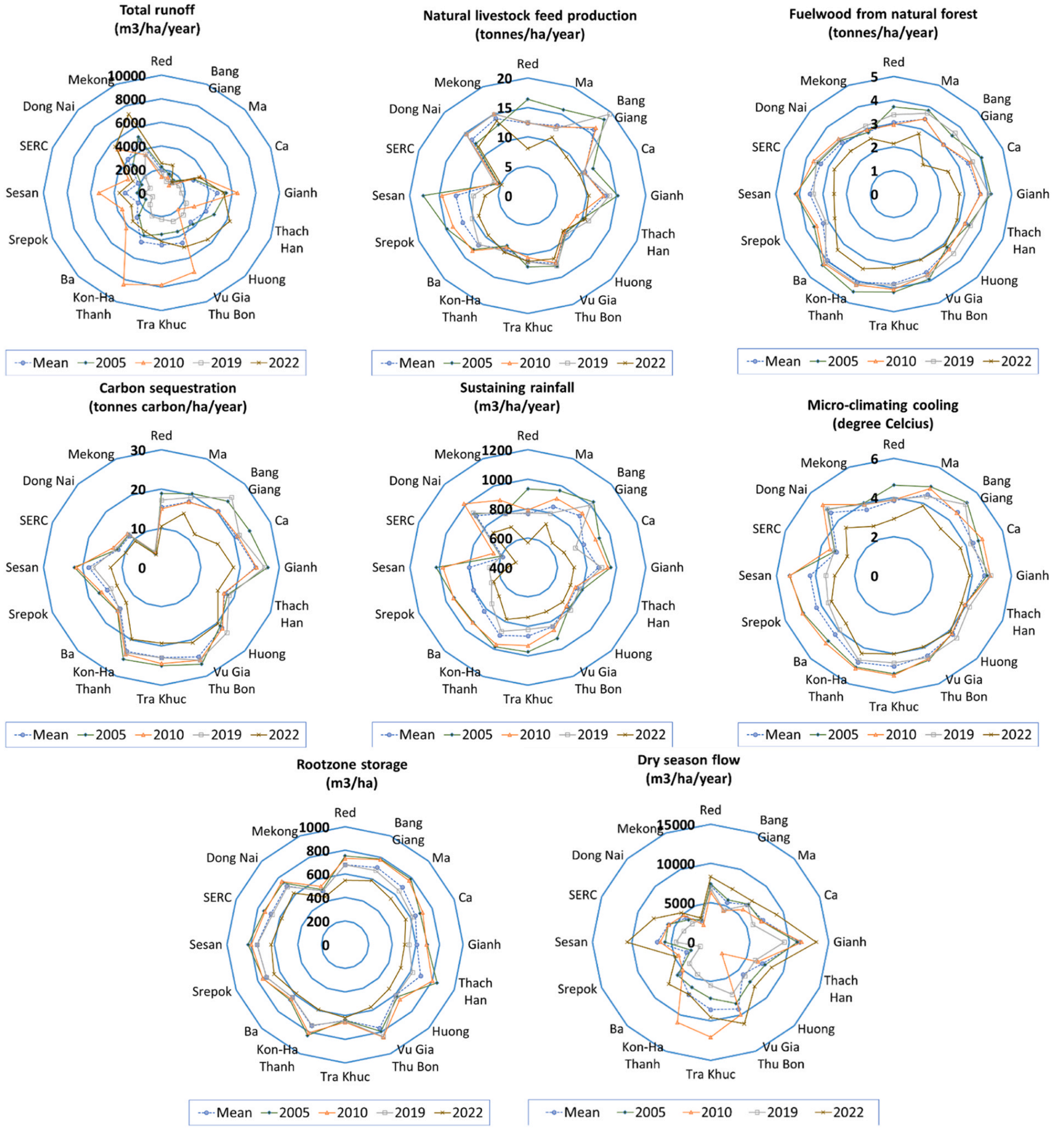


Fig. 8. Changing of HESS for 16 basins for 2005, 2010, 2019 and 2022 for: a) Carbon sequestration; b) Rootzone storage; c) Natural livestock feed production; d) Fuelwood from natural forest; e) Mirco-climate cooling; f) Sustaining rainfall; g) Total runoff; h) Dry season flow.

performance, as evidenced by significant drops or gains in ranking. For example, the Sesan basin ranked 14th and 10th in 2019 and 2022, respectively, despite achieving much higher rankings of 3rd and 2nd in 2005 and 2010. Similar fluctuations are observed in other basins, such as Red and Bang Giang, where ranking changes are significant. These fluctuations indicate a dynamic response, likely driven by climatic conditions and highlights areas where these basins could be improved to sustain a higher score. For instance, enhancing dry season flow or livestock feed production could potentially leverage and improve the rankings of the Red and Bang Giang river basins.

Meanwhile, some basins have demonstrated consistent performance through the period. For example, Vu Gia Thu Bon and Kon-Ha Thanh consistently ranked among the top four in sustainability scores. Notably, Kon-Ha Thanh outperformed the other 15 basins, maintaining a position in the top three across all years. In contrast, basins such as SERC, Mekong consistently ranked from 13th and 16th positions, indicating persistently poor performance. The less dynamic HESS performance ranking these basins highlights

Table 3
Synthesized score for 16 basins under each HESS and average score for overall performance for 2022.

Basin	HESS8 Rootzone water storage	HESS11 Carbon sequestration	HESS3 Natural livestock feed production	HESS4 Fuelwood from natural forest	HESS13 micro-climate cooling	HESS9 Sustaining rainfall	HESS1 Total runoff	HESS5 Dry season flow	Average score
Red	4	3	2	1	2	2	1	9	3
Bang Giang	10	4	5	0	4	10	2	4	4.875
Ma	5	8	11	8	10	3	0	5	6.25
Ca	6	10	6	2	8	5	6	11	6.75
Gianh	1	11	8	9	11	8	11	15	9.25
Thach Han	2	9	10	10	9	9	14	10	9.125
Huong	3	14	3	12	14	12	13	8	9.875
Vu Gia Thu Bon	7	15	13	11	12	11	10	14	11.625
Tra Khuc	13	12	12	13	13	14	9	12	12.25
Kon-Ha Thanh	11	13	9	15	15	15	7	3	11
Ba	9	6	7	14	6	6	5	6	7.375
Srepok	15	5	4	6	5	4	4	1	5.5
Sesan	14	7	1	3	3	1	8	13	6.25
SERC	8	2	0	7	0	0	3	7	3.375
Dong Nai	12	1	14	5	7	13	12	2	8.25
Mekong	0	0	15	4	1	7	15	0	5.25

consistent hotspots where additional efforts are required to improve their sustainability outcomes. Further information on synthesized scores for 16 river basins for the years 2005, 2010 and 2019 is showed in Appendix B: Synthesized scores for 16 river basins for 3 years: 2005, 2010 and 2019

A different manner to present the results is by normalizing HESS by the highest value of each HESS that are attainable in the environmental system of Vietnam. For each HESS, the top three basins with highest HESS are selected to define what is maximally attainable. Table 4 shows the results of these analyses.Where: + best performance + + second best performance + ++ third best performance

It can be seen that there are several HESS indicator such as HESS8 (Rootzone storage), HESS9 (Sustaining rainfall) and HESS13 (Micro-climate cooling) exhibit relatively strong performance across most river basins. Notably, for HESS8, seven river basins attained the highest score, specifically the Red, Ca, Tra Khuc, Srepok, Sesan, SERC, and Dong Nai basins. Similarly, for HESS9 and HESS13, 15 out of 16 river basins have score ranking within the top three positions. It can be concluded that Vietnam internationally contributes to rainfall recycling and cooling of the environment through dense vegetation. The vegetation is also functioning greatly in transferring and storing water from the wet to dry season. On average an amount of 700 m^3/ha is converted which country wide (331,210 km^2) will be a volume of 23 billion m^3. The total reservoir capacity is 28 billion m^3, hence vegetation has a similar functioning as all the artificially created reservoirs altogether (26 % lower though). In contrast, HESS3 (Livestock feed production), HESS1 (Total runoff), and HESS5 (Dry season flow) have fewer river basins achieving high rankings, with each of these HESS metrics having only two river basins in the highest ranking.

