Spatial mapping of hydrological ecosystem services for basin planning and natural capital accounting: Examples from Vietnam

Hà, T.L.

DOI
10.4233/uuid:14083611-5177-47f3-919a-b23dd45c803f

Publication date
2025

Document Version
Final published version

Citation (APA)
Hà, T. L. (2025). *Spatial mapping of hydrological ecosystem services for basin planning and natural capital accounting: Examples from Vietnam*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:14083611-5177-47f3-919a-b23dd45c803f

Spatial mapping of hydrological ecosystem services for basin planning and natural capital accounting: Examples from Vietnam

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen

op Dinsdag, 14 januari, 2025 om 10:00 uur

door

Lan Thanh HA
Master of Science in Hydroinformatics and Water Management
University of Côte d’Azur, France
geboren te Hanoi, Vietnam

Dit proefschrift is goedgekeurd door de promotor[en]:

Samenstelling promotiecommissie bestaat uit:

Rector magnificus,	*voorzitter*
Prof.dr. **W.G.M. Bastiaanssen**	*Technische Universiteit Delft, promotor*
Dr.ir. **G.H.W. Schoups**	*Technische Universiteit Delft, copromotor*

onafhankelijke leden:

Prof.dr. **M.E. McClain**	*Technische Universiteit Delft en IHE-Delft*
Prof.dr. **E. Salvadore**	*Vrije Universiteit Brussel, Belgium*
Dr.ir. **A.M.J. Coenders**	*Technische Universiteit Delft*
Dr. **L.H. Ho**	*Wageningen Universiteit*
Prof.dr. **T.A. Bogaard**	*Technische Universiteit Delft,* reservelid

This research was partially funded by the CGIAR Research Program of Water, Land and Ecosystems (WLE) and USAID Vietnam Forests and Deltas Programme.

Keywords: hydrological ecosystem services, ecohydrological model, remote sensing, river basin planning, natural capital accounting

ISBN: 978-94-6384-714-8

Contents

Symbols and abbreviations

List of abbreviations

ABDI	Algal Bloom Detection Index
APAR	Absorbed Photosynthetically Active Radiation
ARIES	ARtificial Intelligence for Ecosystem Services
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMRSET	CSIRO MODIS ReScaled EvapoTranspiration
CMORPH	Climate Prediction Center Morphing technique
DEM	Digital Elevation Model
EF	Evaporative fraction
ES	Ecosystem Services
ET	Evapotranspiration
EbA	Ecosystem-based Adaptation
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organization
fPAR	Fraction of Absorbed Photosynthetically Active Radiation
GLDAS	Global Land Data Assimilation System
GVMI	Global Vegetation Moisture Index
IPBES	The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
IWRM	Integrated Water Resources Management
HESS	Hydrological Ecosystem Services
HRU	Hydrological Response Units
KGE	Kling Gupta Efficiency
LAI	Leaf Area Index
LST	Land Surface Temperature
LU	Land Use
MSI	Multi-spectral
NbS	Nature-based Solutions
NCA	Natural Capital Accounting
NCAR	National Center for Atmospheric Research
NDRE	Normalized Difference Red-Edge
NDVI	Normalized Difference Vegetation Index
NPP	Net Primary Production
NSE	Nash–Sutcliffe
PEDDR	(IPBES) and the Partnership for Environment and Disaster Risk Reduction (PEDRR)
PERSIANN	Precipitation Estimation from Remotely Sensed Imagery Using Artificial Neural Networks

REDD+	Reducing Emissions from Deforestation and Forest Degradation
RHEAS	Regional Hydrologic Extremes Assessment System
SEBAL	Surface Energy Balance Algorithm for Land
SEBS	Surface Energy Balance System
SM	Soil moisture
SRTM	Shuttle Radar Topography Mission
SSEBop	Operational Simplified Surface Energy Balance
SWAT	Soil Water Assessment Tool
SWAT-CUP	SWAT Calibration and Uncertainty Programs
TIR	Thermal Infrared
TRMM	Tropical Rainfall Measuring Mission
VIC	Variable Infiltration Capacity
WA+	Water Accounting Plus
WaPOR	Water Productivity
VIIRS	Visible Infrared Imaging Radiometer Suite

List of symbols:

CN	Curve Number
H	Surface elevation
A	Surface area
B_riv	River width
ΔS	Change in storage
P	Precipitation
K_c	Crop coefficient
K_{sat}	Saturated hydraulic conductivity
LE	Latent heat flux
E	Evaporation
T	Transpiration
Q	Stream flow
Q_{total}	total runoff
Q_{surf}	horizontal fast overland flow
Q_{lat}	horizontal interflow that occurs from lateral drainage processes in undulating terrain
Q_{bf}	horizontal seepage that drains saturated soil towards rivers
$Chl\text{-}a$	Cholorphyll A

Summary

Hydrological ecosystem services (HESS), also referred to as water-related ecosystem services, highlight the intricate connection between ecosystem services and the hydrological cycle. This relationship underscores that the magnitude of these services is largely dependent on the availability and quality of water. The inclusion of HESS ensures the transition from traditional top-down and single objective systems into multi-criteria and human-centered approaches that can prioritize activities with a broader spectrum of benefits. In particular, HESS ensures the uptake of international guidance, such as Integrated Water Resources Management (IWRM), Nature-based Solutions (NbS) or Natural Capital Accounting (NCA), by achieving a win-win co-development of water with, among others, land and ecosystems, while fully delivering the benefits to humans and society.

The objectives of this dissertation are threefold: first, to formulate a standard framework consisting of a set of HESS indicators aligned with the CGIAR ESR framework, which can be determined from remote sensing technologies and supported by eco-hydrological models; second, to develop algorithms and modeling routines to quantify these HESS indicators at both the river basin and the national scale of Vietnam; and third, to assess sustainability by benchmarking HESS indicators to demonstrate the degree of performance for a larger public. The innovative aspects and research findings of this dissertation are described in each of the chapters which include defining the HESS framework (Chapter 2), transparent calibration and calculation procedures for HESS (Chapter 3 and 4) and demonstration of a country assessment including sustainability assessment (Chapter 5).

This dissertation introduces the Hydrological EcoSystem Services (HESS17) framework, its foundation from existing ecosystem services and hydrological ecosystem services concepts. The formulation and principles of the framework and 17 associated indicators are provided. The framework consists of a minimum list of HESS taken from the existing report on Ecosystem Services and Resilience framework published by CGIAR in 2014 using certain criteria. In the HESS17 framework, each indicator was defined in terms of provisioning, regulating, supporting or cultural services, including main beneficial flows, i.e., freshwater supply, food and fuels provision, disturbance regulation, air quality and climate, water quality and habitat provision. The HESS indicators include a certain spatial and temporal scale and classify the services to either consumptive or non-consumptive water use. In the case of the former, water needs to be considered as a sink of the catchment or river scale water balance and is not available for downstream users, unless water vapor returns as local rainfall.

To quantify HESS using eco-hydrological models, this dissertation uses spatially distributed precipitation, evapotranspiration (ET) and Leaf Area Index (LAI) data from earth observation technologies for calibrating various key soil and vegetation process parameters of eco-hydrological models, also when rivers are ungauged and the water distribution system is complex. An approach to use quasi-open access remote sensing data with the SWAT eco-hydrological model was introduced. The Sequential Uncertainty Fitting (SUFI-2) parameter sensitivity and optimization method was employed to calibrate soil and vegetation model parameters in SWAT using remote sensing ET and LAI data.

To demonstrate and test the HESS and modelling framework using SWAT, the Day River Basin in Vietnam was selected with the application of eleven HESS indicators ranging from direct benefits (e.g., food production, provision of runoff, fuelwood, etc.) to benefits in a larger biophysical context, such as micro-climate regulation, rootzone water storage, meeting environmental-flow requirements, etc.). The consideration of these eleven HESS in the Day Basin highlights hydrological ecosystem services that benefit the basin and its population. The result reveals a thorough assessment and the introduction of more sustainable approaches in land-use planning and basin management practices such as IWRM or NbS to enhance HESS values in the basin.

Finally, the methodology was showcased for all 16 major river basins in Vietnam. A benchmarking system for HESS indicators has been applied to enable cross-examination and comparison between river basins. This provides valuable insights into local efforts to sustain HESS and achieve community resilience. Through comprehensive monitoring and assessment using remote sensing and modeling, the values, distribution and trends of HESS were analyzed. Eight HESS indicators revealed the stock and flow of HESS throughout the study period. Water provision from total runoff, recharge and root zone storage are related to the benefits of consumptive use (feed, wood, livestock, micro-cooling, carbon sequestration, sustaining rainfall). The remote sensing data allows for seamless zooming into the hotspots. This information is crucial for identifying best practices and lessons learned that can be scaled up to reduce ecosystem inequality and enhance the country's sustainability.

This dissertation also highlights the need for future research to explore the application of this HESS framework to other basins on a global scale. Integrating earth observations with eco-hydrological models is a necessary step that deserves more attention from the research community. The UN Food and Agricultural Organization (FAO)'s Water Productivity (WaPOR) offers a valuable vehicle for transferring these indicators to other regions and countries, while Water Accounting Plus (WA+) provides an excellent metric system for realizing HESS assessment and NCA benchmarking.

1 Introduction

1.1 Background

1.1.1 Ecosystem services and natural capital

Ecosystem services are defined as the goods and services provided by ecosystems that contribute directly and indirectly to human well-being [1]. By this definition, ecosystem services encompass the benefits that people and societies receive from ecosystem, such as food, water, nutrient cycling, feed, fuel or cultural aspects such as reducing stress and anxiety. For example, wetlands provide unique functions linked to numerous ecosystem services essential for biodiversity conservation, climate change mitigation, and human health [2]. Similarly, forest ecosystems and green spaces can influence effects such as carbon sequestration, air and water quality purification, and serve as a source for bioenergy and biomass [3,4]. Irrigated crops provide evaporative cooling of the lower part of the atmospheric boundary layer of a few degrees, reducing the vapor pressure deficit and creating better growing conditions for vegetation and crops [5].

The multi-functional contribution to mankind [6] arises primarily from the interconnectedness of biophysical structure and processes. This interconnectedness means that changes in an ecosystem component can result in multiple benefits and tradeoffs observable across various sectors. For instance, water is stored in lakes and wetlands for food production, power supply or domestic uses. Upstream occurrences can have an interference with the downstream supply of ecosystem services. Hence, achieving a broader understanding of multiple ecosystem services that together span interconnected systems to characterize the processes that support ecosystem services in catchments is important to achieve multiple basin development goals in climate change mitigation, Sustainable Development Goals (SGDs) or the implementation of Integrated Water Resources Management (IWRM) is a fundamental characteristics of ES-related studies [7].

According to Costanza (2020) [8], the ecosystems that provide the services are sometimes referred to as natural capital. Office of Management and Budget [9] defines natural capital as “stock” that yields ecosystem services as “flow”. This concept is useful for reconnecting the human economy with its ecological dimensions and is not meant to imply that natural capital can or should be privatized or marketed the same way as built capital. For these benefits to be realized, natural capital, which does not require human activity to build or maintain, must interact with other forms of capital that do require human agency to build and maintain. This form of interaction ensures that natural capital yields needed ecosystem services that at the end will benefit human wellbeing and quality of life.

Highlighting the interaction between natural, societal and human capital necessary to produce these services, many ecosystem services frameworks categorize ecosystem services into four groups [1,3,10,11]:

1) Provisioning services such as water, food
2) Regulating services such as flood, pest, disease control, soil health and micro-climate
3) Cultural services such as leisure, spiritual benefits
4) Supporting services such as nutrient cycling, soil moisture

Figure 1 [12] explains how the recognition of services and that complex interactions and feedbacks are required among built, human, social, and natural capital in order to produce ecosystem services.

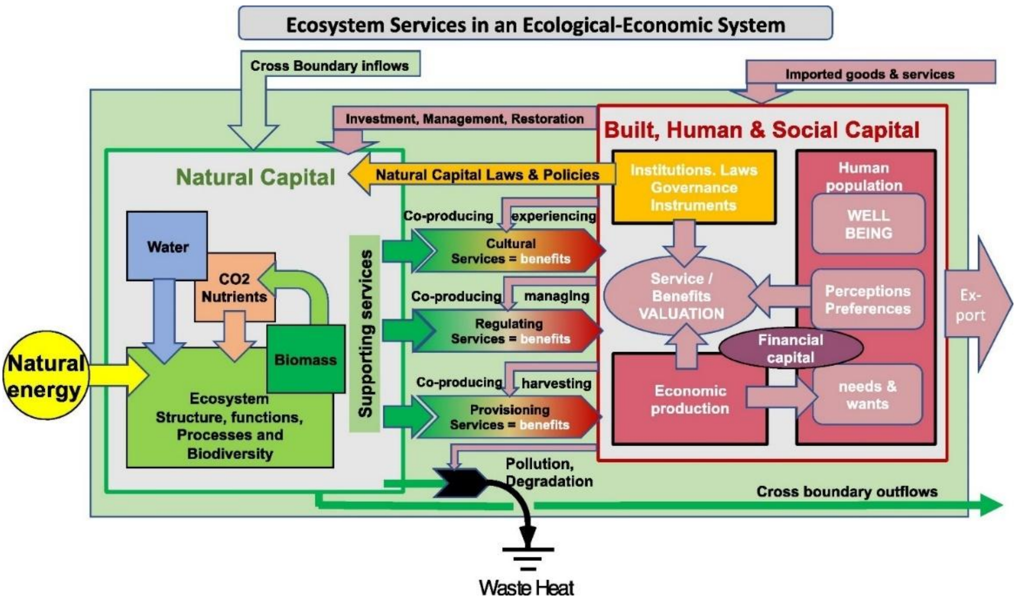


Figure 1. Complex and dynamic interactions between natural capital and build, human, and social capital, which generate ES for enhancing human wellbeing [12]

The uptake of ecosystem services into decision making cannot be done without economic and social considerations. These considerations are increasingly integrated into ecosystem services research, steering exploration in this domain [8]. The consideration results from a belief and trust that the uptake of ES concept can facilitate further incorporation of economic and social considerations. Deriving from this concept are ideas such as Nature based Solutions (NbS) [13,14]. NbS builds on and endorses earlier concepts such as ecological engineering, green infrastructure, ecosystem-based adaptation/mitigation, ecosystem services, and natural capital - acting as an ‘‘umbrella” concept. These notions, at first glance, appear to complement each other but are diverse in terms of starting points, goals pursued, and perspectives. NbS can also provide a range of ecosystem services beneficial for the urban biosphere such as regulation of micro-climates, flood prevention, water treatment, food provision, and more. The advancements in quantifying the benefits of ecosystem services can act as a catalyst to promote the wider application of NbS.

1.1.2 Hydrological ecosystem services (HESS)

Hydrological ecosystem services (HESS), also referred to as water-related ecosystem services, highlight the intricate connection between ecosystem services and the hydrological cycle. This relationship underscores that the magnitude of these services is largely dependent on the availability and quality of water. For example, specific stream flow regimes are essential for sustaining fish populations, bird habitats, and perennial corridors, which in turn provide food and income for local communities [15]. Similarly, recurring rainfall is required for sustaining the productivity of dryland agro-forestry ecosystems [16]. Furthermore, the hydrological processes in the unsaturated zone regulate gaseous exchanges between land and atmosphere, thereby influencing atmospheric greenhouse gas concentrations and, consequently, the warming of the Earth. Vegetated surfaces, which possess significant ecological value, require specific soil moisture regimes to ensure adequate photosynthesis. The critical role of water extends to agricultural ecosystem services and throughout the entire food chain [17]. HESS can serve as a catalyst for transforming agricultural production and achieving several Sustainable Development Goals (SDGs). Figure 2 illustrates the benefits HESS provide to human well-being, emphasizing the critical role these services play in supporting and enhancing ecosystem resilience. The general categories of HESS include freshwater supply, fuels, livestock feeds, habitat provision, water quality, air quality, disturbance regulation and recreational services. Given that HESS should be associated with indicators that possess natural characteristic and are minimally influenced by human activities, food production — being dependent on human land management and considered a non-natural activity — is not part of HESS considerations.

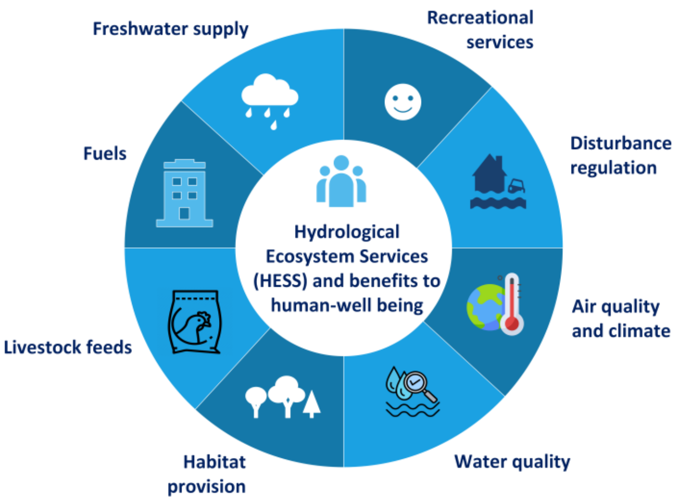


Figure 2. HESS and benefits to human beings (Source: created by the author)

Quantifying HESS presents a challenge due to the complex biophysical processes and interactions between human and nature. Effective measurement and management of HESS require a thorough understanding of the underlying ecosystem processes and components that humans find valuable for their needs and benefits. These include not only direct benefits but also indirect, often subliminal such as regulation and habitat services [18]. Similar challenges are observed in the quantification of water quality related ecosystem services. Linking current ecotoxicity indicators to ecosystem services endpoints necessitates the development of methods to measure effects on ecological processes based on modelling approaches [19]. Furthermore, developing comprehensive HESS framework and accounts, which include consumptive and non-consumptive water flows throughout the system and their variability in space and time, is crucial. These quantified HESS indicators enable well-informed planning and management, as well as increased transparency in decision making [20].

It can be seen that the quantification of HESS has several features that make its assessment more important:

- ***Spatial-temporal variations of HESS:*** Hydrological ecosystem services exhibit significant spatial-temporal variations and heterogeneity, influenced by a multitude of factors. These include meteorological variables such as rainfall and humidity, soil composition and fertility, the health and coverage of vegetation, and anthropogenic impacts encompassing levels of development, resource extraction, and environmental conservation efforts.

- ***Inclusive framework and standardized benchmarking approach:*** Currently, numerous frameworks exist for assessing HESS; however, these frameworks typically focus on provisioning and regulating services rather than cultural and supporting services. This focus arises because provisioning and regulation services are the most apparent and quantifiable. The lack of consideration and assessment of HESS related to supporting and cultural services diminishes the overall effectiveness of HESS evaluations and distorts socio-economic assessments. Furthermore, a solid framework should identify the consumptive/non-consumptive use of water resources because consumptive use implies a sink of water from the catchment and river basin and this water cannot be reused and recycled. Thus, there is a need for a comprehensive HESS framework that encompasses all four groups of services as defined by Millennium Ecosystem Assessment Program (2005) [1].

- ***Implications to decision making and management policies***: One of the key challenges in the uptake HESS is to understand how spatial–temporal information can be effectively integrated into decision making processes. A framework of HESS must recognize the importance of delineating HESS into transparent routines and quantifiable benefits. Decision makers also need to justify their authority concerning geographical boundaries, whether it is at the national level, a larger river basin scale, or within local communities where HESS is utilized. Understanding the temporal aspects of HESS over time and spatially where they occur is vital. A comprehensive approach is needed to ensure that HESS can be effectively integrated into broader environmental and economic strategies, thereby enhancing their role in supporting sustainable development initiatives.

1.2 Policy implications at national and basin scale

Ecosystem services approach has evolved considerably as a global concept since its inception and considered an effective contribution to bridge the gap between economics and ecology [12]. Importantly, ecosystem services have been adopted and integrated into policy and planning at national level [21]. National level is considered an important endpoint of HESS as it really triggers local initiatives and interventions that could at the end, strengthen the benefits to people.

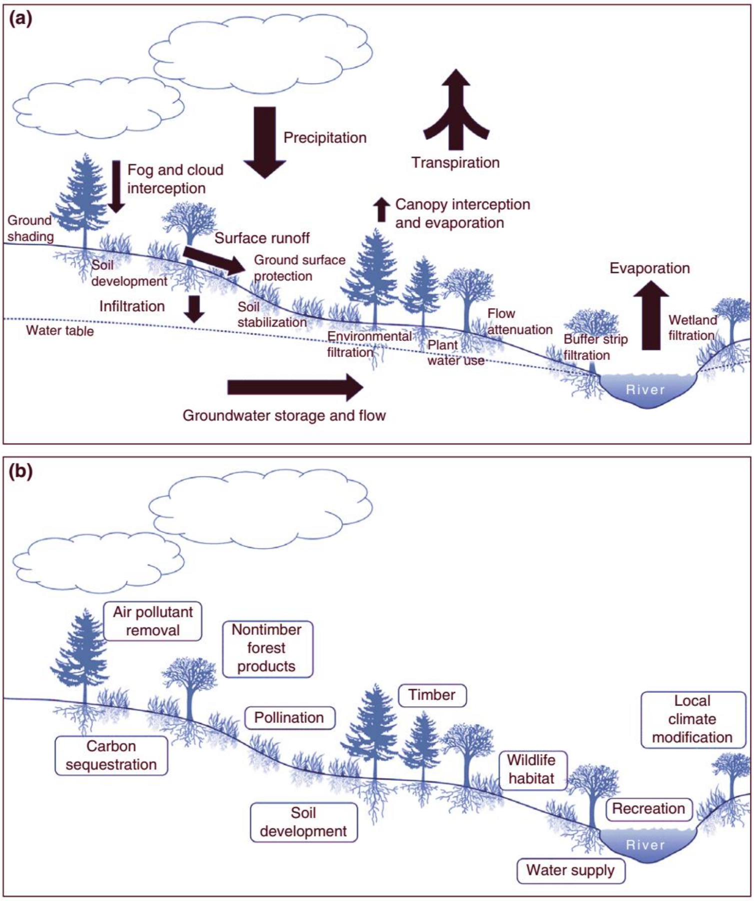


Figure 3. Hydrologic fluxes and ecosystem services in a river basin. The ecosystem services framework allows hydrologic fluxes in a watershed (a) to be organized by their impacts on water for people, such as drinking water supply or recreational resources (b). In addition, the ecosystem service framework can account for the impact the same ecosystem has on other services of interest, such as timber production or removal of air pollutants. (Reprinted from Brauman et al. in the Annual Review of Environment and Resources, Volume 32, 2007)

Addressing HESS at the basin (Figure 3) or national scale ensures a detailed examination of the spatial–temporal connections between locations providing and demanding HESS. It is essential to identify where water resources are produced from runoff and percolation and where they are consumed by evapotranspiration. This approach will help delineate these spatial–temporal relations, identifying both the larger river basin scale and in localities where water is consumed by local communities, and the time aspect of when benefits or potential demands for HESS can be mapped. Furthermore, inclusion of HESS ensures the transition from traditional top-down and single-objective systems into multi-criteria and human-centered approaches that can prioritize activities with a broader spectrum of benefits [3]. Especially, HESS ensures the uptake of international guidance, such as Integrated Water Resources Management (IWRM), by achieving a win-win co-development of water with, among others, land and ecosystems, while fully delivering the benefits to humans and society.

Ecosystem services and natural capital accounting have seen significant advancements in several developed countries. At the national level, several European countries have conducted ecosystem services assessments and natural capital accounting with the aim of providing solutions to protect and sustain ecosystem services [22,23]. The United Kingdom and the Netherlands are among the leading nations in this regard, implementing policies such as Reducing Emissions from Deforestation and Forest Degradation (REDD). A report by the Institute of Chartered Accountants in England and Wales (2022) [24] highlighted several success stories where countries have successfully integrated natural capital accounting into their national accounting systems and the decision-making processes at both governmental and business levels. Examples include creating high-resolution maps and related graphics on ecosystem accounts more user friendly and accessible to several stakeholder groups in the Netherlands or the development of risk register to map locations of high natural capital values and high threat level within the Anglian Water region, both of which are spatial planning priorities.

Other countries, such as Australia, New Zealand, and the United States are adopting new national policies and strategies to enable the implementation of natural capital accounting across sectors. The US government's Office of Management and Budget (OMB) recently launched the Guidance for Assessing Changes in Environmental and Ecosystem Services in Benefit-Cost Analysis [9]. This guideline promotes the adoption of natural capital (or natural assets) as "stock" and ecosystem services as "flow" to help authorities understand the gains and trade-offs among different ecosystem services and their associated costs and benefits. These approaches aim to sustain hydrological ecosystem services while minimizing environmental impacts. Examples of these approaches include rainwater harvesting, the use of natural and manmade wetlands, the combination use of agro-forestry environments, and the improvement of public green spaces in cities and urbanized areas [25,26]. Other notable examples include UN's REDD+, the Reef Credits program in Australia. These examples demonstrate the potential of ecosystem services implications globally, as documented by the Economics for Ecosystems and Biodiversity [11].

Developing countries have made notable progress in piloting the uptake of ecosystem services practices. For example, the People's Republic of China (PRC) has developed a Gross Ecosystem Product (GEP) indicator based on System of Environmental-Economic Accounting (SEEA) approach and used it to promote investments and conservation in several areas including spatial land-use planning, governance performance evaluation, eco-compensation scheme designing and evaluation, and ecological product development. The Asian Development Bank (ADB) highlights the current state the Asia-Pacific's increasing pressure on natural capital, which is driven by a range of factors such as agriculture expansion, urbanization, infrastructure development, and poaching. It aimed to redesign its investment scheme to counterbalance the deficits caused by unsustainable use and degradation of natural capital [27]. Against this backdrop, several business cases were developed such as green urban design and planning for New Clark City in the Philippines, the development of ecologically friendly and sustainable road and rail projects in Asia, the implementation of Nature-based Solutions (NbS) to address threats to surface water quality from agricultural diffuse (or non-point source) pollution in Xin'an River basin in the People's Republic of China, and the proposal of an Integrated Watershed Management Plan (IWMP) for the Siri Toi Watershed in the Zhob river basin in Balochistan, Pakistan.

In the Philippines, progress was achieved in developing ecosystem accounts for mangrove ecosystems. Indonesia has leveraged NCA data to improve national spatial planning and inform the country's Intended Nationally Determined Contributions [26]. Successful lesson learned in applying PES can also be seen in Costa Rica [21], which inspired many other countries' efforts. Since 2011, Vietnam has implemented its own PES version, known as Payment for Forest Environmental Service (PFES). The initiative includes a fixed payment rate for watershed protection, improvement of water regulation and maintenance, and landscape aesthetic services [28]. The United States Agency for International Development (USAID)'s Vietnam Forests and Deltas Program (VFD), implemented by Winrock International [29] has significantly contributed to this process by developing policies and implementing actions aimed at achieving green growth, sustainable forest management, and equitable PFES. Additionally, collective efforts by SNV, the International Union for Conservation of Nature (IUCN) and UN Environment Programme (UNEP) in Vietnam, through the Vietnam Nature-Based Solutions for Adaptation in Agriculture through Private Sector Transformation (VN-ADAPT) initiative (2023-2028), aim to channel private innovation and investment towards the rapid adoption of Nature-Based Solutions (NbS) and Ecosystem-Based Adaptation (EbA) in the agriculture sector of the Mekong Delta provinces [30].

Despite these advancements, the absence of an operational information systems means that policy makers often continue with a business-as-usual approach. To close the policy-practice gap, clear definitions and explanatory methods for the quantification of HESS are essential. Both the benefits and the water volumes needed to establish these benefits must be estimated across areas with spatially variable physiographic conditions. The uptake of the HESS analysis by a larger group of our society can be encouraged by the creation of open-access data bases from where spatial results can be downloaded and the underlying methods are clearly explained. The impression exists that (H)ESS studies are mainly documented in reports accessible to smaller group of experts. Changing this situation requires the preparation of maps, quantify certain HESS indicators and benchmark them so that non-experts can understand the ecological performance. This dissertation helps to set out these desirable directions.

1.3 Existing frameworks on Hydrological EcoSystem Services (HESS)

The concept of hydrological ecosystem services, as suggested by Brauman (2015) [3], can be effectively integrated into policy making through various frameworks that emphasize the link between ecosystem functions and theirs impacts on people. Recognizing the services generated via hydrological processes is a crucial and central component of framing HESS. Ecosystems are responsible for generating, moving and modifying water flow, stock and flux. The aspect of HESS processes is demonstrated not only through the conversion of precipitation into evapotranspiration and runoff but also through the utilization and recycling of soil and carbon stock, which ultimately contributes to water generation and recycle moisture through the atmosphere [31]. Grizzetti et al. (2016) [32] highlighted the lack of agreed definitions of HESS, particularly regarding their quantification and valuation, which has limited the uptake by water practitioners and managers. Existing frameworks often focus primarily on provisioning and regulating services, as these are the most straightforward to quantify. However, this narrow focus can limit the effectiveness of HESS by neglecting the cultural and supporting services that also play a significant role. Therefore, comprehensive frameworks are needed that cover all four categories of HESS as defined by the Millennium Ecosystem Assessment Program (2005) [1]. In Europe, the Mapping and Assessment of Ecosystems and their Services (MAES) Working Group, established to support the implementation of the EU Biodiversity Strategy, has suggested an analytical framework for the implementation of the ecosystem service approach in the EU and tested it in a pilot study on freshwater and marine ecosystems [33]. Additionally, the Consultative Group on International Agricultural Research (CGIAR) on Water, Land and Ecosystems established the Ecosystem Services and Resilience framework (ESR) [34]. Utilizing an approach similar to UNEP (2010) [11], the ESR framework catalyzes the flow of ecosystem services to and from agriculture, thereby enhancing production and subsequently improving food and livelihood security. Within the framework, a set of indicators and metrics is considered essential for monitoring the impacts and outcomes of changes to ecosystem service flows on ecosystems and people. While an inclusive set of quantifiable HESS indicators is not yet available through these efforts, several partners of the CGIAR Water, Land and Ecosystems program have endeavored to develop such indicators to improve the measurement of resilience and socio-economic performance. Examples include Biodiversity International (CIAT) development of twenty indicators to assess the resilience of different aspects of ecological, agricultural, cultural, and socio-economic systems [35], and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)'s proposed monitoring instrument for resilience [36].

For long-term basin's water resources planning, management and allocations, a system for measurement, reporting and validation (MRV) like Water Accounting Plus (WA+) showed a lot of potential. WA+ is an initiative developed by IWMI, FAO and IHE-Delft [37,38] that aims to provide periodic reports on water resources in river basins. WA+ is largely based on remote sensing data and integrates hydrological processes with land use, managed water flows and the services that result from water consumption in river basins. In this way, it aims to provide the information needed to achieve equitable and transparent water governance for all users. Explicit spatial information is provided through this framework on water consumption and withdrawal processes, going beyond flow and runoff accounting. WA+ can be used to evaluate and plan water resources management, to monitor changes in water resources, especially consumptive/non-consumptive use and to assess the impacts of future interventions, ensuring a sustainable water balance. To provide a synthesis on the relationships between a number of hydrological and ecological processes for different river types, frameworks such as ecological limits of hydrologic alteration (ELOHA) [39] provides understanding of the linkages between hydrologic, ecological and social aspects of environmental flow assessment. The Natural Capital Project (NatCap) leverages the use of ecosystem services through a set of analytical platform for mapping and modeling nature's benefits such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), ARtificial Intelligence for Environment & Sustainability (ARIES) [40,41].

Water productivity in agriculture is introduced to recognize that food production requires water ("no crop without water"). It is realized that agricultural water besides food, feed and fiber, also creates economies, jobs and calories [42]. It is less commonly recognized that this agricultural water also creates various co-benefits for the environment such as soil carbon pools, reducing crop water demands, sustaining rainfall and drainage water that increases total runoff. Hence HESS services are included in the same amount of water. It is therefore important to link HESS to existing frameworks, in this case water productivity.

1.4 Quantification of Hydrological EcoSystem Services

In order to assess HESS and implications from water management scenarios and decision making at national and regional scales, hydrological models are needed. The use of models helps to overcome several processes to be able to assess the water-ecosystem-land systems [43]. It requires to use combined techniques and data sets from both biophysical ecology and hydrology. Techniques such as eco-hydrological modelling can help to solve this issue. However, the use of models involves inherent simplifications and assumptions, as well as considerations of the scales at which the systems operate. Modern earth observation methods, including remote sensing of precipitation, evapotranspiration (ET), biomass production [44] can be combined with big data approaches, e.g., Internet of Things, citizen science, and artificial intelligence, to complement traditional in-situ measurement.

Eco-hydrological models can be combined with quasi-open access remote sensing data to improve modelling performance and address data scarcity. Remote sensing has evolved into an advanced technique that significantly strengthens HESS evaluation by directly integrating land surface and climatic parameters into eco-hydrological models [17,45]. For instance, the availability of spatially distributed land cover, land use, precipitation, ET, soil moisture, Leaf Area Index (LAI) and open water gridded data from open access—or partially open access—earth observation data platforms, makes it feasible to calibrate soil and vegetation process parameters of eco-hydrological models, also when rivers are ungauged and the water distribution system is complex. The number of water quality parameters from remote sensing is also growing [46]. For instance, Winsemius et al. (2008) [47] constrained soil and hydrological parameters of a semi-distributed hydrological model using time series of ET. This approach is particularly advantageous for developing standardized HESS evaluation methods, as it allows for the use of a consistent set of input data, regardless of status of data collection and data governance in different parts of the world. Most eco-hydrological models require information such as land cover, soil, and land surface dynamics, which can be obtained through remote sensing. These techniques facilitate the acquisition of HESS information at macro (global, regional, national) or local (basin) scales. This approach provides quality data essential for spatially mapping and scenarios assessment, such as IWRM. Furthermore, it enables the evaluation of the interactions among land use changes, regional hydrological ecosystem services, and human well-being [48].

1.5 Research approach and dissertation outline

Based on the above-mentioned overview, the objectives of this dissertation are threefold: first, to formulate a standard framework consisting of a set of HESS indicators aligned with the CGIAR ESR framework, which can be determined from remote sensing technologies and supported by eco-hydrological models; second, to develop algorithms and modeling routines to quantify these HESS indicators at both the river basin and the national scale of Vietnam; and third to assess sustainability by benchmarking HESS indicators to demonstrate the degree of performance for a larger public. The research findings are described in the following chapters.

Defining the HESS framework (Chapter 2)

The initial step in implementing HESS quantification involves the definition of key indicators related to hydrological ecosystem services. These indicators should be delineated into consumptive and non-consumptive use. The HESS framework should be designed to integrate with existing policy frameworks such as IWRM, NbS, Water Accounting and Water Productivity. Moreover, it must outline the quantification approach for HESS in river basins, utilizing hydrological models. To make this comprehensive, this HESS framework should include all four categories of HESS with indicators categorized into provisioning, regulating, supporting and cultural services.

Transparent calibration and calculation procedures for HESS (Chapter 3 and 4)

The estimation of HESS must be documented through a transparent and standardized procedure. The use of remote sensing data or any model should be structured to allow for straightforward replication. The algorithm employed in analysis should be transparent enough for practitioners and decision-makers in the field of ecosystem services to understand, modify while being robust enough to accommodate a variety of applications.

The Regional Hydrologic Extremes Assessment System (RHEAS) coupled with Variable Infiltration Capacity (VIC), Soil and Water Assessment Tool (SWAT) and Water Productivity through Open-access of Remotely sensed derived data (WaPOR) are recommended as preferred tools for simulating HESS at various scales. For instance, the RHEAS model, coupled with VIC, leverages the use of remote sensing data to incorporate processes related to vertical hydrology flow. Modelling facilitates a multi-scale assessment, both temporal and spatial. However, the assessment of HESS at different scales necessitates different techniques. While input data can be standardized and made robust across various scales, attention should be paid to the temporal and spatial representation of HESS. Therefore, it is crucial to consider the scales of hydrological ecosystem services when applying valuation to support the formulation or implementation of hydrological ecosystem management plans.

Demonstration of a country assessment including sustainability assessment (Chapter 5)

Incorporating a benchmarking system and sustainability index can provide further insights into ecosystem performance. This benchmarking system can be derived from HESS indicators, either as relative or normalized indices. Sustainability assessment and indexing need to be coherent and applicable to every basin or environment. Utilizing the benchmarking and ranking of sustainability performance allows for understanding of benefits, tradeoffs, and identifying hotspots where further efforts are needed.

2 A New Framework of 17 Hydrological Ecosystem Services (HESS17) for Supporting River Basin Planning and Environmental Monitoring[1]

Hydrological ecosystem services (HESS) describe the benefits of water for multiple purposes with an emphasis on environmental values. The value of HESS is often not realized because primary benefits (e.g., food production, water withdrawals) get the most attention. Secondary benefits such as water storage, purification or midday temperature cooling are often overlooked. This results in an incorrect evaluation of beneficial water usage in urban and rural resettlements and misunderstandings when land use changes are introduced. The objective of this study is to propose a standard list of 17 HESS indicators that are in line with the policy and philosophy of the Consultative Group of International Agricultural Research (CGIAR) and that are measurable with earth observation technologies in conjunction with GIS and hydrological models. The HESS17 framework considered indicators that can be directly related to water flows, water fluxes and water stocks; they have a natural characteristic with minimal anthropogenic influence and must be quantifiable by means of earth observation models in combination with GIS and hydrological models. The introduction of a HESS framework is less meaningful without proper quantification procedures in place. Because of the widely diverging management options, the role of water should be categorized as (i) consumptive use (i.e., evapotranspiration and dry matter production) and (ii) non-consumptive use (stream flow, recharge, water storage). Governments and responsible agencies for integrated water management should recognize the need to include HESS17 in water allocation policies, water foot-printing, water accounting, transboundary water management, food security purposes and spatial land-use planning processes. The proposed HESS17 framework and associated methods can be used to evaluate land, soil and water conservation programs. This study presents a framework that is non-exhaustive but can be realistically computed and applicable across spatial scales.

---

[1] Chapter is based on: 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.

2.1 Introduction

Ecosystem services are defined as the goods and services provided by ecosystems that are direct and indirect contributions to human well-being [1,3]. Ecosystem services are the benefits that people and societies receive from nature, such as food, water, pollination, nutrient cycling and many others. Hydrological ecosystem services (HESS), also referred to as water-related ecosystem services, link these services to the hydrological cycle, thus making explicit that the magnitude of the ecosystem service depends on water availability, i.e., quantity and quality. For example, certain stream flow regimes are required for maintaining fish, birds and perennial corridors that provide food and income for local people [15]. Recurring rainfall is required for keeping dryland agro-forestry ecosystems productive. The hydrological processes of the unsaturated zone control gaseous exchanges in water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ammonification (NH_4) and nitrous oxide (N_2O) between land and atmosphere, thereby regulating atmospheric greenhouse gas concentrations and warming of the earth. Vegetated surfaces have great ecological value, but they require certain soil moisture regimes for sufficient photosynthesis. The World Wide Assessment Program [14] synthesized the international developments on nature-based solutions (NbS) for water and highlighted the growing emphasis on the inclusion of ecosystem services as quantifiable benefits into integrated land and water resource management around the world. The Consultative Group of International Agricultural Research (CGIAR) established its Ecosystem Services and Resilience Framework (ESR) defining an ecosystem service-based approach to build community resilience and restore ecosystem services for provisioning goals or in ways that support and regulate these goals, while reducing the negative impacts on the natural resource base that underpins these ecosystem services [34]. CGIAR's ESR provided an excellent entry point for creating a minimal list of HESS indices that followed ES characteristics and quantification methods, i.e., use of earth observation data in combination with GIS and eco-hydrological tools. The use of scenarios and models for HESS quantification allows a pragmatic approach to support decision making in river basin planning and environmental monitoring within time and space boundaries [49]. Examples include assessment of marginal benefits to nature and humans as consequences from basin management alternatives. Furthermore, inclusion of HESS ensures the transition from traditional top-down and single-objective systems into multi-criteria and human-centered approaches that can prioritize activities with a broader spectrum of benefits [50]. Especially, HESS ensures the uptake of international guidance, such as integrated water resources management (IWRM), by achieving a win-win co-development of water with, among others, land and ecosystems, while fully delivering the benefits to humans and society [51].

The quantification of HESS has become one of the fastest growing areas of environmental research [52]. Yet, due to the absence of operational information systems, policy makers continue with business as usual. Clear definitions and explanatory methods for quantification of HESS are vital to close this policy–practice gap. Both the benefits and the water volumes needed to establish these benefits must be estimated across areas with spatially variable physiographic conditions.

The lack of a standardized framework and consensus for quantifying HESS as a spatial process limits the uptake by policy makers and managers [32,53,54]. In this context, the development of a minimum list of HESS indicators is a great contribution to ecosystem services research. Such a framework would improve comparability between river basins and watersheds and help people understand the impacts of longer term policies, implementation plans, projects and investments on achieving a healthier water-related ecosystem.

Analytical tools for spatial assessment of HESS have been developed [50,54] including distributed hydrological models, e.g., soil and water assessment tool (SWAT) [55,56]; ecosystem services-oriented tools, e.g., integrated tool to value ecosystem services (InVEST) [40]; or artificial intelligence for ecosystem services (ARIES) [57]. SWAT has the ability to connect surface water, soil moisture and groundwater hydrologically using local land use and soil information to further water quality and food production [32,58]. Various elements of HESS such as water yield, water purification and sediment retention can be assessed by tools such as InVEST [59,60]. A different form of HESS modelling was outlined by Simons et al. (2017) [45] who demonstrated how publicly available earth observation data sets can be applied to generate HESS assessments at pixel level. Using pixels of 250 m × 250 m or 1 km × 1 km provides new opportunities to locally report HESS.

The objective of the current study is to describe a framework for HESS indicators which is in line with the policy and philosophy of CGIAR WLE's ESR framework [34]. Seventeen HESS indicators will be proposed and possible methodologies to quantify them will be discussed using remote sensing, GIS and hydrological models. This list is not exhaustive and can always be expanded; it should be considered as a first attempt in the direction of standardization.

2.2 Brief literature review of Hydrological Ecosystem Services (HESS)

The Consultative Group on International Agricultural Research (CGIAR) on Water, Land and Ecosystems published a comprehensive report on ecosystem services and a resilience framework [34]. Similar to TEEB (2010) [4], ESR catalyzed the flow of ecosystem services to and from agriculture to increase production and subsequently food and livelihood security. In terms of a HESS framework, Grizzetti et al. (2016) [32] developed an analysis framework for inland waters in European basins considering the links between pressures, ecological status and ecosystem services. In this study, four HESS attributes were identified, i.e., water quantity (including seasonality), water quality, biological quality elements and hydro-morphological/physical structure. Focusing on the way ecosystems affect hydrologic attributes, i.e., water quantity, quality, location of delivery and timing of delivery, Brauman et al. (2007) [61] presented a framework for defining and assessing HESS attributes, which translate eco-hydrological processes into an ecosystem service context useful to decision makers; it included water for municipal use, hydropower, recreation, fish supply, reduction in flood damage, water and nutrients to support vital estuaries and other habitats, preservation of options, etc. With a similar end result, Belmar et al. (2019) [62] assessed the relationships between annual mean discharges, fish populations and shellfish species (prawns and shrimps) in the lower Ebro. The mean annual discharge was able to explain the variation in fish-based ecological quality; model performance increased when aquatic vegetation was incorporated. Among HESS studies focusing on provisioning and regulation, Poff et al. (2010) [39] introduced the ELOHA framework which considers a number of hydrological and ecological processes for different river types to understand the linkages between hydrologic, ecological and social aspects of environmental flow assessment. These relationships are established based on paired streamflow and ecological data from throughout the region of interest. Similarly, Pan and Choi (2019) [63] developed a conceptual framework for HESS consisting of a temporal demonstration of water provision, flood control and sediment regulation in the Milwaukee River Basin (US) based on ground observation of streamflow and sedimentation for calibration.

In terms of HESS quantification and trade-off analyses, Gao et al. (2017) [64] analyzed land-use change and corresponding variations in water-related ecosystem services, i.e., water yield, soil conservation and water purification services in the Guishui River Basin, China. Their study underscored that HESS services were greatly affected by different land-use change scenarios. Thus, land-use and water-use policies should include water-related ecosystem services. Willaarts et al. (2012) [65] empirically assessed the relationship between the use and management of agroecosystems, their hydrological functioning and HESS, through a list of nine HESS indicators including forage, drinking water, flow regulation, recreation, olive crops and cork production, meso-climate regulation, hydropower generation and maintenance of aquatic biodiversity. Bangash et al. (2013) [66] evaluated the impacts of climate change in the water provisioning and erosion control services in the densely populated Mediterranean Llobregat River Basin (Spain). Their study found that drinking water is expected to decrease between 3 and 49%, while total hydropower production will decrease between 5 and 43%. Fan et al. (2016) [67]

determined water yield, inorganic nutrients, organic nutrients and sediment retention in the Teshio watershed (Japan) using the SWAT model. The results indicate that HESS provides an effective trade-off between environmental protection (sediment and organic nutrient retention) and economic development (water yield and inorganic nutrient retention).

The point of this brief review is to highlight that authors often have similar thoughts on the usefulness of water resources for the environment, with diverging and often ambiguous definitions; however, quantification methods are not ambiguous. Existing frameworks on interpretations of HESS are comprehensive and contain indicators that are amenable to quantification. The inclusion of supporting and cultural services is often overlooked and questionable in terms of a quantification method [68]; nonetheless, it seems to be necessary for consideration in any framework. Similar discussions on the segregation of supporting services from provisioning and regulating indicate that different views still exist [1,34,69].

For this reason, this study aims at defining a minimum and standard list of 17 HESS indicators congruent with the CGIAR framework.

2.3 Definition of the Hydrological Ecosystem Services (HESS) framework

2.3.1 Formulation of the HESS17 Framework

A minimum list of HESS indicators was taken from the CGIAR report using certain criteria. The formulation of this non-exhaustive framework on HESS and their quantifications are underpinned by the view that a conceptualized and standardized assessment skeleton of multiple values of hydrological ecosystems and their benefit to humans needs to be recognized and valued. Through this process, priorities on the development pathways and scenarios that most benefit people while adequately address the challenge of sustainability at different scales, e.g., global, river basin or community level [70]. There are numerous frameworks that establish as a priority the use of models for monitoring of provisioning and regulating services, such as water provisioning or soil erosion [40,59]. However, there is a shortage of approaches that can incorporate values of HESS into river basin management and across the nature–human sphere. This shortcoming occurs in two aspects: the first is providing a conceptualization, seamless valuing and representation of hydrological ecosystem services in provisioning, regulating, supporting and cultural functions; the second is their ability to include the development of scenarios and pathways across scales and benchmark the level of sustainability. Another characteristic of the HESS17 framework is its capability to provide an ample space for adding more indicators in the future, following the implementation of SDGs or achievement of human development targets.

Existing frameworks [1,32,39] show a greater abundance and clear imbalance towards provisioning and regulation services rather than cultural and support services; many studies solely focus on the former [52,66]. This drawback results from the characteristics of HESS in that they have a much stronger connection to regulation and provisioning services, i.e., water flows, storage and moisture circulation, than on cultural and/or habitat services. In this framework, we aim to have a full spectrum of indicators from the entire four HESS categories by including HESS that represent supporting and cultural services. The selected set of HESS indicators succinctly defines how multiple values of ecosystems and their contributions to people should be acknowledged. Selected HESS indicators should fulfil certain criteria: they should be water flows, water fluxes and water stocks; they should also be clearly adhered to a natural function or process of the ecosystem with minimal anthropogenic influence; and they must be quantifiable by means of earth observation models in combination with GIS and hydrological models. Apart from considering HESS properties, the HESS17 aims to catalyze the interactions between eco-hydrological components and processes and build up a feedback mechanism that reflects human–nature relationships, e.g., through the simulation of land use changes, urban heatwave, agricultural production and an investigation of NbS outcomes. The valuation and assessment of feedback functions will allow the calculation of benefits and expenses of HESS in spatially and temporally explicit manners [59]. Examples of this are the generation of runoff or maintenance of dry season flows from upstream, which can benefit downstream communities or the improvement in sustaining rainfall within the basin's perimeter through effective water management.

The HESS indicators should not be related to specific remote sensing algorithms or numerical models. McCartney et al. (2013) [71] emphasized that HESS should be based on natural water services in pristine environments and landscapes; this is a narrower view that emphasizes mainly the role of natural lakes and wetlands as natural sponges that retain water and reduce peak flows. While this is fundamental, a broader view of natural benefits from water consumption is necessary. Natural vegetation communities consume vast amounts of water, and their benefits for living organisms are significant, ranging from the provision of shade to biodiversity, to insects that enhance pollination. The consumptive use of water resources in river basins, e.g., evapotranspiration, forms the basis for various environmental services, such as sustaining rainfall or providing micro-climate cooling. It is a key process since these water resources originated from surface water and groundwater flows and stocks; thus, they should be utilized as responsibly as possible [72–76]. The general categories of ecosystem descriptions are fresh water, food, fuels, fresh water supply, disturbance regulation, air climate and quality, water quality, habitat provision and recreation (see Table 1). They can be synthesized into provisioning, regulating, supporting and cultural services. Because of the irreversible character of consumptive use, it is sound to separate HESS into processes that are related to consumptive use (e.g., evapotranspiration) and non-consumptive use (e.g., runoff, percolation, baseflow). Furthermore, one remaining question in addressing HESS is the spatial–temporal connection between locations that are providing and demanding HESS, i.e., where are HESS produced and where are HESS consumed? The proposed HESS framework aims to delineate these spatial–temporal relations by identifying the locations that are providing and those that are demanding, i.e., at the larger river basin scale or in localities where HESS is consumed by local communities, and the time aspect of when benefits or potential demands for HESS can be mapped.

In total, 17 HESS were identified and selected, categorized into provisioning (4), regulating (11), supporting (1) and cultural (1) services.

Table 1. Proposed framework of 17 hydrological ecosystem services (HESS) based on a CGIAR workshop.

General categories	HESS	Ecosystem services/concept	Major principles	Unit	Spatial connection between providing and demanding locations of HESS	Temporal connection between providing and demanding locations of HESS	Consumptive use	Non-consumptive use
Provisioning services (related to water)								
Fresh water	1	Basin runoff	Ultimate source of water available for multiple purposes	m^3/ha	River basin, in-stream directional benefits (downstream)	Annual, seasonal (wet and dry period)		x
Food	2	Inland capture fishery	Catch from lakes, wetlands, rivers	kg/ha	Local, surrounding communities	Annual	x	x
Food	3	Natural livestock feed production	Dry matter production from natural pastures, alpine pastures, wetlands and more	kg/ha	Local, surrounding communities	Annual	x	
Fuels	4	Fuelwood from natural forests	Dry matter production from forests and savannahs	kg/ha	Local, surrounding communities	Annual	x	
Regulating services (related to water)								
Fresh water supply	5	Dry season flow ("baseflow")	Flow from groundwater outflow, lakes, wetlands and upstream runoff	m^3/s	River basin, directional benefits (downstream)	Seasonal (during dry period)		x
Fresh water supply	6	Total groundwater recharge	Vertical transient moisture flow originating from percolation reaching saturated groundwater	m^3/ha	River basin	Annual, seasonal (wet and dry period)		x
Fresh water	7	Surface water storage	Total water stock in natural surface water systems (lakes, wetlands)	m^3	River basin, local, surrounding communities	Annual, seasonal (wet and dry period)		x
Fresh water supply	8	Root zone water storage	Retention of soil moisture in unsaturated zone for carrying over water from wet to dry seasons	m^3	River basin, local, surrounding communities	Annual, seasonal (wet and dry period)		x
Fresh water supply	9	Sustaining rainfall	Sustaining rainfall originating from land evaporation	m^3/ha	River basin	Annual	x	
Disturbance regulation	10	Peak flow attenuation	Attenuated peak flow for safeguarding downstream areas from flooding by means of ecological intervention	%	River basin, directional benefits (downstream)	Seasonal (wet period)		x
Air quality and climate	11	Carbon sequestration	Assimilating atmospheric carbon into crop organs (wood, roots) and soil	kg C/ha	River basin	Annual	x	

Air quality and climate	12	Reduce greenhouse gas emissions	Reduced methane emissions and other trace gasses due to changes in land use and water management	kg C/ha	River basin	Annual	x	
Air quality and climate	13	Micro-climate cooling	Evaporative cooling of the vegetation and near-surface atmosphere due to changes in land and water management	°C	River basin	Annual	x	
Water quality	14	Natural reduction of water eutrophication	Reduction in eutrophication due to changes in land use and water management	%	River basin, directional benefits (downstream)	Annual, seasonal (wet and dry period)		x
Water quality	15	Reduction in soil erosion	Reducing erosion and sedimentation by increased vegetation cover	kg/ha	River basin, directional benefits (downstream)	Annual, seasonal (wet and dry period)	x	
Supporting services								
Habitat provision	16	Meeting environmental flow requirements	Meeting minimum flows and water levels for biodiversity, ecosystem health and endangered (fish) species	%	River basin, in-stream directional benefits (downstream)	Seasonal (wet and dry period)		x
Cultural services								
Recreational	17	Leisure	Socialisation of humans via water sports, golf courses, eco-tourism, aesthetic views, mountain biking, forest BBQs, etc.	Number of visitors	Local, surrounding communities	Annual, seasonal (wet and dry period)	x	x

2.3.2 Definition of HESS Presented in the Framework

HESS1: Basin Runoff

Basin runoff (HESS1) from a river basin is the amount of surface and groundwater resources that are generated internally in a watershed or river basin. Inflows from upstream basins is excluded. Surface runoff creates stream and river flows which are the source for aquatic ecosystems. Excess water from the surface network and the unsaturated soil through leakage and percolations feeds aquifer systems that convey water laterally and interact with streams. Because surface water can become groundwater and vice versa, the term basin runoff is preferred for defining HESS1.

At the aggregate level of the basin, basin runoff is the sum of surface runoff into streams and natural percolation from the root zone into drainage networks and aquifers (this excludes non-natural percolation arising from water resource withdrawals). The baseflow is ultimately available in streams as flows during the dry season. Interflow occurs on undulating or sloping terrain where unsaturated zone moisture has a lateral component due to layered soil properties, perched water tables, etc. Because HESS1 represents the basin runoff, the exact flow path of water to reach streams and rivers, as well as the stream flow, are less relevant.

Basin runoff is the primary source for all multi-purpose withdrawals, both naturally (e.g., floods, lakes, groundwater dependent ecosystems) and manmade withdrawals (e.g., domestic, industry, irrigation). Natural withdrawals can be significant, and blue water resource consumption related to withdrawals is not available for other usage [61,72,77].

A simple t definition of basin runoff is precipitation minus ET from green water resources ($P\text{-}ET_{green}$), sometimes indicated as net precipitation. This definition excludes all water withdrawals (including natural withdrawals). Water stored in permanent surface and groundwater systems should also be subtracted from basin runoff.

Several papers have been published that show how P can be solved from earth observations [78,79]. Different energy balance models can be chosen for the estimation of ET [80,81]. Spatial ET data can also be used for various types of hydrological analysis [55]. The GRACE gravity mission measures the changes in water storage ΔS in an independent manner [82,83]. P, ET and ΔS together can be used to assess basin runoff.

HESS2: Inland Capture Fishery

HESS2 describes the fish catch from inland lakes, rivers, mangroves, lagoons and other natural water bodies. The catch from these waters is of economic value and provides nutrients to local communities. Specific flow regimes are an asset for prawning, fish migration and fish catch. Most freshwater fish have evolved life cycles that are adapted to natural river habitat and flow regimes. The evaporation from these water systems can be considered as the water consumed for achieving the fish catch. Information on the size of open water bodies together with the evaporation from water bodies is required to relate inland capture fisheries to water consumption.

Information on the capture of inland fish can come from standardized statistical records. The database of FAOSTAT (2021) [84] and WorldFish (2014) [85] are good options to obtain data and they reveal a linear growth over the last 50 years. FAO estimates that 12 million tonnes of inland fish were captured in 2018; this was 6.7% of total fish production [86]. Marine capture is seven times more than inland capture. Current data are sufficient only for a general overview of global inland catches of fish, rather than for the detailed analysis needed for management, policy formulation and valuation of inland fisheries [87].

Several studies [88–90] illustrated the use of different spectral indicators to identify the size of water bodies using optical data. During monsoon with frequent cloud cover and floods, the quality of the optical data is hampered, and it is customary to use synthetical active radar (SAR) data. Rebelo et al. (2018) [91] and Donlon et al. [92] showed how Sentinel-3 SAR data can be best utilized. Various techniques consisting of L-band synthetic aperture radar (SAR) [93], Landsat and SPOT [94] were used to monitor the status of and changes in wetlands, both rainfed and water bodies, to calculate fisheries' yield based on a yield-per-unit area approach. The combination of size of the open water area, water level and water evaporation were sufficient to compute the consumptive use of water bodies on a volume basis.

HESS3: Natural Feed for Livestock

HESS3 deals with the natural feed for livestock owned by pastoralists and wild livestock such as mountain sheep, wild mammals, cats, elephants and the like. Cattle and cats graze on several types of natural pastures (grass fields, savannah, steppes, alpine, wetlands). Their feed is a result of photosynthesis and water consumption (ET). HESS3 is essential for many national parks and extensive savannah landscapes.

The physical processes of dry matter production of grasslands are widely studied. Various versions of net primary production (NPP) models exist for the computation of the net carbon flux of pastureland. While NPP models are often made for global ecological studies, they can also be applied on a pixel by pixel basis. Hence satellite measurements can be used to determine NPP and dry matter production. Remotely sensed data from multispectral satellites, e.g., MODIS, Landsat, Sentinel-2, etc., can be used to assess grassland's greenness and thickness while optical sensors can capture biophysical and biochemical information [95]. Monteith's model [96] for the production of pasture is based on absorbed photosynthetically active radiation (APAR) and a light use efficiency (LUE) conversion factor. LUE values for grassland vary typically between 1.6 to 2.8 gr/MJ, depending on soil moisture, temperature, vapor pressure deficit and grass nitrogen status [97].

A first distribution of the crop organs is between above- and below-ground accumulated dry matter productions. This is classically expressed by means of the root/shoot ratio, which is 1.5 to 2.5 for grassland. Hence, above-ground production is approximately 33% of the accumulated total dry matter production. Furthermore, not all above ground dry matter production can be considered livestock feed. An amount of 25% of the accumulated dry matter production of cropland is assumed to be available for feed. In addition, residues from field crops (e.g., stems and leaves not taken away during the harvest process) are also part of the natural feed. Part of the dry matter production from these specific land use classes related to pasture and crop residues should therefore be HESS3 inclusive.

HESS4: Fuelwood

Fuelwood includes firewood, charcoal, chips, sheets, pellets and sawdust. Fuelwood is used for cooking and heating in developing countries, where it is of great value for the livelihoods of local communities. Fuelwood is a co-product of forestry, timber production and woodland management. HESS4 addresses fuelwood from natural forests and savannahs, but not from plantations. Roughly 25% of global fuelwood is produced in sub-Saharan Africa. One ton of charcoal requires five tons of wood [98]. Similar to HESS3, fuelwood can be computed from NPP models or earth observations of APAR and LUE [99].

The ratio of above to total dry matter production of woody vegetation types is typically 60 to 80%. Trischler et al. (2014) [100] found that above-ground carbon assimilates are 65% of the total production value for common tree species in Sweden. In Ethiopia, Pukkala and Pohjonen (1990) [101] showed fresh wood production for eucalypt in a range from 7 to 35 ton/ha/yr. Fresh wood production of 20 ton/ha/yr is approximately 14 ton/ha/yr dry wood. Several remote sensing algorithms are also available for the assessment of ET in forests [102,103].

HESS5: Dry Season Flow

Dry season flow—HESS5 (also called base flow, drought flow, groundwater recession flow)—is the portion of the streamflow that originates from the lateral groundwater flow that seeps into the river channel. The stream flow during the dry season is fundamental for humans disconnected from water utilities, livestock and environmental systems that only survive due to daily access to water resources. Pollutants need to be diluted and evacuated towards seas and oceans, and HESS5 also contributes to that process. HESS5 is a regulating service.

The recession limb of the hydrograph reveals the point where the river's level falls to a level where baseflow becomes the major source of stream flow. The hydrograph is obtained typically from hydrological models, although there is more literature on the assessment of flow from earth observations. Yang et al. (2014) [104] and Donchyts et al. (2016) [105] showed that river widths can be delineated using multi-scale classification approaches. The width of rivers containing water is essential for assessing whether baseflow is occurring. If the water body area dried up, it can be concluded that the base flow has vanished. Bjerklie et al. (2018) [106] demonstrated an integrated methodology to assess discharge, flow depth, and flow velocity determined from remotely observed water surface area, water surface slope, and water surface height for two reaches of the Yukon River. Durand et al. (2016) [107] described the determination of river height, river width and river slope. Michailovsky and Bauer-Gottwein (2014) [108] showed the development of a generic 1D stream flow Manning equation to assess river discharges based on these river dimensions. The surface water and ocean topography (SWOT) satellite mission planned for launch in 2022 will map river elevations and inundated areas globally for rivers > 100 m wide. Figure 4 illustrates an application of Sentinel-3A altimeter data for detecting water level change in river [109].

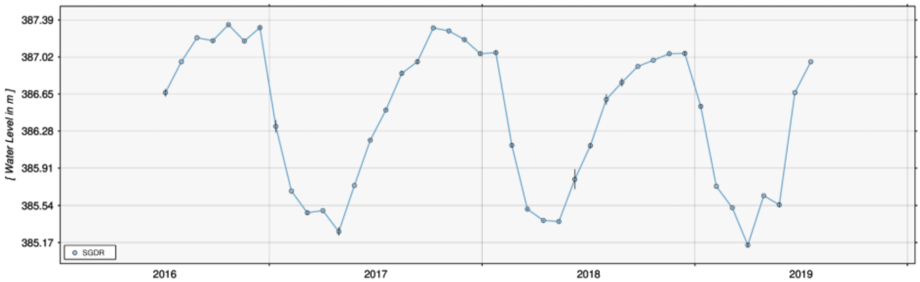


Figure 4. Changes in the water level of the White Nile near Kodok in South Sudan measured by the altimeter on Sentinel-3A. Base flow is pertinent when the water level is at approximately 385.4 m AMSL (source Dahiti, Technical University of Munich) (http://dahiti.dgfi.tum.de/11745/) [109].

HESS6: Total Groundwater Recharge

Aquifers are often considered the "bank savings accounts" to abide periods of drought. Groundwater recharge from rainfall describes the renewable groundwater resources and HESS6 forms the source of multi-sector groundwater abstractions and baseflow to feed streams during periods without surface runoff. It is the source for total water storage underground where there are no evaporation losses. HESS6 is fundamental for preparing long term groundwater allocation plans to ensure sustainable withdrawals for several users. While HESS1 focuses more on natural recharge processes, HESS6 relates to the total recharge from various sources to maintain water in underground stocks for periods when it is needed the most.

While water from leaking irrigation fields, reservoirs and artificially created canals is clearly an example of anthropogenic recharge $q_{anth}^{\downarrow}$ [110], it is believed nevertheless to be valuable for describing total recharge as an ecosystem service, for instance to ensure sufficient drinking water for the domestic sector. Recharge from a leaking river $q_{riv}^{\downarrow}$ is partially natural, but also partially anthropogenic because river flow is a result of upstream interventions in the water cycle. These can be the building of dams and reservoirs, but also diversions of surface water and the changes in land use that accelerate flow after heavy rainfall events.

Percolation occurs when soil moisture of the unsaturated zone exceeds its field capacity and drainable flow limits. Thus, wet soils and water bodies contribute significantly to recharge and more than, for instance, settlements and rainfed cropland that usually have a soil moisture content that is lower than field capacity. The most widely accepted mathematical solution for computing percolation fluxes in the unsaturated zone is Richard's equation for vertical and transient soil moisture flow; it is a combination of Darcy's law for water flux in unsaturated soils and the continuity equation. However, local knowledge on these soil hydraulic properties are not common, and numerical models for solving Richard's equation are difficult to operate [51]. Alternative solutions have been worked out, such as the chloride mass balance (CMB), rainfall infiltration breakthrough (RIB), extended model for aquifer recharge and moisture transport through unsaturated hard rock (EARTH), water table fluctuation (WTF), water balance in the saturated zone (including equal volume spring flow (EVSF) and saturated volume fluctuation (SVF)) and groundwater modelling (GM), see [111] for a review of these processes). Wohling et al. (2010) [112] elaborately summarize various methods for Australia, including the role of rainfall, clay content, vegetation basal area, leaf area index, depth to water table and hydraulic conductivity on estimating recharge in a practical manner. Hessels et al. (2022) [113] introduced an elegant method to compute percolation fluxes from the root zone on the basis of soil water balance residuals of green water pixels.

HESS7: Surface Water Storage

HESS7 describes water stocks, excluding rivers and reservoirs. It is the amount of blue water present in natural surface water systems (lakes, wetlands, lagoons). Rivers provide little storage at a monthly scale and is therefore negligible. Trends in natural water storage are meaningful information for the health of hydrological ecosystems and for the retention of water to carry over resources during drier spells. Water storage in lakes and wetlands enhances ecosystem services because it is indistinguishably linked to various services, such as water retention during floods and attenuation of peak flow; water supply during elongated droughts; water for agriculture (cropping systems on banks; livestock water supply, fish); water-related habitats for migratory birds and water-related mammals; cooling off hot air masses; and leisure opportunities.

Rebelo et al. (2018) [91] conducted an overview of wetland distribution, type and condition across sub-Saharan Africa and showed that local communities highly rely on both wetland agriculture and natural resources. The areal size of open water bodies in lakes, wetlands, lagoons and mangroves can be computed from satellite measurements [114] (see also Figure 5). Water depth can be estimated from water level fluctuations using satellite-based altimetry which, in combination with area, can be used to assess surface water stocks [115].

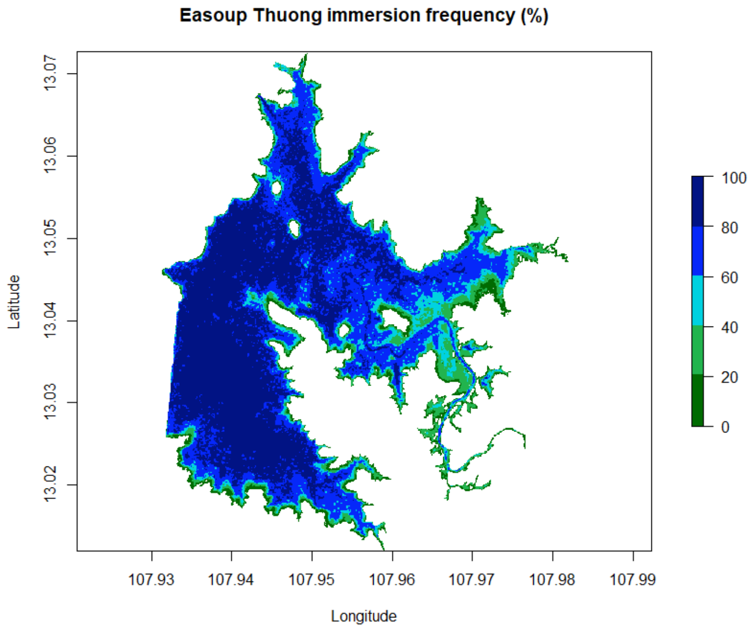


Figure 5. Probability of water occurrences in Easoup Thuong reservoir, central Vietnam, based on satellite images of the open area. During wet periods, the area doubles in size.

HESS8: Root Zone Water Storage

The root zone has an important regulating role in infiltration, retention, storage and root water uptake for the transpiration of local vegetation systems. The root zone connects geology, pedology and biology. The soil water retention characteristic, in conjunction with root depth, dictates the amount of water that can be retained in the sub-surface. The soil water-holding capacity is the difference between soil moisture at field capacity and at wilting point [116]. It varies typically between 50 to 250 mm/m. Deeper root systems (e.g., more than 1 m) can store vast quantities of water (>5000 m^3/ha) and carry water over from the rainy season to the dry season, even from wet winters to dry winters. Root zone water is the first and utmost important supplier of water for vegetation in the dry season [117]. Hence, HESS8 expresses the capture of soil water during periods with a positive rainfall surplus. Because land surface containing roots is significantly larger than open water bodies, HESS8 is a crucial regulator of climatological deficits and excess water.

Most remote sensing techniques for the determination of soil moisture are based on radar and microwave technologies [118,119]. This technique is at best useful for detecting skin moisture under sparse vegetation. Microwave vegetation optical depth (VOD) describes the attenuation of radiation due to scattering and absorption within the vegetation layer, which is caused by the water contained in the vegetation [120]. The optical depth of the vegetation is a serious constraint for measuring skin soil moisture [121].

Moisture in the root zone can therefore be best inferred from the land surface temperature of vegetated surfaces. The temperature of the vegetation reflects sub-soil processes such as root development, storage capacity of the soil and soil water potential. Various remote sensing solutions are therefore based on inferring soil moisture in the root zone from evapotranspiration processes [122–124] or from soil thermal inertia [125]. Carlson and Petropoulos (2019) [126] and Yang et al. (2015) [127], among many others, used the trapezoid between land surface temperature and vegetation index to infer a relative value for soil moisture. These techniques are much simpler than microwave measurements and appeared successful in operational and continental scale applications [128]. The changes of volumetric soil water content in the rootzone between end of dry and end of wet season will specify the amount of water stored in the root zone.

HESS9: Sustaining Rainfall

HESS9 describes the longer term changes in local rainfall due to changes in the catchment's and river basin's water balance. Land evapotranspiration conveys large amounts of water vapour back into the atmosphere which increases the precipitable amount of water. Savenije (1995) [16] showed that evaporation in a transect from west to east Africa can be held responsible for high rainfall events. The total rainfall patterns over Africa could not be explained from advection coming from the Atlantic Ocean only. For areas that are located far away from oceans, it is thus essential to sustain rainfall from sufficient land evaporation.

While recycling of water through physical and chemical treatment processes is often described, recycling of water through the atmospheric cycle is less common [31]. Regional recycling at the river basin scale is an essential process for sustaining local rainfall [129]. Climate change due to greenhouse warming causes a change/shift in local rainfall, consequently damaging production systems [70,130–133].

There are different procedures in place to express the evaporation contribution to local rainfall. Van der Ent et al. (2010) [31] developed the evaporation recycling coefficient α_E that can be computed from a simple track and trace model based on atmospheric water balances.

HESS10: Attenuation of Peak Flow

Floods are hazardous for settlements, human life and living plant organisms. Floods can bring about large death tolls and economic damage. Reduction in flood extent is a necessary course of action. Attenuation of peak flood waves can be achieved from upstream water buffering and retention; this is HESS10. Water can be stored temporarily in natural lakes, wetlands, drainage ponds, depressions and (non-) designated inundation areas (usually low pastureland). The capacity of these local storage systems requires background information on topography, soil type, river morphology and land use. The HESS solution suggested for peak flow attenuation consists of two courses of action: (i) upstream water buffering; (ii) reduction in the runoff coefficient R/P. HESS10 is the percentage of peak flow to be potentially skimmed off.

The baseline value of R/P is taken from the runoff on bare land. The argument is that R/P decreases due to increased vegetation cover because rooted plants increase the infiltration capacity into the soil. Urban areas and paved surfaces increase R/P (and thereby creating more peak flow) while forests decrease peak flow due to infiltration and lower runoff coefficients. Land use thus impacts surface runoff, something generally is known from the concept of curve numbers [134]. The areas covered by paddy fields, wetlands, river pastures and open water bodies are fundamental for high level water storage. Information on land use and water volume to be stored in land surrounding open water systems with an elevation lower than the peak water level can be used to compute the percentage reduction in peak flow.

HESS11: Carbon Sequestration

HESS11 encompasses the water required for net intake of carbon from the atmosphere into carbon pools [135]. This is a critical process and relevant in agro-forestry environments where carbon sequestration significantly correlates with water availability and vice versa, and higher evaporation and transpiration rates reduce generated runoff

[136]. Without transpiration via open stomata, CO_2 will not be captured from the air. Carbon pools consist of living above-ground biomass, living below-ground biomass, deadwood, litter and soil organic matter (SOM) [137]. Above-ground biomass comprises all organic matter (i.e., stems, branches, leaves, flowers, grains, understory and floor layers which includes herbaceous plants). The dead organic matter pool includes dead fallen plant and crop residues, the litter layer and charcoal (or partially charred organic matter) above the soil surface. The below-ground biomass comprises living and dead roots, soil fauna and the microbial community. Clearly, carbon stocks in vegetation change with land use [138]. Hairiah et al. (2011) [137] found that land use conversion can result in a positive or negative net carbon sequestration as it is related to the modification of photosynthesis.

Soil organic matter is the result of carbon humification processes and carbon decomposition into the atmosphere due to mineralization processes. The carbon from litter, stubble and roots is partially stored into the soil. Peat soils are an ultimate example of soil carbon accumulation due to lack of oxygen in flooded or stagnant water systems. Peat soils can store 10–100 times more carbon per unit area than mineral soil types and thus contribute significantly to sequester atmospheric carbon.

The estimation of carbon sequestration can come from (i) inventories based on in-situ measurements of above- and below-ground carbon stocks [86,90] and eddy-covariance flux towers (e.g., carbon flux); (ii) remote sensing algorithms for net primary production (NPP); (iii) global ecology models [139–141]; (iv) eco-hydrological numerical models (e.g., InVest, SWAT). IPCC AFOLU [142] is an internationally recognized framework to compute carbon stocks by land use class. ICRAF developed a database of the density of woody matters in trees:
(http://apps.worldagroforestry.org/sea/Products/AFDbases/WD/Index.htm (accessed on 25 October 2022)). The drawback is that every land use class has the same carbon value, while the spatial variability is significant due to differences in photosynthesis. A comprehensive overview for various methods to assess carbon pools in agricultural soils is provided by Nayak et al. (2019) [143].

The computation of pixel-dependent dry matter production and NPP from spectral radiances and land surface temperature is considered a more solid solution for making accurate assessments of carbon pools (see also HESS3 and HESS4). NPP can be subsequently used to separate carbon assimilates into (i) above ground; (ii) below ground; (iii) soil organic matter; (iv) dead wood and litter. A review of NPP models from remote sensing is provided by Sun (2021) [144]. Figure 6 illustrates an example of carbon capture calculated from NPP and humification process using remote sensing data.

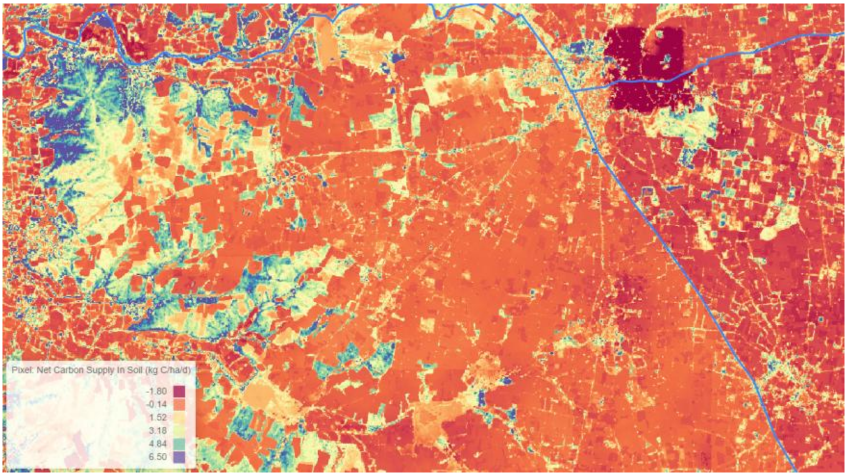


Figure 6. Carbon capture of an agricultural landscape with smallholders in Madyha Pradesh (India) computed from remote sensing algorithms of NPP and a humification process.

HESS12: Reduce Greenhouse Gas Emissions

Public concern about global warming mostly focuses on carbon dioxide, the most prevalent greenhouse gas after water vapor H_20. Methane (CH_4) is also an important greenhouse gas, yet the heating effect of an atmospheric methane increase is approximately half of a carbon dioxide increase [145,146].

The emission from various greenhouse gasses and other trace gasses depends on land use, soil moisture, air content and soil temperature. Industrial and domestic emissions are not included under HESS12. Methane emissions occur under anaerobic conditions. Inland open water such as natural lakes, ponds and reservoirs are net emitters of CH_4, N_2O and CO_2. These water bodies also play important roles in offsetting GHGs sequestered by terrestrial ecosystems [147]. Rice fields have been identified as a major source of atmospheric methane [148]. Flooding a rice field cuts off the oxygen supply from the atmosphere to the soil, which results in anaerobic fermentation of soil organic matter. Methane is a major by-product of anaerobic fermentation. It is released from submerged soils to the atmosphere by diffusion and ebullition and through the roots and stems of rice plants. Dairy farming with outdoor cows generates methane emissions while indoor cattle is also a GHG emitter because dung needs to be spread out to the environment.

HESS12 expresses reduction in greenhouse gas emissions (GHG) covering three major gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The reduction can be achieved from better water management practices, in particular proper drainage networks. Hence the depth to the water table and soil moisture below field capacity are key factors for reducing methane emissions from paddy fields and pastures.

The challenge in assessing CH_4 and N_20 fluxes due to the lack of directly measured data can be overcome with modelling and open-source data. The dynamic land ecosystem model DLEM [149] is a good example of a mathematical framework. DLEM can be developed and implemented at pixel scale if soil moisture and soil temperature are prescribed. The determination of oil moisture was discussed under HESS8. Soil temperature derivation from earth observations has also become feasible using land surface temperatures from thermal infrared radiometers [150,151].

HESS13: Micro-Climate Cooling

The importance of micro-climates for regulating local habitats and modulating water requirements due to changing states of the near-surface atmospheric boundary layer has been recognized by various researchers [152]. Evaporating surfaces from water-dependent environments such as irrigated areas, wetlands and forested areas provide significant values in cooling the atmosphere. HESS13 describes the impact of vegetation cover on cooling of the local near-surface air mass. The lower part of the atmospheric boundary layer is per definition affected by land surface fluxes. A land surface with a high evaporative fraction (i.e., ratio of latent heat flux λE and net available energy $(R_n - G)$) will transport little heat into the atmosphere and the air will remain relatively cold [153]. An air mass with lower temperature from evaporating surfaces such as irrigated areas, wetlands and forested areas will impact the regional air circulation. Villages located near evaporating pastures are always cooler than villages surrounded by dryland. This is a HESS service for mankind.

The role of water on atmospheric cooling by vegetation can be best described by taking a reference situation such as a landscape without vegetation. The energy associated with evapotranspiration is 2.45 MJ/kg and this energy will no longer feed the sensible heat flux that warms up the atmosphere from the land surface. The reduction in sensible heat flux H due to ET can be expressed as a suppression of the vertical air temperature difference (T_0–T_{air}) yielding a colder air mass for bio-organisms and mankind in a layer of air between crops and a 2.0 m elevation at standard observation height.

Figure 7 shows an example of how the presence of vegetation and soil moisture creates many different micro-climatic conditions for an agricultural area in The Netherlands. Fields with a high leaf area index and high soil moisture are 302.7 °K while fields with lower vegetation cover are reaching 305.9 °K, hence a midday air temperature cooling of 3 °K is apparent. Note that this is air temperature at observation height and that land surface temperatures exhibit a significantly higher spatial variability (20 to 30 °K).

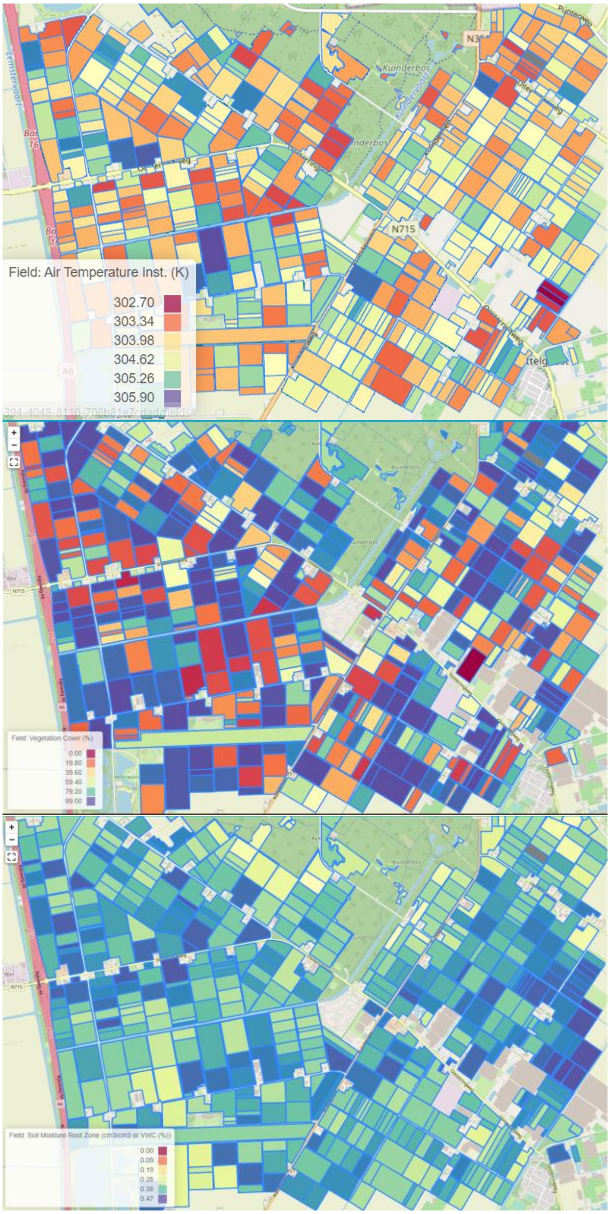


Figure 7. Example of midday air temperature on a field-by-field basis in the Noordoostpolder (The Netherlands) on 12/8/2020 based on actual vegetation cover and soil moisture conditions.

HESS14: Natural Reduction in the Eutrophication of Water

Algae are microscopic phytoplankton, such as bacteria and dinoflagellates that use photosynthesis to turn sunlight into energy. These microorganisms are naturally occurring and live in all types of water, from fresh to salt to brackish water. When water reaches the right mix of sunlight, temperature, low water flows and excessive amounts of nutrients (e.g., eutrophication), algae can multiply very quickly and turn into a “bloom”. Nutrients, such as nitrogen and phosphorus, when in overabundance, become water pollutants and can cause super-charged algal growth. The reduction in eutrophication by sufficient flushing is considered an ecosystem service. If these algae blooms dissipate due to improved water quality upstream and sufficient flow, then natural purification processes occur.

The detection of algae dynamics in space and time can be described from remote sensing water quality data sets. MODIS has particularly designed a fluorescence band (676 nm) that can be used to detect harmful algae blooms (HAB). Water surface temperature information can be used as an additional source of information. Similarly, Landsat-8 ETM+/OLI and Sentinel-2 MSI can be used to retrieve Chl-a information [154,155]. Ma et al. (2021) [156] combined MODIS, Landsat and Sentinel images to collectively assess HAB by evaluating NDVI, floating algae index (FAI) and the chlorophyll reflection peak intensity index (ρ_{chl}). Peppa et al. (2020) [157] used the maximum chlorophyll index (MCI) and maximum peak height (MPH) from Sentinel-2 to extract Chl-a information. Time series of HAB, Chl-a and phytoplankton will reveal the moments when water quality is improving; the hydrological situation at that specific moment needs to be described for understanding the amount of fresh water needed to control eutrophication.

In addition, there is a separate school assessing leaf nitrogen content as an essential indicator of N-uptake in crops. Leaf chlorophyll and nitrogen content can be best determined from red-edge (680–780 nm) reflectance. Satellite sensors such as Sentinel-2 and RapidEye can provide this information [158]. Similar studies were conducted for paddy rice [159,160] using the normalized difference red edge (NDRE) which showed a strong correlation with N present in leaves.

HESS15: Reduction in Soil Erosion

Wind and water create soil erosion. With increasing intensity of rainstorms, erosion is likely to occur more frequently. Erosion destroys the land surface, washes out fertile soil horizons and can be a source for landslides. Constructions are affected if soil washes away. Soil, mud and debris can lead to high-risk situations. Years of carbon sequestration in the soil can be washed out in a few hours.

Mitigation of erosion is essential, and healthy vegetation coverage is important to control soil erosion [161]. Packages of soil conservation practices exist, and they help mitigate erosion. Dang et al. (2014) [162] found that NPP was positively correlated with soil conservation. More vegetation on sloping terrain increases the infiltration of rainwater. However, vegetation for controlling soil erosion will consume water.