The Kon – Ha Thanh river basin achieved first place for three HESS indicators: HESS4 (fuelwood from natural forest), HESS13 (micro-climate cooling), and HESS9 (sustaining rainfall). Additionally, it secured third place for HESS8 (root zone storage). The Tra Khuc basin featured four times in the top three rankings: third in HESS8, HESS4, and HESS13, and second in HESS9. The Vu Gia – Thu Bon and Huong basins also demonstrated strong performance, each appearing three times in the top three rankings. Despite the Mekong basin's overall poor performance in the basin benchmark, ranking 13th out of 16, it achieved first place in HESS4 (fuelwood from natural forest) and HESS1 (total runoff).

In contrast, Red, Bang Giang, Ma, Ca and SERC did not appear in the top three for any HESS. This outcome aligns with their overall ranking results (Fig. 9a), with the Red and SERC basins ranking 16th and 15th, respectively, while the Ca and Ma basins were ranked 10th and 9th, respectively.

The strength of a country analysis is that all these basins are encompassed. Diagnosing HESS for only one large river basin does not necessarily provide a comprehensive picture of the nations' ecosystem services emerging from water resources.

4.4. Trends in time

Over the studied period, multiple HESS indicators have displayed a clear declining trend. For instance, from 2005 to 2022, HESS8: Rootzone storage decreased on average by 21.6 %. Notably, the Thach Han basin experienced a significant decrease of 39 %, followed by the Ma and Red River basin with a reduction of 30.3 % and 27.7 %, respectively (Fig. 10a). Regarding HESS9: Sustaining rainfall

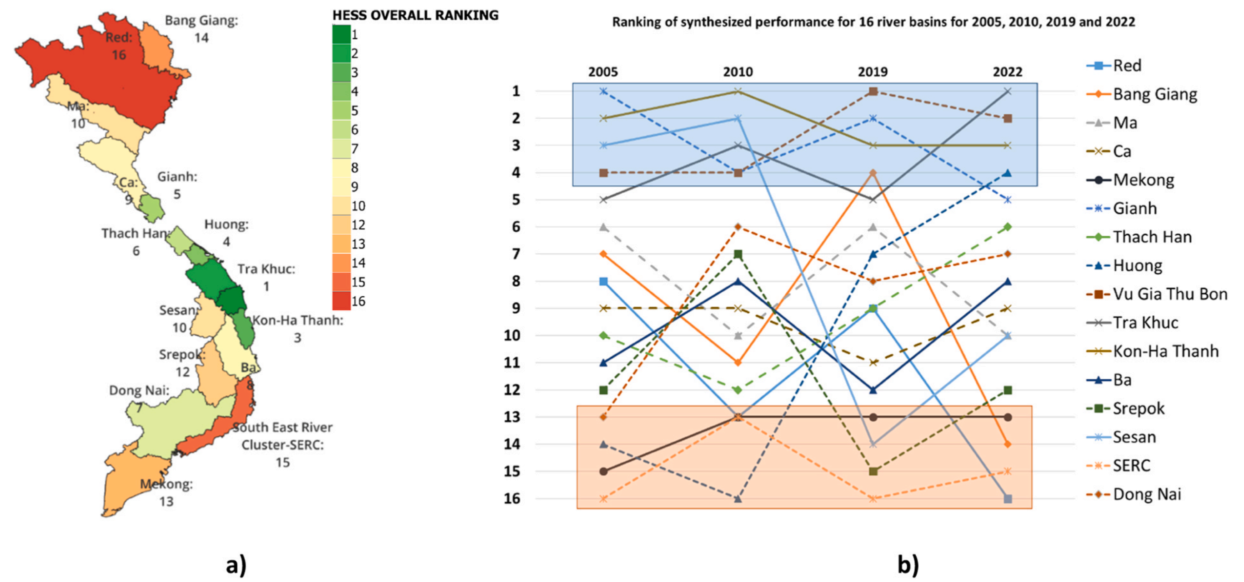


Fig. 9. The final ranking of 16 river basins in term of synthesized performance of HESS with 1 being the highest ranking and 16 being the lowest with a) Result in 2022; b) Changing of ranking over the study period.

Table 4
List of the best HESS performance for each basin and in the small bubbles, the best basins for each HESS.

Basin	HESS8 Rootzone water storage	HESS11 Carbon sequestration	HESS3 Natural livestock feed production	HESS4 Fuelwood from natural forest	HESS13 micro-climate cooling	HESS9 Sustaining rainfall	HESS1 Total runoff	HESS5 Dry season flow
Best basins	1) Srepok 2) Sesan 3) Tra Khuc	1) Vu Gia - Thu Bon 2) Huong 3) Kon - Ha Thanh	1) Mekong 2) Dong Nai 3) Vu Gia - Thu Bon	1) Kon - Ha Thanh 2) Ba 3) Tra Khuc	1) Kon - Ha Thanh 2) Huong 3) Tra Khuc	1) Kon - Ha Thanh 2) Tra Khuc 3) Dong Nai	1) Mekong 2) Thach Han 3) Huong	3) Huong 2) Vu Gia - Thu Bon 3) Sesan
Red	+				+++	++		
Bang Giang	++				+++	+		
Ma	++				+	+++		
Ca	+				++	+++		
Gianh					+++	++		+
Thach Han					++	+	+++	
Huong		+			++	+++		
Vu Gia Thu Bon		+			+++	++		
Tra Khuc	+	+++				++		
Kon-Ha Thanh				+	++	+++		
Ba	++			+		+++		
Srepok	+				+++	++		
Sesan	+			+++				++
SERC	+			++		+++		
Dong Nai	+		+++			++		
Mekong			++			+++	+	

Where: + best performance ++ second best performance +++ third best performance

(Fig. 10b), there was an overall decline of 24.9 % over the same period. The Sesan basin exhibited the highest reduction rate at 47.2 %, followed by the Red River basin at 39.2 % and the Ma basin at 38.3 %. No basin showed an increase in HESS9 values, with the smallest decrease observed in the Huong basin at 7.6 %. Furthermore, carbon sequestration capacity showed an overall decline of 25.8 % across the 16 basins (Fig. 10c). Bang Giang's carbon sequestration decreased by 50 % during the study period from 2005 to 2022. Similarly, HESS13 (Micro-climate cooling) showed an average decline of 23.5 % across the basins (Fig. 10d). Once again, the Sesan basin recorded the most significant reduction, declining by 43.3 % from 5.3 °C (2005) to 3 °C (2022). These trends underscore a warming trend for natural capital programs, attributable to both changing climate and human-induced land-use changes. The result implies climate resilience solutions should include a HESS framework.

The two HESS indicators HESS1 (Total runoff) and HESS5 (Dry season flow did not exhibit a clear upward or downward trend), as showed in Fig. 11a and b respectively. These indicators reflect changes in river discharges, which fluctuated between the different periods. For example, HESS1 in the Srepok basin nearly doubled from approximately 1438 m^3/ha in 2005–2763 m^3/ha in 2022. Similarly, the Sesan basin saw an increase from around 2054 m^3/ha to approximately 3563 m^3/ha by 2022. However, given the limited number of time points and the influence of climatic variability, these observations should be interpreted with caution, and longer-term monitoring would be needed to confirm any persistent patterns.

Since the study spans four specific years (i.e., 2005, 2010, 2019 and 2022), with these years selected based on their representation of different hydrological phenomena (i.e., wet, dry or normal years), the periods between these selected years might reveal greater fluctuations of HESS. Consequently, the trends observed could differ if more years were included in the analysis. Extending the study period to cover additional years could offer more comprehensive insights into the evolution of HESS and how basin performance varies from year to year.

4.5. Interrelationships and trade-offs among HESS

Quantitative analysis of HESS across 16 major river basins in Vietnam reveals strong interconnections and synergies among various provisioning and regulating services. Using correlation analysis and pairwise linear regression models, the relationships among eight key HESS indicators were systematically evaluated for the years 2005, 2010, 2019, and 2022.

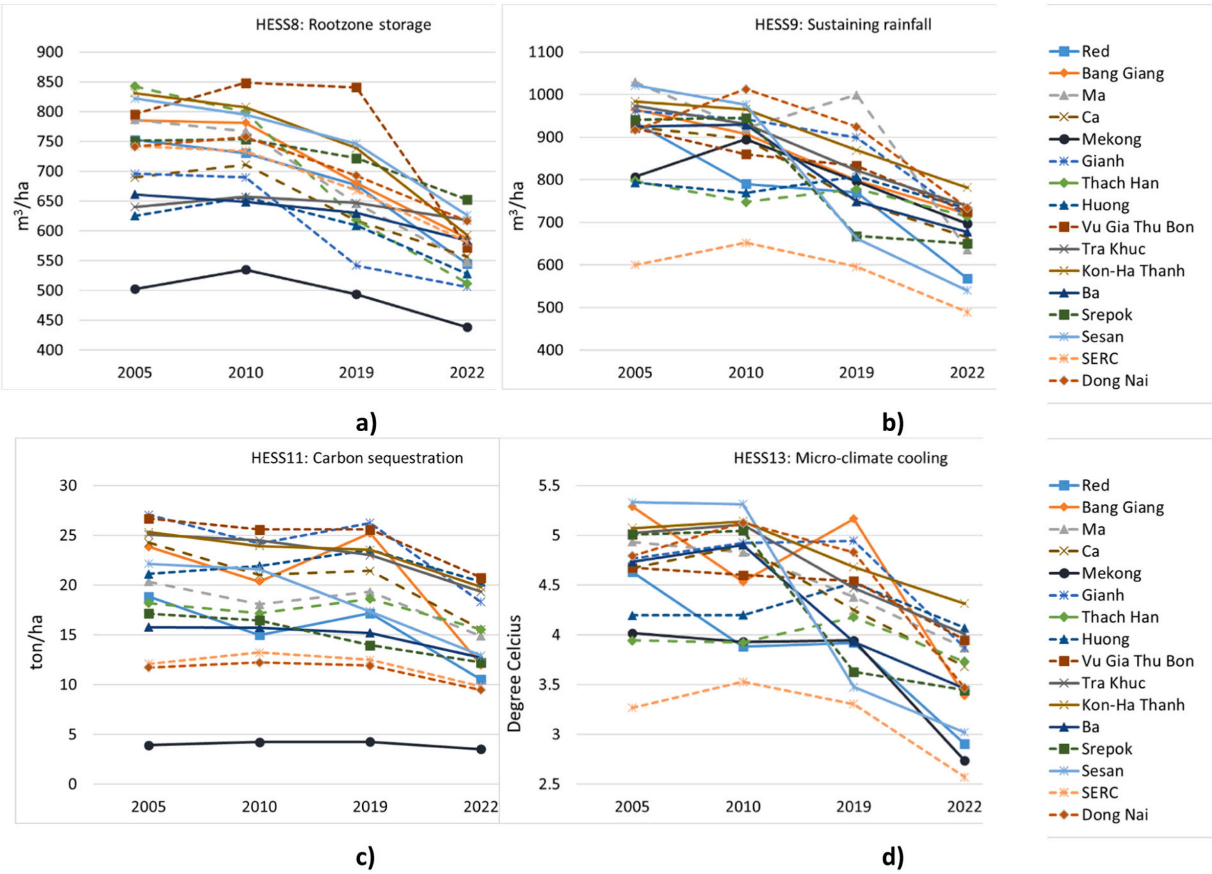


Fig. 10. Trend of HESS that are declining a) HESS8: Rootzone storage; b) HESS9: Sustaining rainfall; c) HESS11: Carbon sequestration and d) HESS13: Micro-climate cooling.

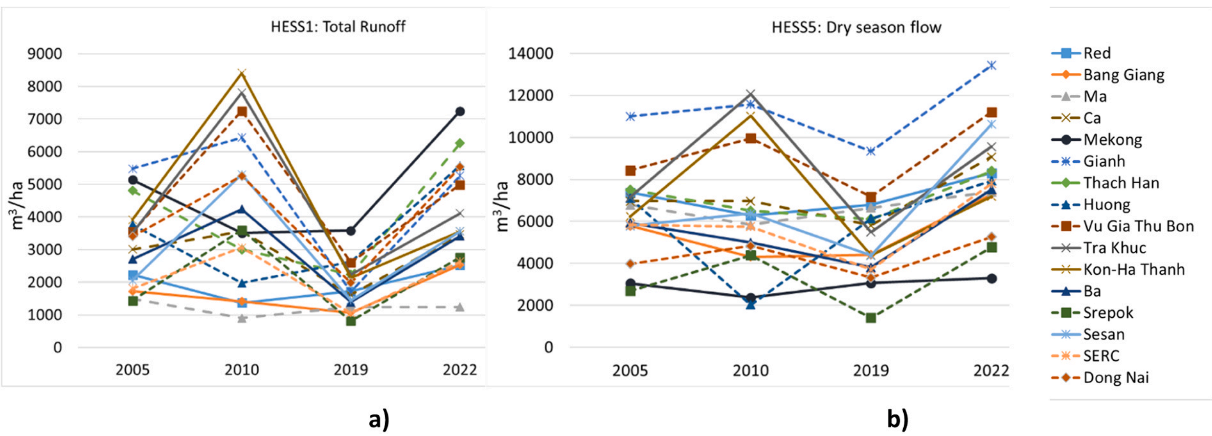


Fig. 11. Trend of HESS that are increasing: a) HESS1: Total runoff; b) HESS5: Dry season flow.

The results in Fig. 12 and Fig. 13 indicate that strong positive synergies dominate the HESS relationships across Vietnamese basins. In particular, a consistent and highly significant relationship was observed between microclimate cooling (HESS13) and sustaining rainfall (HESS9), with an average coefficient of determination (R^2) of approximately 0.76 in 2022. This is due to the fact that HESS13 and HESS9 has a strong reliance on different components of evapotranspiration, i.e. transpiration and actual ET. This finding suggests that basins providing strong cooling services, typically through vegetation and evapotranspiration processes, also tend to support local and regional rainfall patterns. Additionally, livestock feed production (HESS3) showed moderate to strong positive correlations with both rainfall sustainability and microclimate cooling, implying that enhancing biomass productivity can also reinforce regulating services critical for basin resilience.

While strong positive synergies continued to characterize the dominant relationships among HESS, the analysis revealed several important weak relationships and emerging trade-offs that warrant attention. The presence of negative R^2 in regression analysis indicates that the fitted linear models explain none of the variability in the data and may even capture slight opposing tendencies between services. Specifically, total run off (HESS1) indicated a negative (i.e., trade-offs) with rootzone water storage (HESS8) and groundwater recharge (HESS6) in 2022. Similarly, fuelwood extraction from natural forests (HESS4) showed a weak relationship with both rootzone water storage (HESS8) and groundwater recharge (HESS6). Although these negative relationships were statistically weak, their direction suggests that increasing biomass harvesting activities may erode hydrological regulating services by reducing soil water retention capacity and subsurface recharge rates over time. Additionally, a negative trend was observed between fuelwood extraction (HESS4) and microclimate cooling (HESS13), further indicating that deforestation practices could undermine local climate regulation by decreasing canopy cover and evapotranspiration rates. Such degradation of cooling services is particularly concerning given the intensifying effects of climate change in Vietnam's river basins. These findings, though emerging at relatively low correlation strengths, signal early-stage ecological risks that could grow if land use pressures intensify without adequate management. They emphasize the need for urgent adoption of sustainable forest management and ecosystem restoration strategies as part of integrated river basin planning to prevent further trade-offs between provisioning services (e.g., biomass extraction) and essential regulating