The universal soil loss equation (USLE) is the classical solution for determining erosion [163]. Information on slope, vegetation cover and erosivity of the soil needs to be specified. Reduction in soil erosion between vegetated landscapes and bare soil can be calculated from changes in surface runoff and applying the USLE equation for multiple conditions. Hourly or daily surface runoff values need to be computed. The soil moisture deficit is a necessity for computing surface runoff with higher accuracy [164].

HESS16: Meeting Environmental Flow Requirements

The provision of environmental flows is vital for maintaining specific habitats for fish, birds and plants in rivers, wetlands and estuaries. Spawning fish have, for instance, particular requirements of flow regimes. At best, the historic hydrograph under pristine conditions should be used for long term reference. This is from a period with less impact of global warming, fewer populations, catchments with higher forest cover and fewer reservoirs.

Climate change, human water withdrawals and dam constructions have a strong impact on hydrographs and can constitute a potential detriment for environmental flow requirements. While HESS14 is related to water quality through eutrophication, HESS16 describes minimum flows and minimum water levels.

There are various techniques to assess environmental flows and their condition. Xue et al. (2015) [165] quantified the environmental flow requirements (e-flows) to maintain different ecosystem functions from minimum monthly runoff. A maximum of 20% modification to a river’s natural flow is proposed by Hoekstra et al. (2012) [73] in their water scarcity analysis of 405 river basins for the period 1996–2005. When river flow deviates by more than 20% from its original discharges, it can be assumed that the environment is affected. It is not uncommon to consider flows from 50 years ago (e.g., 1960s and 1970s). Smakhtin et al. (2004) [166], for instance, assessed the mean environmental flow requirements for 128 major basins and drainage regions worldwide using measured and simulated hydrographs. They introduced five different environmental classes and assigned fractions of the mean annual flow.

Winsemius et al. (2009) [167] and Poortinga et al. (2017) [76] developed procedures to integrate a streamflow model with remote sensing data of P, ET and soil moisture for the creation of hydrographs. Return periods of a certain f stream flow could be quickly detected, and such data are a perfect input to define flow during the 20% wettest years.

Figure 8 shows the anomalies of annual runoff in the El Nino year 2009–2010 from December until February. This is a great method for utilizing earth observation data to assess environmental flow requirements.

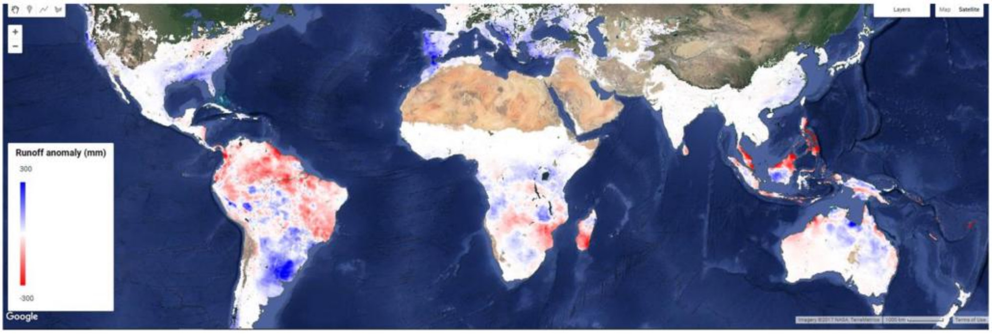


Figure 8. Anomalies of surface runoff during El Nino. Areas with reduced and enhanced stream flow can be seen. This information can be used to check whether environmental flow requirements are met [76].

HESS17: Leisure

HESS17 leisure indicates the value from socialization and purification of humans via water sports, swimming, recreational fishing, sightseeing, aesthetic views, hiking, mountain biking, forest BBQs, etc. The common factor is that this requires water flows, water fluxes and open water bodies in pristine landscapes. While HESS16 is meant for habitats, HESS17 unravels the benefits for human satisfaction to be surrounded by pristine natural landscapes. Quantification of HESS17 can be conducted through the collection of visitor statistics of natural and urban parks. The number of leisure-oriented businesses (e.g., rental of fishboats or canoes), tourist taxes going to local communities and bars and restaurants in rural and remote areas is an indication of leisure activities.

2.4 Proposed HESS determination processes

This section describes a set of suggested formulations for HESS. The inclusion of remote sensing makes it feasible to relate hydrological processes to land use information. Various procedures based on earth observation data are summarized in Table 2. Table 3 presents the type of satellite systems.

Table 2. Summary of HESS quantification methods.

Indicator	Remote sensing outputs	Other quantification methods
HESS1	P, ET, ΔS	Hydrological models
HESS2	A, H, E	FAOSTAT, WorldFish, statistics (mean annual discharge and water bodies)
HESS3	NPP	Look-up table for LULC
HESS4	NPP	Look-up table for LULC
HESS5	B_{riv}, H	Hydrograph measurements, rainfall-runoff models
HESS6	P, ET, ΔS, Vc	Tracers, hydrological model
HESS7	A, H	Bathymetry, gauge readings
HESS8	EF, LST, NDVI	Soil moisture and root length measurement, unsaturated zone hydrology models
HESS9	P, ET, Vc	Atmospheric models
HESS10	LU, A, H	Rainfall–runoff models
HESS11	LU, Vc, NPP	IPCC–AFOLU method
HESS12	LU, Vc, NPP	IPCC–AFOLU method
HESS13	LST,Vc, LU	Air temperature and air humidity measurements, global/regional climate model
HESS14	LU, ABDI, FAI, Chl-a, MCI, MPH, SRRE	Optical and laboratory measurement
HESS15	Vc, NPP	No. of landslides, erosion measurements
HESS16	B_{riv}, A, P, ET, ΔS, Vc	Historic and current hydrographs
HESS17	ET, A, H	Visitor statistics, no. of leisure businesses

Table 3. Summary of satellite measurements required for an operational HESS system.

Satellite	Sensor	Spatial resolution (Nadir, m)	HESS	RS Parameters
LANDSAT	OLI-2, TIRS-2 (Landsat 9) OLI, TIRS (Landsat 8) ETM+ (Landsat 7) MSS (Landsat 1, 2, 3) TM (Landsat 4, 5)	15–90 m	HESS3, HESS4, HESS11	EF, SM, H, NPP
			HESS14	Chl-a, FAI, SRRE, NDRE
			HESS1, HESS5	Q
			HESS7, HESS10, HESS17	B_{riv}, A, ΔS, Q
Terra/Aqua	MODIS	250–1000 m	HESS3, HESS4, HESS11, HESS14	NPP, SRRE, NDRE, FAI
PROBA-V	Vegetation	120 m	HESS3, HESS4, HESS11	NPP
IRS	WiFS	188 m	HESS3, HESS4, HESS11	NPP
Suomi	VIIRS	375 m	HESS3, HESS4, HESS11	NPP, LST
JASON	Poseidon	na	HESS1, HESS5, HESS7, HESS10, HESS16	ΔS, H
Sentinel-3	Altimeter	variable	HESS1, HESS5	ΔS, H, LST
Sentinel-3 Sentinel-2	Altimeter MSI	variable 10 m	HESS7, HESS10, HESS16	ΔS, H
			HESS1, HESS5	Q
Sentinel-2 Sentinel-1	MSI C-band SAR	10 m	HESS14	Vc, chl-a, FAI, NDRE
			HESS7, HESS16	B_{riv}, A, Q
			HESS1, HESS5	Q
Sentinel-1 ISS	C-band SAR EcoStress	10 m 70 m	HESS 8	SM
			HESS7, HESS10, HESS16	B_{riv}, A, ΔS, Q
			HESS9, HESS13	LST, NDVI

2.5 Discussion

Water is by definition a multi-purpose natural resource. Its value to the environment is obvious and endless. Yet, it is also important to define limited metrics for expressing the role of water in the environment. The magnitude of ecological benefits depends on water fluxes, flows and stocks. With the presence of vegetation, there is less erosion, cooler atmospheres and less atmospheric CO_2 due to carbon capture. HESS12 considers reduced greenhouse gas emissions as the service. This implies that a reference must be defined, using either a record with sufficient monitoring of in situ measurements of hydrological features or remote sensing or through a baseline established in hydrological models. For HESS definitions focusing on changes, non-vegetated land can be taken as the reference for highlighting the contribution of hydrological regimes, such as peak flow attenuation or soil erosion. In other cases, good quality water or sufficient water for fish spawning is the reference. Hence the definition and selection of the reference is not univocal.

The determination of biophysical processes in a spatial context and in dynamic fashion is complex. Many eco-hydrological research teams have created great analytical tools and contributed to provide insights into interactions between water resources and benefits that people and societies receive from nature. The use of eco-hydrological models plays a crucial role when it comes to better recognize and understand disturbances, land use and management and climate change scenarios. At the same time, earth observations have developed considerably during the last three decades, and the opportunities to use the growing number of open access databases on, for instance, water body occurrences, NPP and evapotranspiration should be exploited more frequently (see Tables 2 and 3). The availability of a new sensor generation (e.g., Landsat 9, SWOT, Sentinel 3 etc.) provides more capabilities to start monitoring and reporting HESS on a regular basis, provided that an analytical framework such as HESS17 exists. The HESS framework also requires local statistical data or globally accepted data, such as FAOSTAT and WorldFISH.

The metrics of HESS17 include gross simplifications. Chlorophyll-A is, for instance, the only indicator selected for eutrophication of water bodies. The extent of firewood use as a source of daily energy does not reflect the integrated dependence of rural populations on ecosystems in low-income countries. Fish catch statistics have certain limits of accuracy as the reporting process is different for each country. Figure 8 provides exciting new opportunities to fill data voids for regions without hydrographs for baseflow and fish health. However, modelled data do not have the same accuracy as flow measurements (although flow meters also contain errors). Hydro-meteorological observatories represent point measurements, and energy balance models driven by remote sensing data can help to assess fluxes and soil moisture in a truly spatially distributed context. The conclusion is that the combination of in situ measurements, remote measurements and modelling is the way forward. As an international community, we had not previously reached the technical capabilities we now have thanks to the Internet of Things.

On the other hand, despite showing great strengths and advantages, the use of spatial data sets and eco-hydrological models needs careful assessment [139]. There are limitations resulting from the complexities of climate, eco-hydrology and ecosystems, as well as interactions with human factors. Therefore, the sensitivities and limitations of these tool sets need cautious evaluation and transparent communication during the HESS quantification.

There is an imbalance in the list of HESS proposed in this research, i.e., in the number of presented provisioning and regulating services as compared with cultural and support services. Evidently, this drawback results in a potential distortion while assessing the benefits of HESS to human and non-human use, as well as in the optimization of HESS performance at various scales. Further refinement of HESS definitions and categorizations is needed to minimize this ambiguity in the future. Once HESS are re-defined or more HESS are needed, the HESS framework proposed in this study can be revised and extended.

It is suggested that the integration of earth observations with eco-hydrological models is a necessary step that deserves more attention from research for the next 10 years. A good review on modelling soil as the centerpiece for environmental systems was provided by Vereecken et al. (2016) [168]. Attention should be given to the fact that integrating multiple remote sensing data sets will create noise coming from the uncertainties of each individual parameter. Error propagation should be limited by developing hydrological consistency. Schoups and Nasseri (2021) [169] describe a Bayesian hierarchical model that fuses monthly water balance data and estimates the corresponding data errors and error-corrected water balance components (precipitation, evaporation, river discharge and water storage); this type of work needs to expand for acquiring more accurate HESS values.

The HESS17 framework can be used to assess how agricultural production practices affect ecosystem services. For basin planners, the HESS framework can provide answers on how watershed management can be improved to enhance HESS. The possibility of a seamless zoom from global to regional to basin scale is crucial, not only for understanding the flow and allocation of HESS at large and “acceptable” thresholds, but also for close monitoring and managing by decision makers, as well as leveraging in policy and planning instruments.

2.6 Conclusions

Since the concept of ecosystem services extends across many research domains and expertise, a consistent and comprehensible approach for the quantification of HESS should be available for larger audiences. This study evaluated the status of different hydrological ecosystem services as a critical step in the planning process for sustainable development. The new HESS17 framework describes a standard list of 17 carefully defined indicators. Although not exhaustive, it is a proper balance between essential water quantity and water quality indices being presented as an integrated framework that is supported by CGIAR. In fact, HESS should be classified into consumptive use and non-consumptive use. Consumptive use leads to various services, but the water evaporated into the atmosphere is no longer available (except for local atmospheric recycling). Non-consumptive water can be reused and recycled.

The potential strengths and drawbacks of quantification methods such as remote sensing, hydrological modelling and empirical calculations are provided. Most remote sensing algorithms are meant for solving one biophysical process. The innovation of this study is that we sketch potential procedures to integrate multiple open access data bases and remote sensing algorithms for quantifying a package of 17 standard HESS indicators. The study warns that error propagation should be controlled by recognizing the uncertainties of each parameter and seeking hydrological consistency.

Eco-hydrological models are extremely useful to estimate complex processes such as non-source pollution contaminant transport. The fusion of remote sensing and eco-hydrological models should be encouraged to establish more accurate HESS values under conditions of climate change, water scarcity and land–water–soil conservation programs. Earth observations cannot be used for future predictions, but they are useful for calibrating historic eco-hydrological processes.

In conclusion, the technology and science are sufficiently mature to provide clear-cut and policy-oriented spatial information on HESS. Decades of development and new technologies in sensors, satellite platforms, data storage and computational power have resulted in advanced tools that can be used for assisting policy change by HESS implications. As the digital information era advances, future progress is expected to enable further upscaling and standardization of operational monitoring of hydrological ecosystem services.

3 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 [2]

In this chapter, evapotranspiration (ET) and leaf area index (LAI) were used to calibrate the SWAT model, whereas remotely sensed precipitation and other climatic parameters were used as forcing data for the 6300 km^2 Day Basin, a tributary of the Red River in Vietnam. The efficacy of the Sequential Uncertainty Fitting (SUFI-2) parameter sensitivity and optimization model was tested with area specific remote sensing input parameters for every Hydrological Response Units (HRU), rather than with measurements of river flow representing a large set of HRUs, i.e., a bulk calibration. Simulated monthly ET correlations with remote sensing estimates showed an R^2 = 0.71, Nash–Sutcliffe Efficiency NSE = 0.65, and Kling Gupta Efficiency KGE = 0.80 while monthly LAI showed correlations of R^2 = 0.59, NSE = 0.57 and KGE = 0.83 over a five-year validation period. Accumulated modelled ET over the 5-year calibration period amounted to 5713 mm compared to 6015 mm of remotely sensed ET, yielding a difference of 302 mm (5.3%). The monthly flow at two flow measurement stations were adequately estimated (R^2 = 0.78 and 0.55, NSE = 0.71 and 0.63, KGE = 0.59 and 0.75 for Phu Ly and Ninh Binh, respectively). This outcome demonstrates the capability of SWAT model to obtain spatial and accurate simulation of eco-hydrological processes, also when rivers are ungauged and the water withdrawal system is complex.

3.1 Introduction

Managing river basins and environmental systems in a sustainable manner is receiving growing attention from national water resources institutes, the United Nations, non-governmental-organizations, and international research institutes. The newly adopted Sustainable Development Goals (SDGs) prescribe key hydrological, environmental, and economical processes to be expressed in terms of performance indicators. Water

[2] 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.

accounting systems are currently under development to facilitate the mapping and description of these SDG indicators at river basin scale [38,170–172]. Water availability, water consumption, utilizable water, and water withdrawals are key elements of such accounting processes, as well as the services and benefits rendered. At the global scale, 60% of ET is from green water (precipitation stored in soil moisture), the rest being withdrawals from blue water sources (rivers, reservoirs, lakes, and aquifers) [173]. Eco-hydrological modelling tools have been developed to quantify a wide range of natural ecosystem services as well as human intervention derived from these significant volumes of water [49,53,174]. A comparison of different hydrological models that are suitable for modelling hydrological ecosystem services was conducted in [175], among them are the Soil Water Assessment Tool (SWAT) [176], Variable Infiltration Capacity VIC [177], Integrated Valuation of Ecosystem Services and Trade-offs INVEST [40], and ARtificial Intelligence for Ecosystem Services ARIES [41]. SWAT was indicated as a preferred tool in a rigorous review of the modelling of certain ecosystem services [178] for simulation of provisioning and regulating services, because hydrological, flow dynamics, water quality, plant growth and nutrient loading processes are included in the model. SWAT was also recommended as the most suitable model for long-term simulations in watersheds dominated by agricultural land uses [179], since its original design was to assess the impact of land management practices on water, sediments, and agricultural residues. SWAT model is also preferred in studies in ungauged basins [180,181].

Classically, the SWAT model is calibrated using a few hydro-meteorological stations [182–186]. Large uncertainties in observed stream flow data are common [187], and that more sophisticated calibration method needed to be developed. SWAT Calibration and Uncertainty Programs (SWAT-CUP) [188] was developed for automatically computing sensitive model parameters and calibrating SWAT by means of parameter optimization. Most SWAT-CUP applications are using Sequential Uncertainty Fitting (SUFI-2) algorithms and flow observations to define the best parameter set. Additional uncertainty bounds are computed according to the good parameter sets and typical SWAT parameters are calibrated by means of parameter optimization. The current study investigates how SWAT can be set up for assessing ecosystem services in ungauged basins using remote sensing data and auto-calibration facilities.

Several review papers on remote sensing technology for hydrology [189,190] and water management [191,192] indicate that land cover, land use, precipitation, ET, soil moisture, snow cover, and water levels can be determined from spectral radiances measured remotely. Several open access databases on precipitation have recently been developed on the basis of remote sensing data; see [193,194]. A simultaneous development took place on operationalizing remote sensing-based energy balance models to accurately determine and upscale ET from local heterogeneous watersheds [195] to continental scale [117].

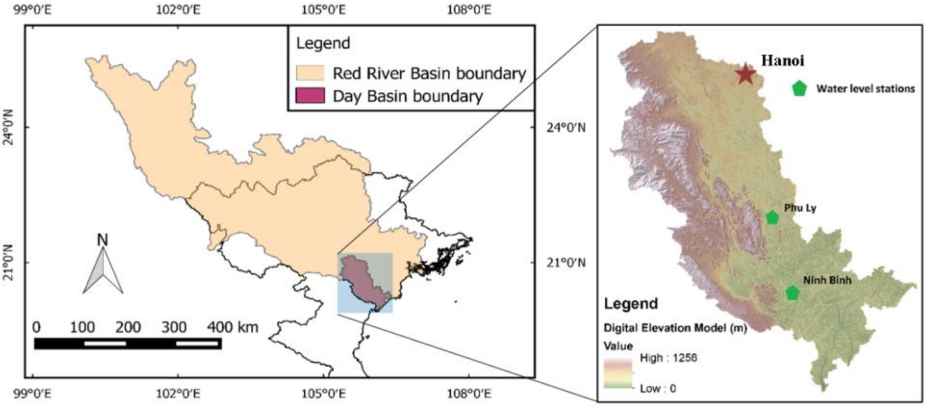
Extensive reviews of remote sensing-based approaches to derive ET were carried out earlier [196–199]. Remote sensing provides a great source of data to study vegetation indices and Leaf Area Index (LAI) from multi-spectral bands [200].

Some hydrological studies utilized remote sensing data before—or a combination of remote sensing and in situ data—to calibrate hydrological models [201–205]. Earlier research demonstrated the capacity to calibrate SWAT with remotely sensed ET data [206–210] and LAI [211,212]. Several studies in Vietnam integrated SWAT and remote sensing data, including [183], on the impact of climate change on stream flow in Dakbla River Basin. The objective of this Vietnamese case study is to use quasi-open access remote sensing data to improve SWAT modelling performance using the standard SUFI-2 functionalities, both as forced variable, i.e., precipitation or calibration dataset, i.e., ET and LAI. The innovation is that the standard calibration module is based on remote sensing data instead of classical discharge data, and that it incorporates soil and vegetation parameters of individual Hydrological Response Units (HRU). The anticipated result of such a calibration approach is a better quantification of the natural and anthropogenic eco-hydrological processes in ungauged basins, which is vital for reporting ecosystem services to governments and the United Nations. The novelty of this study is the application of SUFI-2 in the optimization of 15 input parameters of the soil vegetation processes using observations of actual water management processes, such as irrigation and conservation of water in wetlands in a local context. Such level of detail and reflection of real-world interferences of mankind on the natural hydrological cycle can never be achieved from flow measurements, and opens better opportunities for simulation of local eco-hydrological processes that occur locally in ungauged basins, which can never be interpreted from bulk flow measurements, if there are any.

3.2 Study area

The Day Basin is located between 19°55′ to 21°10′ N and 105°20′ to 106°25′ E. The Day Basin is a sub-basin of the transboundary Red River basin (see Figure 9). The total area of the basin is nearly 6300 km^2. The highest elevation is 1256 m in the western part of the basin. The Day Basin comprises several river tributaries, among which the largest is the Day River, with a total length of approximately 250 km. The Day Basin has a high biodiversity, with abundant flora and fauna in the forested hills, freshwater aquatics, and wetland. The land use is also diversified, although agricultural land use is dominant (64%).

The Day Basin encompasses the capital city of Hanoi (population in 2015: 7.5 million inhabitants) in the northeast and several major economic centers located downstream, such as Nam Dinh (population: 1.8 million) and Ninh Binh (population: 0.9 million). Both the Red River and Day Basin have been exposed to various hydrological research activities before [174,213–215]. Using the rating curve suggested in Luu et al. (2010) [214], discharge at two locations (i.e., Ninh Binh and Phu Ly) was reconstructed from the year 2000 up to 2013.



a) b)

Figure 9. a) Geographical location of the Day Basin as part of the Red River delta in Northern Vietnam; b) Digital Elevation Model from Shuttle Radar Topography Mission (SRTM) for the Day River Basin and the location of two water level stations.

The annual total precipitation is around 1700 mm per year, and reference evapotranspiration (ET_o) is approximately 1100 mm per year. The climate in the Day Basin has a monsoonal character. The wet season lasts from May to September, and dry season from October to April. Precipitation can reach up to 450 mm per month in some parts of the basin, and as low as a few mm during January and February. Precipitation is measured at nine stations across the basin, and is available up to 2013. These measurements will be used to validate the open access precipitation product based on satellite measurements.

The water withdrawals for irrigation in the Day Basin are rather difficult to assess because various pumping stations lift water from the Red River, and also many inlets divert water from the river gravitationally. This diffusive and unmetered inter-basin water withdrawal complicates the computation of the irrigation hydrology and the water accounts related to that. The irrigation supplies in SWAT will therefore be adjusted to reproduce an ET value that matches with ET estimates from satellites.

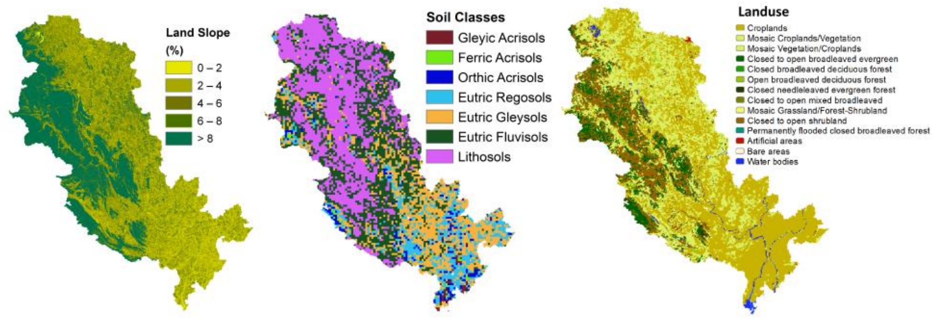


Figure 10. a) Land slope, b) Soil classes and c) Land use maps used in Soil Water Assessment Tool (SWAT) to determine the Hydrological Response Unit (HRU).

3.3 Model and methodology

3.3.1 Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) [56,176] has been set up for the Day Basin to compute flows, fluxes, and stocks. A total amount of 119 sub-basins and 7909 HRU has been included for ensuring sufficient detail. HRU is a modeling unit that exists of a unique combination of land slope, land use, and soil type [216]. SWAT simulates eco-hydrological processes, i.e., surface runoff, groundwater recharge, baseflow, water stocks, erosion, plant production, and water quality. The production of food, feed, and timber, and the sequestration of carbon can be inferred from the biomass production [216]. SWAT estimates the fate and transport of nutrients, sediment, pesticides, and bacteria in both land and water phases [217]. This mathematical framework provides a great basis for the determination of various ecosystem services and SDG indicators. The soil water balance is conceptualized in SWAT using Equation (1), as described in Neitsch et al. (2011) [56]:

$$SW_t = SW_0 + \sum_{i=1}^{t} (P - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad \textbf{(1)}$$

in which t is the time (days), SW_t is the final soil water content at day t (mm H_2O); SW_o is the initial soil water content, P is the amount of precipitation, Q_{surf} is the amount of surface runoff, E_a is the amount of actual evapotranspiration, w_{seep} is the amount of percolation entering the vadose zone from the soil profile, and Q_{gw} is the volume of streamflow originating from groundwater, all measured in mm H_2O on day i. The reference evapotranspiration (ET_0) is computed with Global Land Data Assimilation System (GLDAS) meteorological input data. SWAT does not allow reading layers of ET_0 directly, and therefore, meteorological records need to be prescribed. The chosen method for reference ET in SWAT is the Penman–Monteith method, as described in Neitsch et al. (2011) [56]. Compared with other equations in SWAT, i.e., Hargreaves [218] and Priestley–Taylor [219], the Penman–Monteith method fully takes advantage of remote sensing and global data source, such as GLDAS.

3.3.2 Model Calibration Using SUFI-2

The calibration of a semi-distributed and physical based model, such as SWAT, requires various plant and soil model parameters to be optimized, to ensure a rigorous representation of a basin's processes, e.g., streamflow, ET, ecological change, etc. The calibration task can become difficult and almost infeasible in large-scale applications [216]. A number of auto-calibration and uncertainty analysis tools for SWAT were developed to support solving this problem, and are currently available to assist the optimization process. This study is based on the SUFI-2 model that is part of the SWAT-CUP supporting software package [220]. SWAT-Calibration and Uncertainty Program (SWAT-CUP) [220,221] is an auto-calibration and uncertainty analysis module program based on the SWAT engine that can deal with a range of input parameters. The optimization algorithm of SWAT-CUP allows model parameters to be predefined and optimized throughout the auto calibration process or manually adjusted iteratively between calibration batches. The employment of SUFI-2 is suitable for both new and advanced users of hydrological models, even though a good understanding of hydrologic processes and of parameter sensitivity is recommended in general terms [216]. In order to assess the efficacy of using remote sensing data and to compare with traditional discharge station-based for calibration, SWAT-CUP was run with two settings: a) entirely based on remote sensing data (ET and LAI) and b) entirely based on river discharge measurements. Among various evaluation coefficients allowed in SUFI-2, Nash–Sutcliffe (NSE) and Kling Gupta Efficiency (KGE) were chosen. For this particular study, a total number of 15 plant and soil parameters were pre-selected according to their sensitivity to the evolution of ET and LAI. The selection of these parameters was based on detailed reviews and analyses on SWAT parameters carried out before by various authors [180,202,208,216,222].

3.4 Spatial input datasets for SWAT

3.4.1 Physiographical Maps

The Digital Elevation Model (DEM) was downloaded from the Shuttle Radar Topography Mission (SRTM) with a resolution of 1 arc-second or 30 m (Figure 9b). The DEM is used to calculate slope, slope lengths, and to extract the stream network, solar angles, and air temperature corrections. The land use map is downloaded from Globcover [223].

Globcover is developed by the European Space Agency (ESA) and University of Louvain, with a spatial resolution of 300 m × 300 m. The satellite input data used for the classification was the MEdium Resolution Imaging Spectrometer (MERIS) sensor on the Environmental Satellite (ENVISAT) during 2009. While this dataset exists for several years, it captures the time span of the SWAT analysis very well. The major land cover in the Day Basin is agricultural land (64%), followed by forests (24%), and mixed mosaic (12%). Three thousand hectares (76%) of agricultural land is irrigated. The soil map used in this study originates from the International Soil Reference Information Centre (ISRIC) [224] and Food and Agricultural Organization (FAO) Digital Soil Map of the World [225]. The SoilGrids database (ISRIC, Wageningen, The Netherlands) [224] has a spatial resolution of 1 km × 1 km, and is produced during 2014. The physical properties included in the dataset are (i) soil organic carbon (g/kg), (ii) pH index (H2O solution) (%), (iii) sand, silt and clay content (kg/kg), (iv) coarse fragments (volumetric) (%), (v) bulk density (kg/m^3), (vi) cation-exchange capacity (fine earth fraction) (cmol+/kg), and (vii) depth to bedrock (cm). A new soil map was created in this study by combining the two ISRIC and FAO soil maps with the aims to both (i) increase the spatial representation, and (ii) maintain the soil classification and soil properties from the FAO database. This task was accomplished by using standard unsupervised classification procedures (see Figure 10b). Based on the distribution of land slope, soil type, and land use classes, the basin is divided into 119 sub-basins and 7909 HRUs.

3.4.2 Meteorological Data

Precipitation

Satellite precipitation data offers an attractive alternative to supplement in situ precipitation measurements in hydrological modelling, particularly in poorly gauged basins [194,226]. An evaluation of various open access precipitation products, such as the Tropical Rainfall Measuring Mission (TRMM 3B42V6, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.), Climate Prediction Center Morphing technique (CMORPH, NOAA Climate Prediction Center, Silver Spring, Maryland, U.S.), and Precipitation Estimation from Remotely Sensed Imagery Using Artificial Neural Networks (PERSIANN, The University of Arizona, Tucson, Arizona, U.S.) at a resolution of 0.25° × 0.25° for a subtropical watershed in China, concluded that TRMM 3B42 had the best performances, and was deemed to be reliable for hydrological applications, while PERSIANN had the worst performance [227]. In a similar study for Australia and Southeast Asia, TRMM and CMORPH outperformed, and an ensemble precipitation product was suggested as a reduction of system-specific and random errors [228]. TRMM data, in situ measurements and other atmospheric and climatology models were assimilated in Funk et al. (2014) [229] to create an ensemble precipitation product Climate

Hazards Group InfraRed Precipitation with Station data (CHIRPS, University of California Santa Barbara - Climate Hazards Group, Santa Barbara, California, U.S.) with a superior resolution at 0.05° × 0.05°. Precipitation from CHIRPS performed well statistically for flood and drought monitoring, particularly for meteorological complex regions [230]. The current study combines TRMM7.0 and CHIRPS2.0 rainfall products. The absolute precipitation data are taken from TRMM, and the spatial patterns from CHIRPS. The refined TRMM dataset with a resolution of 0.05° × 0.05°, so obtained, has been used as input data for SWAT. The combined precipitation product, so obtained, showed a good performance when compared to rain gauge measurements (Figure 11). Percent bias (PBIAS), NSE, Mean Absolute Error (MAE) denoted percent bias, Nash–Sutcliffe efficiency, and mean absolute error, respectively. The newly created precipitation product significantly improved the performance of the two original datasets in term of bias correction (PBIAS = −0.6) when averaging the errors from TRMM and CHIRPS. Nash–Sutcliffe efficiency slightly improved when comparing the ensemble precipitation to the CHIRPS (0.75 compared to 0.74), even though the MAE was marginally larger (45.98 compared to 44.31).

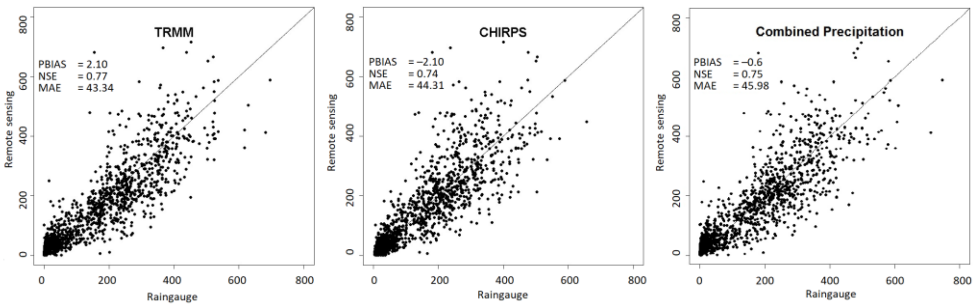


Figure 11. Performance of precipitation products Tropical Rainfall Measuring Mission (TRMM), Climate Hazards Group InfraRed Precipitation with Station (CHIRPS), and the Combined Precipitation against field measurements. Remotely sensed precipitation (mm) is displayed in the vertical axes while the horizontal axes show in situ measurement.

Meteorology

The meteorological dataset includes daily estimates of solar radiation, wind speed, air temperature (maximum, minimum) and relative humidity. The dataset was derived from GLDAS (NASA Goddard Earth Sciences Data and Information Services Center (GES DISC), Greenbelt, Maryland, U.S.). GLDAS simulates meteorological data with a numerical weather prediction model having a cell size of 0.25 degrees. The NOAH Land Surface Model (NOAH, National Center for Atmospheric Research (NCAR), Boulder, Colorado, U.S.), coupled to an atmospheric boundary layer model, assimilates satellite and in situ measurements to produce various land surface states and fluxes [231]. GLDAS meteorological data was downloaded as 3-hour intervals, and accumulated into 1-day time step as required by SWAT model to calculate evapotranspiration, plant growth etc.

Actual Evapotranspiration

The most common global scale ET dataset, developed with energy balance models using remote sensing data as input, a Penman–Monteith type of equation, is MOD16 (University of Montana, Missoula, Montana, U.S.) [232]. Several years of data can be downloaded if one is registered. MOD16 is based on a simplified stomatal conductance model governed by LAI, vapor pressure deficit, and air temperature. Soil evaporation is limited by a complementary relationship hypothesis which defines land–atmospheric interactions from vapor pressure deficit and relative humidity [232]. Various ET comparison studies using MOD16 data have been undertaken, see for instance [117,204,233]. MOD16 ET was validated [234] using flux towers in South Africa, and found that ET was systematically underestimated by 7.5 to 26.3 mm per month [235,236]. On the contrary, studies conducted in Asia showed that MOD16 consistently overestimates ET for forested land cover [201].

Another example of a global energy balance model is SEBS (University of Twente, Enschede, The Netherlands) [237,238] that has a quasi-open accessibility to acquire the data. SEBS applies an analytical solution of surface roughness for heat transfer, and it was used to create a global scale dataset that is quasi-open access. It limits the sensible heat flux estimates with upper and lower boundaries of the surface resistance to evaporation. The upper boundary is determined by latent heat flux equal to zero; the lower limit by potential evapotranspiration with a minimum bulk surface resistance. CMRSET (Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia) [239] calculates actual ET from the Priestley and Taylor reference ET for water unlimited land surfaces [219] and a crop factor (Kc) based on an enhanced vegetation index (EVI). A global vegetation moisture index (GVMI) is used to account for non-optimal moisture conditions. This method is generally empirical, and aims to develop an ET dataset that GVMI is independent from land cover classification.

Another energy balance method is the Operational Simplified Surface Energy Balance (SSEBop) by USGS EROS Center, Sioux Falls, South Dakota, U.S. [199] that employs a relationship between ET_0 and a land surface temperature-based scalar (ET_{rf}) to express land wetness. An operational version of SSEB was proposed [240,241] by assimilating air temperature to account for the topographical and latitudinal heterogeneity impact on surface temperature. The SSEBop model defines the temperature scalar using hot and cold reference values for any pixel. The cold reference value is estimated as an empirically established fraction of the daily maximum air temperature; the hot reference value is obtained by adding a vertical temperature difference (dT) to the cold reference value [199].

Though progressing significantly in the past years and gaining maturity enough for calibration of hydrological models, remote sensing-based ET products still induce various uncertainties [235,236,242]. These uncertainties come in various forms, such as from temperature and net radiation [199], and the aerodynamic component [243]. An uncertainty of up to 4 to 18% can be linked to sources of net radiation [199]. The largest uncertainty originates, however, from the impact of soil moisture on the regulation of the ET process. While thermal infrared measurements are excellent indicators of evaporative cooling [244], they are sensitive to cloud cover. Solutions based on microwave measurements are therefore suggested simultaneously for a long time [245,246]. Consequently, a suite of ET algorithms have been built during the last 25 years, and every algorithm will have its own model formulation and accuracy. Only physically-based algorithms with thorough validation in several environmental conditions should be considered for the calibration of hydrological models.

Because existing global scale ET products have different predictive capabilities, and there is no reliable ground truth dataset available in Day Basin to select any one of them, an ensemble ET product has been created in addition to the original datasets, on the basis of a simple linear average value for the Day Basin. The ensemble ET product used in this study is based on the combination of SEBS (5 km × 5 km), CMRSET (5 km × 5 km), SSEBop (1 km × 1 km), and MOD16 data (1 km × 1 km), and has a spatial resolution of 1 km × 1 km grid. A finer ET map is deemed necessary to assess water balances at HRUs spatial level. The same downscaling procedure as described in CMRSET using the Enhanced Vegetation Index (EVI), and Global Vegetation Moisture Index (GVMI) was applied. The Residual Moisture Index (RMI) was used to describe the impact of vegetation moisture content on the crop coefficient.

The selection criteria for a certain ET product were based on the hydrological consistency between the annual totals of precipitation (ΣP) and discharge (ΣQ) for a time span of 10 consecutive years (2003 to 2012). The stream flow data (ΣQ) from the 2 stations (Phu Ly and Ninh Binh) were used (see Figure 12). In the case of the Day Basin, there is an unknown withdrawal from the Red River, which makes a direct comparison weaker. The analysis of the Day Basin demonstrates that SEBS produces the highest ET values, and MOD16 the lowest. CMRSET and MOD16 performed similarly for annual and seasonal periods, and both were lower than the ensemble ET. Of all five ET datasets (4 individual and 1 ensemble product), the ensemble ET, SSEBop, and CMRSET delivered similar annual ET rates, averaged for the drainage area at Phu Ly (ΣET of 1073 mm, 1041 mm, and 1007 mm, respectively) and Ninh Binh (ΣET of 1103 mm, 1044 mm, and 1031 mm, respectively). This is because the ensemble ET compensated for the difference between higher end and lower end ET products. Of all four ET datasets, SSEBop gave the most similar results compared to the ensemble ET. Albeit minor, differences were spotted during the dry period. For the dry season, ET from MOD16 is comparable with the ensemble ET (ΣET of 361 mm and 359 mm for Phu Ly, 376 mm and 369 mm for Ninh Binh, respectively), while SSEBop tends to give lower ET. The performance of a certain actual evapotranspiration (ET_{act}) algorithm is dependent on factors such as land use land cover type, climate, and the presence of mountains [174], meaning that the accuracy of ET_{act} predictions will vary across the basin. The seasonal performance of the ensemble ET values mismatch, due to storage changes in the soil water balance and the regulating role of lakes and reservoirs on river discharge. During the dry season, ET was much higher than precipitation hence, the displayed axis scale differed from the yearly average and the seasonal wet period. The interim conclusion is that the ensemble ET product generated from linear average SEBS, CMRSET, SSEBop, and MOD16 provided accurate and most stable results for the Day Basin. Accordingly, the ensemble ET data was tested further before being used in the optimization process.

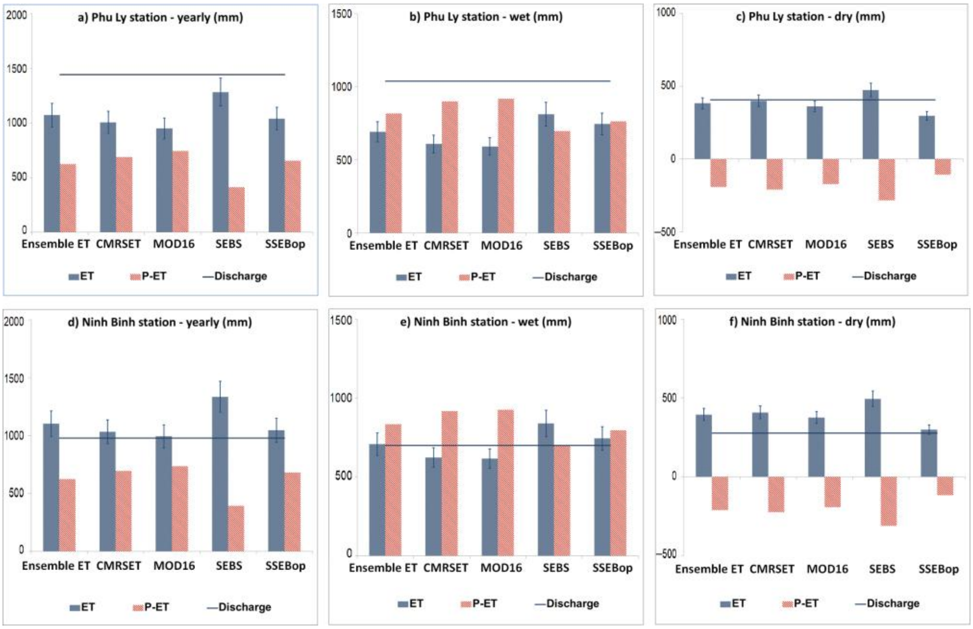


Figure 12. Comparison of accumulated evapotranspiration (ΣET), rainfall surplus ΣP-ΣET, and discharge ΣQ over the 2007 to 2010 period at yearly (a,d), wet months (b,e), and dry months (c,f) at two stations, Phu Ly and Ninh Binh.

Crop Coefficient

Crop coefficient (K_c) was defined in [247] for unlimited soil water conditions, as the ratio of actual evapotranspiration to reference evapotranspiration (ETo). The K_c value for paddy rice is suggested in various studies such as by [248–250]. K_c for rice varies between 1.02 and 1.23 [251] throughout various growth stages. The cropping pattern in the Day Basin consists of mainly paddy rice (2 seasons from February to April/May, and from May/June to September) and some other crops (vegetables, September/October to January). The ensemble ET data is assumed to represent paddy rice as the dominant crop. The K_c derived from the ensemble ET and reference ET was tested to see if it falls within the range found in the literature.

In order to validate the accuracy of actual ET derived from satellites, reference evapotranspiration (ETo) was calculated using the FAO56 Penman–Monteith equation [247]. GLDAS is a good example of global standardized datasets, in this case, being climate related. Figure 13 illustrates the average monthly Kc in the Day Basin. The maximum Kc values are experienced in the wet season (June to July). Kc is much lower in the dry months of January to February, because the crop intensity is strongly reduced by the lack of rainfall, and rice becomes fully dependent on irrigation water supply.