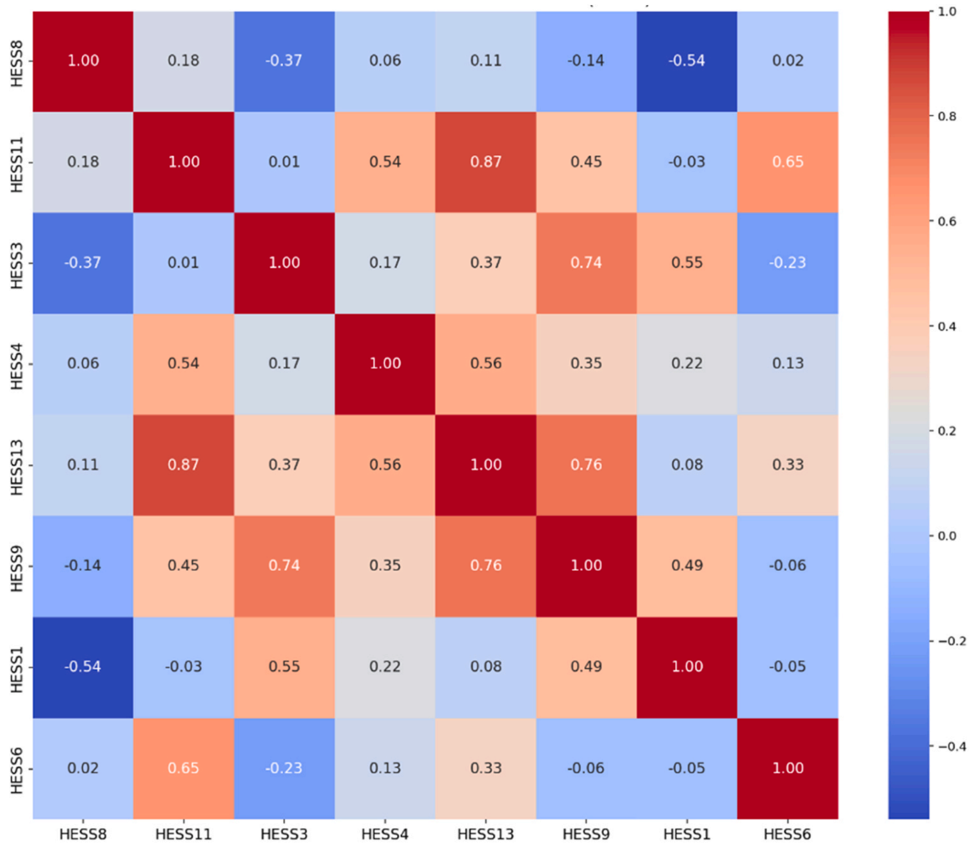


Fig. 12. Interrelationship between HESS in 2022.

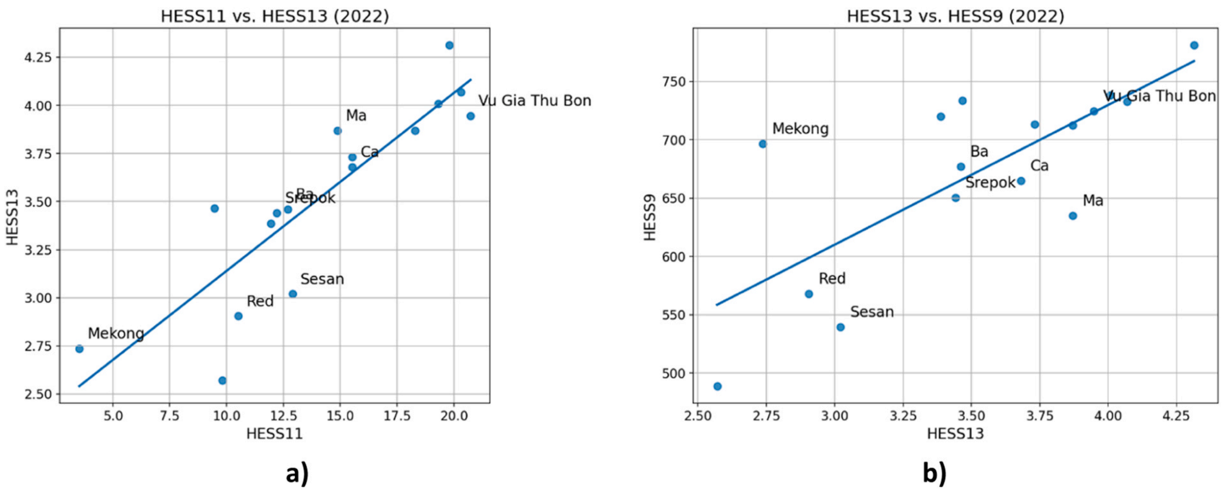


Fig. 13. Strong correlation between HESS in 2022: a) HESS11 vs. HESS13 and b) HESS13 vs. HESS9.

services (e.g., water storage, microclimate stability). Further analysis of upstream-downstream dynamics highlights the importance of headwater basins, such as the Red River, Ma, and Dong Nai basins as critical sources of runoff and groundwater recharge supporting downstream ecosystems and human settlements. The strong relationships observed between total runoff (HESS1) and groundwater recharge (HESS6) reinforce the need to protect these upstream landscapes through sustainable land and water management practices.

In conclusion, the quantification of interrelationships and synergies among HESS indicators provides robust scientific evidence for adopting multifunctional and sustainability-oriented river basin management strategies. The results also demonstrate the value of combining remote sensing data and statistical modelling to inform practical policy recommendations for enhancing resilience and sustainable development across Vietnam's river basins.

4.6. Uncertainties and limitations

While this study demonstrates the feasibility of mapping HESS using integrated remote sensing and hydrological modelling approaches, several sources of uncertainty should be recognized. Input data uncertainties, particularly in precipitation (e.g., biases in CHIRPS or ERA5 datasets), evapotranspiration calculations, and biomass estimations, propagate through the water and carbon balances. Structural uncertainties arise from model assumptions embedded in RHEAS and WaPOR, including simplified canopy resistance formulations, groundwater dynamics, and spatially aggregated land-use representations. Parameter transfer errors are also possible when applying model parameters across heterogeneous physiographic regions without localized calibration.

Furthermore, while national-level hydrological validation studies (e.g., Ha et al., 2018; Ha and Bastiaanssen, 2023) show good predictive skill ($R^2 > 0.7$, NSE > 0.65), basin-specific ground-truthing remains limited for Vietnam's smaller and transboundary basins. These factors necessitate careful interpretation of the absolute magnitude of HESS indicators.

To mitigate these uncertainties, the present study emphasizes the analysis of trendlines, interannual variability, and relative spatial patterns rather than absolute estimates. This approach enhances the robustness of the findings, particularly for comparative assessments and hotspot identification. Future improvements should include the application of formal uncertainty quantification techniques, such as ensemble modelling, Monte Carlo simulations, Sequential Uncertainty Fitting (SUFI-2) and Bayesian calibration frameworks. These methods can provide probabilistic confidence intervals around HESS estimates, thereby strengthening their reliability for informing basin planning, resource allocation, and environmental management

A key limitation remains the limited availability of in-situ ground observations across Vietnam's river basins, particularly for smaller or transboundary systems. Proxy validation using national hydrological records and agricultural statistics partly addresses this gap. However, as highlighted by Ha and Bastiaanssen (2023), even in the absence of dense field monitoring, relative differences and multi-year patterns in HESS estimates provide actionable insights for water resource planning. Future work should prioritize incorporating citizen-science data, long-term ground campaigns, and advanced uncertainty quantification methods.

5. Conclusions

The quantification and mapping of HESS are essential for advancing river basin planning, supporting Integrated Water Resources Management (IWRM), NbS and SDGs. Benchmarking HESS across basins and administrative districts offers valuable insights into sustaining ecosystem services and enhancing community resilience. This study demonstrates the application of this approach across 16 major basins in Vietnam. This study applied this approach across 16 major river basins in Vietnam, analyzing eight HESSS indicators over four hydrological years using integrated remote sensing and modelling techniques.

The spatial and temporal distributions revealed variability in HESS stock and flow, highlighting basins with abundant or limited services and enabling hotspot identification through gridded analyses. These results provide a foundation for scaling best practices to reduce ecosystem inequality and promote sustainability.

Several HESS indicators represent consumptive use (e.g., total runoff, recharge, root zone storage), while others capture the co-benefits of this consumptive use (feed, wood, livestock, micro-cooling, carbon sequestration, sustaining rainfall). Quantifying these co-benefits, often overlooked in traditional water resources allocation, enhances understanding of water's broader value.

It is concluded that national scale HESS studies can be executed with remote sensing data having an attractive spatial resolution (30–250 m pixels). Total runoff and dry season flow were derived from VIC hydrological model, based primarily on soil moisture and vegetation processes. Future HESS studies should utilize the option to compute runoff and recharge from satellite data as well.

The HESS results depend strongly on the Koppen climate class and the land-use conditions. The method presented in this paper to identify attainable values under optimum conditions can be used for benchmarking HESS.