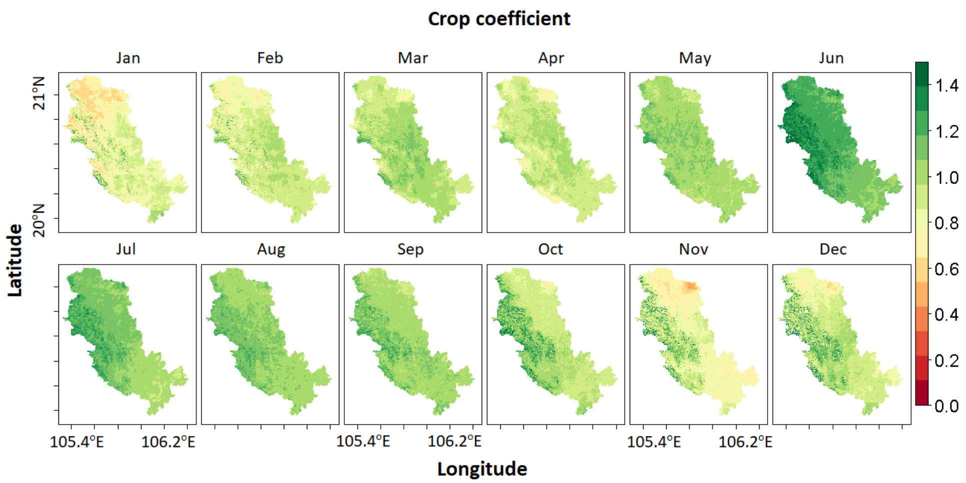


Figure 13. Monthly crop coefficient (K_c) derived from the ratio between the ensemble ET and reference ET.

The K_c values are plotted with a 3-month Simple Moving Average (SMA) filter (Figure 14). The K_c values during different growing stages typically vary between 0.70 and 1.00 (initial stage), and 0.90 to 1.20 (mid-season stage). The differences in Kc are due to the variety of cultivated paddy rice, as well as irrigation management. The Kc in June to July and October to November 2008 was exceptionally high, since this was a very wet year. The mid-season K_c reached 0.81 to 1.00, and 0.96 to 1.21, in March and June respectively. These values are similar to previous findings [249] with mid-season K_c reported to be around 1.23. The K_c during end-season (April to May for dry season rice and September for wet season rice) varies around 0.90 to 1.10, similar to crop coefficients estimations earlier [249,251]. Hence, the K_c values are falling within the acceptable range, indicating that the ensemble ET performed well for the Day Basin and can be used for SWAT model calibration.

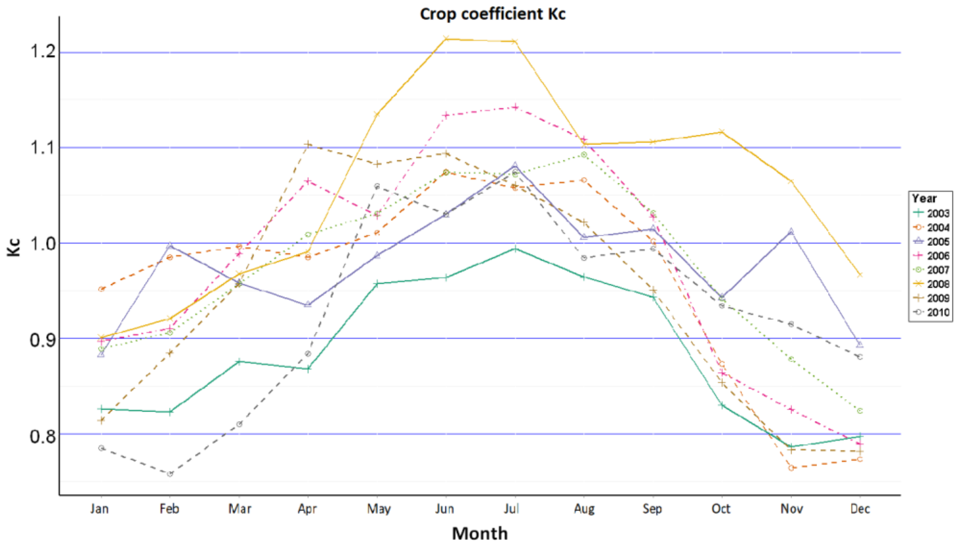


Figure 14. Simple Moving Average (SMA) for crop coefficient (K_c) for paddy rice in the Day Basin.

Leaf Area Index

Leaf Area Index (LAI) is defined as the area of green leaf per ground area. It is an important variable for eco-hydrological modelling and quantifying ecosystem services [252]. LAI influences the evapotranspiration rate and its partitioning into transpiration (T), soil evaporation (E), and interception (I). At the same time, LAI determines the amount of Absorbed Photosynthetically Active Radiation (APAR), which determines the energy level for photosynthesis. MOD15-LAI data (NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, U.S.) with an 8-day temporal resolution was downloaded from open access databases. Monthly average LAI values with a spatial resolution of 1 km have been reconstructed for the period of 2005–2011.

The SWAT model estimates LAI values assuming a certain upper boundary function of growth that is corrected for stress factors (temperature, water, and nutrients). These stress factors can vary greatly and have an empirical character. The calibration of the model including LAI measurements is therefore crucial. The empirical LAI parameters to be prescribed in SWAT use an internal crop development database [56].

3.5 SWAT parameters to be optimized

A summary of various sets of parameters used in model calibration of different processes, i.e., surface runoff, snow, plant growth etc. [216]. A similar list of parameters was also suggested [180,202,222]. Calibration of ET is less common, because this dataset is usually not available. More recent studies [174,206,208] demonstrated that SWAT can be calibrated against spatial ET data as well. Key parameters for the calibration of ET and their value range were derived from the SWAT user's manual [56]. Since the purpose of this study is to calibrate the model for ET and LAI, the model parameters to be optimized were divided into two groups: ET and LAI. This grouping indicates which parameters are most sensitive to ET and LAI, and thus, suitable for optimizing the model performance for these two processes. The list is long because one parameter might control more than one process, e.g., the available water capacity of soil layers affects the generation of surface runoff, but simultaneously determines the amount of water that is evaporated (ET) and percolated to the underground. SUFI-2 automatically optimizes the selected parameters within their predefined range, hence this aspect of parameter selection is following the default guidelines of the tool.

Six parameters ESCO, EPCO, REVAPMN, SOL_K, SOL_AWC, and SOL_BD have been selected to optimize the ET simulations. The baseflow recession constant ALPHA_BF and SCS runoff curve number (CN2) were also included because of their influences on the surface–subsurface hydrological processes, and thus, on the water availability for evapotranspiration. Seven other parameters are identified that influence the leaf area index development [56]: BLAI, ALAI_MIN, DLAI, LAIMX1, LAIMX2, FRGRW1, and FRGRW2. SUFI-2 thus optimizes 15 model parameters for different sub-basins and HRUs. Since SWAT-CUP is unable to read spatial data, time series of ET and LAI was derived and used as input into the model. While ET process is more dependent on the local climate and land cover properties, LAI is strictly driven by the plant type, and hence, the calibration should be done at sub-basin, land cover, and HRU levels. The utilization of high resolution spatial datasets as input into HRU analysis in SWAT (i.e., land use, DEM, soil maps) ensures fair distribution of HRUs, and hence, spatially distributed ET and LAI across the watershed.

In the case of conventional calibration using discharge, two river discharge points (i.e., Phu Ly and Ninh Binh) were used (500 simulations for both calibration and validation) and the acquired result was used to compare against the output from calibration technique using remotely sensed data.

In the first step of calibration technique using remote sensing data, average ET and LAI for 119 sub-basins and all land-cover groups was extracted from ensemble ET and Moderate Resolution Imaging Spectroradiometer (MODIS) and used as observed data in SWAT-CUP. Derived time series of ET and LAI from each sub-basin and land cover type was used to calibrate 15 parameters in each sub-basin and land cover group individually (500 simulations each run for calibration and validation). This first estimation of ET and LAI ensures a good agreement in term of average ET, LAI, and subsequently, water balance. In the second batch of calibration, a number of HRUs from each sub-basin representing all land use classes and ensuring a total coverage of at least 50% the sub-basin's area were selected in the calibration (500 simulations each run for calibration and validation). The calibration result yields a set of soil and plant parameters which varies from sub-basins and land cover groups, and that reflects the local eco-hydrological processes, and is therefore highly valuable. This unprecedented spatial variability from SUFI-2 optimization cannot be obtained from soil surveys and soil maps, which makes this investigation interesting. The classical SUFI-2 calibration will give the same parameter value to all sub-basins and HRUs encompassed in a certain drainage area, and hence, the new system of calibration provides much more insight into the local characteristic of the soil and vegetation system.

3.6 Results and discussions

The simulation covered the period 2000 to 2013 using 3 years of initialization (2000 to 2002) as modelling warm up period. Because remotely sensed data had a different temporal coverage—2003 to 2012 for ET and 2005 to 2011 for LAI—SWAT was calibrated from 2003 to 2007 for ET, and validated from 2008 to 2012. LAI was calibrated from 2005 to 2007, and validated from 2008 to 2011.

The monthly simulation for the entire Day Basin, as one bulk system, was presented in Figure 15. The simulated values related satisfactorily to the observed ensemble ET values. The ET peak value from remote sensing did not exceed 140 mm/month, while the modelled ET was as high as 160 mm/month. For remote sensing-based calibration, simulated ET in SWAT is underestimated by 5 to 10 percent in the irrigated agricultural land downstream, while the forest land showed good correlation. NSE yielded from 0.61 (calibration) to 0.65 (validation). R^2 for calibration and validation was 0.71, while Kling Gupta Efficiency (KGE) ranged from 0.80 to 0.83, respectively. The high values from

KGE were due to the fact that low values were well represented for bias and correlation, as compared to NSE's reputation on overemphasizing peak values. By contrast, traditional discharge-based calibration performed statistically more inferior with NSE, which were only at −0.01 and −0.20, and KGE at 0.46 and 0.47, while R^2 was of significant values 0.77 and 0.76, for calibration and validation, respectively. Discharge-based calibration results also encountered a consistent underestimation of ET temporally as compared to remote sensing-based method. Another observation in both cases is that the lower ET values simulated during winter were always lower than the observed values from remote sensing, even though this difference was much lower when using ET and LAI as calibration inputs. This could be related to the dry period in which SWAT computes water stress due to a lack of soil moisture. This could suggest that the storage capacity of the soil in reality is higher, or it could also be related to lower vertical water fluxes between the top soil, sub-soil, and the unconfined shallow aquifer, or the sensitivity of vegetation to soil moisture. A very low reference ET_0 during winter could also be an explanation. SUFI-2 ensured, however, that the spatial patterns match rather well. Some local differences occur unavoidably due to the inaccuracy of the various mathematical expressions used to compute a complex hydrological process such as ET. Remote sensing ET values reflect more the real world conditions as they are based on observations [196,198,199]. The agreement between SWAT and remote sensing data was expressed by means of the correlation coefficient and the bias. Using spatial dataset in the calibration yields resulted in much higher agreement, and reveals that both the ET formulations in SWAT as well as the SUFI-2 optimization techniques are adequate. The same conclusion was drawn earlier by other researchers that validate SWAT on the basis of ET data series.

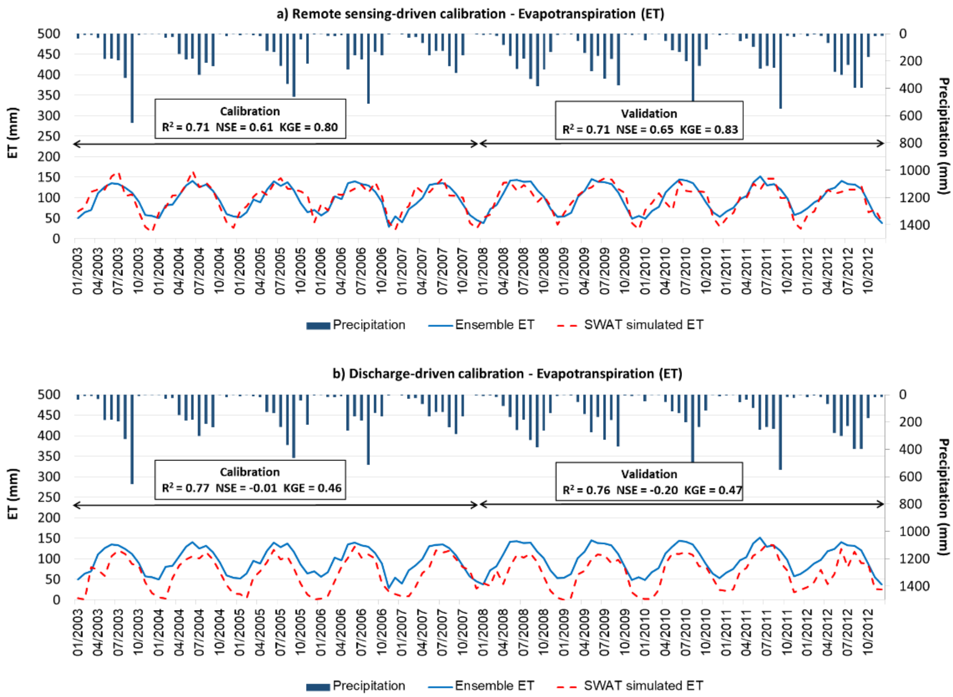


Figure 15. Temporal variability estimated from SWAT and the "observed" values from remote sensing in (a) remote sensing-driven calibration, and (b) conventional discharge-driven calibration.

Further to the evapotranspiration simulations of SWAT, the vegetation response to water can be evaluated by means of a comparison of the simulated LAI (see Figure 16) in two cases: (a) remote sensing-driven, and (b) discharge-driven calibration. The remote sensing-based calibration yielded acceptable NSE ranging from 0.50 for calibration and 0.57 for validation. R^2 for calibration and validation was 0.51 and 0.59, while Kling Gupta Efficiency (KGE) ranged from 0.59 to 0.75. Conventional discharge-based calibration performed poorly, in term of statistics, with NSE of only 0.35 and 0.43, KGE of −0.34 and 0.03, while R^2 was higher at 0.67 and 0.77 for calibration and validation, respectively. LAI values in discharge-based calibration were consistently underestimated compared with observation from MODIS. With regard to remote sensing-based calibration, the timing of the green cover development seems acceptable. The peak LAI values during Spring 2005 and 2006 are not accurate. This may be due to constancy of the LAI related calibration parameters for all the different simulation years. It would be better to make the maximum LAI parameter variable for each year, to enable it to better respond to years with weather anomalies. A good description of LAI evolution will improve the timing of rice emergence, which in turn, affects the irrigation and transpiration processes.

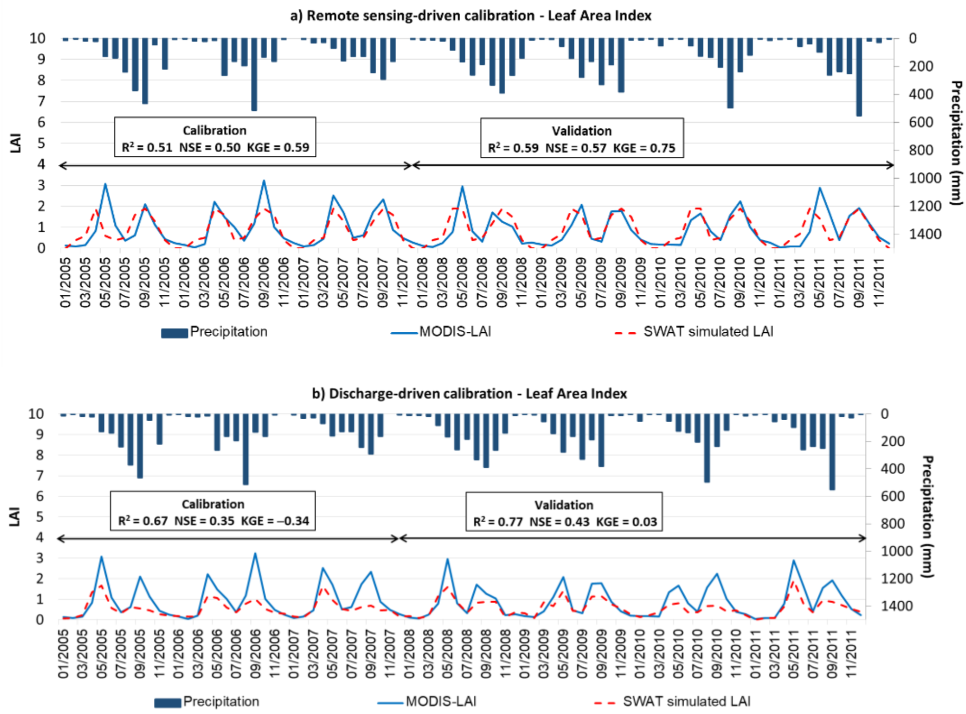


Figure 16. Determination of the LAI from MODIS and SWAT simulation for an HRU consisting of paddy rice for (a) remote sensing-driven calibration and (b) conventional discharge-driven calibration.

Figure 17 represents the accumulated ET during the calibration (2003 to 2007) and validation (2008 to 2012) period for remote sensing-based calibration. The total simulated ET is 5855 mm, compared with 5727 mm for the ensemble ET during the calibration, hence a difference of 128 mm (2.2%). The model performs consistently during the validation period with 5713 mm (simulated ET), as compared to 6015 mm (ensemble ET), leading to a difference of 302 mm (5.3%). In very general terms, the set of ET related equations in SWAT has a limited capacity to mimic the complex processes of soil evaporation, plant interception, and plant transpiration that occur in reality, due to the dynamic meteorological and hydrological processes. The results indicate that SUFI-2 succeeded in generating a close to reality ET in both calibration and validation of ET, both spatially and temporally.

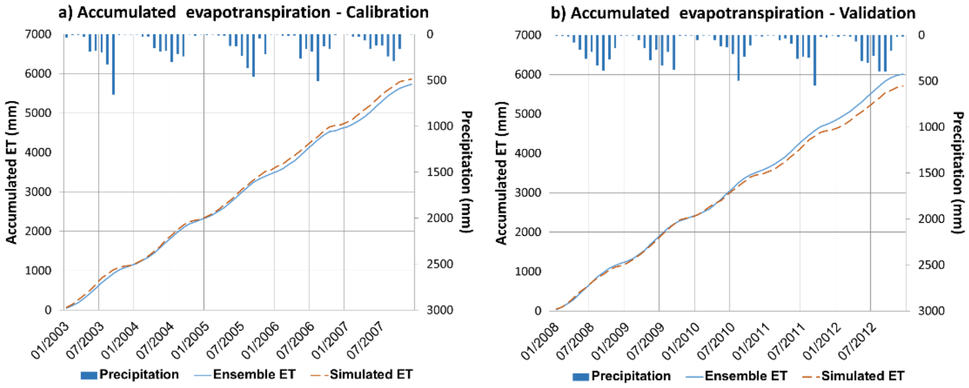


Figure 17. Accumulated ET for the period of five years for a) calibration and b) validation

Figure 18 shows, for every HRU, the distributed ET from the SWAT model and ensemble ET over the period 2003 to 2012. These graphs showed a spatial coherence between the two datasets.

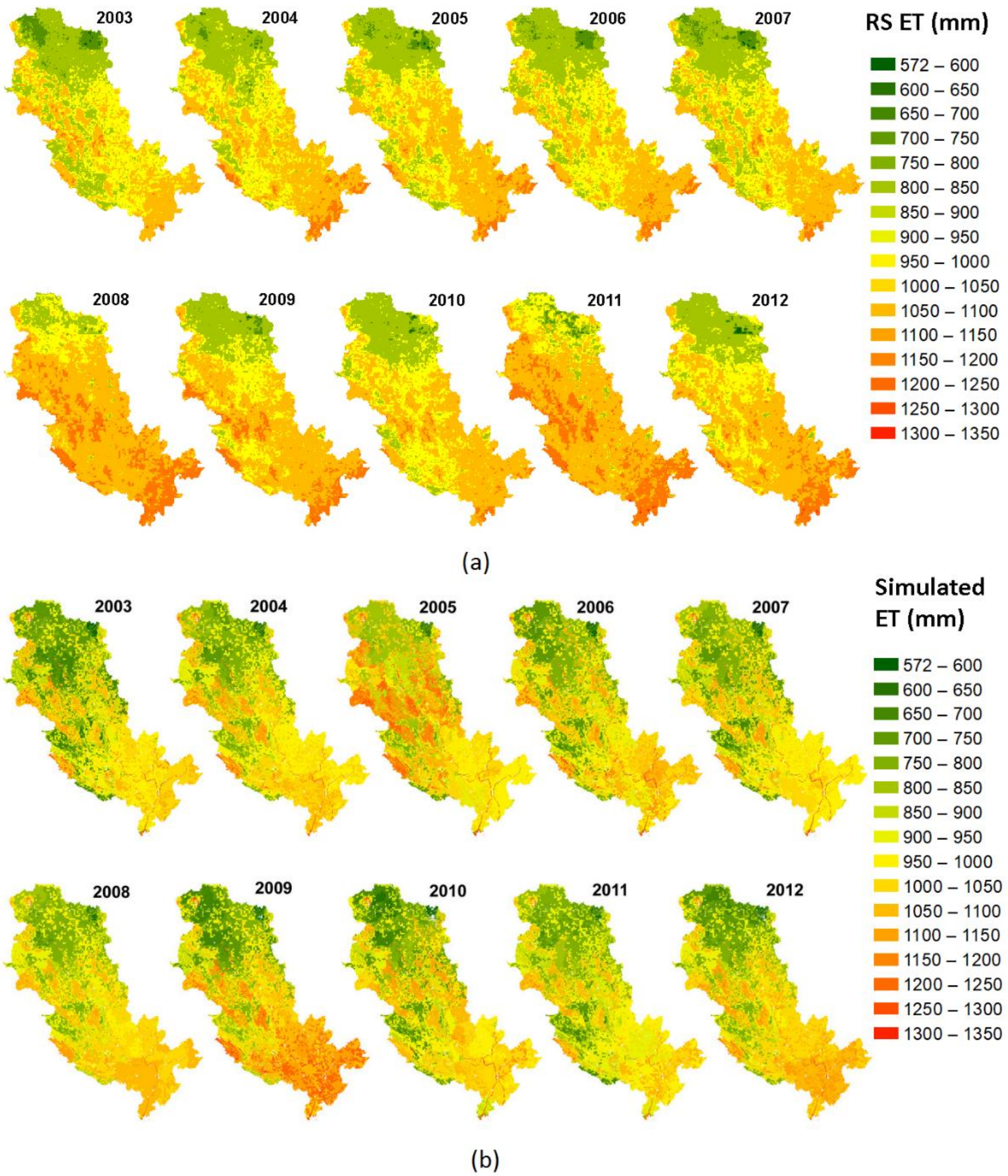


Figure 18. Spatial agreement between the ensemble ET from remote sensing (a) and the SWAT simulated ET (b) at an annual basis.

To verify simulated streamflow from the remote sensing-driven calibration, the relationship between monthly river flow simulations and flow measurements at the Phu Ly and Ninh Binh stations was assessed, as shown in Figure 19. The discharges in several cross sections was constructed using the rating curve of measured flows and water levels during restricted periods, measured using acoustic Doppler current profilers [215].

The agreement between simulated river flow and station discharge measurements was expressed through R^2, ranging from 0.71 (Phu Ly) to 0.78 (Ninh Binh), and Nash–Sutcliffe from 0.55 to 0.63, respectively. Considering that river discharge was computed from measured water level [215], the agreement between simulated river flow and station discharge measurements is good. Measured river flow data were not used in the calibration process, which shows that a good simulation of ET facilitates the prediction of stream flow. Note that the flow in these rivers is far from being natural, due to all the irrigation practices that are occurring. Measured river flow data were not used in the calibration process, which shows that a good simulation of ET will make it possible to calculate flows directly (streamflow and ET being the two largest components of the water balance) without having to optimize flow in the calibration process. Hence, this shows that flow data can be replaced by ET to optimize SWAT model performance, and that the ET is reflecting actual anthropogenic processes of the water cycle.

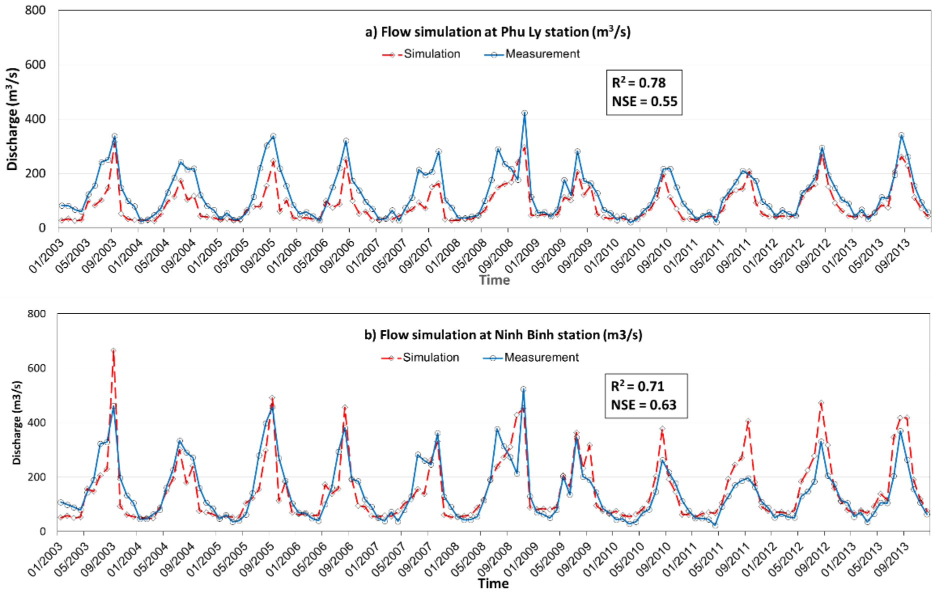


Figure 19. Flow simulation vs. station measurements at Phu Ly (a) and Ninh Binh station (b).

To make the fit between remotely sensed precipitation and ET feasible, extra water has to be supplied to the land use class irrigated land in certain months. The total amount of irrigation water supply is computed to be 1.934 billion m^3/y, and this amount of water is thus withdrawn from the Red River through various ungauged inlet points. This number can now be estimated with more precision because ET is known [180,201,208]. The main water intake for irrigation is between January and March (during the Winter–Spring paddy rice) with a maximum amount of 98 mm during February. During the Summer–Autumn paddy rice season, the water intake is concentrated in July with an amount of 113 mm per month. The total storage change ΔS for the entire Day Basin indicates the difference between all inflow and outflow terms. ΔS during 2003 to 2013 for unsaturated and saturated zones are 11.7 and 9.6 mm/y, respectively, due to the fact that there is water locally stored in lakes, streams, and also moving within the saturated layers to the deep aquifer. This is a realistic number, and confirms that the water balance of the total system is rather accurately simulated.

The total water balance for the basin in average rainfall, a dry (2007), and a wet (2008) year, is shown in Table 4. While the average annual rainfall was 1710 mm/y, it reached 2121 mm/y in 2008 and 1496 mm/y in 2007. The ET in 2007 and 2008, was 985 and 1010 mm/y, respectively, compared to 958 mm/y on average. This quasi-constancy of ET is noticed more often in other studies. The regulating role of soil water storage in the vadose zone, and the lower evaporative demand in wet years and higher demand during dry years, are some major causing factors for restriction of ET dynamics. Due to the impact of rainfall variation to overall water budget, the change in soil water content (ΔSW) for 2007 was indeed negative (ΔSW= −27 mm/y) while for 2008, it was positive (ΔSW = +80 mm/y). The final calibrated range of 15 parameters is expressed in Table 5.

Table 4. Monthly water balance for an average precipitation year, expressed in mm/y for unsaturated and saturated zone.

Unsaturated Zone									
Year	**Input**			**Output**					**Δu**
	P	**IRR**	**Revap**	**Q_{runoff}**	**Q_{lat}**	**ET**	**PERC**	**ΔER**	
Average	1709.5	309.2	19.4	586.9	14.0	957.9	441.5	49.5	−11.7
2007	1496.1	302.0	3.6	447.2	11.1	985.0	347.9	−27.1	37.7
2008	2121.1	375.7	0.7	789.1	15.8	1009.5	606.2	80.1	−3.2

Saturated Zone					
Year	**Input**	**Output**			**Δu**
	PERC	**Revap**	**GW_RCH**	**SA_ST**	
Average	441.5	19.4	436.1	−23.6	9.6
2007	347.9	3.6	358.0	−7.8	−5.9
2008	606.2	0.7	487.7	0.0	117.9

P: precipitation; ET: evapotranspiration; Revap: water revap from saturated to unsaturated layer; ΔSW: change in soil water content; Q_{runoff}: generated surface flow, including surface runoff, Q_{lat}: later flow from vadose zone; IRR: applied amount of irrigation water; PERC: percolation to shallow aquifer; GW_RCH: recharge to deep aquifer r; SA_ST: change in shallow aquifer storage; Δu: the difference between input and output

Table 5. Final values of fifteen parameters optimized in SWAT model used to mimic ET and LAI.

Parameter	Unit **	Default Range *	Final Value
ESCO	-	0–1	0–0.22
EPCO	-	0–1	0.88–1.00
REVAPMN	mm	0–500	248–395
SOL_K	mm/hr	0–2000	0.44–1262
SOL_AWC	mm water/mm soil	0–1	0.50–1
SOL_BD	mg/m^3 or g/cm^3	1.1–1.9	1.2–1.62
CN2	-	35–98	72.9–98
ALPHA_BF	-	0–1	0.42–0.75
BLAI	m^2/m^2	0.5–10	0.89–10
ALAI_MIN	m^2/m^2	0–0.99	0–0.98
DLAI	-	0.15–1	0.30–0.95
LAIMX1	-	0–1	0–0.75
LAIMX2	-	0–1	0–0.99
FRGRW1	-	0–1	0–0.76
FRGRW2	-	0–1	0–0.74

Note: *: Taken from Arnold et al. (2012) [216]; **: dimensionless parameters are shown as '-'.

3.7 Conclusions

The availability of spatially distributed precipitation, ET and LAI gridded data from open access—or partially open access—earth observation data platforms, makes it feasible to calibrate soil and vegetation process parameters of eco-hydrological models, also when rivers are ungauged and the water distribution system is complex. In this study, four individual ET models were averaged linearly to match the simulations of ET from SWAT. No in situ measurements were available to verify the performance of individual ET models. From inspection of the water balance, a simple linear average value gave best results as compared to streamflow and K_c crop coefficients, described in the international literature. Nevertheless, it is required to undertake more studies on the ensemble ET product to provide further progressive insights on averaging of individual estimates.

Secondly, this chapter demonstrates the capabilities of SWAT and the auto-calibration SUFI-2 to render biophysical processes in data scarce basins in a distributed manner. A total of 15 essential biophysical parameters of the unsaturated zone and exchange processes seem to be adequately calibrated in SWAT for each of the 7907 HRUs. Otherwise, there would not have been such a good agreement with the spatio-temporal variability of the remote sensing parameters, as in the case of conventional discharge-driven calibration. Furthermore, this level of spatial detail cannot be obtained from soil maps. The hydrological formulations in SWAT are thus adequate for simulating eco-hydrological processes. In the near future, remote sensing data on soil moisture, net primary production, and water quality will become available as well, which will undoubtedly further enrich the options to calibrate additional SWAT model parameters.

The approach proposed in this study using SWAT-CUP and SUFI-2 will improve the facilitation and standardization of calibration process for basins with scant field data. By optimizing evapotranspiration and photosynthesis for Hydrological Response Unit, swift estimates of surface runoff, erosion, groundwater recharge, baseflow, storage changes, withdrawals, and carbon assimilation can be determined and used to quantify ecosystems services. The availability of the system parameters will allow future predictions of the basin water cycle in response to external factors, such as climate and land-use changes, and computing scenarios for green growth, i.e., conservation plans, reduction of greenhouse gas emissions, etc.

4

Determination of Spatially Distributed Hydrological Ecosystem Services (HESS) in the Red River Delta Using a Calibrated SWAT Model [3]

The principles of Integrated Water Resources Management (IWRM), conservation of natural capital, and water accounting requires Hydrological Eco-System Services (HESS) to be determined. This study presents a modeling approach for quantifying the HESS framework using the Soil Water Assessment Tool (SWAT). SWAT was used–after calibration against remote sensing data–to quantify and spatially identify total runoff, natural livestock feed production, fuelwood from natural forests, dry season flow, groundwater recharge, root zone storage for carrying over water from wet to dry season, sustaining rainfall, peak flow attenuation, carbon sequestration, microclimate cooling, and meeting environmental flow requirements. The environmental value of the current land use and vegetation was made explicit by carrying out parallel simulations for bare soil and vegetation conditions and reporting the incremental ecosystem services. Geographical areas with more and fewer HESS are identified. The spatial and temporal variability of annual HESS services is demonstrated for the Day Basin–which is part of the Red River delta (Vietnam)-for the period 2003 to 2013. The result shows that even though the basin is abundant with HESS, e.g., 7482 m^3/ha of runoff, 3820 m^3/ha of groundwater recharge, the trend for many HESS values, e.g., micro-climate cooling, meeting environmental flow requirements, and rootzone storage, are declining. It is found and proven that quantified HESS indicators highlighted the provisioning and regulating characters of ecosystem services, as well as geographical hotspots across the basin. The SWAT model shows the capability of simulating terrestrial eco-hydrological processes such as climate, soil, and current land use. The methodology illustrates how eco-hydrologists can benchmark ecosystem values and include HESS in exploring river basin management scenarios, climate change studies, and land use planning.

[3] Chapter is based on: Ha, L.T.; Bastiaanssen, W.G.M. Determination of Spatially-Distributed Hydrological Ecosystem Services (HESS) in the Red River Delta Using a Calibrated SWAT Model. Sustainability 2023, 15, 6247. https://doi.org/10.3390/su15076247.

4.1 Introduction

Ecosystem services are defined as the benefits that people obtain from natural systems [1,61]. The concept of ecosystem services is relevant for connecting people to nature [253,254]. Hydrological Eco-System Services (HESS), also known as Water-related Ecosystem Services, comprise those ecosystem services that explicitly describe the services rendered from and regulated by water resources [3]. Because regions with local water scarcity are expanding and intensifying [73], it is becoming more important to understand and quantitatively describe the environmental benefits of water in longer-term water policy plans. Too often, multiple-use aspects of water allocation and water resources evaluation are restricted to food production, industrial use, domestic sector, and hydropower (e.g., FAO AquaStat database [84]. A HESS is less common because it is a co-product of given practices. For instance, crops are grown to generate food, not for the reduction of erosion or sequestration of carbon. Nevertheless, this co-product can be very valuable for conserving the environment and sometimes have economic benefits such as certified carbon pools. The lacking of standardized processing and reporting of the HESS process limits the uptake by policymakers [32,69,255].

Based on an internationally recognized framework for Ecosystem Services and Resilience produced under the CGIAR Research Program on Water, Land, and Ecosystems (2014) [34], Ha et al. (2023) [256] described key HESS indicators that are ascribed to consumptive use and non-consumptive use. The HESS framework can be used for implementing policy frameworks such as Water Accounting [38].

The quantification of HESS in heterogeneous watersheds and river basins requires modeling efforts. This is especially a challenge in low-income countries such as Vietnam, where data on water resources and the environment are scarce and not easily available. Conceptually different approaches have been used for modeling, mapping, and quantifying of hydrological ecosystem services [58,138,257–259]. Quantification of these hydrological ecosystem services is based on empirically established relationships and look-up tables [260,261], hydrological-based simulation models [4], remote sensing measurements [262], or big data sets where various data sources are merged [174,263]. The main advantage of hydrological models is their great flexibility in forecasting changing conditions and assessing trade-offs if certain interventions are implemented, i.e., what is the impact of deforestation on peak flow attenuation and groundwater recharge? Some examples of modeling provisioning services are water yield, carbon stock in vegetation and soil [264], carbon fluxes [265], crop biomass production [74,178], and feed biomass production [266]. Regulating services can be described using numerical simulations of dry season base flow and groundwater recharge [267], nutrient load, sediment [54], etc.

Various types of hydrological models are suitable for modeling hydrological ecosystem services, such as SWAT [176], ARIES [41,175], InVEST [40], and VIC [177]. SWAT was recommended as a preferred tool to simulate provisioning and regulating services due to the inclusion of processes on hydrological, flow dynamics, water quality, as well as plant growth, and nutrient loading as well as in basins with no or little field measurements [179,182,186]. As a hydrological model, SWAT has been used at various temporal scales to simulate plot size as well as continental watersheds [268]. Its multiple input parameters and process-based biogeochemical sub-models strengthen the model's applicability to simulate not only water flow dynamics but also estimate several water quality and plant growth variables that can be used in the assessments of land and agricultural management impacts on ES. Various authors used SWAT to simulate crop growth and soil water modules [269], water and carbon fluxes [270], nutrient and sediment transport related to best management practices, wetlands, irrigation, bioenergy crops, climate change, land use change, and others [271,272].

While Ha et al. (2023) [256] defined a standard set of HESS indicators and pleaded for determination by means of earth observation data, not all of them can be determined from remote sensing measurements. Certain hydrological processes, such as base flow, environmental flow, and peak flow mitigation, need to be derived from a hydrological model. Ha et al. (2018) [55] showed how SWAT and SWAT-CUP could be employed to calibrate key eco-hydrological processes for the Day River Basin using remote sensing data on land use, rainfall, actual evapotranspiration, and Leaf Area Index (LAI). Knowledge of soil and vegetation parameters is a proper basis for quantification of the natural and anthropogenic eco-hydrological processes at un-gauged basins. This is the novelty of the study as it demonstrated a methodology to assess terrestrial eco-hydrological processes and the translation into ecosystem services that are benefiting human beings in the Day River Basin, such as total runoff, natural livestock feed production, fuelwood from natural forests, dry season flow, groundwater recharge, root zone storage for carrying over water from wet to dry season, sustaining rainfall, peak flow attenuation, carbon sequestration, microclimate cooling, and meeting environmental flow requirements. It is shown that eleven selected HESS from Ha et al. (2023) [256] can be computed from a SWAT model that is calibrated with remote sensing data and that this methodology could become a routine effort to support the preparation of longer-term water resource plans.

4.2 Materials

4.2.1 Study Area

The Day Basin, located in Northern Vietnam, is a sub-basin within the transboundary Red River system (Figure 20). The area is approximately 6300 $km^{2,}$ and the rainfall is 1700 mm/y. The Day Basin comprises several river tributaries, among which the largest is the Day River, with a total length of approximately 250 km. The Day Basin has a high biodiversity with abundant flora and fauna in the forested hills, freshwater aquatics, and wetlands, although agricultural land use is dominant. Topographical elevation ranges from low-lying delta (~0 m amsl) to mountainous areas (~1100 m amsl). The major land cover in the Day Basin is agricultural land (64%), followed by forested land (24%) and mixed mosaic (12%). An amount of 3100 km^2 (76%) of agricultural land is irrigated. The land use–land cover map contains 14 classes, and they form an essential input for the evaluation of HESS.

The Day Basin hosts the country's capital of Hanoi, an essential economic hub with an impact on prosperity in the basin. The climate in the Day Basin has a monsoonal character. The wet season elapses from May to October, and the dry season from November to April. The contribution of precipitation is mainly from rainfall, as there is no snowfall in the Day Basin. Precipitation can reach up to 450 mm per month in some parts of the basin. Over against that, precipitation can be as low as a few mm during January and February.

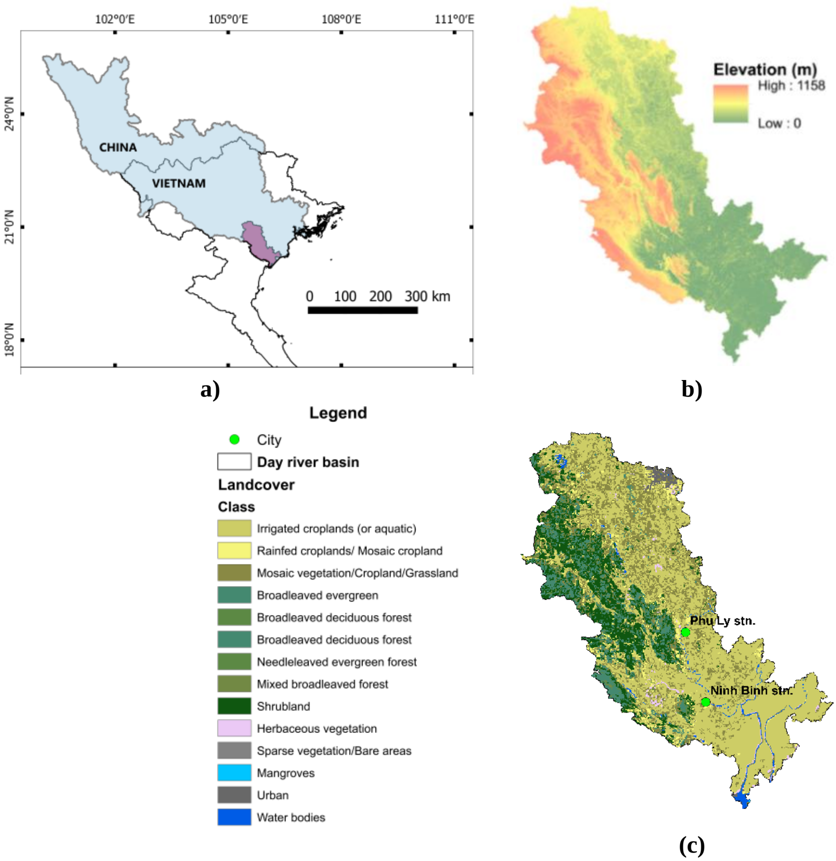


Figure 20. (a) Geographical location of Day Basin as part of the Red River Delta in Northern Vietnam; (b) Digital Elevation Map of the basin; and (c) Land cover map of Day Basin.

4.2.2 SWAT model input data

The input data into SWAT is based on spatial input data layers, wherever possible. Following Ha et al. (2018), precipitation (P) in SWAT is derived from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) data. Other climatic forcing data, e.g., radiation, wind speed, wind direction, daily minimum and maximum temperature, etc., was derived from the Global Land Data Assimilation System (GLDAS). The actual evapotranspiration (ET) used for SWAT was an ensemble product of 4 different datasets, namely CMRSET, SSEBop, MOD16, and SEBS [80,81]. The Leaf Area Index data is taken from the routine MODIS products. Observed streamflow data from 2003–2013 has been used in this study to calibrate the soil water balance. Daily measurements were taken from the discharge stations of Ninh Binh and Phu Ly (Figure 20c). Ha et al. (2023) [256] composed a list of remote-sensing datasets and derived parameters that can be used to quantify HESS. For instance, biomass production-related parameters, e.g., land surface temperature, Net Primary Production (NPP), can be derived from Landsat, MODIS Terra/Aqua, or Sentinel missions. Other parameters, such as precipitation, were reviewed and assessed the accuracy using criteria such as percent bias (PBIAS), Nash-Sutcliffe Error (NSE), and mean absolute error (MAE). Ha et al. (2018) [55] concluded that precipitation product such as CHIRPS shows a good correlation with field measurements as compared with other products such as TRMM. Table 6 summarizes the input data used to execute the SWAT model for the Day Basin.