Managing river basins and environmental systems sustainably is increasingly emphasized by national water agencies, the United Nations, NGOs, and international research institutions. The SDGs call for key hydrological, environmental, and economic processes to be expressed as measurable performance indicators. In this context, frameworks like HESS17, combined with water accounting systems, offer robust tools for mapping and describing SDG indicators at basin scales. Furthermore, the HESS17 framework provides flexibility to accommodate additional indicators as new sustainability targets or human development goals emerge. It enables the development of scenarios and benchmarking across different spatial and temporal scales, thereby supporting adaptive water management and policy planning aligned with evolving SDG agendas.

Funding sources

Support is made available through the Vietnam Ministry of Science and Technology (MOST) (grant no. NDT/e-Asia/22/26). The authors would like to express our gratitude for this support.

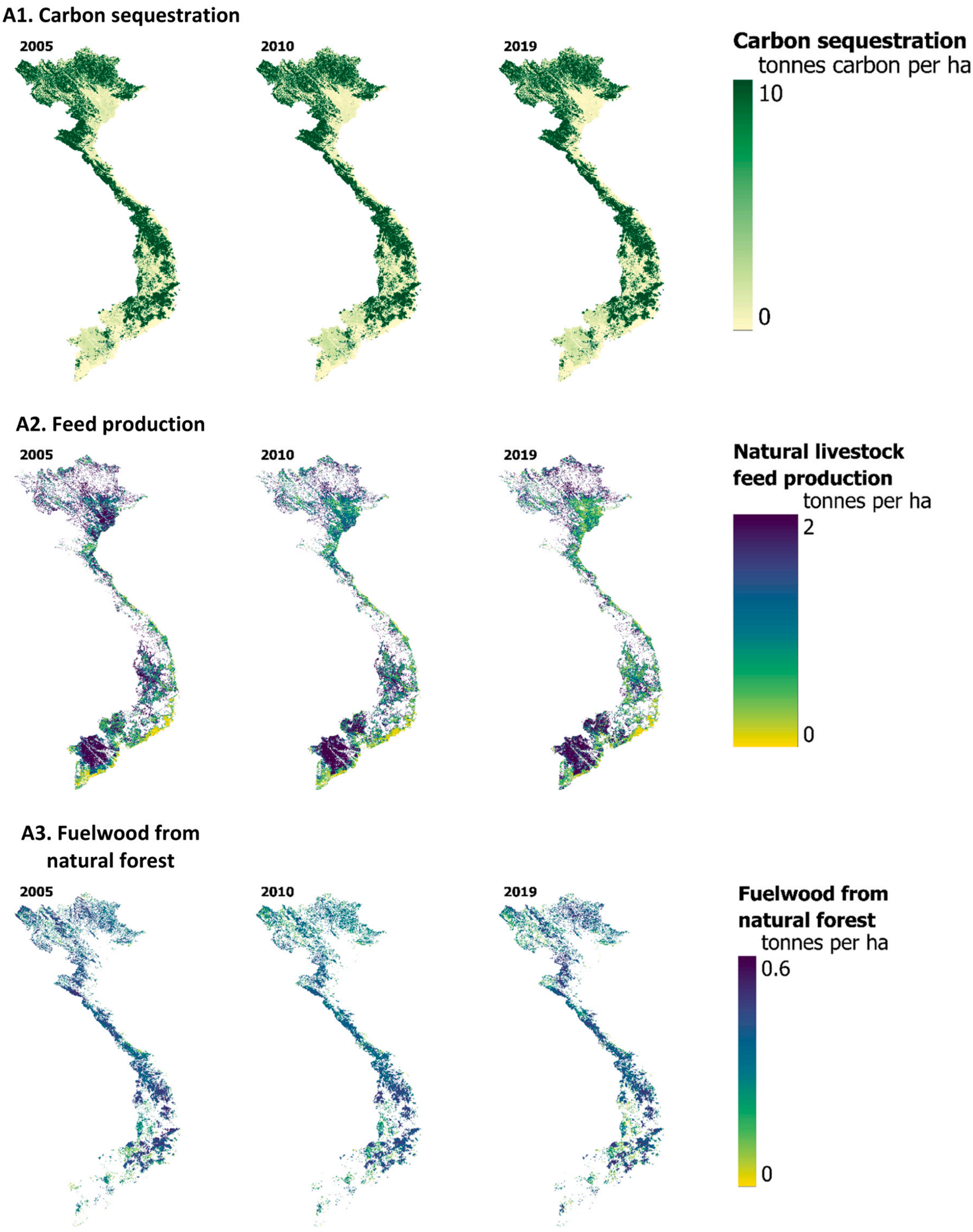
CRediT authorship contribution statement

Narendra Das: Writing – review & editing, Methodology. **Tim Hessels:** Writing – review & editing, Methodology. **Ha Lan:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Bastiaanssen Wim:** Writing – review & editing, Supervision, Methodology, Conceptualization.

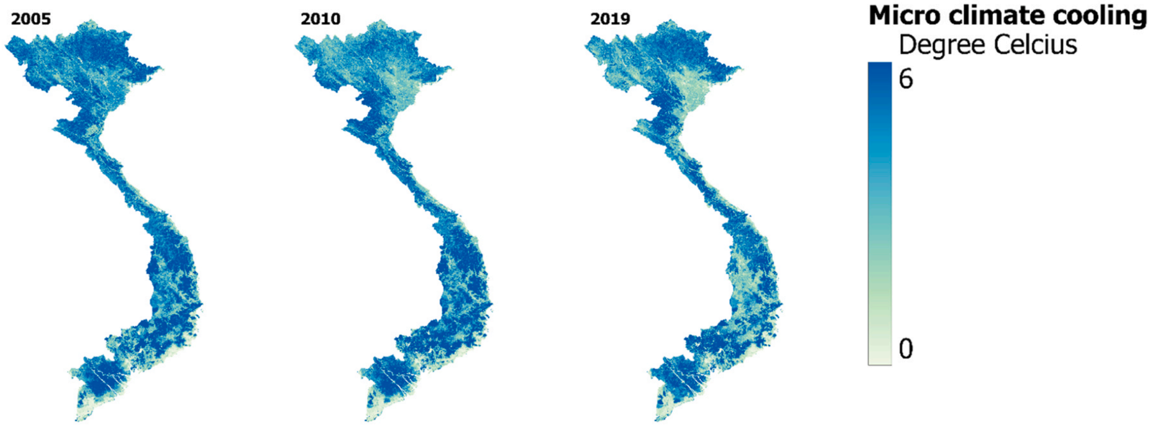
Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Lan Thanh Ha reports travel was provided by Socialist Republic of Vietnam Ministry of Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

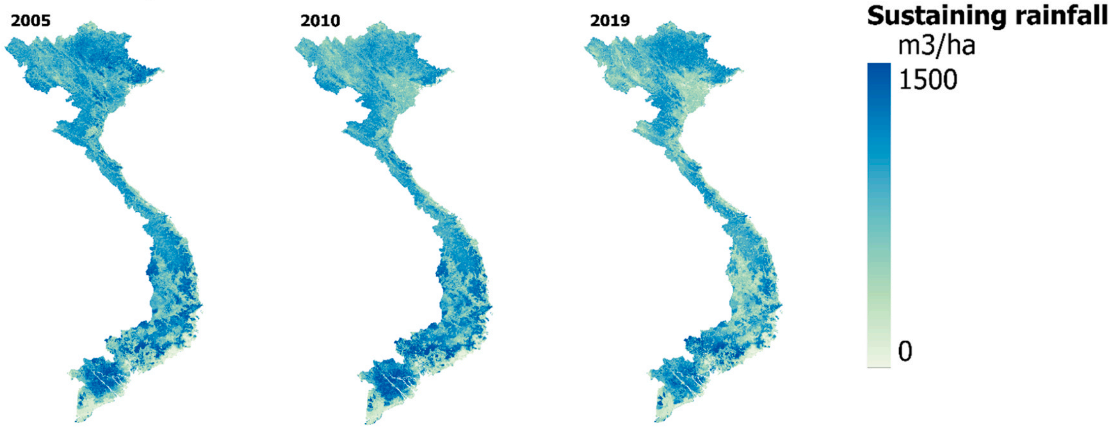
Appendix A: HESS results for 3 years: 2005, 2010 and 2019


A1. Carbon sequestration
2005
2010
2019
Carbon sequestration
tonnes carbon per ha
10
0
A2. Feed production
2005
2010
2019
Natural livestock feed production
tonnes per ha
2
0
A3. Fuelwood from natural forest
2005
2010
2019
Fuelwood from natural forest
tonnes per ha
0.6
0