Table 6. Description of open access spatial data and their resolutions used in the study.

Data	Description	Resolution	Source
DEM	SRTM 30 m global DEM	30 m	[273]
Soil	Coupled FAO and ISRIC soil maps	1 km	[55]
Land cover	GlobCover global land cover map	300 m	[223]
Precipitation	Daily precipitation from CHIRPS	5 km	[55]
Meteorology	GLDAS	25 km	[231]
ET	Ensemble ET	500 m	[55]
LAI	MODIS LAI	250 m	MOD15-LAI data (NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, U.S.) [274]

4.2.3 Remote sensing and SWAT modeling approach

The SWAT computes vertical and horizontal water flows and fluxes for each Hydrological Response Unit (HRU). One HRU has similar soil and vegetation properties but can be geographically dispersed so that they can be located in different parts of the sub-basin. There is no spatial variability present within HRU. The unsaturated zone is a combination of the root zone, a transition zone, and the capillary fringe that together form the vadose zone. The saturated zone is composed of a shallow and deep aquifer (see Figure 21). Lateral flow or interflow occurs from the unsaturated zone. Base flow occurs from the shallow aquifer.

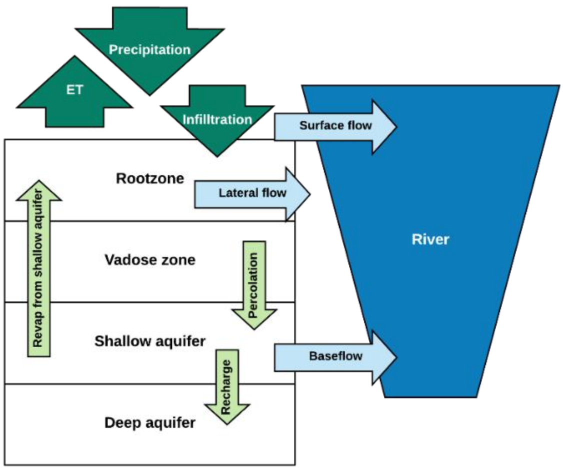


Figure 21. Schematization of vertical and horizontal water fluxes in an HRU in SWAT.

The calibration of SWAT requires various soil and vegetation parameters to be optimized to ensure a rigorous representation of surface runoff, recharge, base flow, soil moisture storage, net primary production, etc. SWAT-CUP appeared to be a very useful auto-calibration and uncertainty analysis tool for SWAT. A total number of 15 SWAT model parameters that are closely linked to the evolution of ET and LAI have been optimized. The numerical range of these model parameters affecting ET and LAI was derived from the SWAT user's manual [56]. The long list is based on the fact that one parameter might control more than one physical process, e.g., soil water-holding capacity affects the generation of overland flow but also determines water uptake by roots and percolation losses to the deeper underground. Earlier works with SWAT and sensitivity assessment recommended different parameters needed for the calibration [208,216,222].

SWAT parameters ESCO, EPCO, REVAPMN, SOL_K, SOL_AWC, and SOL_BD mainly affect ET. ESCO is the soil evaporation compensation factor that reflects the effect of capillary rise, crusting, and cracks. EPCO is the plant uptake compensation factor that controls the amount of water uptake by roots and the drought sensitivity of vegetation. REVAPMN is the threshold depth of water (in mm) in the shallow water aquifer for 'revap' or capillary rise from the deep aquifer to occur. SOL_K, or saturated hydraulic conductivity, relates soil water flow rate or flux density (in mm/h) to hydraulic conductivity. SOL_AWC is the plant's available water (in mm H20/mm soil). SOL_BD, or the moist bulk density (in mg/m^3 or g/cm^3), is the ratio of the mass of solid particles to the total volume of the soil. The baseflow recession constant ALPHA_BF and SCS runoff curve number (CN2) influence the actual water storage in the unsaturated zone and root zone.

Apart from soil evaporation parameters, the calibration of a distributed SWAT model involved modeling plant physiological characteristics to ensure a well-represented river basin's terrestrial eco-hydrological processes such as runoff, evapotranspiration, and plant and crop growth. With regard to plant physiology, six parameters are identified that influence the leaf area index development, see Neitsch et al. (2011) [56], which are very important for the quantification of the photosynthesis and the subsequent carbon assimilation process: BLAI, ALAI_MIN, LAIMX1, LAIMX2, DLAI, FRGRW1, and FRGRE2. BLAI is the maximum potential leaf area index (m^2/m^2). ALAI_MIN is the minimum leaf area index for the plant during the dormant period (m^2/m^2). LAIMX1 and LAIMX2 are the fractions of the maximum leaf area index corresponding to the 1st and 2nd points, respectively, on the optimal lead area development curve. FRGRW1 and FRGRW2 are fractions of the plant growing season or fractions of total potential heat units corresponding to the 1st and 2nd point, respectively, on the optimal leaf area development curve. DLAI is the fraction of the growing season when the leaf area begins to decline. These parameters are crucial to obtain plant physiological characteristics as described in Equation (19). More details on the calibration process are described and demonstrated in Ha et al. 2018 [55]. SWAT-CUP solves all these model parameters for every Hydrological Response Unit. An HRU exists of various non-contiguous polygons with commonalities in soil type, slope, and land use. There are approximately 7000 HRUs in the Day Basin. The water balance, and hence all HESS values presented later, are computed for each HRU.

The results are displayed for HRU (e.g., distributed representation) for the HESS on total runoff, natural livestock feed production, fuelwood from natural forest, groundwater recharge, root zone storage, sustaining rainfall, carbon sequestration, and microclimate cooling. HESS, such as dry season flow (baseflow), peak flow attenuation, and meeting environmental flow requirements, are shown for river sections (i.e., directional polygonal representation).

4.3 SWAT-modeling framework for HESS

There are different analytical solutions to quantify the remaining HESS indicators. Ha et al. (2023) [256] presented a framework of 17 HESS that could be measured to support river basin plans and environmental monitoring. Within this framework, HESS is categorized into Provisioning services (HESS1: Total runoff, HESS2: Inland capture fishery, HESS3: Natural livestock feed production, HESS4: Fuelwood from natural forest), Regulating services (HESS5: Dry season flow ("baseflow"), HESS6: Total groundwater recharge, HESS7: Surface water storage, HESS8: Root zone water storage, HESS9: Sustaining rainfall, HESS10: Peak flow attenuation, HESS11: Carbon sequestration, HESS12: Reduce Greenhouse Gas Emissions, HESS13: Micro-climate cooling, HESS14: Natural reduction of eutrophication in water, HESS15: Reduction of soil erosion), Supporting services (HESS16: Meeting environmental flow requirements), Cultural services (HESS17: Leisure). This study aims to present the spatial determination of eleven selected HESS, i.e., HESS1, HESS3, HESS4, HESS5, HESS6, HESS8, HESS9, HESS10, HESS11, HESS13, and HESS16, which were computed from a SWAT model combined with remote sensing data.

4.3.1 Water-related provisioning services

Total Runoff (HESS1)

Total runoff is the source of all blue water resources (streams, rivers, lakes, lagoons, aquifers), and it describes the longer-term renewable water resources provided to mankind and is originally based on rainfall and snowfall somewhere in the catchment. Some of this water is withdrawn by natural ecosystems, including groundwater ecosystems, and is thus not available for withdrawal. Total runoff is the combination of surface runoff, lateral flow, and base flow, see Equation (2):

$$Q_{total} = Q_{surf} + Q_{lat} + Q_{bf} \quad \textbf{(2)}$$

where Q_{total} p(m^3/ha) represents the total runoff, Q_{surf} (m^3/ha) is the horizontal fast overland flow, Q_{lat} (m^3/ha) is the horizontal interflow that occurs from lateral drainage processes in undulating terrain, and Q_{bf} (m^3/ha) represents the horizontal seepage that drains saturated soil towards rivers. The determination of these component flows was extensively discussed in the literature [275]. Appendix A explains a step-wise calculation of Q_{surf}, $Q_{lat,}$ and Q_{bf} that can be used to determine HESS1. For the sake of science and progressive insights into the HESS mechanisms, runoff is computed with current and historic land use; hence historic land use is taken as the reference. Landscape modifications such as the building of reservoirs and urban areas have affected the natural rainfall–runoff process. Pristine land cover with more forests and pastures will increase the total runoff generated in the Day Basin.

Natural Livestock Feed Production (HESS3)

The livestock in the Day Basin consists of buffalo, cows, and goats. Feed production for livestock comprises approximately 48% of grasses [276]. The other part has to come from feed crops or remnants of food crops. Three land cover classes in the Day Basin are found potentially suitable for grazing: mosaic crop, cropland, and mosaic vegetation crop. The cropland is, however, not natural for livestock, and mosaic crops are planted for food production, so only the land-cover class of mosaic vegetation crop is considered in the following analysis. The mosaic vegetation crop in the Day Basin comprises 2746 km^2. The plant physiological equation demonstrating actual plant growth in SWAT is showed in Equation (3):

$$\Delta Bio = \Delta Bio_{max}.\{1 - \max(w_{strs}, t_{strs}, n_{strs}, p_{strs})\} \quad \textbf{(3)}$$

where ΔBio_{max} is the potential increase in total plant biomass on a given day ($g/m^2/d$) derived from the light use efficiency of the plant (LUE) and the amount of Absorbed Photosynthetically Active Radiation (APAR) as described in Appendix A. $w_{strs}, t_{strs}, n_{strs}, p_{strs}$ describe the stress scalars that represent water, temperature, nitrogen, and phosphorous. Contrary to other crop growth models, SWAT considers only the maximum stress indicator out of these four. The water stress factor is governed by the actual and potential transpiration fluxes. The annual biomass production is a simple accumulation of ΔBio for the entire cycle and reflects the total dry matter production of fresh leaves, stems, roots, flowers, grains, tubers, and bulbs. The first distribution of the crop organs is between above-ground and below-ground accumulated biomass. This is classically expressed by means of the shoot/root ratio. Further to that, not all above-ground biomass production is taken for livestock feed. The fraction of above-ground biomass production was taken as 65 percent of the total biomass production, and 40 percent of this amount is taken as natural livestock.

Fuelwood from Natural Forest (HESS4)

Forests are important sources of fuelwood [277]. The broadleaved, deciduous, and evergreen land-cover classes are considered to be representative of natural forests. The ratio of the above and below-ground biomass production for natural landscapes has been measured for several biomes. [278] estimated the below-ground biomass to be 0.25–0.30 of the above-ground biomass, using plant growth simulation models. The fraction of above-ground biomass production usable as firewood is taken as five percent (e.g., dead wood, debris). The simulation of the increase in biomass is demonstrated in Equations (18) and (19) in the Appendix A.

The SWAT computes the net carbon assimilation for natural forests in a similar biophysical manner as was done for crops and mosaic vegetation. Woody plants are–however–characterized by secondary growth and continuous conversion of structural tissue into non-living, therefore non-respiring biomass. To simulate the smaller amount of biomass accumulation seen in seedlings/saplings, tree growth within a single year is limited to a fixed amount determined by the age of the tree relative to the number of years for the tree species to reach full development. Parameters in the plant growth database define the total number of years for trees to reach full development as well as the biomass of a fully-developed tree. Once the total growth in biomass in a year, bio reaches the annual limit; no more growth occurs until the next year when a new annual limit is calculated.

4.3.2 Water-related regulating services

Dry Season Flow (HESS5)

Base flow is highly desirable to meet the water demands from domestic and industrial requirements during the dry season, besides keeping a minimum environmental flow for fish stocks. Water percolating past the bottom of the root zone is partitioned into two fractions: a shallow and deep aquifer. Water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions by means of capillary rise or be directly removed by deep rooting plants (REVAP). Groundwater-dependent ecosystems, for instance, tap directly into these unconfined aquifers. The remaining water stored in the shallow aquifer flows to the river as a classical lateral drainage flow. Water from the deep aquifer flows out of the watershed and does not contribute to dry season river flow.
The dry season flow in Day Basin relates to the dry period between November-April (6 months). For all the major streams of Day Basin, the average dry season flow (m^3/s) is computed as:

$$Q_{bf,i} = Q_{bf,i-1}.\,exp\left(-\alpha_{gw,shi}.\,\Delta t\right) + w_{rchrg,sh,i}.\,[1 - exp\left(-\alpha_{gw,sh}.\,\Delta t\right)] \quad \textbf{(4)}$$

where $Q_{bf,i}$ is the baseflow from a shallow aquifer on day i (mm), α_{gw} is the baseflow recession constant, Δt is the time step (1 day), $w_{rchrg,sh,i}$ is the amount of recharge entering the shallow aquifer (mm).

Total Groundwater Recharge (HESS6)

Groundwater recharge describes the replenishment of aquifers. Aquifers should be considered as savings accounts for periods of water storage, and this describes the cap of groundwater withdrawals. The total recharge to the aquifer on a given day is calculated as an exponential decay weighting function based on hydrological conditions. It is neither related to land use nor the source of water. Hence the total recharge includes water from floods, irrigations, leaking rivers, and more. The delay function accommodates situations where the recharge from the soil zone to the aquifer is not instantaneous:

$$w_{rchrg,i} = \left[1 - exp\left(-\frac{1}{\delta_{gw}})\right)\right].\,w_{perc} + exp\left(-\frac{1}{\delta_{gw}}\right).\,w_{rchrg,i-1} \quad \textbf{(5)}$$

where $w_{rchrg,i}$ is the amount of recharge entering the aquifers on day i (mm/d), δ_{gw} is the delay time or drainage time of the overlying geologic formations (day), w_{perc} is the total amount of water exiting the bottom of the soil profile on day i (mm) (calculated as in Appendix A), and $w_{rchrg,i-1}$ is the amount of recharge entering the aquifers on day i − 1 (mm). Without the delay time δ_{gw}, recharge equals seepage. Percolation occurs if the drainable volume of water in the soil layer on a given day exceeds field capacity. If a given HRU has a seasonably high water table, then percolation is not allowed.

Root Zone Storage (HESS8)

The root zone depth is the depth within the soil profile that commodity crop (cc) roots can effectively extract water and nutrients for growth. The presence of roots in the soil matrix develops certain matric potentials that increase the retentive forces to hold water for a certain period. For many vegetation types, the root zone depth is constant with time, and the deeper the roots, the more water can be retained. For non-perennial vegetation, SWAT computes root development on the basis of heat units. The root depth and root density are a fraction of the total biomass production and the shoot/root ratio. In addition to that, soil moisture is also stored in the vadose zone between the lower part of the root zone and the depth of the unconfined groundwater table. Reference work [279] showed a simplified method to assess changes in soil moisture in the entire vadose zone based on the average soil moisture content in the root zone and an equilibrium soil water potential distribution below up to the phreatic level where retention is absent. In SWAT, the change in soil moisture between the end of the rainy season and the start of the next rainy season is used as an indicator for storage change:

$$\Delta S_\theta = \int \theta(z).dz(t) - \int \theta(z).dz(t+1) \quad \textbf{(6)}$$

where ΔS_θ is the storage change for the entire unsaturated soil profile, thus including the root zone and the vadose zone at t (end of rainy season) and t + 1 (end of the dry season), $\theta(z)$ is the moisture content at depth z at t (end of rainy season) and t + 1 (end of the dry season), and dz is the soil profile depth. For practical reasons, the total soil depth of 100 cm is considered for HESS8 because the underground is rocky at locations, although this could be improved with the inclusion of a root depth for each land-use land-cover class.

Sustaining Regional Rainfall (HESS9)

Usually, the evaporated water is considered to have been consumed and is no longer available for downstream water use. However, regional rainfall processes can also be triggered by local evaporation processes. Convectional rainfall occurs, for instance, when the warm air deflected from a landform rises and is full of water vapor originating from land surface evaporation. Convectional rainfall is more severe in tropical areas where climates are warmer. Reference work [280] demonstrated that the tropical forests in Africa generate their own rainfall. Hence, it seems that not all evaporated water is truly consumed, and it is very interesting to understand which part of the evaporated water contributes to sustaining regional rainfall within the same basin.

Reference work [281] showed that globally, nearly 20% of the total yearly precipitation on land originates from vegetation evaporation-regulated moisture recycling, with large spatial variability. For the Day Basin, 40% of the annual rainfall originates from upwind, continental-scale land evaporation [31]. A lower evaporation recycling ratio is expected when the evaporative surface has to be located inside the geographic boundaries of the Day Basin. An unpublished study [282], using a simple atmospheric moisture accounting scheme, showed that less than 10% of rainfall in the Day Basin is recycled from evapotranspiration.

$$\boldsymbol{P_{sus} = P - P_{adv} = \alpha ET} \tag{7}$$

where P_{sus} is the sustained rainfall due to local evaporation processes (mm/y), P_{adv} is the rainfall that originates from external sources (mm/y), α is the evaporation recycling ratio, P is precipitation rate (mm/y), and ET is the evapotranspiration rate (mm/y). A pragmatic value of α = 7.5% has been applied for this Day Basin study.

Peak Flow Attenuation (HESS10)

The purpose of HESS 10 is to show to which extent the presence of vegetation reduces peak flow. A more comprehensive modeling should also include the presence of (wet) land located nether rivers that can be used for inundation. Consumptive use of vegetation has several by-products, and peak flow attenuation due to decreased surface runoff is one of them. SWAT automatically generates main categories of reaches on the basis of the Digital Elevation Model. Stream flow in every reach of the catchment was computed first on the basis of 100% bare soil conditions. A monthly flood with a return period of 1 out of 10 years was used as a baseline in every HRU above which flood hazard prevails. For practical reasons, longer periods of consideration were not feasible due to the absence of high-quality remote sensing data. Monthly flows between June and October were considered for every reach of a major stream.

During a second SWAT model run, actual land use and LAI status were used instead of bare soil. Due to a different Curve Number value and antecedent soil moisture, the retention will increase, and surface runoff Q_{surf} will decrease. A reduction of Q_{surf} will undoubtedly lower the number of events with flow exceeding the threshold value. The calculation of the retention parameter is provided in Appendix A. The peak flow attenuation (%) was calculated as the relative difference of the number of peak flows; the results confirm that the number of peak flow events decreases due to the presence of vegetation.

Carbon Sequestration (HESS11)

Net carbon assimilation is responsible for the growth of plant organs. The different organs have various life cycles. Crop residues and litter are generally conceived as short-term carbon storage; carbon from these organs is often released again into the atmosphere during the same year. Soil organic carbon and harvested stems have a significantly longer time scale. The sequestration of carbon for HESS11 relates to wood from trees and soil organic carbon.

Carbon sequestration 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 consists entirely of carbon hydrates. Because of other substances present, it is more convenient to use a factor of 0.45. IPCC 2006 Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry, and Other Land Use [142] also suggested a range between 0.43 and 0.55.

Further to C/biomass ratios, the shoot/root ratio is a critical element in describing organ distributions. Trischler et al. (2014) [100] found that for most tree species in Sweden above-ground biomass is 65% of the total biomass production value, being equivalent to a shoot/root ratio of 1.85. Cereal crops have typical shoot/root ratios of 2.0 (barley), 4.0 (rice), to 5.0 (wheat). Root crops have much lower shoot/root ratios (0.25 to 0.5) because the harvestable product is essentially formed below ground. Carbon sequestration is not computed in SWAT but can be approximated using the partitioning factors. For trees and shrubs, the above-ground carbon stored per year can be approximated is:

$$C_{ag} = \frac{0.45.S_r}{(S_r + 1)} \sum Bio \qquad \textbf{(8)}$$

where *Sr* is the shoot/root ratio being 1.85 for trees, $\sum Bio$ is the increase in biomass. The above-ground C-sequestration is $0.29 \sum Bio$.

The below-ground biomass is partitioned into root mortality and exudation, as well as soil organic matter from litter, dead wood, root mortality, and exudation. The humification coefficient for converting dry matter into soil organic matter is typically 0.35 [283]. If we, for simplicity, assume 35% of below-ground biomass to be sequestered, then it can be approximated mathematically as:

$$C_{bg} = 0.35x0.45x \left\{1 - \frac{S_r}{(S_r + 1)}\right\} \sum Bio \qquad \textbf{(9)}$$

Note that above-ground crop residues can also be considered as an input for soil organic carbon, but then this material must be plowed or disked in. Rice is a key crop in Day Basin, and a shoot/root ratio of 4.0 is taken, see [284]. The annual carbon storage for rice then becomes $0.02\sum Bio$. Hence, the sequestrated carbon is 2% and 34% of the total crop biomass production for crops and woody vegetation (shrubs and trees), respectively.

Microclimate Cooling (HESS13)

Photosynthesis creates evaporative cooling over green and biologically active vegetation. The transpiration process requires a considerable amount of energy (1 mm/d is equivalent to approximately 2.5 MJ/d). This energy is not available for sensible heat flux H, so H over an evaporative surface is usually small. Reference work [115] reviewed H flux measurements over water-evaporating surfaces and concluded that H is negligibly small. Climatic cooling at the local scale not only reduces the vegetation water requirements but also suppresses the land surface and air temperature in, for instance, urban heat islands [285]. The change in sensible heat flux can be converted into a change in air temperature. H is not computed explicitly in SWAT but was determined afterward by subtracting net radiation Rn and latent heat flux LE (W/m^2) (as described in Appendix A).

The conceptual model of HESS13 is that it lowers the difference in temperature (ΔT) as compared to ΔT under conditions of bare soil (with lower ET fluxes). Presumably, the change in the surface roughness's effect on heat transfer is negligible, and R_n stays constant in the two cases; the microclimate cooling (degree Celsius) was calculated as:

$$\Delta T_{cooling} = \Delta T_{soil} - \Delta T_{veg} = \frac{r_{ah}}{\rho_a . C_p}\left(H_{soil} - H_{veg}\right) = \frac{r_{ah}}{\rho_a . C_p}(LE_{veg} - LE_{soil}) \quad \textbf{(10)}$$

With ΔT_{soil} being the difference in temperature with bare soil as a reference land cover, ΔT_{veg} being the difference in temperature with vegetation cover (current land cover), H and LE is sensible and latent heat flux (W/m^2), ρ_a being the density of moist air, C_p is the specific heat at constant pressure for air (1004 J/kg·K), and r_{ah} is aerodynamic resistance to heat transfer that was fixed at 70 s/m following Senay et al. (2013) [240].

4.3.3 Water-related habitat/supporting services

While SWAT has pesticide fate components, cycles for nutrients and bacteria, and route metals through reaches [56], all these functions require proper parameter estimations that could not be accomplished. For this sake, soil formation, erosion, and nutrient simulations are excluded from the analysis in the Day River, and the emphasis will be more on environmental flow requirements.

Meeting Environmental Flow Requirements (HESS16)

The vitality and biodiversity of riverine and wetland ecosystems require a certain flow regime such as (i) magnitude, (ii) frequency, (iii) timing, (iv) duration, and (v) the rate of change of inter and intra-annual events. According to the Brisbane Declaration of 2018, these aquatic ecosystems include rivers, streams, springs, riparian, floodplain, and other wetlands, lakes, coastal waterbodies, including lagoons and estuaries, and groundwater-dependent ecosystems. This flow regime results in a certain minimum low flow and consumes water through the ET from open water bodies and wetland vegetation [286].

Reference work [166] assessed the mean environmental flow requirements for 128 major basins and drainage regions worldwide using measured and simulated hydrographs. Five different environmental classes were considered. While his work has a good solid basis, in the end, they came up with very generic guidelines. A fraction of 0.28 of the mean annual flow is suggested as the environmental flow for the Mekong Basin region. For the Red River Basin, Smakhtin and Eriyagama (2008) [287] suggests a fraction of 0.29. While we recognize that water demands associated with the maintenance of the health of riverine ecosystems in the Day River can be improved, we just use the 0.29 fraction as suggested. HESS16 is defined as the degree of satisfaction to meet the environmental flow requirement ($Eflow_{sat}$) on a yearly basis:

$$\boldsymbol{Eflow_{sat} = 100\% \quad if \; \frac{Q_{lowflow}}{Q_{yr-longterm}} \geq 0.29} \tag{11}$$

$$\boldsymbol{Eflow_{sat} = \frac{Q_{lowflow}}{0.29Q_{yr-longterm}}.100\% \quad if \; \frac{Q_{lowflow}}{Q_{yr-longterm}} < 0.29} \tag{12}$$

$Q_{lowflow}$ is the total flow during six dry months (November–April). $Q_{yr\text{-}longterm}$ is the average annual flow.

4.4 Spatial mapping of HESS for Day Basin

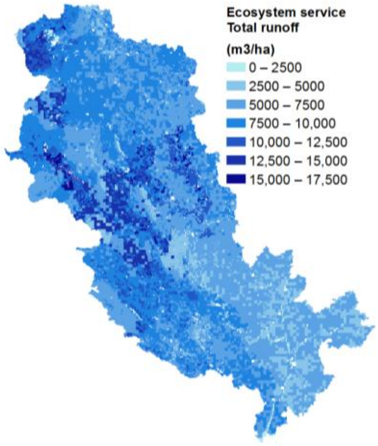
The HESS values of the Day River were simulated for the period 2000 to 2013 using three years of initialization (2000–2002) as a warming-up period. The period 2000–2013 was chosen as the study period under the CGIAR WLE's funded project *"Inclusive development paths for healthy Red River landscapes based on ecosystem services."* Although the time step of the model is daily, most outputs are presented as an annual result or longer time scale. The spatial discretization is by HRU.

4.4.1 Water-related provisioning services

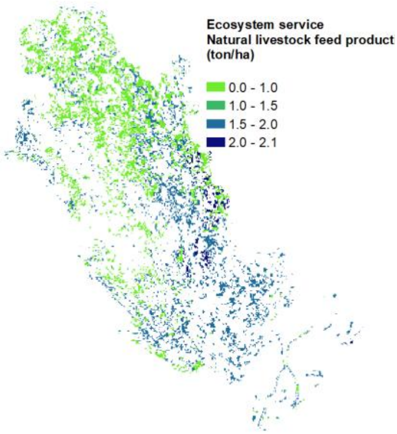
Figure 22a shows the spatial distribution of HESS1 on generated total runoff in the basin. The areas with high capacities for total runoff are in the mountainous and highly dense forest cover on sloping terrain (15,000 m^3/ha and more). The urban area of the basin shows a higher total runoff due to poor infiltration and overall large CN numbers. The Day Basin averaged total runoff is 7482 m^3/ha/y.

Figure 22b shows the mean annual distribution of HESS3 on natural livestock feed production (ton/ha/y) in the Day Basin during the study period. The results relate to mosaic crop areas only because other land use classes do not provide natural feed for livestock. The western part of the basin experiences areas without feed production. The Day Basin average feed production for livestock (including land surfaces with zero values) is 0.3 tons/ha/y.

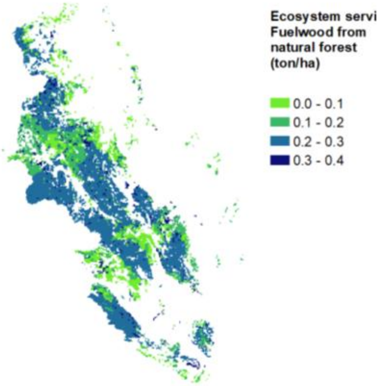
The HESS4 on fuelwood production (ton/ha/y) taken from the natural forest of the Day Basin is presented in Figure 22c. Since this service originated only from natural forest land cover, the results reflect the dry matter production of forests. The areas in the mountainous part of the basin in the west experienced a higher production (0.3–0.4 ton/ha) as compared with other areas. The average value for the Day Basin (including land surfaces with zero values) is 0.013 tons/ha/y.



(a)



(b)



(c)

Figure 22. Provisioning service for Day Basin during 2003–2013 for (a) HESS1: Total runoff (m3/ha/y); (b) HESS3: Natural livestock feed production (ton/ha/y); (c) HESS4: Fuelwood from the forest (ton/ha/y).

4.4.2 Water-related regulating services

HESS5 on dry season flow (m^3/s) in Figure 23a is a very important natural ecosystem service that provides a source of water for local communities during the long dry season, apart from being key to meeting the water demands of fluvial ecosystems. The discharge is low at the origin of streams (0–10 m^3/s), and this swells to more than 100 m^3/s in the tail end of the basin. This flow is averaged for the six dry months running from November to April. Communities at the downstream end thus have more access to dry season water resources. The average flow for these major tributaries is 113 m^3/s, while the basin average, including upstream and downstream areas, is 12 m^3/s.

HESS6 on total groundwater recharge (m^3/ha/y) displayed in Figure 23b shows higher HESS contributions in the forests of the northwest of the Day Basin (6000–7200 m^3/ha/y). This is mainly related to the higher rainfall regimes that are common for forested mountains. The forests have a positive impact on enhanced infiltration and reduced surface runoff (unless grown on sloping terrain). This total recharge presents vast quantities of groundwater that will be exploited for both natural and anthropogenic usages. The average total groundwater recharge is 3820 m^3/ha/y.

The root zone storage (i.e., HESS8) is shown in Figure 23c. HRUs that contain open water bodies are excluded from the analysis to comply with root systems only. The results show a nice complementary relationship between HESS6 and HESS8; Areas with high HESS8 in the delta will have a low HESS6 and vice versa. Clearly, every agroecosystem in a complex river basin has its own share of the overall HESS performance. The average root zone storage for Day Basin is 1493 m^3/ha/y.

The delta contributes more to sustaining rainfall, i.e., HESS9 (Figure 23d), provided that the wind direction is inland in the direction of the hills. Moist air advection into the air mass over the Gulf of Tonkin will not sustain rainfall in the Day Basin. A similar conclusion was drawn by Tuinenburg et al. (2014) [288], who demonstrated that most of the rainfall in the Himalayas originates from irrigated wheat-rice crop rotations on the Indo-Gangetic plain. The average sustainable rainfall is 701 m^3/ha/y. Rice fields are thus obviously efficient contributors for generating rainfall in the upstream mountains that enhance recharge and dry season flow. It is an important finding that the consumptive use of rice is providing HESS in addition to provisioning food.

The attenuation of peak flow (i.e., HESS10) mainly follows the partitioning between infiltration and runoff by means of overland flow (Figure 23f). First, the SWAT model was executed with bare soil conditions to define the hydrograph statistics under reference conditions with an emphasis on daily peak flows. The reduction of these peak flow events was determined after running SWAT again with current land use practices. It is witnessed that natural landscapes such as forests and wetlands provide a wealth of regulating ecosystem services in detaining excess rainfall and, therefore, delaying peak flows. The average reduction of peak flow varies between 5 to 10%. An upstream-to-downstream accumulation is visible in Figure 23e; the lower part of the Day Basin is getting less susceptible to peak flows (15 to 20% reduction of natural peak flows). The role of forests in reducing peak flow has also been marked by others [289]. The average peak flow attenuation due to the current land use is 5.1%.

Atmospheric carbon sequestration in the Day Basin (HESS11) was quantified to vary between 0.01 to 2.4 tons/ha/y (Figure 23f). Natural forest in the western part of the basin sequesters up to 2.4 tons/ha/y. Urban areas and settlements have a much lower sequestration process of approximately 0.01 to 0.1 ton ha/y. The Day Basin has an average atmospheric carbon sequestration of 0.22 tons/ha/y.

The role of a vegetation pack on reduced air temperatures (i.e., HESS13) is shown in Figure 23g. All values are positive, which implies that every landscape element creates a microclimate that can potentially offset temperature rises from global warming. The maximum cooling is 4.5 to 5 degrees Celsius, and this occurs in dense forests. The basin’s average microclimate cooling is 2.7 degrees.

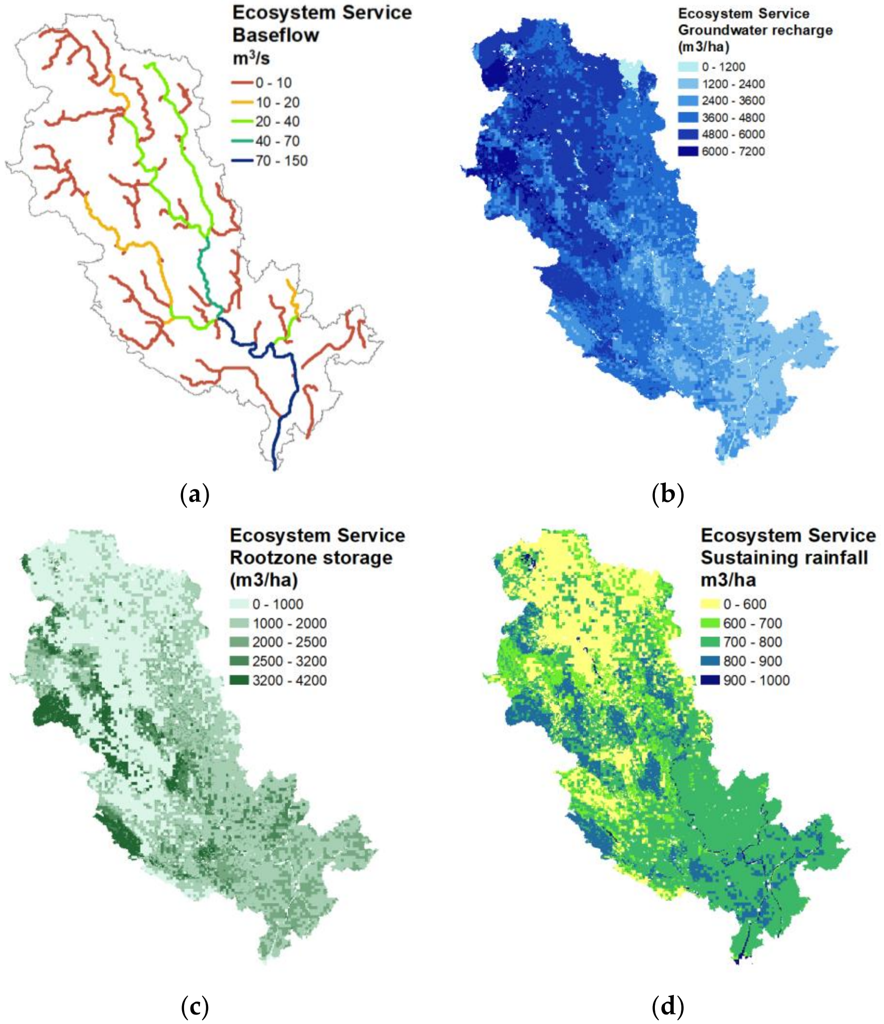
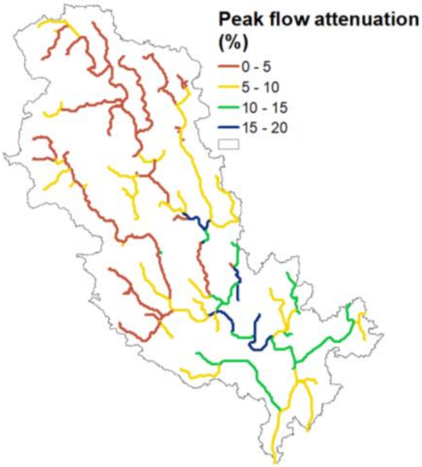
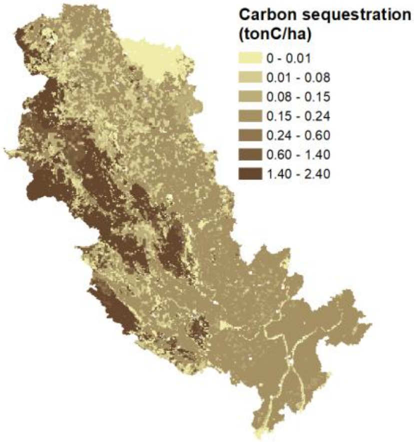


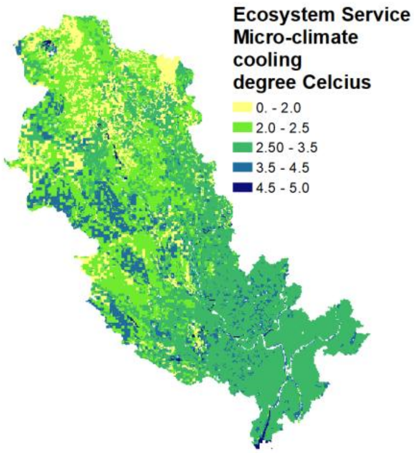
Figure 23. Regulating services for Day Basin with average value during 2003–2013 for (a) HESS5: Dry season flow or baseflow (m^3/ha); (b) HESS6: Groundwater recharge (m^3/ha); (c) HESS8: Root zone storage (m^3/ha); (d) HESS9: Sustaining rainfall (m^3/ha)



(e)



(f)



(g)

Figure 23. (*cont.)* Regulating services for Day Basin with average value during 2003–2013 for (e) HESS10: Peak flow attenuation (%); (f) HESS11: Carbon sequestration (ton C/ha); (g) HESS13: Microclimate cooling (degree Celsius).

4.4.3 Water-related habitat/supporting services

The satisfaction of meeting environmental flow, i.e., HESS16 for a dry (2011) and wet year (2013), is illustrated in Figure 24. For every reach, the longer-term river flow was computed from SWAT, and the environmental flow was defined as 29% of the annual volume. The dry season flow in the six-month dry period in each year was compared against the environmental flow (e-flow), indicating whether it satisfied the threshold amount ($Eflow_{sat} = 1$) or not ($Eflow_{sat} < 1$). There is a clear-cut effect of wet and dry years on meeting the environmental flow (e-flow) requirement. While in the dry 2011, e-flow ranged from 20–80% in most upstream river stretches, this increased to nearly 80–100% in the wet year of 2013. In general terms, the lower delta in the Southeast better meets the environmental flows because the hydrograph responds to a larger catchment area where most variations in discharge are averaged out. The environmental flow satisfaction is 82% and 95% in a dry and wet rainfall year, respectively.

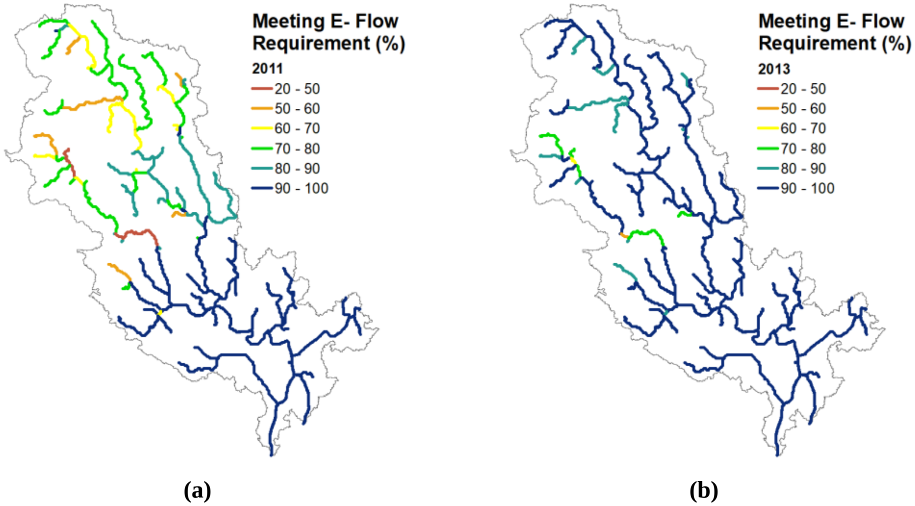


Figure 24. Habitat services for Day Basin during 2003–2013 for meeting environmental flow for (a) dry year (2011) and (b) wet year (2013).

While Figure 24 shows the spatial variabilities of the HRUs, Figure 25 describes the temporal variation of ecosystem services in the Day Basin during the period between 2003 and 2013. The standardized boxplots show the trade-offs between the HESS indicators and years. Total runoff (HESS1) and groundwater recharge (HESS6) show a tighter coupling to rainfall than biomass-related services such as feed production, fuelwood, and carbon sequestration. Adding a simple trend line through the average values and the quartiles will show the following insight: For HESS 1, 3, 4, and 6, the average values increase. For HESS 8 and 13, the average value decreases while the rest of the HESS, i.e., 5 and 11, show a more constant trend. Overall, the quartile values have more variation with time than the average values do. Hence, these mild extreme values are more vulnerable to external factors, such as rainfall and inflow from upstream rivers, than the average values.

For benchmarking between river basins mutually, and also for studying the impact of land use and water use planning scenarios on HESS, it is good to synthesize the major findings. Similar results were found with the Day sub-basin in the Red River by [45]. They investigated the impact of deforestation by thinning existing forests and projected climate change (by 2050, an increase of 1.5 °C and 6% rainfall). It was observed that the removal of forests increased sediment yield from the basin substantially and increased peak flows and corresponding flood hazards. In their study, seven out of 11 HESS values increased with climate change.

Focusing on a single HESS value thus provides an incomplete picture. Against this background, a synthesis table for the Day Basin was created (see Table 7).