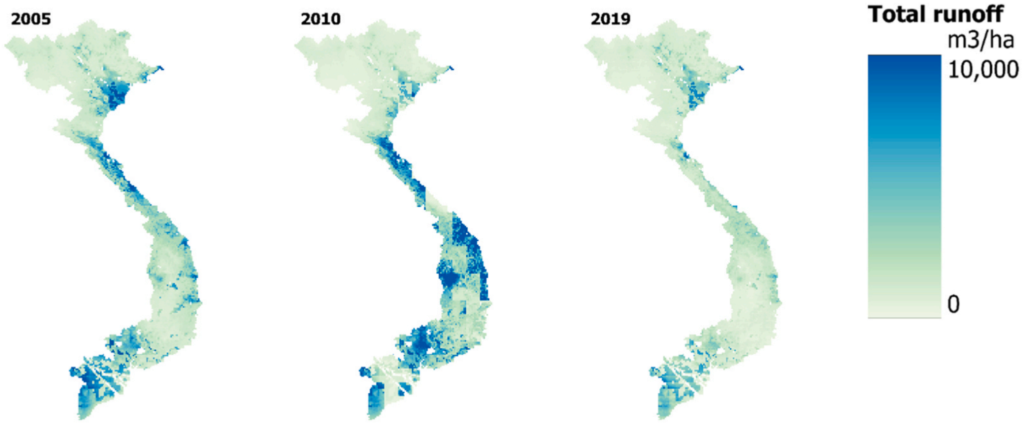
A4. Micro-climate cooling



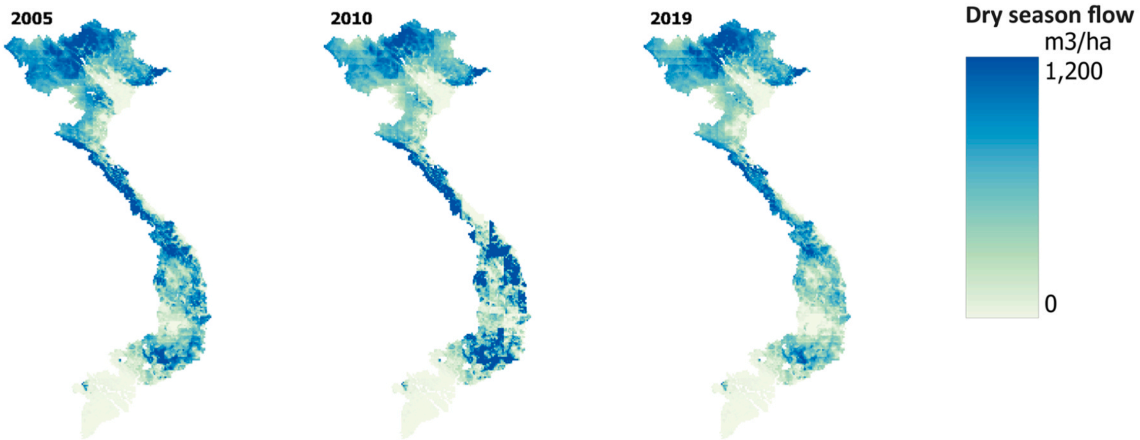
A5. Sustaining rainfall



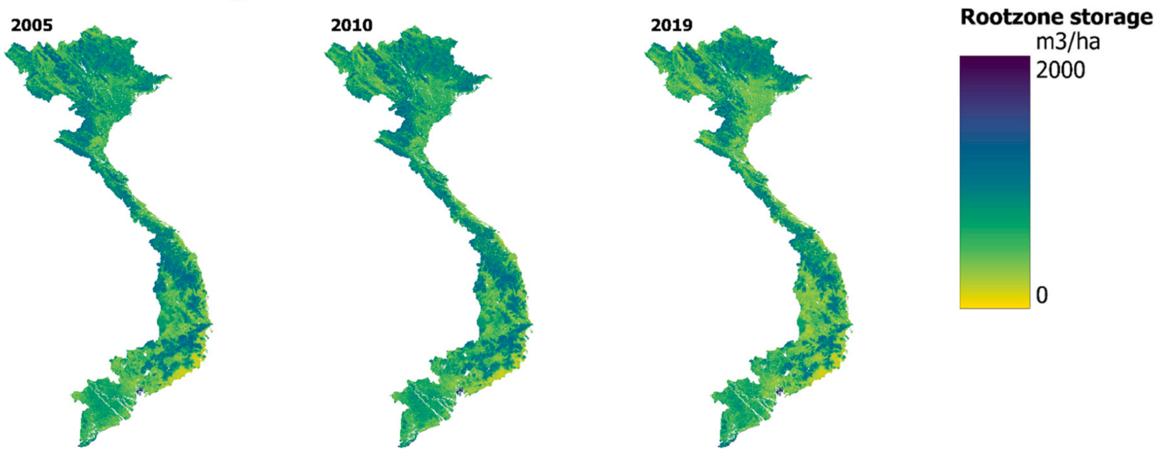
A6. Total runoff



A7. Dry season flow



A8. Rootzone storage



Appendix B: Synthesized scores for 16 river basins for 3 years: 2005, 2010 and 2019

B1
Synthesized score for 16 basins under each HESS and average score for overall performance for 2005

Basin	**HESS8 Rootzone water storage**	**HESS11 Carbon sequestration**	**HESS3 Natural livestock feed production**	**HESS4 Fuelwood from natural forest**	**HESS13 micro-climate cooling**	**HESS9 Sustaining rainfall**	**HESS1 Total runoff**	**HESS5 Dry season flow**	**Average score**
Basin	HESS1 Total runoff	HESS3 Natural livestock feed production	HESS4 Fuelwood from natural forest	HESS5 Dry season flow	HESS8 Rootzone water storage	HESS9 Sustaining rainfall	HESS11 Carbon sequestration	HESS13 micro-climate cooling	Average score
Red	6	13	7	4	8	5	12	8	6
Bang Giang	10	15	5	14	11	2	4	8.875	10
Ma	7	12	8	10	15	1	8	9	7
Ca	11	4	10	5	6	7	9	7	11
Gianh	15	11	11	8	10	15	15	11.25	15
Thach Han	5	3	3	1	2	13	13	6.875	5
Huong	8	1	1	3	1	11	10	4.5	8

(continued on next page)

B1 (*continued*)

Basin	HESS8 Rootzone water storage	HESS11 Carbon sequestration	HESS3 Natural livestock feed production	HESS4 Fuelwood from natural forest	HESS13 micro-climate cooling	HESS9 Sustaining rainfall	HESS1 Total runoff	HESS5 Dry season flow	Average score
Vu Gia Thu Bon	14	8	9	6	5	10	14	9.75	14
Tra Khuc	12	5	13	12	12	9	11	9.5	12
Kon-Ha Thanh	13	2	15	13	13	12	7	11.125	13
Ba	3	7	14	7	7	6	6	6.625	3
Srepok	4	10	6	11	9	0	0	6	4
Sesan	9	14	12	15	14	4	3	10.5	9
SERC	2	0	4	0	0	3	5	2.625	2
Dong Nai	1	6	2	9	4	8	2	4.75	1
Mekong	0	9	0	2	3	14	1	3.625	0

B2

Synthesized score for 16 basins under each HESS and average score for overall performance for 2010

Basin	HESS8 Rootzone water storage	HESS11 Carbon sequestration	HESS3 Natural livestock feed production	HESS4 Fuelwood from natural forest	HESS13 micro-climate cooling	HESS9 Sustaining rainfall	HESS1 Total runoff	HESS5 Dry season flow	Average score
Red	6	3	6	1	1	3	1	8	3.625
Bang Giang	11	8	15	2	5	7	2	2	6.5
Ma	10	7	8	6	7	8	0	7	6.625
Ca	5	9	4	7	8	6	7	11	7.125
Gianh	4	13	9	10	10	11	12	14	10.375
Thach Han	13	6	2	3	2	1	4	10	5.125
Huong	2	11	1	4	4	2	3	0	3.375
Vu Gia Thu Bon	15	15	7	11	6	4	13	12	10.375
Tra Khuc	3	14	5	12	12	10	14	15	10.625
Kon-Ha Thanh	14	12	3	15	14	13	15	13	12.375
Ba	1	4	10	14	9	9	9	5	7.625
Srepok	8	5	11	8	11	12	8	3	8.25
Sesan	12	10	12	13	15	14	11	9	12
SERC	7	2	0	9	0	0	5	6	3.625
Dong Nai	9	1	13	5	13	15	10	4	8.75
Mekong	0	0	14	0	3	5	6	1	3.625