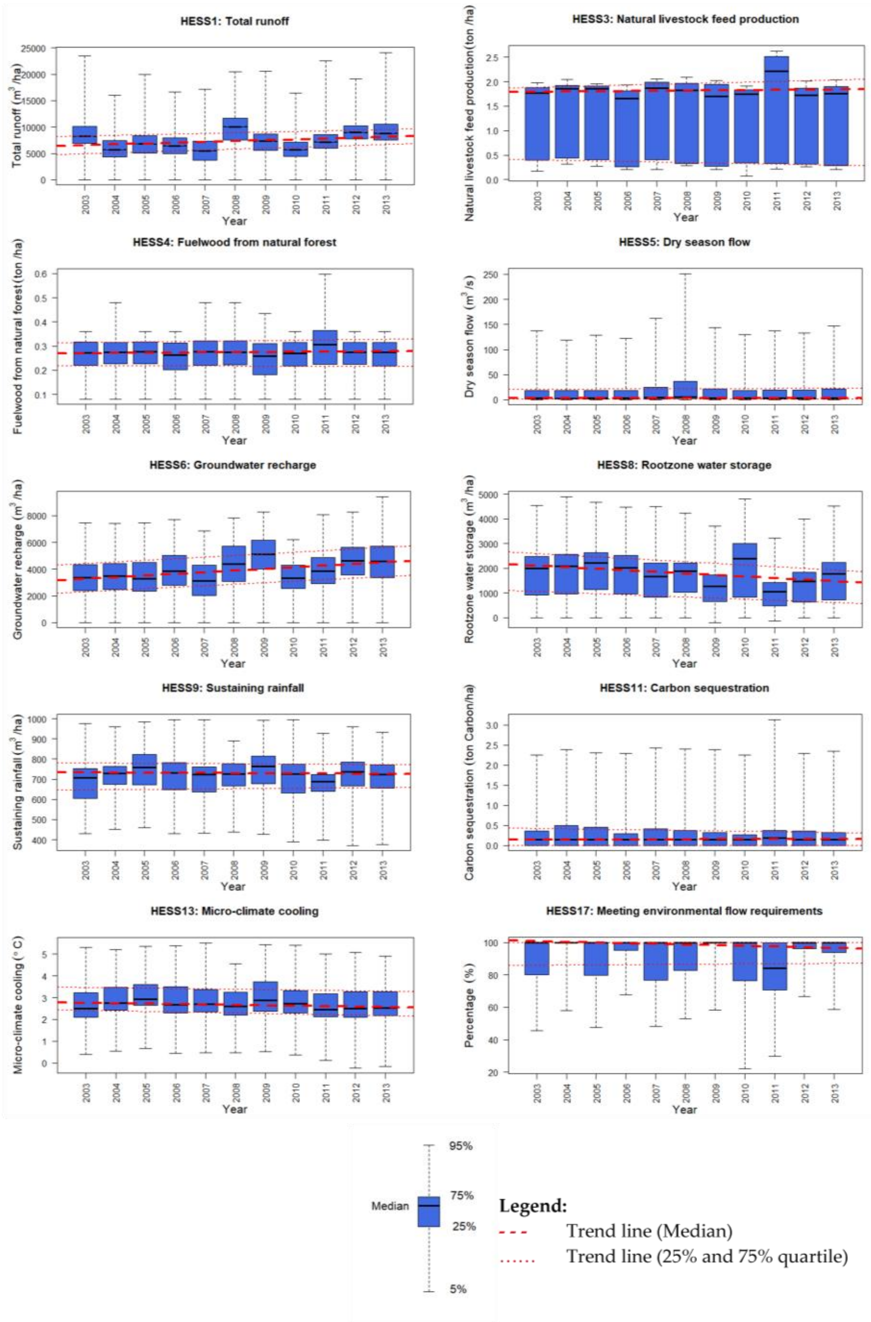


Figure 25. Boxplot values of ecosystem services for Day Basin from 2003–2013 and yearly average with median, quantile (5%, 95%), and quartile (25% and 75%). The dashed and dotted red lines show a trend line through the median, 25%, and 75% quartile, respectively.

Table 7. Synthesis table based on SWAT outputs as yearly average, gross value, and per capita.

Ecosystem Services	Average		Gross Value		Per Capita	
	Unit	Value	Unit *	Value	Unit	Value
HESS 1: Total runoff	m^3/ha	7482	MCM	4706	m^3/cap	392
HESS 3: Natural livestock feed production	ton/ha	0.3	MTonnes	0.2	ton/cap	0.01
HESS 4: Fuelwood from natural forest	ton/ha	0.013	MTonnes	0.008	ton/cap	0.001
HESS 5: Dry season flow ("baseflow")	m^3/s	12	MCM	372	m^3/cap	31
HESS 6: Groundwater recharge	m^3/ha	3820	MCM	2403	m^3/cap	200
HESS 8: Rootzone water storage	m^3/ha	1493	MCM	939	m^3/cap	78
HESS 9: Sustaining rainfall	m^3/ha	701	MCM	441	m^3/cap	37
HESS 10: Peak flow attenuation	%	5.1	-	-	-	-
HESS 11: Carbon sequestration	ton/ha	0.22	MTonnes	0.14	ton/cap	0.01
HESS 13: Micro-climate cooling	°C	2.7	-	-	-	-
HESS 16: Meeting environmental flow requirements	%	92	-	-	-	-

* MCM: million cubic meter; MTonnes: million tonnes

Table 7 shows a synthesis of HESS values in terms of average, gross value, and per capita. The population of the Day River Basin in 2015 was 12 million. The average generated total runoff in the basin is 7482 m^3/ha, which contributes to a total gross value of 0.38 million m^3 (MCM) per year and a net per capita of 392 m^3. Other flow-related services, such as groundwater recharge, rootzone storage, and sustaining rainfall, achieved average values of 3820, 1493, and 701 m^3/ha, respectively. Gross groundwater recharge was 2403 MCM while per capita reached 200 m^3/cap. The average HESS8 on rootzone water storage and HESS9 sustaining rainfall was 1493 and 701 m^3/ha translating to a per capita of 78 and 37 m^3, respectively. Interestingly, microclimate cooling (HESS 13) indicated that the ecosystem of the Day Basin reduces the air temperature by 2.7 degrees Celsius (as compared to bare soil land cover). HESS 17 reached 92% during the period from 2003–2013, indicating that only during certain periods the requirement for environmental flow was not satisfied. Biomass-related HESS such as HESS 3 and 4 averaged at 0.3 and 0.013 ton/ha leading to gross values of 0.2 and 0.008 and per capita of 0.01 and 0.001 ton/ha, respectively. The sequestered carbon (HESS11) was 0.01 ton/cap/y.

Table 8 further describes the trend line established in Figure 25 for each HESS. The gradient and intercept of the trend line were derived, which display the observed trend of HESS. This information is crucial in indicating whether a HESS is maintained at a healthy state (upward trend) or degrading (downward trend). Based on this analysis, basin planners and water managers can justify their plans and policies in order to sustain or restore the functions of degrading HESS.

Table 8. Statistical performance of HESS trendline (gradient/slope) and implications into river basin plans.

Ecosystem Services	Gradient/slope of HESS Trend	Interpretation of Trend and Impacts on HESS	Implication into River Basin Plans and Management
HESS1: Total runoff	159	Increasing	Sustain basin management practices, implementation of IWRM
HESS3: Natural livestock feed production	0.0044	Increasing	Sustain basin management practices
HESS4: Fuelwood from natural forest	0.0008	Increasing	Sustain basin management practices
HESS5: Dry season flow ("baseflow")	0.0215	Increasing	Improve application of IWRM and land-water management or Natural-based Solutions (NbS) practice
HESS6: Groundwater recharge	122.3	Increasing	Apply Managed Aquifer Recharge (MAR) to better improve groundwater management
HESS8: Rootzone water storage	−61.7	Decreasing	Improve basin management to facilitate soil-water interaction. Improve basin permeability through green building and permeable landscapes.
HESS9: Sustaining rainfall	−0.68	Decreasing	Improve basin management, IWRM, and NbS to improve basin-scale soil moisture circulation
HESS11: Carbon sequestration	0.0013	Increasing	Sustain current basin management practices, apply carbon credit system
HESS13: Micro-climate cooling	−0.0191	Decreasing	Apply NbS, green building to reduce urban heat island effect. Improve IWRM and land-use planning
HESS17: Meeting environmental flow requirements	−0.4249	Decreasing	Introduce IWRM in the basin, revise water plans, including sharing and allocation to prioritize e-flow contribution

4.5 Discussions

HESS have received public attention for a considerable time. The definition and quantification of HESS are rather complex and touch base with the core of multi-disciplinary environmental sciences. The assessment of important ecosystem processes with a minimum of anthropogenic influences requires complex algorithms. There are many good examples available using eco-hydrological models and remote sensing techniques [290,291]. Often these studies are, however, restricted to solving a few elements only, and they are applied in a local context where supporting input data are available. Ha et al. (2023) [256] established a HESS framework presenting 18 HESS that can be measured to support river basin plans and environmental monitoring, categorized into Provisioning services (four HESS such as total runoff, inland capture fishery, natural livestock feed production, fuelwood from natural forest), Regulating services (eleven HESS such as dry season flow, total groundwater recharge, surface water storage, root zone water storage, sustaining rainfall, peak flow attenuation, carbon sequestration, reduce greenhouse gas emissions, micro-climate cooling, natural reduction of eutrophication in water, natural reduction of (agro-) chemical in water, reduction of soil erosion), Supporting services (one HESS on meeting environmental flow requirements), Cultural services (one HESS on leisure). This study touches base with 11 HESS indicators, which provides a more comprehensive picture than many other studies. Selected HESS, i.e., HESS1, HESS3, HESS4, HESS5, HESS6, HESS8, HESS9, HESS10, HESS11, HESS13, and HESS16 are deemed relevant to represent a broad spectrum of benefits to people in the Day Basin. It ranges from direct and primary benefits (e.g., food production, provision of runoff, fuelwood, etc.) to a larger biophysical context such as micro-climate regulation, rootzone moisture, meeting e-flow requirement, etc.). These assessments provide a synthesized snapshot of marginal benefits to ecosystems and humans resulting from basin management activities. The consideration of these eleven HESS in the Day Basin paves the way for human-centered and multi-criteria objectives for development and conservation.

The distribution and valuation of HESS highlight hydrological ecosystem services that benefit the basin and its population. While showing the Day Basin’s abundant generation of the HESS in the total runoff, carbon sequestration, groundwater recharge, and rootzone water storage as compared to other global study sites [54,58,60], the high population significantly reduces per capita performance. Moreover, several HESS indicate a downward trend, e.g., rootzone water storage, microclimate cooling, and meeting e-flow requirements suggesting a thorough assessment and introduction of more sustainable approaches in land-use planning and basin management practices, such as Integrated

Water Resources Management (IWRM) or Natural-based Solutions (NbS) to enhance HESS values in the basin.

Potentially more HESS indicators could be included in the list, such as soil erosion, natural reduction of eutrophication and agrochemical in water, water storage in lakes, etc. The SWAT model has the capacity to include these extra HESS indicators as the model design is intrinsically meant to deal with describing the total environment of agroecosystems. Hence, the results presented in this study are not exhaustive but should be regarded as a first step further in a direction with gradually more understanding and tools available to quantify HESS in a more routine manner.

Water productivity is a concept introduced to pinpoint the benefits and services of water consumption [170,292]. Various studies computed the biophysical and economic water productivities, e.g., [293], and others also included the job opportunities for water availability and water consumption. This study shows that the concept of water productivity should be amended with a HESS component. Water consumption is not only good for food security, but it also generates rainfall, cools the atmosphere, sequesters carbon, and reduces soil erosion, to mention a few. Productive use of water resources should recognize these ecological services.

Regarding e-flow, while the fractions proposed by Smakhtin and Eriyagama (2008) [287] are generic and can be applied to catchments of any size and in any physiographic conditions, it undermines the importance of emulating the natural flow regime with its seasonal variability, flow magnitude, frequency, event duration, and rise and fall of the hydrograph.

The lack of standardized processing and inclusion of HESS processes in river basin profiles prevents policymakers from realizing the value of water for provisioning and regulating services.

The methodology demonstrated by this study proves that eco-hydrological models are proper tools to quantify complex hydrological ecosystem services. Future works can focus on the fusion of eco-hydrological models and remote sensing to provide a seamless zoom of HESS's spatial and temporal variation as well as stimulating policy impacts on nature and humans.

4.6 Conclusions

The principles of Integrated Water Resources Management (IWRM), conservation of natural capital, and water accounting require Hydrological Eco-System Services (HESS)

to be determined. In this study, a number of HESS indicators were modeled for the Day River Basin in Vietnam using remote sensing and the SWAT model based on the definition of the framework initiated by CGIAR and IWMI's Water Land and Ecosystem Program. The spatial and temporal distribution of 11 HESS indicators quantified across the basin highlighted the provisioning and regulating character of our living environment in Southeast Asia. Geographical hotspots with lower and higher contribution could be identified, being a logical result of combinations of hydrological processes, climate, soil type, and the current land use.
These types of HESS assessments can be used by water resources planners in exploring multiple management scenarios and their implications for ecosystem services or "dis-services." Think about reforestation, irrigation development, land consolidation, and urban growth: a scenario analysis requires an eco-hydrological simulation model; this cannot be done by means of earth observations. Models such as SWAT host a wide suite of simulation options and can provide the data at a daily time step. The latter is required to cover dynamic processes, such as peak flow attenuation and flood hazard. This feature was also highlighted by demonstrating the capabilities in HESS quantification by combining the use of SWAT and SWAT-CUP to model complex terrestrial eco-hydrological processes. Various biophysical processes were modeled in a spatial-temporal context to reveal interactions between ecosystems and benefits to humans.

A crucial step in achieving progress in eco-hydrological modeling is the inclusion of advanced earth observation data. With the arrival of many new algorithms, there are new technical opportunities to spatially calibrate specific eco-hydrologic processes. More future research on the integration of remote sensing data and eco-hydrological models should therefore be encouraged.

4.7 Appendix

Appendix A: Calculation of Intermediate Parameters for HESS Quantification

Horizontal Fast Overland Flow

Fast surface runoff in SWAT is calculated per unit of land using the common SCS curve number procedure [275]:

$$Q_{surf} = \frac{(P - I_a)^2}{(P - I_a + S)} \quad \textbf{(13)}$$

where Q_{surf} is the surface runoff (mm/d) calculated on daily timestep, and P is the precipitation from rainfall and snowfall (mm/d). In the case of the Day Basin, precipitation is contributed by rainfall. I_a is the initial abstraction which includes surface storage and interception (mm/d), and S is an empirical retention parameter that reflects infiltration capacity and soil moisture deficit (mm/d). The retention parameter *S* varies spatially and depends on soil type, land use, the slope of the terrain, and soil moisture deficit.

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad \textbf{(14)}$$

where CN is the Curve Number for the day (mm/d). Note that soil moisture content and S have to be dynamic [294]. SWAT defines three antecedent moisture conditions: dry (wilting point), average, and wet (field capacity), and will adjust *S* accordingly. This is an example of semi-dynamic water retention. The surface runoff computed in the context of HESS relates to rainfall and snowfall only.

Percolation

The equation used to calculate the amount of water that percolates to the layer underneath—without bypass in cracked soils—is:

$$w_{perc} = SW_{excess}\left\{1 - exp^{\left(-\frac{\Delta t}{TT_{perc}}\right)}\right\} \quad \textbf{(15)}$$

where w_{perc} being the amount of water percolating to the underlying soil layer (mm H_20), SW_{excess} is the drainable volume of water in the soil layer on a given day (mm), Δt is the length of the time step (d), and TT_{perc} is the travel time for percolation (d). The travel time can be computed as the ratio of the layer of water that percolates from the root zone and the value of the saturated hydraulic conductivity K_{sat}.

Lateral Groundwater Movement

The lateral groundwater flow Q_{lat} will be significant in areas with soils having high hydraulic conductivities in surface layers and an impermeable or semipermeable layer at a shallow depth. In such a system, rainfall will percolate vertically until it encounters the impermeable layer. The water then ponds above the impermeable layer, forming a saturated zone of water, i.e., a perched water table. This saturated zone is the source of water for lateral subsurface flow. The mathematical expression for Q_{lat} is based on Neitsch et al. [56]:

$$Q_{lat} = 0.024.\left(\frac{2.SW_{ly,excess}.K_{sat}.slp}{\varphi_d.L_{hill}}\right) \quad \textbf{(16)}$$

where: $SW_{ly,excess}$ is the drainable volume of water stored in the saturated zone of the hillslope per unit area (mm/d), L_{hill} is the hillslope length (m), φ_d is the drainable porosity of the soil layer (mm/mm), K_{sat} is the saturated hydraulic conductivity (mm/h), and *slp* is the increase in elevation per unit distance. SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed, and a deep, confined aquifer which contributes return flow to streams outside the watershed [33]. The outflow from the unconfined aquifer to the stream Q_{bf} is approximated as being a stationary drainage flow formulated according to the Hooghoudt drainage equation provided that the shallow aquifer exceeds a threshold value [295]:

$$Q_{gw} = \frac{8000\, K_{sat}}{L_{gw}^2}\, h_{wtbl} \qquad (17)$$

where Q_{gw} is the groundwater flow into the stream or river on day i (mm/d), K_{sat} is the hydraulic conductivity of the aquifer (mm/d), h_{wtbl} is the height of the water table (m), and L_{gw} is the distance between the HRU to the main channel (m).

Maximum Increase in Biomass

The maximum increase in biomass (ΔBio_max) on a given day that will result from the intercepted photosynthetically active radiation is estimated by [294] as:

$$\Delta Bio\_max = LUE.APAR \qquad (18)$$

where ΔBio_max is the potential increase in total plant biomass on a given day (g/m^2/d), LUE is the Light-use efficiency of the plant (g/MJ), and APAR is the amount of Absorbed Photosynthetically Active Radiation on a given day (MJ m^{-2}). It is also known as net carbon assimilation because corrections for respiration have been applied already. The photosynthetic rate of a canopy is a linear function of radiant energy. *APAR* can be calculated using Beer's formula:

$$APAR = 0.5.K\downarrow.[1 - exp(-k_l.LAI)] \qquad (19)$$

where $K\downarrow$ the global radiation incident to the land surface (MJ m^{-2}), k_l is the light extinction coefficient, and *LAI* is the leaf area index. The *LAI* development is strongly coupled to prevailing heat units and a number of plant species-dependent *LAI* values. *LAI* from the SWAT model was calibrated against *LAI* derived from MODIS 15 to derive plant physiology and plant growth as described in [55].

Heat Fluxes

Sensible heat flux (*H*) is calculated using the following formula:

$$H = Rn - LE \qquad (\mathrm{W/m^2}) \qquad (20)$$

Latent heat flux (*LE*) is related to actual *ET* as follows:

$$LE = \rho_w L\, ET \qquad (\mathrm{W/m2}) \qquad (21)$$

with ρ_w being the density of water (kg/m^3), L is the latent heat of vaporization (J/kg), and *ET* is the water vapor flux expressed in m/s. The net radiation in SWAT is computed according to the suggestions of Doorenbos and Pruitt (1977) [296] and Allen et al. (1998) [247]:

$$\boldsymbol{R_n} = (\mathbf{1} - \boldsymbol{\alpha})\boldsymbol{K}_{\downarrow} - [\mathbf{0.9}(\mathbf{1} - \boldsymbol{cc}) + \mathbf{0.1}][\mathbf{0.34} - \mathbf{0.139}\sqrt{\boldsymbol{e}}]\boldsymbol{\sigma}\boldsymbol{T}^{\mathbf{4}} \ \left(\frac{\boldsymbol{W}}{\boldsymbol{m}^{\mathbf{2}}}\right) \qquad \textbf{(22)}$$

where α is the surface albedo, *cc* is cloud cover, e is the actual vapor pressure (mbar), σ is the Stefan Boltzmann constant ($W/m^2/K^4$), and T is the air temperature (K).

5 Mapping Hydrological Ecosystem Services (HESS) in major Vietnamese river basins using remote sensing and hydrological modelling to promote Nature-based Solutions and sustainable water management [4]

Monitoring and assessing Hydrological EcoSystem Services (HESS) requires a more crucial role in water resources management and in mitigating hydrological extreme events. With the growing emphasis on Nature-based Solutions (NbS) and ecosystem-based adaptation, HESS should be recognized more often in water allocation plans. This study presents the quantification results of HESS for 16 major river basins in Vietnam, many of which are important transboundary rivers. These rivers provide food and water, regulate (micro) climatic conditions, and maintain soil and water stocks. The methodology demonstrated in this paper relies on the integration of various 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. The paper presents results for four different annual periods: 2005 (wet year), 2010 (average year), 2019 (dry year) and 2022. The results exhibit a diverse distribution of HESS across basins. For instance, some basins show relatively high values for total runoff (i.e., Mekong basin), or dry season flow (i.e., Gianh basin). In terms of micro-climate cooling and fuelwood provision, Kon-Ha Thanh and Tra Khuc demonstrates a significant contribution. This study illustrates how remote sensing data and their spatial algorithms can be used to determine various aspects of HESS across different landscapes and ecosystems. A synthesized score was introduced to benchmark sustainability level of these basins throughout the period. 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.

Keywords: hydrological ecosystem services, eco-hydrological modelling, remote sensing, river basins, Vietnam.

[4] Chapter is based on: Ha, L.T., Bastiaanssen, W.G.M., Das, N., Hessels, T., 2024. Mapping of Hydrological Ecosystem Services (HESS) of all major river basins in Vietnam using remote sensing and hydrological modelling to promote Nature-based Solutions and sustainable water management. *Submitted*.

5.1 Introduction

To address ongoing challenges posed by climate change and degrading ecosystems [133,297], water resource planners and environmental advocates are increasingly endorsing ecosystem-based strategies like Nature-based Solutions (NbS) and green infrastructure [1,298,299]. These strategies offer multiple benefits for both nature and humans. For example, restoring wetlands can enhance resilience to floods and droughts, improve water quality through the removal of organic and non-organic pollutants [2], and positively improve human well-being [1,13]. Reforestation in upstream catchments can reduce surface runoff and soil erosion [300], enhance groundwater recharge, regulate micro-climate and sequester carbon [6]. Additionally, restored natural forests can provide livelihoods for communities through the provision of wood and other recreational values [301]. These NbS approaches are designed to mitigate further ecosystem degradation while simultaneously meeting the demands of human development and activities [14,26].

To enhance the effectiveness of NbS and Integrated Water Resources Management (IWRM) approaches, it is crucial to monitor and assess hydrological ecosystem services (HESS) [32,49]. A comprehensive understanding of HESS is essential for developing robust responses to water scarcity [73,302] 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 [3,138,303]. 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 [17], or adjusting water management practices to ensure more renewable water for supply during [304].

Ha et al. (2023) [256] 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 [38,256] as well as for Nature-based Solutions [14].

Global hydrological models and remote sensing data sets are used to assess Hydrological Ecosystem Services (HESS) at national and regional scales. An example is the International Water Management Institute (IWMI) conducted a global assessment of ecological flow requirements that are based on river flow statistics from the global hydrology model PCR-GlobWB by University of Utrecht, The Netherlands [305]. In this process, remote sensing has evolved into an advanced techniques that significantly strengthens HESS evaluation by directly integrating land surface and climatic parameters into eco-hydrological models. The incorporation of remote sensing into eco-hydrological models overcomes the limitations of local and river basin scales by utilizing global remote sensing and publicly available datasets, such as land use and soil information [224] and Digital Elevation Map [306]. For instance, NASA's RHEAS model, coupled with VIC leverages remote sensing data to incorporate processes related to vertical hydrology flow, making it suitable for areas with limited or no field measurements. Typical river basin and watershed models are SWAT+, SWEO and InVEST and they simulate provisioning and regulating services [40,55,113,186,307,308]. The utilization and assimilation of spatial earth observation data enhances the applicability of models like RHEAS, WaPOR, and SWAT. The capabilities to simulate water flow dynamics as well as estimate various water quality and plant growth variables are crucial for assessing the impacts of land and agricultural management on ecosystem services. 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) [229]. 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) [309]. WaPOR has a global coverage starting from 2020. This study adopts the approach by FAO's WaPOR approach and customizes the code using Python to run it for all 16 major river basins in Vietnam. WaPOR is based on the ETLook energy balance model [310] that processes evaporation and transpiration, along with and 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) [308]. In this study, WaPOR and RHEAS were run for entire Vietnam for four years: 2005 (normal year), 2010 (wet year), 2019 (dry year) and 2022. 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 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.

5.2 Study area

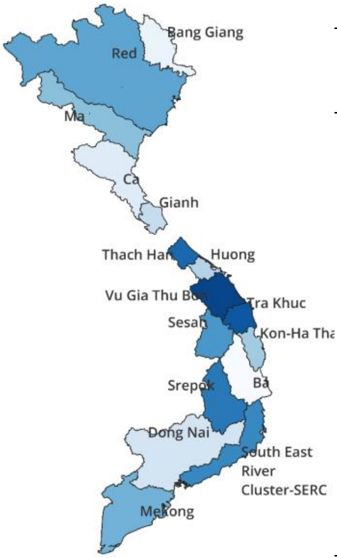


Figure 26. 16 major basins in the country

Table 9. 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	0,406	-
Thach Han	0,385	-
Huong	3,066	-
Vu Gia – Thu Bon	10,035	-
Tra Khuc	3,337	-
Sesan	11,510	-
Srepok	18,230	-
Kon-Ha Thanh	3,809	-
Ba	13,417	-
South-Eastern River Cluster	6,402	-
Dong Nai	36,530	44,100
Mekong	39,945	795,000

*: if only different from Area in Vietnam

Figure 26 illustrates the geographical distribution of the 16 major basins across the country, while Table 9 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 [185]. 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 plays essential roles despite their smaller size. They significant economic and tourism hubs in Vietnam, including Da Nang, Hue, Ho Chi Minh City, among others.

5.3 Research methodologies

5.3.1 FAO's Water Productivity model (WaPOR)

Actual evapotranspiration

The method to calculate evaporation (E) and transpiration (T) is based on the ETLook model, as outlined by Bastiaanssen et al. (2012) [310]. This model is based on the Penman-Monteith (P-M) method with remote sensing as input data. Originally developed by Penman [311] and Monteith [96], this approach has been employed by FAO as the standard method for calculating crop reference evapotranspiration [247]. Equation (23) illustrates the P-M method.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad \textbf{(23)}$$

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].

Dry matter production

Total biomass production (TBP) 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 fPAR), the meteorological influences (via PAR) and the soil moisture conditions of the root zone (via LUE). The seasonal value represents the total accumulated biomass during one growing season or annual cycle:

$$TBPtotal_S = \sum_{end}^{start} (0.864\ x\ fPAR\ x\ PAR\ x\ LUE) \quad \textbf{(24)}$$

Soil moisture

Different soil moisture models exist in the international remote sensing society [312,313], and solutions based on Land Surface Temperature (LST) has a preference because they can look into the subsoil via stomatal responses [314]. Relative soil moisture content (S_e) and soil moisture stress (S_t) in WaPOR are determined based on the correlation between Land Surface Temperature derived from thermal infrared imagery and vegetation cover derived from the NDVI [127]. The trapezoidal corners A, B, C and D are estimated for each pixel (Figure 27). The relative soil moisture content S_e of a specific location (e.g. point E) determined using following equations:

$$\boldsymbol{S_e = \frac{b}{a+b}} \quad \textbf{(25)}$$

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

Where: LST: Land surface temperature; F_c: vegetation cover, $T_{s,min}$ is estimated as wet-bulb temperature, $T_{c,min}$ is estimated as air temperature at full vegetation, $T_{s,max}$ and $T_{c,max}$ are estimated using modified P-M equation (Yang et al., 2015).

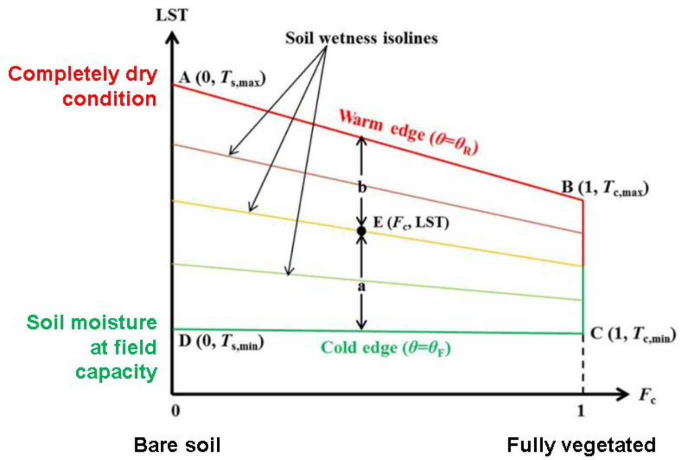
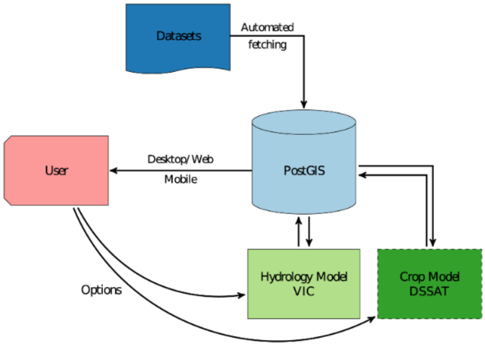


Figure 27. Trapezoidal method for estimating four extreme conditions (i.e., four corners) representing vegetation coverage/land surface temperature (Fc/LST) space (WaPOR database methodology, 2020; Yang et al., 2015)

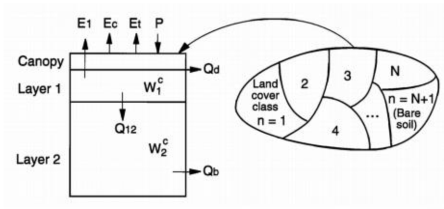
5.3.2 Hydrology and water balance using RHEAS

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 [307]. The schematization of RHEAS and the water balance component in VIC are illustrated in Figure 28, 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.



a)



b)

Figure 28. Schematization of a) RHEAS model [307] and b) the water balance component using VIC model [177]

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 [307]. 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.

5.3.3 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 10). Some HESS indicators were excluded due to relevance for river basin scale. The selected indicators are consistent with those used in Ha and Bastiaanssen (2023) [308]. In this manner, we have one standard set of HESS indicators that are "easily done" and can be provided at river basin scale. Indicators are highly specific and designed for local geographies, such as leisure and fish stock, and thus were not included in the broader analysis.

Table 10. List of HESS to be considered for mapping of Vietnam

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

5.3.4 Methodologies

Data flow & sources

Figure 29 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 models.

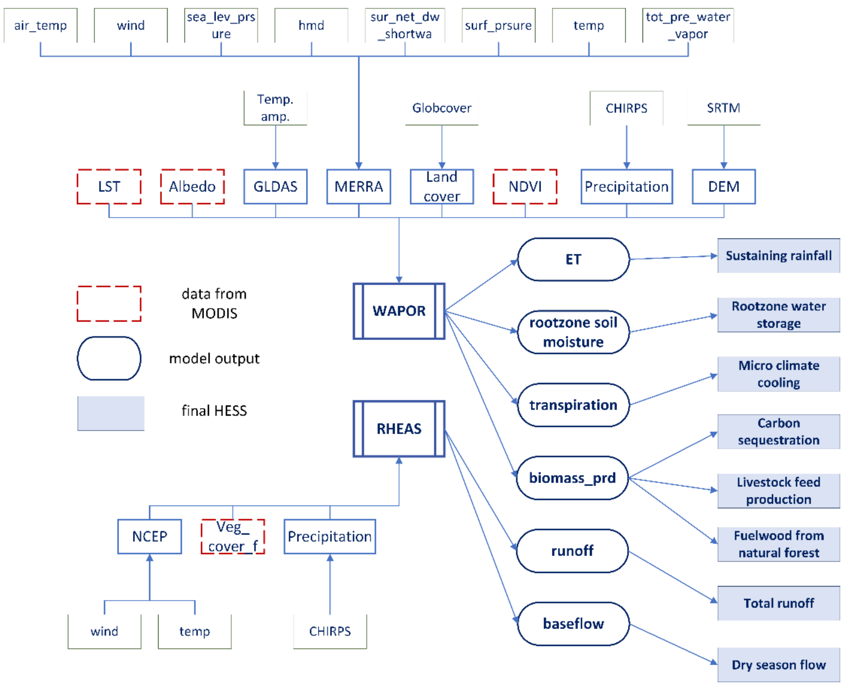


Figure 29. Hydrological Ecosystem Services (HESS) calculation routine with WaPOR and RHEAS model

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 [177,307]. 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) is calculated from biomass production using the WaPOR model, combined with a land use map from GlobCover [315]. 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) [308], 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:

$$\boldsymbol{Natural\ livestock\ feed\ production = f_{ABG} \times \alpha_{feed} \times TBP} \quad \textbf{(26)}$$

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

Similarly, fuelwood from natural forest (HESS4) is calculated from WaPOR's biomass production and the GlobCover land use 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 recommended by Ponce-Hernandez et al. (2004) [278]. The fraction of above ground biomass production usable as firewood ($\alpha_{fuelwood}$) is taken as 5% (e.g., dead wood and debris).

$$\boldsymbol{Fuelwood\ from\ natural\ forest = \alpha_{fuelwood} \times AGB} \quad \textbf{(27)}$$

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) [308]. 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 [308]:

$$P_{sus} = P - P_{adv} = \alpha ET \quad \textbf{(28)}$$

Where P_{sus} is the sustained rainfall due to local evaporation processes (mm/yr); P_{adv} is the rainfall originating from external sources (mm/yr) and α is the evaporation recycling ratio. As demonstrated by Coerver (2007) [282], 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:

$$\Delta T_{cooling} = \frac{r_{ah}}{\rho_a . C_p} . T \quad \textbf{(29)}$$

With T being transpiration, ρ_a being the density of moist air, C_p is the specific heat at constant pressure for air (1004 J/kg.K), r_{ah} is aerodynamic resistance to heat transfer that was fixed at 70 s/m following Senay et al. (2013) [240].

5.4 Results and discussions

5.4.1 Intermediate results from WaPOR

The 250m results of ET, soil moisture and biomass production are presented in Figure 30. 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 Figure 31, which shows zoom in results of the same parameters as in Figure 30 for ET, rootzone soil moisture and biomass production from WaPOR.

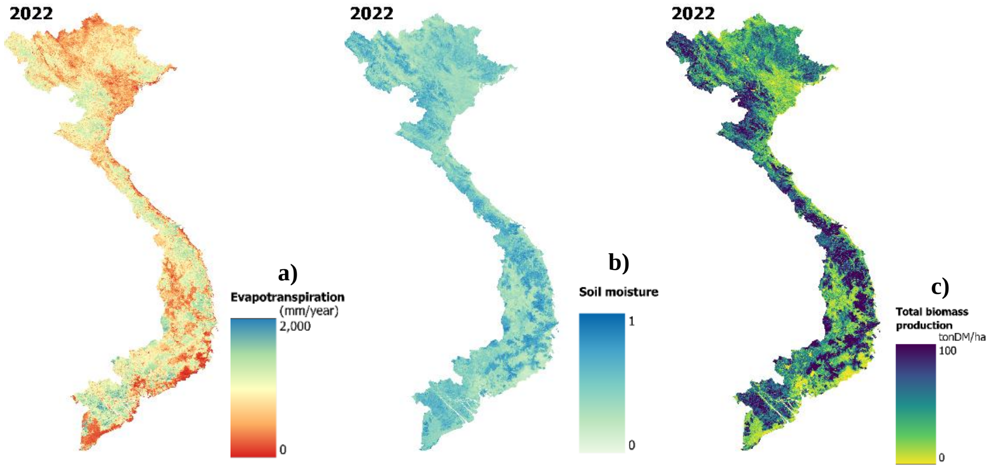


Figure 30. Intermediate results from WaPOR in 2022 for: a) evapotranspiration (ET); b) Soil moisture; c) Biomass production;

Spatial variability is substantial and this creates also questions on whether global scale models can properly assess the effective behavior of composite landscapes. Validation papers of WaPOR have been published by others [316–319] and it is therefore believed these detail results are acceptable for the purpose of HESS mapping.

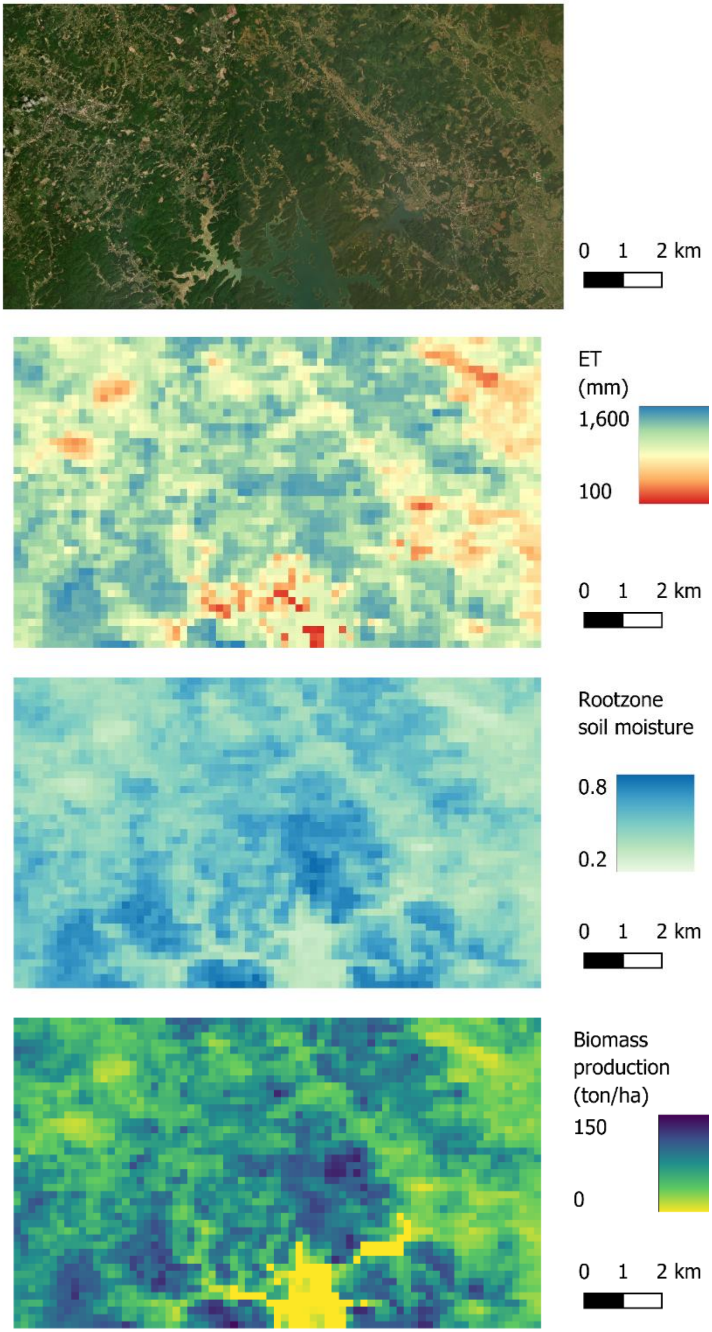


Figure 31. Zoom in results for 250m ET, rootzone soil moisture and biomass production in 2022

5.4.2 Spatial patterns of HESS

The result for HESS for Vietnam's major river basins for the year 2005 and 2022 is displayed in Figure 32.

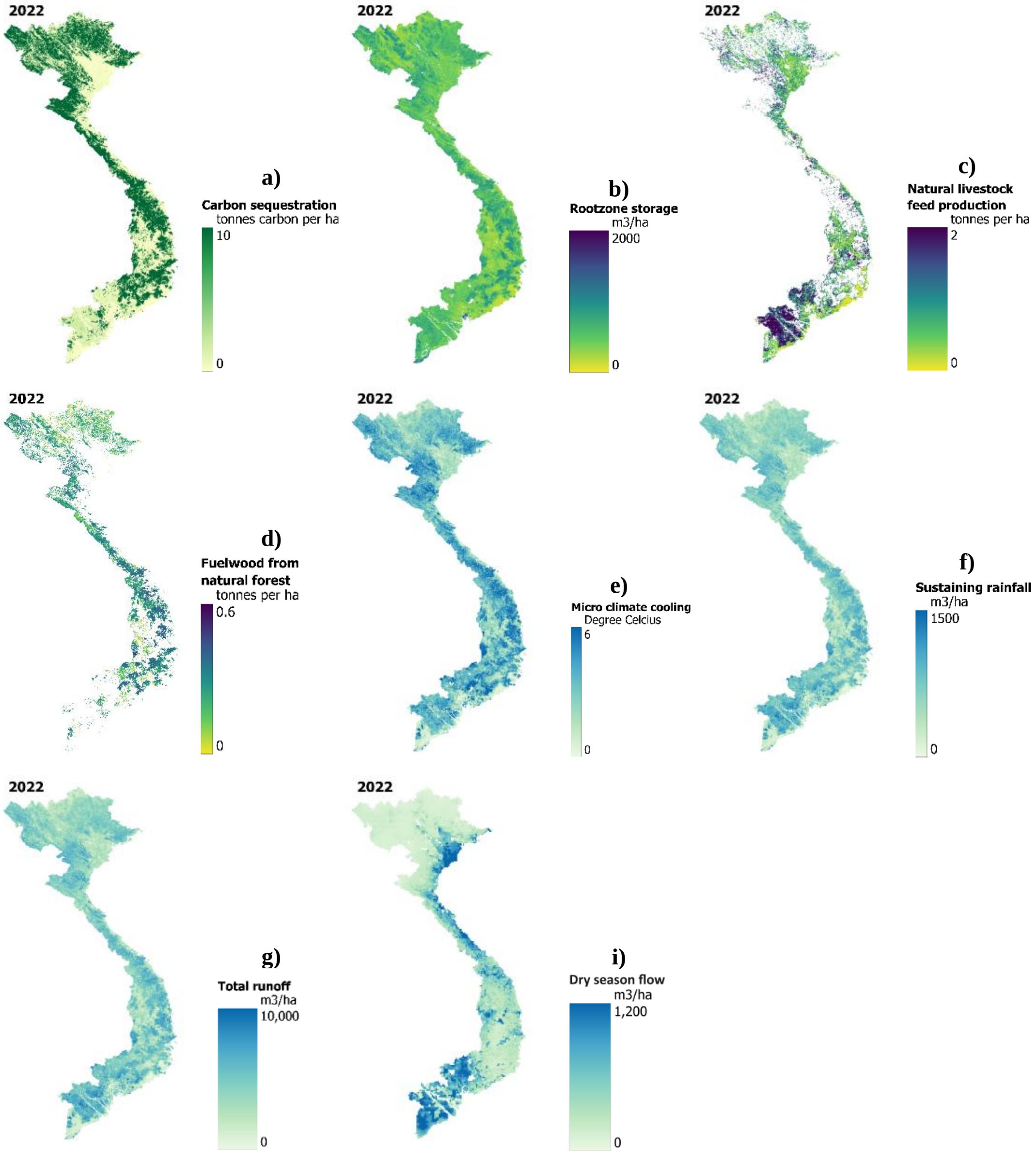


Figure 32. HESS results for 2022: a) Carbon sequestration; b) Rootzone storage; c) Natural livestock feed production; d) Fuelwood from natural forest; e) Mirco-climate cooling; f) Sustaining rainfall; g) Total runoff; h) Dry season flow

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 4,868 m^3/ha annually. This is a large volume of renewable water resources that can be allocated to multi-purpose water use. Locally, 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 1,700 and 1,220 m^3/ha/yr respectively. Notably, in 2010 – a wet year – total runoff increased exponentially to 8,400 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 1,100 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 use 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 [320] or introducing reforestation initiatives.

The spider graph (Figure 33) 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 the 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).

5.4.3 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 11).