B3

Synthesized score for 16 basins under each HESS and average score for overall performance for 2005

Basin	HESS8 Rootzone water storage	HESS11 Carbon sequestration	HESS3 Natural livestock feed production	HESS4 Fuelwood from natural forest	HESS13 micro-climate cooling	HESS9 Sustaining rainfall	HESS1 Total runoff	HESS5 Dry season flow	Average score

(*continued on next page*)

B3 (*continued*)

Basin	HESS8 Rootzone water storage	HESS11 Carbon sequestration	HESS3 Natural livestock feed production		HESS4 Fuelwood from natural forest	HESS13 micro-climate cooling	HESS9 Sustaining rainfall	HESS1 Total runoff	HESS5 Dry season flow	Average score
Red	9	5	10	3	3	5	8	13	7	
Bang Giang	10	13	15	9	15	8	2	7	9.875	
Ma	6	8	9	10	8	15	3	12	8.875	
Ca	3	9	3	8	7	3	6	9	6	
Gianh	1	15	12	13	14	13	7	15	11.25	
Thach Han	4	7	6	5	6	6	12	10	7	
Huong	2	12	1	7	10	9	14	11	8.25	
Vu Gia Thu Bon	15	14	11	11	11	11	13	14	12.5	
Tra Khuc	7	10	7	12	9	10	11	8	9.25	
Kon-Ha Thanh	13	11	5	15	12	12	10	6	10.5	
Ba	5	4	8	14	4	4	4	4	5.875	
Srepok	12	3	4	0	2	2	0	0	2.875	
Sesan	14	6	2	4	1	1	5	5	4.75	
SERC	8	2	0	6	0	0	1	3	2.5	
Dong Nai	11	1	13	2	13	14	9	2	8.125	
Mekong	0	0	14	1	5	7	15	1	5.375	

Data availability

Data will be made available on request.

References

Anav, A., Proietti, C., Menut, L., Carnicelli, S., De Marco, A., Paoletti, E., 2018. Sensitivity of stomatal conductance to soil moisture: implications for tropospheric ozone. Atmos. Chem. Phys. 18, 5747–5763. https://doi.org/10.5194/acp-18-5747-2018.

Andreadis, K.M., Das, N., Stampoulis, D., Ines, A., Fisher, J.B., Granger, S., Kawata, J., Han, E., Behrangi, A., 2017. The regional hydrologic extremes assessment system: a software framework for hydrologic modeling and data assimilation. PLOS ONE 12, e0176506. https://doi.org/10.1371/journal.pone.0176506.

Apurv, T., Cai, X., 2020. Impact of droughts on water supply in U.S. Watersheds: the role of renewable surface and groundwater resources. Earths Future 8, e2020EF001648. https://doi.org/10.1029/2020EF001648.

Asian Development Bank, 2018. Project No. 42384-012 Knowledge and Innovation Support for ADB's Water Financing Program Viet Nam: Water Accounting in 16 River Basins.

Bagstad, K.J., Johnson, G.W., Voigt, B., Villa, F., 2013. Spatial dynamics of ecosystem service flows: a comprehensive approach to quantifying actual services. Ecosyst. Serv. 4, 117–125. https://doi.org/10.1016/j.ecoser.2012.07.012.

Bastiaanssen, W.G.M., Cheema, M.J.M., Immerzeel, W.W., Miltenburg, I.J., Pelgrum, H., 2012. Surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLook model. Water Resour. Res. 48, 2011WR010482. https://doi.org/10.1029/2011WR010482.

Blatchford, M.L., Mannaerts, C.M., Njuki, S.M., Nouri, H., Zeng, Y., Pelgrum, H., Wonink, S., Karimi, P., 2020. Evaluation of WaPOR V2 evapotranspiration products across Africa. Hydrol. Process 34, 3200–3221. https://doi.org/10.1002/hyp.13791.

Bontemps, S., Defourny, P., Radoux, J., Van Bogaert, E., Lamarche, C., Achard, F., Mayaux, P., Boettcher, M., Brockmann, C., Kirches, G., Zulkhe, M., Kalogirou, V., Seifert, F.M., Arino, O., 2013. Consistent Global Land Cover Maps For Climate Modelling Communities: Current Achievements Of The ESA' Land Cover CCI. in: ESA Living Planet Symposium. ESA Special Publication, p. 62.

Brauman, K.A., 2015. Hydrologic ecosystem services: linking ecohydrologic processes to human well-being in water research and watershed management. WIREs Water 2, 345–358. https://doi.org/10.1002/wat2.1081.

Chishtie, F., Jayasinghe, S., Andreadis, K., Ines, A., Markert, K., Anderson, E., Weigel, A., Saah, D., Towashiraporn, P., 2019. Drought monitoring and forecasting for Lower Mekong Countries via the Regional Hydrological Extremes Assimilation System (RHEAS). Earth Space Sci. Open Arch. https://doi.org/10.1002/essoar.10500407.1.

Choi, E., Kim, R., Chae, J., Yang, A.-R., Jang, E., Lee, K.Y., 2023. Analysis of nature-based solutions research trends and integrated means of implementation in climate change. Atmosphere 14, 1775. https://doi.org/10.3390/atmos14121775.

Coerver, B., 2007. Regional precipitation and evaporation patterns in South East Asia based on ERA5 data (Internal note)..

Das, N.N., Entekhabi, D., Dunbar, R.S., Colliander, A., Chen, F., Crow, W., Jackson, T.J., Berg, A., Bosch, D.D., Caldwell, T., Cosh, M.H., Collins, C.H., Lopez-Baeza, E., Moghaddam, M., Rowlandson, T., Starks, P.J., Thibeault, M., Walker, J.P., Wu, X., O'Neill, P.E., Yueh, S., Njoku, E.G., 2018. The SMAP mission combined active-passive soil moisture product at 9 km and 3 km spatial resolutions. Remote Sens. Environ. 211, 204–217. https://doi.org/10.1016/j.rse.2018.04.011.

Dhonthi, A., Fonseca Aponte, F.H., Nemer, Z., Hadj Ali, C., Tebbouche, M.Y., Van Der Kwast, H., 2024. Advancing water productivity monitoring: WaPLUGIN for the analysis and validation of FAO WaPOR data in QGIS. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLVIII-4/W12-2024, 35–41. https://doi.org/10.5194/isprs-archives-XLVIII-4-W12-2024-35-2024.

Dunlop, T., Khojasteh, D., Cohen-Shacham, E., Glamore, W., Haghani, M., Van Den Bosch, M., Rizzi, D., Greve, P., Felder, S., 2024. The evolution and future of research on Nature-based Solutions to address societal challenges. Commun. Earth Environ. 5, 132. https://doi.org/10.1038/s43247-024-01308-8.

Ferreira, C.S.S., Kašanin-Grubin, M., Solomun, M.K., Sushkova, S., Minkina, T., Zhao, W., Kalantari, Z., 2023. Wetlands as nature-based solutions for water management in different environments. Curr. Opin. Environ. Sci. Health 33, 100476. https://doi.org/10.1016/j.coesh.2023.100476.

Fu, B., Liu, Y., Lü, Y., He, C., Zeng, Y., Wu, B., 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecol. Complex 8, 284–293. https://doi.org/10.1016/j.ecocom.2011.07.003.

Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., Miao, C., 2017. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the loess Plateau of China. Annu. Rev. Earth Planet. Sci. 45, 223–243. https://doi.org/10.1146/annurev-earth-063016-020552.

Funk, C.C., Peterson, P.J., Landsfeld, M.F., Pedreros, D.H., Verdin, J.P., Rowland, J.D., Romero, B.E., Husak, G.J., Michaelsen, J.C., Verdin, A.P., 2014. A quasi-global precipitation time series for drought monitoring (Report No. 832), Data Series. Rest. VA. https://doi.org/10.3133/ds832.