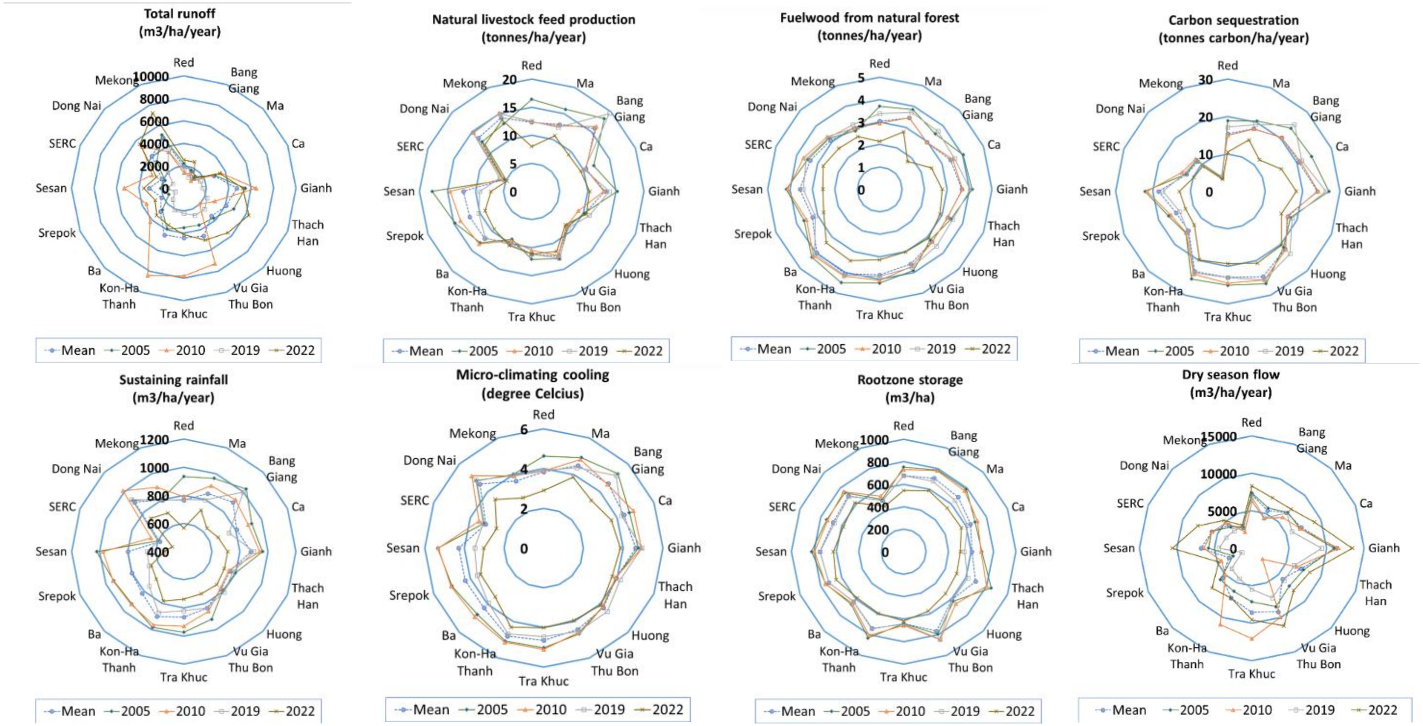


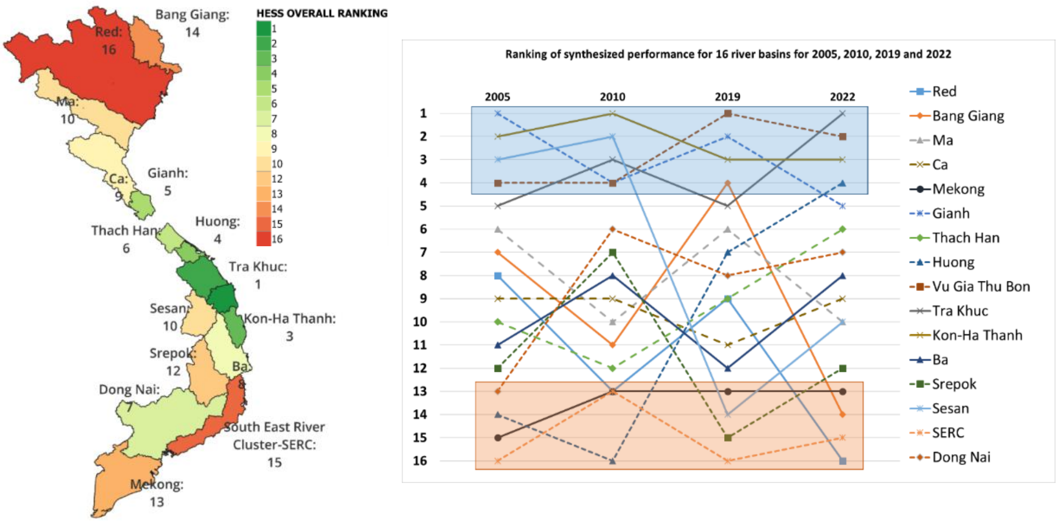
Figure 33. Changing of HESS for 16 basins for 2005, 2010, 2019 and 2022 for: a) Carbon sequestration; b) Rootzone storage; c) Natural livestock feed production; d) Fuelwood from natural forest; e) Mirco-climate cooling; f) Sustaining rainfall; g) Total runoff; h) Dry season flow

Table 11. 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

Figure 34a 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 decadal 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 [321,322]. 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) [323] found that flow rates in Southeast Asia basins have significant increased, leading to elevated risk of flooding. Landuse change is also associated with quickly change of services, especially those related to food and feed production in Vietnam [15].



a) **b)**

Figure 34. The final ranking of 16 river basins in terms 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.

Figure34b 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 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 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 consistent hotspots where additional efforts are required to improve their sustainability outcomes. Further information on synthesized scores for 16 river basins for year 2005, 2010 and 2019 is showed in Appendix C.

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 12 shows the results of these analysis.

Table 12. List of the best HESS performance for each basin and in the small bubbles, the best basins for each HESS

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

1) Srepok
2) Sesan
3) Tra Khuc

3) Huong
2) Vu Gia - Thu Bon
3) Sesan

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
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

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 contribute to rainfall recycling and cooling of the environment through dense vegetation. The vegetation is also functioning greatly in converting 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 the 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, 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.

5.4.4 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 (Figure 35a). Regarding HESS9: Sustaining rainfall (Figure 35b), 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 (Figure 35c). Bang Giang's carbon sequestration decreased by 50% during the study period from 2005-2022. Similarly, HESS13 (Micro-climate cooling) showed an average decline of 23.5% across the basins (Figure 35d). Once again, the Sesan basin recorded the most significant reduction, declining by 43.3% from 5.3 ^{o}C (2005) to 3 ^{o}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.

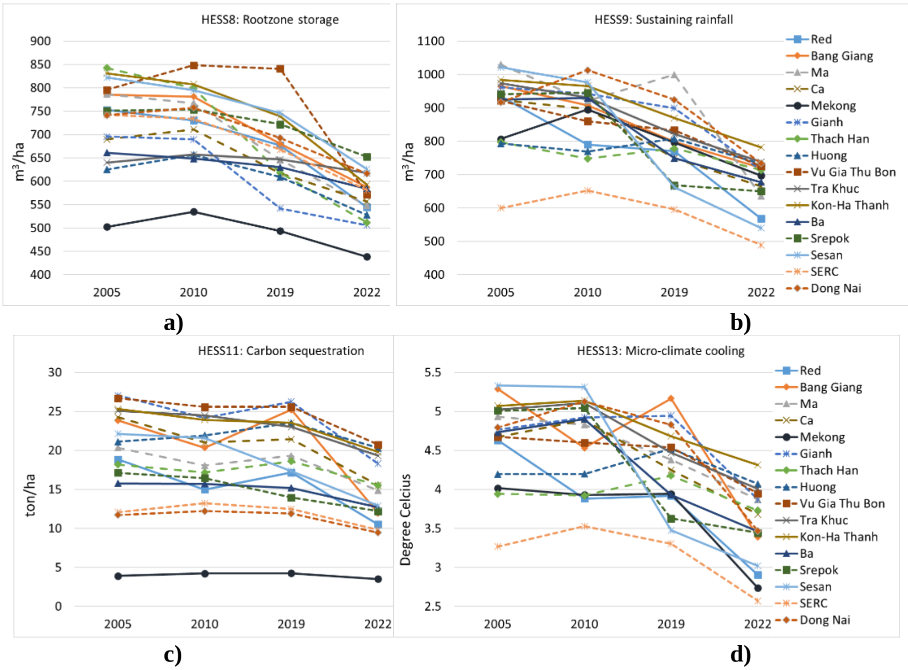
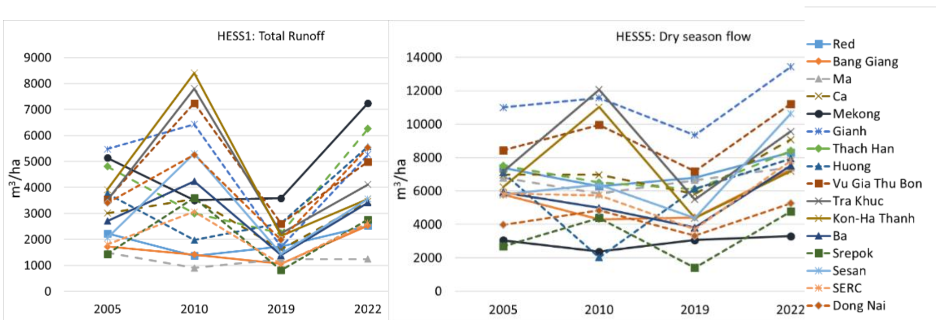


Figure 35. Trend of HESS that are declining a) HESS8: Rootzone storage; b) HESS9: Sustaining rainfall; c) HESS11: Carbon sequestration and d) HESS13: Micro-climate cooling

The only two HESS indicators demonstrated an increase with time: HESS1 (Total runoff) and HESS5 (Dry season flow) as showed in Figure 36a and Figure 36b respectively. These indicators reflect increased river discharges, which provides more water for various sectors. HESS1 in the Srepok basin nearly doubled from approximately 1438 m^3/ha in 2005 to 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.



a) b)

Figure 36. Trend of HESS that are increasing: a) HESS1: Total runoff; b) HESS6: Dry season flow

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.

5.5 Conclusions

The quantification and mapping of Hydrological EcoSystem Services (HESS) are essential for effective river basin and catchment planning and management, including the implementation of Integrated Water Resources Management (IWRM) and Nature-based Solutions (NbS) approaches. A benchmarking system that enables cross-examination and comparison between basins and administrative districts provides valuable insights into local efforts to sustain HESS and achieve community resilience. This study demonstrates the application of this approach across 16 major basins in Vietnam. Through comprehensive monitoring and assessment using remote sensing and modelling, the values, distribution and trends of HESS were analyzed. The spatial and temporal distribution of eight HESS indicators across 16 major river basins in Vietnam revealed the stock and flow of HESS throughout the study period. Basins with abundant or lesser HESS were identified with potential seamless zoom into their hotspots using the gridded display. This information is crucial for identifying best practices and lessons learned that can be scaled up to reduce ecosystem inequality and enhance the country's sustainability.

Some HESS indicators are the source of consumptive use (total runoff, recharge, root zone storage) and other express the benefits of this consumptive use (feed, wood, livestock, micro-cooling, carbon sequestration, sustaining rainfall). This paper demonstrates that evapotranspiration creates several HESS-related co-benefits that are often ignored in evaluation and allocation of water resources. By having a framework and methodology to quantify them, this can be changed.

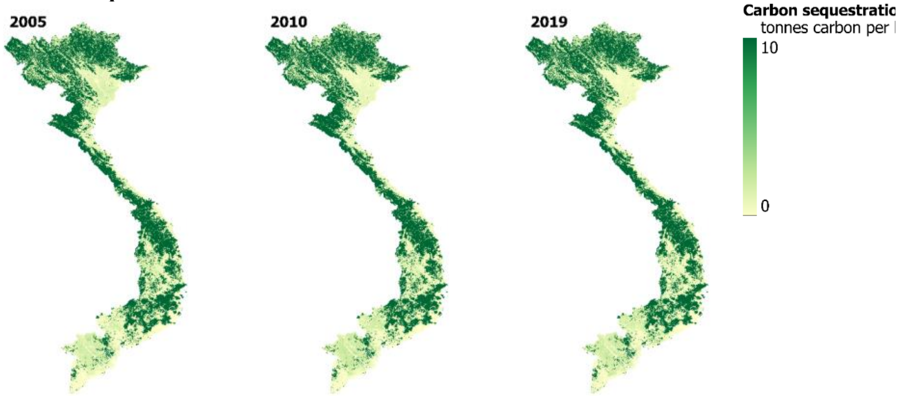
It is concluded that national scale HESS studies can be executed with remote sensing data having an attractive spatial resolution (30 to 250 m pixels). In this study total runoff and dry season flow was taken from VIC hydrological model. The basic analytical equations in these type of global hydrological models are essentially based on soil moisture and vegetation cover. 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.

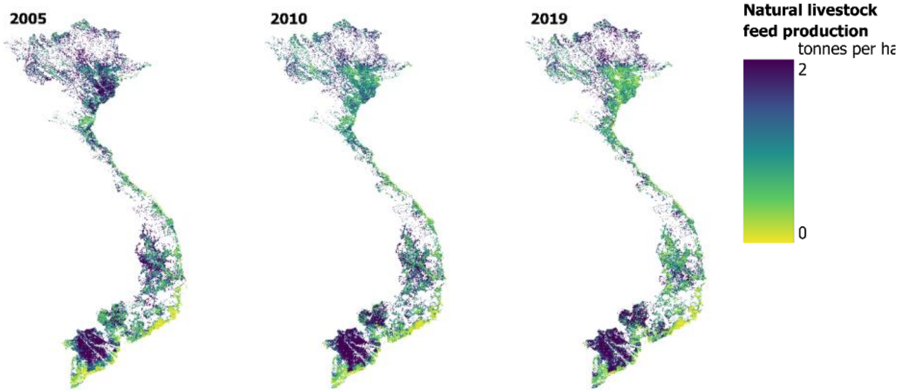
5.6 Appendix

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

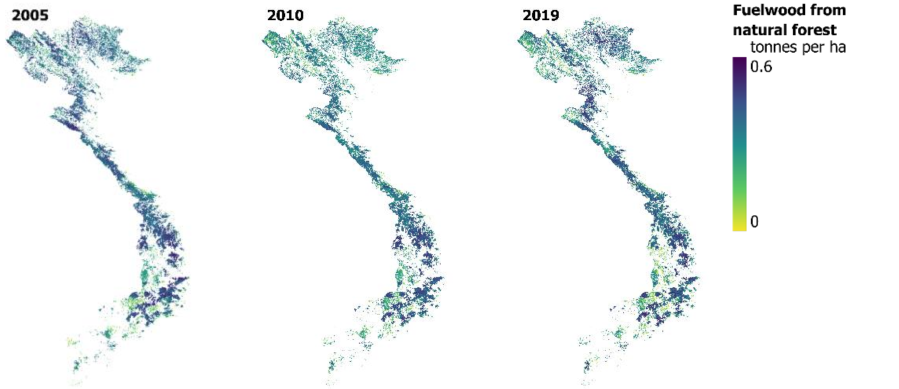
B1. Carbon sequestration



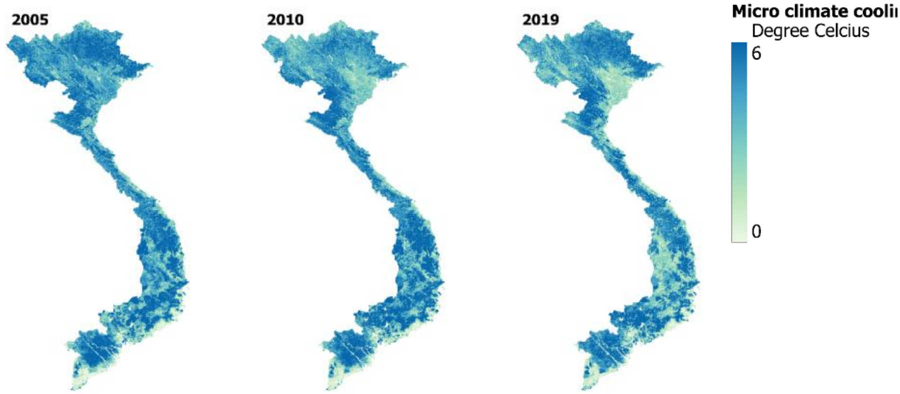
B2. Feed production



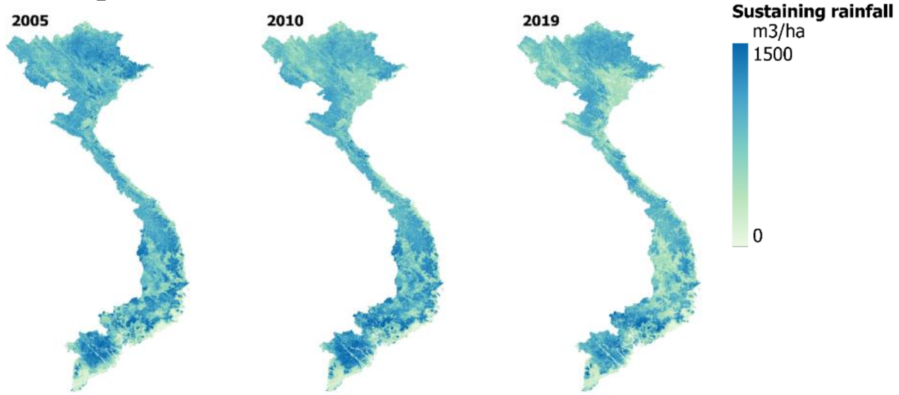
B3. Fuelwood from natural forest



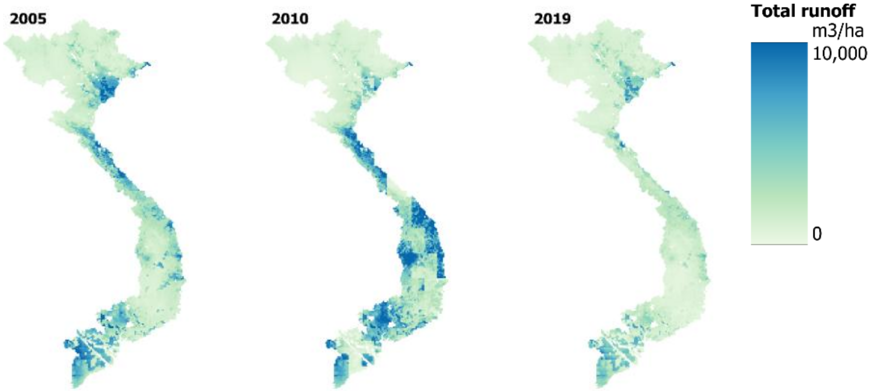
B4. Micro-climate cooling



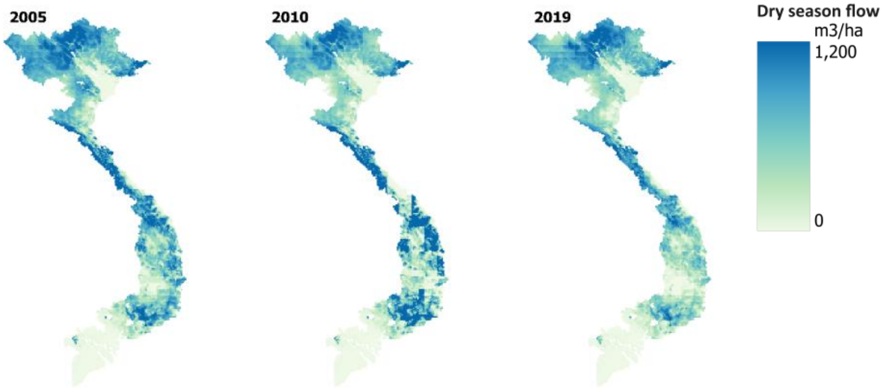
B5. Sustaining rainfall



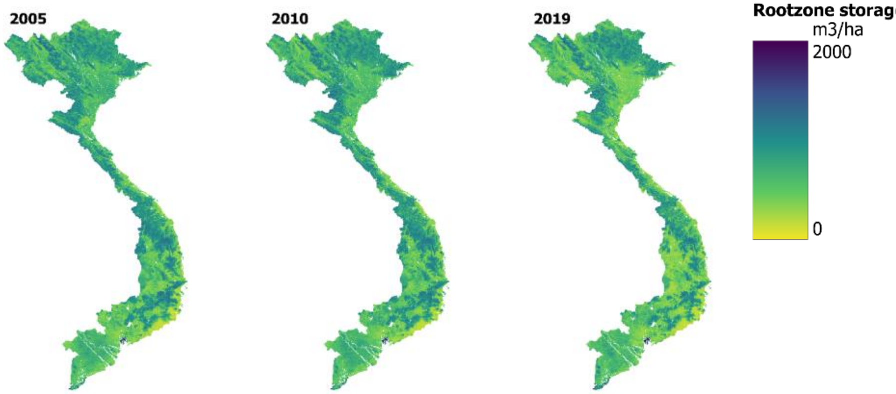
B6. Total runoff



B7. Dry season flow



B8. Rootzone storage



Appendix C: Synthesized score of HESS results for 3 years: 2005, 2010 and 2019

C1. 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
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

C2. 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

C3. 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
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

6 Conclusions and Future Research

6.1 Summary of research approach and objectives

6.1.1 Establishing the new Hydrological EcoSystem Services (HESS17) framework

Chapter 2 of this dissertation introduces the Hydrological EcoSystem Services (HESS17) framework, its foundation from existing ecosystem services and hydrological ecosystem services concepts. The formulation and principles of the framework and 17 associated indicators are provided. The formulation of this non-exhaustive framework on HESS and their quantifications are underpinned by the view that multiple values of hydrological ecosystems and their benefit to humans need to be recognized and valued. The framework consists of a minimum list of HESS taken from the existing report on Ecosystem services and resilience framework published by CGIAR in 2014 using certain criteria. The advantage of using CGIAR's selective indicators is that their importance is well recognized by a group of international bio-hydrologists and certain agencies being exposed to the concepts. A standardized process is required to define HESS indicators that are related explicitly to certain hydrological processes.

In the HESS17 framework, each indicator was defined in terms of provisioning, regulating, supporting or cultural services, including main beneficial flows, i.e., freshwater supply, food and fuels provision, disturbance regulation, air quality and climate, water quality and habitat provision. The HESS indicators include a certain spatial and temporal scale and classify the services to either consumptive or non-consumptive water use. In the case of the former, water needs to be considered as a sink of the catchment or river scale water balance and is not available for downstream users, unless water vapor returns as local rainfall.

The HESS17 framework allows the ability to include the development of scenarios and pathways across scales and benchmark the level of sustainability. Another characteristic of the HESS17 framework is its capability to provide an ample space for adding more indicators in the future, following the implementation of SDGs or achievement of human development targets.

6.1.2 Developing ensemble remote sensing products based on satellite observations of precipitation and evapotranspiration

Chapter 3 discusses the availability of spatially distributed precipitation, ET and LAI data from earth observation technologies for calibrating various key soil and vegetation process parameters of eco-hydrological models, also when rivers are ungauged and the water distribution system is complex. In this study, two open access precipitation products, i.e., TRMM7.0 and CHIRPS2.0 were combined to enhance spatial performance while four individual ET products were averaged linearly (SEBS, CMRSET, SSEBop and MOD16). No in situ measurements were available to verify the performance of individual ET models. A simple linear average ET value gave best results as compared to streamflow data from two stations and k_c crop coefficients, described in the international literature.

For precipitation, the combined precipitation product with a resolution of 0.05° × 0.05° showed a good performance when compared to rain gauge measurements in the Day river basin. The newly created precipitation product significantly improved the performance of the two original datasets in terms of bias correction (PBIAS) and Nash–Sutcliffe efficiency, even though the MAE was marginally larger.

The ensemble evapotranspiration ET product had a spatial resolution of 1 km × 1 km. The spatial resolution of ET can be improved by downscaling procedures using for instance the Enhanced Vegetation Index (EVI), Global Vegetation Moisture Index (GVMI) and Residual Moisture Index (RMI). It has been demonstrated that adopting an ensemble ET is essential, since the principle of "one size fits all" does not apply. An ensemble method operates under the assumption that spatial differences from different ET algorithms will tend to cancel in the ensemble average. An ensemble approach should become a standard for eco-hydrological analysis, as evidenced by its use in global water accounting procedures, such as Water Accounting Plus (WA+) or in ET portals, such as OpenET (https://etdata.org/). For instance, estimations of irrigation water flows can be achieved using independent ensemble ET estimates, which otherwise would require ET information from flux towers or water diversions and water withdrawals from sources (being rarely available). This application illustrates the power of inclusion of ensemble ET data to determine irrigation water supplies at the farm gate from mass conservation principles.

6.1.3 Developing an auto-calibration routine of eco-hydrological model using remote sensing datasets

The focus of Chapter 3 of this dissertation presents an approach to use quasi-open access remote sensing data to improve SWAT modelling performance. The Sequential Uncertainty Fitting (SUFI-2) parameter sensitivity and optimization model was employed to force model input in terms of precipitation and use simultaneously ET and LAI data to calibrate soil and vegetation model parameters. The innovation is that SUFI-2 is based on remote sensing data instead of classical discharge data that is rarely available. Calibrated soil and vegetation parameters of individual Hydrological Response Units (HRU) are extremely valuable to quantify key hydrological and biophysical watershed and river basin processes. The natural and anthropogenic eco-hydrological processes in ungauged basins, being vital for reporting ecosystem services are in this manner much better understood. The simulation of local eco-hydrological processes in ungauged basins can never be interpreted from bulk flow measurements, if there are any.

The hydrological formulations in SWAT are thus adequate for simulating eco-hydrological processes. In the near future, remote sensing data on soil moisture, net primary production, and water quality will become available as well, which will undoubtedly further enrich the options to calibrate additional SWAT model parameters.

6.1.4 Testing HESS and modelling framework using SWAT for a river basin

Chapter 4 demonstrates the application of 11 HESS indicators ranging from direct benefits (e.g., food production, provision of runoff, and fuelwood, etc.) to benefits in a larger biophysical context, such as micro-climate regulation, rootzone water storage, meeting environmental-flow requirements etc.). The consideration of these eleven HESS in the Day Basin highlights hydrological ecosystem services that benefit the basin and its population. The result reveals a thorough assessment and the introduction of more sustainable approaches in land-use planning and basin management practices, such as Integrated Water Resources Management (IWRM) or Natural-based Solutions (NbS) to enhance HESS values in the basin.

Multiple management scenarios can be evaluated by their implications on ecosystem services or “disservices.” For instance, scenario analysis for reforestation, irrigation development, land consolidation, and urban growth requires an eco-hydrological simulation model, which cannot be achieved through earth observations alone. Models such as SWAT, which host a wide suite of simulation options, can provide data at a daily time step, essential for covering dynamic processes like peak flow attenuation and flood hazard. This capability was highlighted by demonstrating the integrated use of SWAT and SWAT-CUP.

The SWAT model has the capacity to include soil erosion, natural reduction of eutrophication and agrochemical in water, and water storage in lakes. Hence, the results presented are not exhaustive but should be regarded as a first step towards a more comprehensive understanding and the availability of tools to quantify HESS in a more routine manner.

6.1.5 Demonstrating HESS assessment for all Vietnam's major river basins

Chapter 5 presents the quantification and mapping of Hydrological EcoSystem Services (HESS) including all 16 major river basins in Vietnam. Quantifiable HESS are essential for effective river basin and catchment planning and management, including the implementation of Integrated Water Resources Management (IWRM) and Nature-based Solutions (NbS) approaches. A benchmarking system for HESS indicators has been applied to enable cross-examination and comparison between river basins. This provides valuable insights into local efforts to sustain HESS and achieve community resilience. Through comprehensive monitoring and assessment using remote sensing and modeling, the values, distribution and trends of HESS were analyzed. Eight HESS indicators revealed the stock and flow of HESS throughout the study period. Water provision from total runoff, recharge and root zone storage are related to the benefits of consumptive use (feed, wood, livestock, micro-cooling, carbon sequestration, sustaining rainfall). The remote sensing data allows seamless zooming into the hotspots. This information is crucial for identifying best practices and lessons learned that can be scaled up to reduce ecosystem inequality and enhance the country's sustainability.

It is concluded that national scale HESS studies can be executed with remote sensing data having an attractive spatial resolution (i.e., 250 m pixels). Total runoff and groundwater recharge was taken from VIC hydrological model. The basic analytical equations in these type of global hydrological models is essentially based on soil moisture and vegetation cover. 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 research to identify attainable values under optimum conditions can be used for benchmarking HESS.

6.2 Limitations

The quantification of HESS is based on the hypothesis that there exists a commonly and agreed understanding of HESS indicators. However, this is not an endpoint but rather a process, given the diverse understandings and knowledge about the properties of nature and its interactions. The HESS17 framework aimed to fairly represent indicators from the four categories of ecosystem services – provisioning, supporting, regulating and cultural services. The first limitation is an imbalance between the ecosystem categories. The number of regulating services (i.e., 12 services) far exceeding those in other categories (i.e., 1 service each for supporting and cultural, and 4 services for provisioning). The greater attention and more straight-forward assessment given to regulating and provisioning services is related to the nature of water as a key resource for nature and humas.

Secondly, it is a fact that more indicators do not necessarily provide more insights. The key element is that water should be considered as a prerequisite for natural services for people. The success of ecosystem services depends on the connection between the locations of service provision and the use of these services by people. Furthermore, a common scale should be defined where all indicators are spatially and temporally aligned. Although the HESS17 framework aims at delineating HESS indicators in spatial and temporal dimensions, it falls short in providing direct solutions for people.

Thirdly, the implementation of the HESS17 framework requires the development of computational routines based on remote sensing and eco-hydrological modelling. These routines should capture and represent the components and interactions of nature, such as the complexity of climate, eco-hydrology and ecosystems, as well as interactions with human factors. However, there are limitations, as remote sensing and hydrological models inevitably introduce uncertainties. Therefore, the sensitivities and limitations of these tools should be carefully evaluated and transparently communicated. For example, the use of remote sensing data, such as precipitation, evapotranspiration, Leaf Area Index (LAI), soil moisture, requires a thorough discussion of the uncertainties in these products. Nevertheless, remote sensing remains a measurement (at a distance) with high spatial detail, something that eco-hydrological models cannot always provide. Models such as SWAT and RHEAS/VIC are relatively user-friendly, although specific skills are required for model setup, calibration and validation. More complex models, such as WaPOR and DLEM reflect a higher level of biophysical system complexity, requiring deeper understanding and skills from users. With the current rapid development of new open access databases (e.g. WaPOR), it is not inconceivable that CGIAR and the United Nations will work on a platform where HESS indicators can be obtained directly in the form of maps and tables. This dissertation provides good examples for this.

6.3 Future research

This dissertation introduces the Hydrological EcoSystem Services (HESS17) framework with demonstrated case studies in Vietnam. Future research should explore the application of this framework to other basins on a global scale. FAO's WaPOR offers a valuable vehicle for transferring these indicators to other regions and countries, while Water Accounting Plus (WA+) provides an excellent metric system for realizing HESS assessment and Natural Capital Accounting (NCA) benchmarking.

Integrating earth observations with eco-hydrological models is a necessary step deserving more attention from the research community. It is crucial to consider that integrating multiple remote sensing data sets introduces noise and bias due to the uncertainties inherent in each parameter. Error propagation should be mitigated by developing hydrological consistency. Approaches such as Bayesian hierarchical modeling, which can fuse monthly water balance data and estimate the corresponding data errors and error-corrected water balance components (precipitation, evaporation, river discharge and water storage) [169], are recommended. Improved modeling routines of all HESS metrics are also needed, particularly to understand development scenarios and trade-offs. This would provide deeper insights into global and regional biodiversity and ecosystem services issues and assess the impacts of drivers on state of nature and nature's contributions to people. Scenario analyses should be extended to integrate quantification, valuation and policy implications to better represent HESS trade-offs. Global platforms such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Partnership for Environment and Disaster Risk Reduction (PEDRR) can advocate for policy change and best practice in ecosystem management.

There is an imbalance in the list of HESS proposed in this dissertation, particularly in the number of provisioning and regulating services as compared with cultural and support services. This drawback may lead to potential distortions while assessing the benefits of HESS for human and non-human use and in optimizing of HESS performance at various scales. Further refinement of HESS definitions and categorizations is necessary to minimize this ambiguity in the future. Once HESS are re-defined or additional HESS indicators are needed, the HESS framework proposed in this dissertation can be revised and extended.

7 Samenvatting

7.1 Inleiding

Deze thesis heeft als doel de volgende kwesties te onderzoeken:

Definiëren van een HESS-raamwerk (Hoofdstuk 2)
De eerste stap in de implementatie van een HESS-raamwerk omvat het definiëren van belangrijke indicatoren met betrekking tot hydrologische ecosysteemdiensten. Deze indicatoren kunnen worden onderverdeeld in consumptief en niet-consumptief watergebruik. Het HESS-raamwerk kan gemakkelijk worden gekoppeld aan bestaande beleidskaders zoals Integraal Waterbeheer (en: Integrated Water Resources Management, IWRM), Natuurlijke Oplossingen (en: Nature-based Solutions (NbS)), Water Accounting en Water Productiviteit. Traditioneel worden hydrologische rekenmodellen gebruikt om de HESS indicatoren te bepalen voor riviersystemen. Dit Proefschrift laat zien dat aardobservatie hiervoor ook kan worden gebruikt en dat er meer detail mee kan worden gehaald. Om de volledigheid te waarborgen, moet dit HESS-raamwerk alle vier de categorieën van ecosysteemdiensten omvatten, met indicatoren ingedeeld in voorzienende, regulerende, ondersteunende en culturele diensten.

Transparante kalibratie- en berekeningsprocedures voor HESS (Hoofdstuk 3 en 4)
De schatting van HESS indicatoren moet worden uitgevoerd door middel van een transparante en gestandaardiseerde berekeningprocedures. Het gebruik van remote sensing-algoritmes of hydrologische modellen moet gestructureerd zijn om replicaties eenvoudiger te maken. HESS-indicatoren kunnen rechtstreeks worden afgeleid uit remote sensing of worden berekend door eco-hydrologische modellering. Het algoritme dat in data analyse wordt gebruikt, moet voldoende transparant zijn zodat praktijkmensen en besluitvormers op het gebied van ecosysteemdiensten het kunnen begrijpen en aanpassen, terwijl het robuust genoeg moet zijn om een verscheidenheid aan toepassingen te accommoderen.

RHEAS, SWAT en VIC zijn bekende eco-hydrologische modellen die vaak worden gebruikt en aanbevolen voor het simuleren van HESS indicatoren op verschillende ruimtelijke schalen. Bijvoorbeeld, het RHEAS-model, gekoppeld met VIC, gebruikt remote sensing gegevens om bepaalde bio-fysische processen te bepalen.

Kalibratietechnieken zoals de standaard SUFI-2-functionaliteiten kunnen worden toegepast, hetzij als invoergegevens (bijv. neerslag) of om de uitvoer te testen (bijv. verdamping (ET) en bladerindex (LAI)). Modellering faciliteert de beschrijving van systemen op verschillende schalen, zowel temporeel als ruimtelijk. De beoordeling van HESS op verschillende schalen vereist zekere technieken. Terwijl invoergegevens kunnen worden gestandaardiseerd voor uiteenlopende ruimte- en tijdschalen, moet er ook aandacht worden besteed aan de schaal van de HESS rapportage. Daarom is het cruciaal om de schalen van hydrologische ecosysteemdiensten expliciet te definiëren.

Evaluatie van duurzaamheid (Hoofdstuk 5)
Het koppelen van HESS indicatoren aan richtlijnen geeft extra inzicht in de prestatie van ecosysteemdiensten. Een dergelijk vergelijkingssysteem kan worden uitgevoerd met relatieve lokale waarden of worden genormaliseerde met internationale standaarden. Duurzaamheidsevaluatie en -indexering moeten coherent en toepasbaar zijn op elk geografisch studiegebied zodat het systeem beter begrepen wordt en gemakkelijker kan worden vergeleken. Het benutten van een vergelijkingsstudie en evalueren van duurzaamheidsprestaties maakt het mogelijk om hotspots te ontdekken waar verdere inspanningen nodig zijn.

7.2 Samenvatting onderzoeksbenadering en doelstellingen

Hoofdstuk 2 van dit proefschrift introduceert het Hydrological EcoSystem Services (HESS17) raamwerk. De concepten van ecosysteemdiensten worden uitgelegd en de link met hydrologische processen wordt toegelicht. De bijbehorende 17 indicatoren worden geïntroduceerd. De formulering van het incomplete HESS raamwerk en hun kwantificering is gebaseerd op het idee dat hydrologische ecosystemen een voordeel voor de mens heeft. Het raamwerk bestaat uit een minimumlijst van HESS indicatoren, overgenomen uit een bestaand CGIAR-rapport dat standaarden beschrijft (Water, Land and Ecosystems WLE, 2014). Diverse criteria zijn gehanteerd om een minimum lijst van HESS indicatoren te creeëren. Het voordeel van het gebruik van CGIAR indicatoren is dat hun belang internationaal wordt erkend door diverse vakmensen en het bredere publiek. Dit benadrukt de noodzaak om gestandaardiseerde indicator te gebruiken en te zorgen dat HESS kan worden geïntegreerd met bestaande systemen om water – land – ecosystemen in hun onderlinge afhankelijkheid te beschrijven.

Hoofdstuk 3 verkent de beschikbaarheid van ruimtelijk verdeelde neerslag, verdamping (ET) en bladerindex (LAI) gegevens verkregen uit aardobservaties. Dit maakt het mogelijk om bodem- en vegetatieparameters van eco-hydrologische modellen te kalibreren, zelfs voor situaties in stroomgebieden en complexe watersystemen waar weinig wordt gemeten. In deze studie zijn twee neerslagproducten, TRMM7.0 en CHIRPS2.0, gecombineerd om de best ruimtelijke en absolute prestaties te verbeteren. Verder zijn rt vier individuele verdampingsproducten lineair gemiddeld. Er waren geen in situ metingen beschikbaar van het stroomgebied om de prestaties van individuele ET-modellen te verifiëren. Uit inspectie van de waterbalans bleek dat een eenvoudige lineaire gemiddelde waarde de beste resultaten opleverde in vergelijking met gemeten afvoer op twee meetlocaties en gewascoëfficiënten (kc) beschreven in de internationale literatuur.

Het derde hoofdstuk van dit proefschrift presenteert een oplossing om remote sensing gegevens te gebruiken voor het verbeteren van de SWAT prestaties. Het Sequential Uncertainty Fitting (SUFI-2) gevoeligheid- en optimalisatiemodel werd gebruikt om het verschil met neerslag, ET en LAI, te minimaliseren. De innovatie is dat de standaard kalibratiemodule gebaseerd is op remote sensing data in plaats van klassieke afvoergegevens. Ook is het zo dat bodem- en vegetatieparameters van individuele Hydrological Response Units (HRU) worden gekalibreerd om een zo goed mogelijke match met de satllietmetingen te krijgen. Het resultaat van een dergelijke kalibratiebenadering is een betere kwantificering van de natuurlijke en antropogene eco-hydrologische processen in stroomgebieden zonder afvoermetingen, wat essentieel is voor het rapporteren van ecosysteemdiensten aan overheden en de Verenigde Naties. Een hoog detailniveau samen met een goede procesbeschrijving biedt betere mogelijkheden voor de simulatie van lokale eco-hydrologische processen, welke nooit kunnen worden geïnterpreteerd uit gebiedsmetingen zoals de afvoer uit een gebied, indien deze er al zijn.

Hoofdstuk 4 demonstreert de toepassing van het HESS17-raamwerk voor de Day river, waarbij 11 indicatoren worden geïntegreerd, variërend van directe voordelen zoals bijvoorbeeld voedselproductie, stromend water, brandhout tot indirecte voordelen zoals de regulering van microklimaat, opslaan van water in de bodem en het voldoen aan zekere minimale stroming in rivieren om de visstand en biodiversiteit van de vegetatie te waarborgen. Deze laatst genoemde diensten bieden een momentopname van de voordelen van ecosystemen voor mensen. De keuze voor deze 11 HESS indicatoren in het stroomgebied van de Day helpen bij de ontwikkeling en het behoud van de natuurwaarden van het stroomgebied. De HESS waarde benadrukt hoe hydrologische ecosysteemdiensten ten goede van de bevolking komen. De resultaten onthullen hoe de planning van landgebruik, integraal waterbeheer en natuurlijke oplossingen kunnen worden verbeterd.

Hoofdstuk 5 presenteert de kwantificatie van Hydrologische Ecosysteemdiensten (HESS) voor alle 16 grote rivierbekkens in Vietnam. Een vergelijking van water-gerelateerde ecodiensten voor elk administratief district wordt hiermee mogelijk gemaakt. Het geeft waardevolle inzichten in lokale inspanningen om HESS te behouden en te verbeteren. Door middel van uitgebreide monitoring en beoordeling met behulp van remote sensing en modellering werden de waarden, verdeling en trends van HESS indicatoren geanalyseerd. De ruimtelijke en temporele verdeling van acht HESS-indicatoren over deze gebieden onthulde de totale hoeveelheid water beschikbaar voor mensen en het nut daarvan.

Sommige HESS-indicatoren geven de hoeveelheid water weer (totale afstroming, bergingscapaciteit in de bodem), en andere indicatoren drukken de directe voordelen uit (voedsel, hout, vee, micro-koeling, koolstofvastlegging, behoud van regenval). Stroomgebieden met overvloedige HESS of minder HESS werden geïdentificeerd, met de mogelijkheid om zeer lokaal de situatie te beschrijven ahv een 250 m grid. Vooral de locale informatie is cruciaal voor het identificeren van de beste praktijken en lessen die kunnen worden opgeschaald om de ongelijkheid in water-gerelateerde ecosysteemdiensten te verminderen en de duurzaamheid van Vietnam te verbeteren.