Geneletti, D., 2013. Assessing the impact of alternative land-use zoning policies on future ecosystem services. Environ. Impact Assess. Rev. 40, 25–35. https://doi.org/10.1016/j.eiar.2012.12.003.

Grizzetti, B., Lanzanova, D., Liquete, C., Reynaud, A., Cardoso, A.C., 2016. Assessing water ecosystem services for water resource management. Environ. Sci. Policy 61, 194–203. https://doi.org/10.1016/j.envsci.2016.04.008.

Ha, L.T., Bastiaanssen, W.G.M., 2023. Determination of spatially-distributed hydrological ecosystem services (HESS) in the red river delta using a calibrated SWAT model. Sustainability 15, 6247. https://doi.org/10.3390/su15076247.

Ha, L.T., Bastiaanssen, W.G.M., Simons, G.W.H., Poortinga, A., 2023. A new framework of 17 hydrological ecosystem services (HESS17) for supporting river basin planning and environmental monitoring. Sustainability 15, 6182. https://doi.org/10.3390/su15076182.

Ha, L.T., Bastiaanssen, W.G.M., Van Griensven, A., Van Dijk, A.I.J.M., Senay, G.B., 2018. Calibration of Spatially Distributed Hydrological Processes and Model Parameters in SWAT Using Remote Sensing Data and an Auto-Calibration Procedure: A Case Study in a Vietnamese River Basin. Water 10. https://doi.org/10.3390/w10020212.

Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalez, M.R., 2014. SoilGrids1km — global soil information based on automated mapping. PLoS ONE 9, e105992. https://doi.org/10.1371/journal.pone.0105992.

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. PLoS ONE 7, e32688. https://doi.org/10.1371/journal.pone.0032688.

IUCN, International Union for Conservation of Nature, 2020. IUCN Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS: first edition, 1st ed. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.08.en.

Johnson, B.A., Kumar, P., Okano, N., Dasgupta, R., Shivakoti, B.R., 2022. Nature-based solutions for climate change adaptation: a systematic review of systematic reviews. Nat. Based Solut. 2, 100042. https://doi.org/10.1016/j.nbsj.2022.100042.

Karimi, P., Bastiaanssen, W.G.M., Molden, D., 2013. Water Accounting Plus (WA+) – a water accounting procedure for complex river basins based on satellite measurements. Hydrol. Earth Syst. Sci. 17, 2459–2472. https://doi.org/10.5194/hess-17-2459-2013.

Kolokotsa, D., Lilli, A.A, Lilli, M.A., Nikolaidis, N.P., 2020. On the impact of nature-based solutions on citizens' health & well being. Energy Build. 229, 110527. https://doi.org/10.1016/j.enbuild.2020.110527.

Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., Alcamo, J., Oki, T., 2017. Water scarcity assessments in the past, present, and future. Earths Future 5, 545–559. https://doi.org/10.1002/2016EF000518.

Lu, C., Sidai, G., Yangli, L., 2024. Discerning changes and drivers of water yield ecosystem service: a case study of Chongqing-Chengdu District, Southwest China. Ecol. Indic. 160, 111767. https://doi.org/10.1016/j.ecolind.2024.111767.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M.G., Field, C.B., Knowlton, N., 2020. Climate change and ecosystems: threats, opportunities and solutions. Philos. Trans. R. Soc. B Biol. Sci. 375, 20190104. https://doi.org/10.1098/rstb.2019.0104.

Marloes, M., Bastiaanssen, W.G.M., 2019. WaPOR quality assessment. Technical report on the data quality of the WaPOR FAO database version 1.0.

Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being: wetlands and water synthesis: a report of the Millennium Ecosystem Assessment (Ed.). World Resources Institute, Washington, DC.

Penman, H., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. Lond. Ser. Math. Phys. Sci. 193, 120–145. https://doi.org/10.1098/rspa.1948.0037.

Pereira, P., 2020. Ecosystem services in a changing environment. Sci. Total Environ. 702, 135008. https://doi.org/10.1016/j.scitotenv.2019.135008.

Ponce-Hernandez, R., Koohafkan, P., Antoine, J., 2004. Assessing carbon stocks and modelling win-win scenarios of carbon sequestration through land-use changes.

Poortinga, A., Nguyen, Q., Tenneson, K., Troy, A., Saah, D., Bhandari, B., Ellenburg, W.L., Aekakkararungroj, A., Ha, L., Pham, H., Nguyen, G., Chishtie, F., 2019. Linking earth observations for assessing the food security situation in Vietnam: a landscape approach. Front. Environ. Sci. 7, 186. https://doi.org/10.3389/fenvs.2019.00186.

Rama, H.-O., Roberts, D., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B., Ayanlade, S., 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009325844.

Rau, M.I., Julzarika, A., Yoshikawa, N., Nagano, T., Kimura, M., Setiawan, B.I., Ha, L.T., 2024. Application of topographic elevation data generated by remote sensing approaches to flood inundation analysis model. Paddy Water Environ. 22, 285–299. https://doi.org/10.1007/s10333-023-00967-1.

Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. B Biol. Sci. 375, 20190120. https://doi.org/10.1098/rstb.2019.0120.

Senay, G.B., Bohms, S., Singh, R.K., Gowda, P.H., Velpuri, N.M., Alemu, H., Verdin, J.P., 2013. Operational evapotranspiration mapping using remote sensing and weather datasets: a new parameterization for the SSEB approach. JAWRA J. Am. Water Resour. Assoc. 49, 577–591. https://doi.org/10.1111/jawr.12057.

Shrestha, B., Babel, M.S., Maskey, S., van Griensven, A., Uhlenbrook, S., Green, A., Akkharath, I., 2013. Impact of climate change on sediment yield in the Mekong River basin: a case study of the Nam Ou basin, Lao PDR. Hydrol. Earth Syst. Sci. 17, 1–20. https://doi.org/10.5194/hess-17-1-2013.

Shrestha, S., Bae, D.-H., Hok, P., Ghimire, S., Pokhrel, Y., 2021. Future hydrology and hydrological extremes under climate change in Asian river basins. Sci. Rep. 11, 17089. https://doi.org/10.1038/s41598-021-96656-2.

Singh, G., Das, N.N., 2022. A data-driven approach using the remotely sensed soil moisture product to identify water-demand in agricultural regions. Sci. Total Environ. 837, 155893. https://doi.org/10.1016/j.scitotenv.2022.155893.

Sood, A., Smakhtin, V., Eriyagama, N., Villholth, K.G., Liyanage, N., Wada, Y., Ebrahim, G., Dickens, C., 2017. Global environmental flow information for the sustainable development goals. International Water Management Institute (IWMI). https://doi.org/10.5337/2017.201.

Uhlenbrook, S., Yu, W., Schmitter, P., Smith, D.M., 2022. Optimising the water we eat—rethinking policy to enhance productive and sustainable use of water in agri-food systems across scales. Lancet Planet. Health 6, e59–e65. https://doi.org/10.1016/S2542-5196(21)00264-3.

UNESCO, 2018. Nature-based solutions for water, The United Nations world water development report (Ed.). UNESCO, Paris.

WaPOR database methodology, 2020. FAO. https://doi.org/10.4060/ca9894en.

Weerasinghe, I., Bastiaanssen, W., Mul, M., Jia, L., Van Griensven, A., 2020. Can we trust remote sensing evapotranspiration products over Africa? Hydrol. Earth Syst. Sci. 24, 1565–1586. https://doi.org/10.5194/hess-24-1565-2020.

Xu, K., Chen, J., Feng, Y., Wang, J., Bai, Z., 2023. How are nature-based solutions contributing to the improvement of ecosystem quality in China: a systematic review. Ecol. Indic. 155, 110985. https://doi.org/10.1016/j.ecolind.2023.110985.

Yang, Y., Guan, H., Long, D., Liu, B., Qin, G., Qin, J., Batelaan, O., 2015. Estimation of surface soil moisture from thermal infrared remote sensing using an improved trapezoid method. Remote Sens 7, 8250–8270. https://doi.org/10.3390/rs70708250.

Zhou, Yihan, Huang, Q., Wu, P., Hou, Y., Zhou, Yuchen, Chen, P., Duan, X., 2024. Seasonal variations in ecosystem service supply and demand based on the SWAT model: a case study in the Guanting Reservoir Basin, China. Ecol. Indic. 158, 111552. https://doi.org/10.1016/j.ecolind.2024.111552.