7.3 Beperkingen

De keuze van HESS indicatoren is gebaseerd op de hypothese dat er een algemeen begrip bestaat van hun betekenis. Dit is echter geen feit, maar eerder een leerproces van erkenning van hun nut, gezien de diverse begrippen en kennis over de eigenschappen van de natuur geen algemene kennis is. De complexiteit van interacties binnen de natuur bemoeilijkt dit verder. Een beperking van het HESS17-raamwerk is dat een gelijke vertegenwoordiging van indicatoren uit de vier categorieën van ecosysteemdiensten – voorziening, ondersteuning, regulering en culturele diensten – niet is geslaagd. Het aantal water-gerelateerde regulerende diensten (d.w.z. 12 diensten) ligt boven dat van andere categorieën ligt (d.w.z. 1 dienst elk voor ondersteuning en cultuur, en 4 diensten voor de categorie voorziening). De grotere aandacht en meer rechttoe-rechtaan beoordeling van regulerende en voorzienende diensten, in vergelijking met culturele en ondersteunende diensten, kan als een tekortkoming worden beschouwd. Het is echter ook een gevolg van water als een cruciale regulerende factor voor het menselijke leven.

Ten tweede is het een feit dat meer indicatoren niet noodzakelijkerwijs meer inzicht verschaffen. Het belangrijkste element is dat water moet worden beschouwd als een vereiste voor natuurlijke diensten voor mensen. Het succes van ecosysteemdiensten hangt af van de verbinding tussen de locaties van de levering van de diensten en het gebruik van deze diensten door mensen. Bovendien moet een gemeenschappelijke schaal worden gedefinieerd waar alle indicatoren ruimtelijk en temporeel op elkaar zijn afgestemd. Hoewel het HESS17-raamwerk gericht is op het afbakenen van HESS-indicatoren in ruimtelijke en temporele dimensies, schiet het tekort in het bieden van directe oplossingen voor mensen.

Ten derde vereist de implementatie van het HESS17-raamwerk de ontwikkeling van rekenroutines op basis van remote sensing en eco-hydrologische modellering. Deze routines moeten de componenten en interacties van de natuur vastleggen en vertegenwoordigen, zoals de complexiteit van klimaat, eco-hydrologie en ecosystemen, evenals interacties met menselijke factoren. Er zijn echter beperkingen, aangezien elk model onvermijdelijk onzekerheden met zich meebrengt. Daarom moeten de gevoeligheden en beperkingen van deze hulpmiddelen voorzichtig worden geëvalueerd en transparant worden gecommuniceerd. Bijvoorbeeld, het gebruik van remote sensing-gegevens zoals neerslag, verdamping (ET), Leaf Area Index (LAI), landgebruike en bodemvocht vereist een grondige discussie over de onzekerheden van deze dataproducten. Toch blijft remote sensing een meting (op afstand) met veel ruimtelijk detail, iets wat eco-hydrologische modellen niet altijd kunnen bieden. Een gevoeligheidsanalyse voor eco-hydrologische modellen is cruciaal om de respons van het stroomgebied op specifieke data beschikbaarheid te onderzoeken. Modellen zoals SWAT en RHEAS/VIC zijn relatief gebruiksvriendelijk, hoewel specifieke vaardigheden vereist zijn voor modelinstelling, kalibratie en validatie. Complexere modellen zoals WaPOR en DLEM weerspiegelen een hoger niveau van biophysische systeemcomplexiteit, wat diepgaander begrip en vaardigheden van gebruikers vereist. Met de huidige snelle ontwikkeling van nieuwe open access databestanden (bijvoorbeeld WaPOR), is het niet ondenkbaar dat CGIAR en Verenigde Naties gaan werken aan een platform waar HESS indicatoren direct kunnen worden verkregen in de vorm van kaarten en tabellen. Dit proefschrift geeft hier goede voorbeelden voor en hoopt hiervoor een inspiratie te zijn.

Bibliography

1. *Ecosystems and Human Well-Being: Wetlands and Water Synthesis: A Report of the Millennium Ecosystem Assessment*; Millennium Ecosystem Assessment Program, Ed.; World Resources Institute: Washington, DC, 2005; ISBN 978-1-56973-597-8.
2. Ferreira, C.S.S.; Kašanin-Grubin, M.; Solomun, M.K.; Sushkova, S.; Minkina, T.; Zhao, W.; Kalantari, Z. Wetlands as Nature-Based Solutions for Water Management in Different Environments. *Curr. Opin. Environ. Sci. Health* **2023**, *33*, 100476, doi:10.1016/j.coesh.2023.100476.
3. Brauman, K.A. Hydrologic Ecosystem Services: Linking Ecohydrologic Processes to Human Well-being in Water Research and Watershed Management. *WIREs Water* **2015**, *2*, 345–358, doi:10.1002/wat2.1081.
4. *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*; Kumar, P., Economics of Ecosystems and Biodiversity (Project), Eds.; Earthscan: London ; Washington, DC, 2010; ISBN 978-1-84971-212-5.
5. Liu, J.; Li, S.; Yang, X.; Wei, Z.; Liu, F. Effects of Soil Drought and Vapour Pressure Deficit (VPD) on Water Use Efficiency of Tomato Plants with Contrasting Endogenous ABA Levels. *Sci. Hortic.* **2022**, *295*, 110797, doi:10.1016/j.scienta.2021.110797.
6. Choi, E.; Kim, R.; Chae, J.; Yang, A.-R.; Jang, E.; Lee, K.Y. Analysis of Nature-Based Solutions Research Trends and Integrated Means of Implementation in Climate Change. *Atmosphere* **2023**, *14*, 1775, doi:10.3390/atmos14121775.
7. Brown, C.J.; Saint Ange, C.; Connolly, R.M.; Hasan, S.; Jackson, S.; McMahon, J.M.; Smart, J.C.R. Ecosystem Services in Connected Catchment to Coast Ecosystems: Monitoring to Detect Emerging Trends. *Sci. Total Environ.* **2023**, *869*, 161670, doi:10.1016/j.scitotenv.2023.161670.
8. Costanza, R. Valuing Natural Capital and Ecosystem Services toward the Goals of Efficiency, Fairness, and Sustainability. *Ecosyst. Serv.* **2020**, *43*, 101096, doi:10.1016/j.ecoser.2020.101096.
9. Office of Management and Budget (OMB) Guidance for Assessing Changes in Environmental and Ecosystem Services in Benefit-Cost Analysis 2024.
10. *Water Ecosystem Services: A Global Perspective*; Martin-Ortega, J., Ferrier, R.C., Gordon, I.J., Khan, S., Eds.; 1st ed.; Cambridge University Press, 2015; ISBN 978-1-107-10037-4.
11. *Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of Teeb*; UNEP, Ed.; The economics of ecosystems & biodiversity; UNEP: Geneva, 2010; ISBN 978-3-9813410-3-4.
12. Costanza, R.; De Groot, R.; Braat, L.; Kubiszewski, I.; Fioramonti, L.; Sutton, P.; Farber, S.; Grasso, M. Twenty Years of Ecosystem Services: How Far Have We Come and How Far Do We Still Need to Go? *Ecosyst. Serv.* **2017**, *28*, 1–16, doi:10.1016/j.ecoser.2017.09.008.

13. Kolokotsa, D.; Lilli, A.A.; Lilli, M.A.; Nikolaidis, N.P. On the Impact of Nature-Based Solutions on Citizens' Health & Well Being. *Energy Build.* **2020**, *229*, 110527, doi:10.1016/j.enbuild.2020.110527.
14. *Nature-Based Solutions for Water*; UNESCO, Ed.; The United Nations world water development report; UNESCO: Paris, 2018; ISBN 978-92-3-100264-9.
15. Poortinga, A.; Nguyen, Q.; Tenneson, K.; Troy, A.; Saah, D.; Bhandari, B.; Ellenburg, W.L.; Aekakkararungroj, A.; Ha, L.; Pham, H.; et al. Linking Earth Observations for Assessing the Food Security Situation in Vietnam: A Landscape Approach. *Front. Environ. Sci.* **2019**, *7*, 186, doi:10.3389/fenvs.2019.00186.
16. Savenije, H.H.G. New Definitions for Moisture Recycling and the Relationship with Land-Use Changes in the Sahel. *J. Hydrol.* **1995**, *167*, 57–78, doi:10.1016/0022-1694(94)02632-L.
17. Uhlenbrook, S.; Yu, W.; Schmitter, P.; Smith, D.M. Optimising the Water We Eat—Rethinking Policy to Enhance Productive and Sustainable Use of Water in Agri-Food Systems across Scales. *Lancet Planet. Health* **2022**, *6*, e59–e65, doi:10.1016/S2542-5196(21)00264-3.
18. Hauck, J.; Görg, C.; Varjopuro, R.; Ratamäki, O.; Jax, K. Benefits and Limitations of the Ecosystem Services Concept in Environmental Policy and Decision Making: Some Stakeholder Perspectives. *Environ. Sci. Policy* **2013**, *25*, 13–21, doi:10.1016/j.envsci.2012.08.001.
19. Maltby, L.; Van Den Brink, P.J.; Faber, J.H.; Marshall, S. Advantages and Challenges Associated with Implementing an Ecosystem Services Approach to Ecological Risk Assessment for Chemicals. *Sci. Total Environ.* **2018**, *621*, 1342–1351, doi:10.1016/j.scitotenv.2017.10.094.
20. Karimi, P.; Bastiaanssen, W.G.M.; Molden, D. Water Accounting Plus (WA+) – a Water Accounting Procedure for Complex River Basins Based on Satellite Measurements. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 2459–2472, doi:10.5194/hess-17-2459-2013.
21. Sangha, K.K.; Gordon, I.J.; Costanza, R. Ecosystem Services and Human Wellbeing-Based Approaches Can Help Transform Our Economies. *Front. Ecol. Evol.* **2022**, *10*, 841215, doi:10.3389/fevo.2022.841215.
22. *Accounting for Ecosystems and Their Services in the European Union (INCA) Final Report from Phase II of the INCA Project Aiming to Develop a Pilot for an Integrated System of Ecosystem Accounts for the EU*; 2021 edition.; Publications Office of the European Union: Luxembourg, 2021; ISBN 978-92-76-17401-1.
23. Schröter, M.; Albert, C.; Marques, A.; Tobon, W.; Lavorel, S.; Maes, J.; Brown, C.; Klotz, S.; Bonn, A. National Ecosystem Assessments in Europe: A Review. *BioScience* **2016**, *66*, 813–828, doi:10.1093/biosci/biw101.
24. Institute of Chartered Accountants in England and Wales *Improving the Natural Capital Data Flow Between Governments and Businesses in the EU*; European Valuing Nature Programme and Network Project (EU-VNP-Net); 2022; p. 60;.
25. Almeida, A.P.; Liberalesso, T.; Silva, C.M.; Sousa, V. Combining Green Roofs and Rainwater Harvesting Systems in University Buildings under Different

Climate Conditions. *Sci. Total Environ.* **2023**, *887*, 163719, doi:10.1016/j.scitotenv.2023.163719.
26. Johnson, B.A.; Kumar, P.; Okano, N.; Dasgupta, R.; Shivakoti, B.R. Nature-Based Solutions for Climate Change Adaptation: A Systematic Review of Systematic Reviews. *Nat.-Based Solut.* **2022**, *2*, 100042, doi:10.1016/j.nbsj.2022.100042.
27. Asian Development Bank *Technical Assistance Number 9461: Completion Report on Protecting and Investing in Natural Capital in Asia and the Pacific*; Project Number: 50159-001; 2023; p. 13;.
28. Truong, D.D. Impacts of Payment for Forest Environmental Service Policy in Vietnam: A Case Study of Muong Nhe Protected Area. *Trees For. People* **2022**, *7*, 100198, doi:10.1016/j.tfp.2022.100198.
29. Winrock International *Vietnam Forests and Deltas Program*; Hanoi, Vietnam, 2020; p. 1;.
30. SNV Viet Nam Nature-Based Solutions for Adaptation in Agriculture through Private Sector Transformation (VN-ADAPT) Available online: https://www.snv.org/project/viet-nam-nature-based-solutions-for-adaptation-in-agriculture (accessed on 11 August 2024).
31. van der Ent, R.J.; Savenije, H.H.G.; Schaefli, B.; Steele-Dunne, S.C. Origin and Fate of Atmospheric Moisture over Continents. *Water Resour. Res.* **2010**, *46*, doi:10.1029/2010WR009127.
32. Grizzetti, B.; Lanzanova, D.; Liquete, C.; Reynaud, A.; Cardoso, A.C. Assessing Water Ecosystem Services for Water Resource Management. *Environ. Sci. Policy* **2016**, *61*, 194–203, doi:10.1016/j.envsci.2016.04.008.
33. Maes, J.; Liquete, C.; Teller, A.; Erhard, M.; Paracchini, M.L.; Barredo, J.I.; Grizzetti, B.; Cardoso, A.; Somma, F.; Petersen, J.-E.; et al. An Indicator Framework for Assessing Ecosystem Services in Support of the EU Biodiversity Strategy to 2020. *Ecosyst. Serv.* **2016**, *17*, 14–23, doi:10.1016/j.ecoser.2015.10.023.
34. CGIAR Research Program on Water, Land and Ecosystems (WLE) *Ecosystem Services and Resilience Framework*; International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE): Colombo, Sri Lanka, 2014; p. 46;.
35. Bergamini, N.; Dunbar, W.; Eyzaguirre, P.B.; Ichikawa, K.; Matsumoto, I.; Mijatović, D.M.; Morimoto, Y.; Remple, N.; Salvemini, D.; Suzuki, W.; et al. Toolkit for the Indicators of Resilience in Socio-Ecological Production Landscapes and Seascapes.; 2014.
36. Hills, T.; Pramova, E.; Neufeldt, H.; Ericksen, P.; Thornton, P.K.; Noble, A.D.; Weight, E.; Campbell, B.M.; McCartney, M.P. *A Monitoring Instrument for Resilience*; CCAFS Working Paper no. 96; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS): Copenhagen, Denmark, 2015;

37. Bastiaanssen, W.G.M. *Water accountants: de nieuwe generatie waterbeheercontroleurs*; Inaugural Address; Delft University of Technology: Delft, The Netherlands, 2009; p. 16;.
38. Karimi, P.; Bastiaanssen, W.G.M.; Molden, D. Water Accounting Plus (WA+) &Ndash; a Water Accounting Procedure for Complex River Basins Based on Satellite Measurements. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 2459–2472, doi:10.5194/hess-17-2459-2013.
39. Poff, N.L.; Richter, B.D.; Arthington, A.H.; Bunn, S.E.; Naiman, R.J.; Kendy, E.; Acreman, M.; Apse, C.; Bledsoe, B.P.; Freeman, M.C.; et al. The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards: Ecological Limits of Hydrologic Alteration. *Freshw. Biol.* **2010**, *55*, 147–170, doi:10.1111/j.1365-2427.2009.02204.x.
40. Tallis, H.; Polasky, S. Mapping and Valuing Ecosystem Services as an Approach for Conservation and Natural-Resource Management. *Ann. N. Y. Acad. Sci.* **2009**, *1162*, 265–283, doi:10.1111/j.1749-6632.2009.04152.x.
41. Villa, F.; Athanasiadis, I.N.; Rizzoli, A.E. Modelling with Knowledge: A Review of Emerging Semantic Approaches to Environmental Modelling. *Environ. Model. Softw.* **2009**, *24*, 577–587, doi:10.1016/j.envsoft.2008.09.009.
42. Molden, D.; Oweis, T.; Steduto, P.; Bindraban, P.; Hanjra, M.A.; Kijne, J. Improving Agricultural Water Productivity: Between Optimism and Caution. *Agric. Water Manag.* **2010**, *97*, 528–535, doi:10.1016/j.agwat.2009.03.023.
43. Johnson, G.W.; Bagstad, K.J.; Snapp, R.R.; Villa, F. Service Path Attribution Networks (SPANs): Spatially Quantifying the Flow of Ecosystem Services from Landscapes to People. In *Computational Science and Its Applications – ICCSA 2010*; Taniar, D., Gervasi, O., Murgante, B., Pardede, E., Apduhan, B.O., Eds.; Lecture Notes in Computer Science; Springer Berlin Heidelberg: Berlin, Heidelberg, 2010; Vol. 6016, pp. 238–253 ISBN 978-3-642-12155-5.
44. Nasseri, M.; Schoups, G.; Taheri, M. A Spatiotemporal Framework to Calibrate High-Resolution Global Monthly Precipitation Products: An Application to the Urmia Lake Watershed in Iran. *Int. J. Climatol.* **2022**, *42*, 2169–2194, doi:10.1002/joc.7358.
45. Simons, G.; Poortinga, A.; Bastiaanssen, W.G.M.; Saah, D.S.; Troy, D.; Hunink, J.E.; Klerk, M. de; Rutten, M.; Cutter, P.; Rebelo, L.-M.; et al. On Spatially Distributed Hydrological Ecosystem Services: Bridging the Quantitative Information Gap Using Remote Sensing and Hydrological Models.; 2017.
46. Gholizadeh, M.; Melesse, A.; Reddi, L. A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors* **2016**, *16*, 1298, doi:10.3390/s16081298.
47. Winsemius, H.C.; Savenije, H.H.G.; Bastiaanssen, W.G.M. Constraining Model Parameters on Remotely Sensed Evaporation: Justification for Distribution in Ungauged Basins? *Hydrol Earth Syst Sci 12 1403-1413* **2008**, doi:https://doi.org/10.5194/hess-12-1403-2008, 2008.

48. Jin, G.; Deng, X.; Hasan, S.S.; Zhao, C.; Gibson, J. Hydrological Ecosystem Services for Integrated Water Resources Management. In *River Basin Management*; Deng, X., Gibson, J., Eds.; Ecohydrology; Springer Singapore: Singapore, 2018; pp. 1–27 ISBN 978-981-10-0841-2.
49. Bagstad, K.J.; Johnson, G.W.; Voigt, B.; Villa, F. Spatial Dynamics of Ecosystem Service Flows: A Comprehensive Approach to Quantifying Actual Services. *Ecosyst. Serv.* **2013**, *4*, 117–125, doi:10.1016/j.ecoser.2012.07.012.
50. Terrado, M.; Momblanch, A.; Bardina, M.; Boithias, L.; Munné, A.; Sabater, S.; Solera, A.; Acuña, V. Integrating Ecosystem Services in River Basin Management Plans. *J. Appl. Ecol.* **2016**, *53*, 865–875, doi:10.1111/1365-2664.12613.
51. Bastiaanssen, W.G.M.; Allen, R.G.; Droogers, P.; D'Urso, G.; Steduto, P. Twenty-Five Years Modeling Irrigated and Drained Soils: State of the Art. *Agric. Water Manag.* **2007**, *92*, 111–125, doi:10.1016/j.agwat.2007.05.013.
52. Nedkov, S.; Campagne, S.; Borisova, B.; Krpec, P.; Prodanova, H.; Kokkoris, I.P.; Hristova, D.; Le Clec'h, S.; Santos-Martin, F.; Burkhard, B.; et al. Modeling Water Regulation Ecosystem Services: A Review in the Context of Ecosystem Accounting. *Ecosyst. Serv.* **2022**, *56*, 101458, doi:10.1016/j.ecoser.2022.101458.
53. Crossman, N.D.; Burkhard, B.; Nedkov, S.; Willemen, L.; Petz, K.; Palomo, I.; Drakou, E.G.; Martín-Lopez, B.; McPhearson, T.; Boyanova, K.; et al. A Blueprint for Mapping and Modelling Ecosystem Services. *Ecosyst. Serv.* **2013**, *4*, 4–14, doi:10.1016/j.ecoser.2013.02.001.
54. Schulp, C.J.E.; Alkemade, R.; Klein Goldewijk, K.; Petz, K. Mapping Ecosystem Functions and Services in Eastern Europe Using Global-Scale Data Sets. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2012**, *8*, 156–168, doi:10.1080/21513732.2011.645880.
55. Ha, L.T.; Bastiaanssen, W.G.M.; Van Griensven, A.; Van Dijk, A.I.J.M.; Senay, G.B. 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* **2018**, *10*, doi:10.3390/w10020212.
56. Neitsch, S.; Arnold, J.; Kiniry, J.; Williams, J.R. Soil and Water Asessment Tool Theoritical Documentation: Version 2009, Texas Water Resources Institute Technical Report No. 406. Texas Water Resources Institute, Texas A&M University, Texas. *USA* **2011**.
57. Villa, F.; Bagstad, K.J.; Voigt, B.; Johnson, G.W.; Portela, R.; Honzák, M.; Batker, D. A Methodology for Adaptable and Robust Ecosystem Services Assessment. *PLoS ONE* **2014**, *9*, e91001, doi:10.1371/journal.pone.0091001.
58. Leh, M.D.K.; Matlock, M.D.; Cummings, E.C.; Nalley, L.L. Quantifying and Mapping Multiple Ecosystem Services Change in West Africa. *Agric. Ecosyst. Environ.* **2013**, *165*, 6–18, doi:10.1016/j.agee.2012.12.001.

59. Hoyer, R.; Chang, H. Assessment of Freshwater Ecosystem Services in the Tualatin and Yamhill Basins under Climate Change and Urbanization. *Appl. Geogr.* **2014**, *53*, 402–416, doi:10.1016/j.apgeog.2014.06.023.
60. Terrado, M.; Acuña, V.; Ennaanay, D.; Tallis, H.; Sabater, S. Impact of Climate Extremes on Hydrological Ecosystem Services in a Heavily Humanized Mediterranean Basin. *Ecol. Indic.* **2014**, *37*, 199–209, doi:10.1016/j.ecolind.2013.01.016.
61. Brauman, K.A.; Daily, G.C.; Duarte, T.K.; Mooney, H.A. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. *Annu. Rev. Environ. Resour.* **2007**, *32*, 67–98, doi:10.1146/annurev.energy.32.031306.102758.
62. Belmar, O.; Ibáñez, C.; Forner, A.; Caiola, N. The Influence of Flow Regime on Ecological Quality, Bird Diversity, and Shellfish Fisheries in a Lowland Mediterranean River and Its Coastal Area. *Water* **2019**, *11*, 918, doi:10.3390/w11050918.
63. Pan, F.; Choi, W. A Conceptual Modeling Framework for Hydrologic Ecosystem Services. *Hydrology* **2019**, *6*, 14, doi:10.3390/hydrology6010014.
64. Gao, J.; Li, F.; Gao, H.; Zhou, C.; Zhang, X. The Impact of Land-Use Change on Water-Related Ecosystem Services: A Study of the Guishui River Basin, Beijing, China. *J. Clean. Prod.* **2017**, *163*, S148–S155, doi:10.1016/j.jclepro.2016.01.049.
65. Willaarts, B.A.; Volk, M.; Aguilera, P.A. Assessing the Ecosystem Services Supplied by Freshwater Flows in Mediterranean Agroecosystems. *Agric. Water Manag.* **2012**, *105*, 21–31, doi:10.1016/j.agwat.2011.12.019.
66. Bangash, R.F.; Passuello, A.; Sanchez-Canales, M.; Terrado, M.; López, A.; Elorza, F.J.; Ziv, G.; Acuña, V.; Schuhmacher, M. Ecosystem Services in Mediterranean River Basin: Climate Change Impact on Water Provisioning and Erosion Control. *Sci. Total Environ.* **2013**, *458–460*, 246–255, doi:10.1016/j.scitotenv.2013.04.025.
67. Fan, M.; Shibata, H.; Wang, Q. Optimal Conservation Planning of Multiple Hydrological Ecosystem Services under Land Use and Climate Changes in Teshio River Watershed, Northernmost of Japan. *Ecol. Indic.* **2016**, *62*, 1–13, doi:10.1016/j.ecolind.2015.10.064.
68. Costanza, R.; d'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; et al. The Value of the World's Ecosystem Services and Natural Capital. *Ecol. Econ.* **1998**, *25*, 3–15, doi:10.1016/S0921-8009(98)00020-2.
69. Hansen, R.; Frantzeskaki, N.; McPhearson, T.; Rall, E.; Kabisch, N.; Kaczorowska, A.; Kain, J.-H.; Artmann, M.; Pauleit, S. The Uptake of the Ecosystem Services Concept in Planning Discourses of European and American Cities. *Ecosyst. Serv.* **2015**, *12*, 228–246, doi:10.1016/j.ecoser.2014.11.013.
70. Abbas, A.; Zhao, C.; Waseem, M.; Ahmed khan, K.; Ahmad, R. Analysis of Energy Input–Output of Farms and Assessment of Greenhouse Gas Emissions:

A Case Study of Cotton Growers. *Front. Environ. Sci.* **2022**, *9*, 826838, doi:10.3389/fenvs.2021.826838.

71. McCartney, M.; Cai, X.; Smakhtin, V. *Evaluating the Flow Regulating Functions of Natural Ecosystems in the Zambezi Basin*; International Water Management Institute (IWMI)., 2013;
72. Bastiaanssen, W.; Karimi, P.; Rebelo, L.-M.; Duan, Z.; Senay, G.; Muttuwatte, L.; Smakhtin, V. Earth Observation Based Assessment of the Water Production and Water Consumption of Nile Basin Agro-Ecosystems. *Remote Sens.* **2014**, *6*, 10306–10334, doi:10.3390/rs61110306.
73. Hoekstra, A.Y.; Mekonnen, M.M.; Chapagain, A.K.; Mathews, R.E.; Richter, B.D. Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability. *PLoS ONE* **2012**, *7*, e32688, doi:10.1371/journal.pone.0032688.
74. Kiptala, J.K.; Mohamed, Y.; Mul, M.L.; Van der Zaag, P. Mapping Evapotranspiration Trends Using MODIS and SEBAL Model in a Data Scarce and Heterogeneous Landscape in Eastern Africa: Mapping ET Using Modis and Sebal in a Landscape in E. Africa. *Water Resour. Res.* **2013**, *49*, 8495–8510, doi:10.1002/2013WR014240.
75. Perry, C.; Steduto, P.; Allen, Richard.G.; Burt, C.M. Increasing Productivity in Irrigated Agriculture: Agronomic Constraints and Hydrological Realities. *Agric. Water Manag.* **2009**, *96*, 1517–1524, doi:10.1016/j.agwat.2009.05.005.
76. Poortinga, A.; Bastiaanssen, W.; Simons, G.; Saah, D.; Senay, G.; Fenn, M.; Bean, B.; Kadyszewski, J. A Self-Calibrating Runoff and Streamflow Remote Sensing Model for Ungauged Basins Using Open-Access Earth Observation Data. *Remote Sens.* **2017**, *9*, 86, doi:10.3390/rs9010086.
77. van Eekelen, M.W.; Bastiaanssen, W.G.M.; Jarmain, C.; Jackson, B.; Ferreira, F.; van der Zaag, P.; Saraiva Okello, A.; Bosch, J.; Dye, P.; Bastidas-Obando, E.; et al. A Novel Approach to Estimate Direct and Indirect Water Withdrawals from Satellite Measurements: A Case Study from the Incomati Basin. *Agric. Ecosyst. Environ.* **2015**, *200*, 126–142, doi:10.1016/j.agee.2014.10.023.
78. Cheema, M.J.M.; Bastiaanssen, W.G.M. Land Use and Land Cover Classification in the Irrigated Indus Basin Using Growth Phenology Information from Satellite Data to Support Water Management Analysis. *Agric. Water Manag.* **2010**, *97*, 1541–1552, doi:10.1016/j.agwat.2010.05.009.
79. Mohd Zad, S.; Zulkafli, Z.; Muharram, F. Satellite Rainfall (TRMM 3B42-V7) Performance Assessment and Adjustment over Pahang River Basin, Malaysia. *Remote Sens.* **2018**, *10*, 388, doi:10.3390/rs10030388.
80. Paca, V.H. da M.; Espinoza-Dávalos, G.E.; Hessels, T.M.; Moreira, D.M.; Comair, G.F.; Bastiaanssen, W.G.M. The Spatial Variability of Actual Evapotranspiration across the Amazon River Basin Based on Remote Sensing Products Validated with Flux Towers. *Ecol. Process.* **2019**, *8*, 6, doi:10.1186/s13717-019-0158-8.
81. Sriwongsitanon, N.; Suwawong, T.; Thianpopirug, S.; Williams, J.; Jia, L.; Bastiaanssen, W. Validation of Seven Global Remotely Sensed ET Products

across Thailand Using Water Balance Measurements and Land Use Classifications. *J. Hydrol. Reg. Stud.* **2020**, *30*, 100709, doi:10.1016/j.ejrh.2020.100709.
82. Simons, G.W.H.; Bastiaanssen, W.G.M.; Cheema, M.J.M.; Ahmad, B.; Immerzeel, W.W. A Novel Method to Quantify Consumed Fractions and Non-Consumptive Use of Irrigation Water: Application to the Indus Basin Irrigation System of Pakistan. *Agric. Water Manag.* **2020**, *236*, 106174, doi:10.1016/j.agwat.2020.106174.
83. Troch, P.; Durcik, M.; Seneviratne, S.; Hirschi, M.; Teuling, A.; Hurkmans, R.; Hasan, S. New Data Sets to Estimate Terrestrial Water Storage Change. *Eos Trans. Am. Geophys. Union* **2007**, *88*, 469–470, doi:10.1029/2007EO450001.
84. *AQUASTAT FAO's Information System on Water and Agriculture*; FAO,: [Rome] :, 2021;
85. Froese, R.; Pauly, D. FishBase. World Wide Web Electronic Publication.; 2014.
86. FAO *The State of World Fisheries and Aquaculture 2020*; FAO, 2020; ISBN 978-92-5-132692-3.
87. Welcomme, R.L. An Overview of Global Catch Statistics for Inland Fish. *ICES J. Mar. Sci.* **2011**, *68*, 1751–1756, doi:10.1093/icesjms/fsr035.
88. Acharya, T.D.; Subedi, A.; Lee, D.H. Evaluation of Water Indices for Surface Water Extraction in a Landsat 8 Scene of Nepal. *Sensors* **2018**, *18*, doi:10.3390/s18082580.
89. Huang, C.; Chen, Y.; Zhang, S.; Wu, J. Detecting, Extracting, and Monitoring Surface Water From Space Using Optical Sensors: A Review. *Rev. Geophys.* **2018**, *56*, 333–360, doi:10.1029/2018RG000598.
90. Pekel, J.-F.; Cottam, A.; Gorelick, N.; Belward, A.S. High-Resolution Mapping of Global Surface Water and Its Long-Term Changes. *Nature* **2016**, *540*, 418–422, doi:10.1038/nature20584.
91. Rebelo, L.-M.; Finlayson, C.M.; Strauch, A.; Rosenqvist, A.; Perennou, C.; Tøttrup, C.; Hilarides, L.; Paganini, M.; Wielaard, N.; Siegert, F.; et al. *The Use of Earth Observation for Wetland Inventory, Assessment and Monitoring*; An information source for Ramsar Convention on Wetlands; Secretariat of the Ramsar Convention: Switzerland, 2018; Vol. 10;.
92. Donlon, C.; Berruti, B.; Buongiorno, A.; Ferreira, M.-H.; Féménias, P.; Frerick, J.; Goryl, P.; Klein, U.; Laur, H.; Mavrocordatos, C.; et al. The Global Monitoring for Environment and Security (GMES) Sentinel-3 Mission. *Remote Sens. Environ.* **2012**, *120*, 37–57, doi:10.1016/j.rse.2011.07.024.
93. Lucas, R.; Rebelo, L.-M.; Fatoyinbo, L.; Rosenqvist, A.; Itoh, T.; Shimada, M.; Simard, M.; Souza-Filho, P.W.; Thomas, N.; Trettin, C.; et al. Contribution of L-Band SAR to Systematic Global Mangrove Monitoring. *Mar. Freshw. Res.* **2014**, *65*, 589, doi:10.1071/MF13177.
94. Hortle, K.G.; Bamrungrach, P. *Fisheries Habitat and Yield in the Lower Mekong River Basin: Technical Paper No.47*; Mekong River Commission Secretariat: Vientiane, Lao PDR, 2015;

95. Reinermann, S.; Asam, S.; Kuenzer, C. Remote Sensing of Grassland Production and Management—A Review. *Remote Sens.* **2020**, *12*, 1949, doi:10.3390/rs12121949.
96. Monteith, J.L. Solar Radiation and Productivity in Tropical Ecosystems. *J. Appl. Ecol.* **1972**, *9*, 747, doi:10.2307/2401901.
97. Gómez, S.; Guenni, O.; Bravo de Guenni, L. Growth, Leaf Photosynthesis and Canopy Light Use Efficiency under Differing Irradiance and Soil N Supplies in the Forage Grass *Brachiaria Decumbens* Stapf. *Grass Forage Sci.* **2013**, *68*, 395–407, doi:10.1111/gfs.12002.
98. *Simple Technologies for Charcoal Making*; FAO, Ed.; FAO forestry paper; Food and Agriculture Organization of the United Nations: Rome, 1983; ISBN 978-92-5-101328-1.
99. Ahl, D.E.; Gower, S.T.; Mackay, D.S.; Burrows, S.N.; Norman, J.M.; Diak, G.R. Heterogeneity of Light Use Efficiency in a Northern Wisconsin Forest: Implications for Modeling Net Primary Production with Remote Sensing. *Remote Sens. Environ.* **2004**, *93*, 168–178, doi:10.1016/j.rse.2004.07.003.
100. Trischler, J.; Sandberg, D.; Thörnqvist, T. Estimating the Annual Above-Ground Biomass Production of Various Species on Sites in Sweden on the Basis of Individual Climate and Productivity Values. *Forests* **2014**, *5*, 2521–2541, doi:10.3390/f5102521.
101. Pukkala, T.; Pohjonen, V. Yield Models for Eucalyptus Globulus Fuelwood Plantations in Ethiopia. *Biomass* **1990**, *21*, 129–143, doi:10.1016/0144-4565(90)90054-N.
102. Boegh, E.; Thorsen, M.; Butts, M.B.; Hansen, S.; Christiansen, J.S.; Abrahamsen, P.; Hasager, C.B.; Jensen, N.O.; van der Keur, P.; Refsgaard, J.C.; et al. Incorporating Remote Sensing Data in Physically Based Distributed Agro-Hydrological Modelling. *J. Hydrol.* **2004**, *287*, 279–299, doi:10.1016/j.jhydrol.2003.10.018.
103. Running, S.W.; Nemani, R.R.; Hungerford, R.D. Extrapolation of Synoptic Meteorological Data in Mountainous Terrain and Its Use for Simulating Forest Evapotranspiration and Photosynthesis. *Can. J. For. Res.* **1987**, *17*, 472–483, doi:10.1139/x87-081.
104. Yang, K.; Li, M.; Liu, Y.; Cheng, L.; Duan, Y.; Zhou, M. River Delineation from Remotely Sensed Imagery Using a Multi-Scale Classification Approach. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2014**, *7*, 4726–4737, doi:10.1109/JSTARS.2014.2309707.
105. Donchyts, G.; Schellekens, J.; Winsemius, H.; Eisemann, E.; Van de Giesen, N. A 30 m Resolution Surface Water Mask Including Estimation of Positional and Thematic Differences Using Landsat 8, SRTM and OpenStreetMap: A Case Study in the Murray-Darling Basin, Australia. *Remote Sens.* **2016**, *8*, doi:10.3390/rs8050386.
106. Bjerklie, D.M.; Birkett, C.M.; Jones, J.W.; Carabajal, C.; Rover, J.A.; Fulton, J.W.; Garambois, P.-A. Satellite Remote Sensing Estimation of River Discharge:

Application to the Yukon River Alaska. *J. Hydrol.* **2018**, *561*, 1000–1018, doi:10.1016/j.jhydrol.2018.04.005.
107. Durand, M.; Gleason, C.J.; Garambois, P.A.; Bjerklie, D.; Smith, L.C.; Roux, H.; Rodriguez, E.; Bates, P.D.; Pavelsky, T.M.; Monnier, J.; et al. An Intercomparison of Remote Sensing River Discharge Estimation Algorithms from Measurements of River Height, Width, and Slope. *Water Resour. Res.* **2016**, *52*, 4527–4549, doi:10.1002/2015WR018434.
108. Michailovsky, C.I.; Bauer-Gottwein, P. Operational Reservoir Inflow Forecasting with Radar Altimetry: The Zambezi Case Study. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 997–1007, doi:10.5194/hess-18-997-2014.
109. Schwatke, C.; Dettmering, D.; Bosch, W.; Seitz, F. DAHITI – an Innovative Approach for Estimating Water Level Time Series over Inland Waters Using Multi-Mission Satellite Altimetry. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 4345–4364, doi:10.5194/hess-19-4345-2015.
110. Simons, G.; Droogers, P.; Contreras, S.; Sieber, J.; Bastiaanssen, W. Virtual Tracers to Detect Sources of Water and Track Water Reuse across a River Basin. *Water* **2020**, *12*, 2315, doi:10.3390/w12082315.
111. Xu, Y.; Beekman, H.E. Review: Groundwater Recharge Estimation in Arid and Semi-Arid Southern Africa. *Hydrogeol. J.* **2019**, *27*, 929–943, doi:10.1007/s10040-018-1898-8.
112. Wohling, D.; Petheram, C.; Leaney, F.; Jolly, I.; Crosbie, R. Review of Australian Groundwater Recharge Studies. **2010**, doi:10.4225/08/58503A7F5AAD4.
113. Hessels, T.; Davids, J.C.; Bastiaanssen, W. Scalable Water Balances from Earth Observations (SWEO): Results from 50 Years of Remote Sensing in Hydrology. *Water Int.* **2022**, *47*, 866–886, doi:10.1080/02508060.2022.2117896.
114. Guo, M.; Li, J.; Sheng, C.; Xu, J.; Wu, L. A Review of Wetland Remote Sensing. *Sensors* **2017**, *17*, 777, doi:10.3390/s17040777.
115. Duan, Z.; Bastiaanssen, W.G.M. Evaluation of Three Energy Balance-Based Evaporation Models for Estimating Monthly Evaporation for Five Lakes Using Derived Heat Storage Changes from a Hysteresis Model. *Environ. Res. Lett.* **2017**, *12*, 024005, doi:10.1088/1748-9326/aa568e.
116. Hillel, D.; van Bavel, C.H.M. Simulation of Profile Water Storage as Related to Soil Hydraulic Properties. *Soil Sci. Soc. Am. J.* **1976**, *40*, 807–815, doi:10.2136/sssaj1976.03615995004000060009x.
117. Wang-Erlandsson, L.; Bastiaanssen, W.G.M.; Gao, H.; Jägermeyr, J.; Senay, G.B.; van Dijk, A.I.J.M.; Guerschman, J.P.; Keys, P.W.; Gordon, L.J.; Savenije, H.H.G. Global Root Zone Storage Capacity from Satellite-Based Evaporation. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 1459–1481, doi:10.5194/hess-20-1459-2016.
118. Jackson, T.J.; Le Vine, D.M.; Hsu, A.Y.; Oldak, A.; Starks, P.J.; Swift, C.T.; Isham, J.D.; Haken, M. Soil Moisture Mapping at Regional Scales Using Microwave Radiometry: The Southern Great Plains Hydrology Experiment. *IEEE Trans. Geosci. Remote Sens.* **1999**, *37*, 2136–2151, doi:10.1109/36.789610.

119. Schmugge, T.J.; Meneely, J.M.; Rango, A.; Neff, R. Satellite Microwave Observations of Soil Moisture Variations. *J. Am. Water Resour. Assoc.* **1977**, *13*, 265–282, doi:10.1111/j.1752-1688.1977.tb02023.x.
120. Woodhouse, I.H. *Introduction to Microwave Remote Sensing*; 1st ed.; CRC Press, 2017; ISBN 978-1-315-27257-3.
121. Owe, M.; de Jeu, R.; Walker, J. A Methodology for Surface Soil Moisture and Vegetation Optical Depth Retrieval Using the Microwave Polarization Difference Index. *IEEE Trans. Geosci. Remote Sens.* **2001**, *39*, 1643–1654, doi:10.1109/36.942542.
122. Hain, C.R.; Crow, W.T.; Mecikalski, J.R.; Anderson, M.C.; Holmes, T. An Intercomparison of Available Soil Moisture Estimates from Thermal Infrared and Passive Microwave Remote Sensing and Land Surface Modeling. *J. Geophys. Res.* **2011**, *116*, D15107, doi:10.1029/2011JD015633.
123. Neale, C.M.U.; Geli, H.M.E.; Kustas, W.P.; Alfieri, J.G.; Gowda, P.H.; Evett, S.R.; Prueger, J.H.; Hipps, L.E.; Dulaney, W.P.; Chávez, J.L.; et al. Soil Water Content Estimation Using a Remote Sensing Based Hybrid Evapotranspiration Modeling Approach. *Adv. Water Resour.* **2012**, *50*, 152–161, doi:10.1016/j.advwatres.2012.10.008.
124. Scott, R. The Understory and Overstory Partitioning of Energy and Water Fluxes in an Open Canopy, Semiarid Woodland. *Agric. For. Meteorol.* **2003**, *114*, 127–139, doi:10.1016/S0168-1923(02)00197-1.
125. Hu, G.; Jia, L. Monitoring of Evapotranspiration in a Semi-Arid Inland River Basin by Combining Microwave and Optical Remote Sensing Observations. *Remote Sens.* **2015**, *7*, 3056–3087, doi:10.3390/rs70303056.
126. Carlson, T.N.; Petropoulos, G.P. A New Method for Estimating of Evapotranspiration and Surface Soil Moisture from Optical and Thermal Infrared Measurements: The Simplified Triangle. *Int. J. Remote Sens.* **2019**, *40*, 7716–7729, doi:10.1080/01431161.2019.1601288.
127. Yang, Y.; Guan, H.; Long, D.; Liu, B.; Qin, G.; Qin, J.; Batelaan, O. Estimation of Surface Soil Moisture from Thermal Infrared Remote Sensing Using an Improved Trapezoid Method. *Remote Sens.* **2015**, *7*, 8250–8270, doi:10.3390/rs70708250.
128. FAO *WaPOR V2 Quality Assessment – Technical Report on the Data Quality of the WaPOR FAO Database Version 2*; FAO, 2020; ISBN 978-92-5-133654-0.
129. Kunstmann, H.; Jung, G. Influence of Soil-moisture and Land Use Change on Precipitation in the Volta Basin of West Africa. *Int. J. River Basin Manag.* **2007**, *5*, 9–16, doi:10.1080/15715124.2007.9635301.
130. Abbas, A.; Waseem, M.; Ahmad, R.; khan, K.A.; Zhao, C.; Zhu, J. Sensitivity Analysis of Greenhouse Gas Emissions at Farm Level: Case Study of Grain and Cash Crops. *Environ. Sci. Pollut. Res.* **2022**, *29*, 82559–82573, doi:10.1007/s11356-022-21560-9.
131. Elahi, E.; Khalid, Z.; Tauni, M.Z.; Zhang, H.; Lirong, X. Extreme Weather Events Risk to Crop-Production and the Adaptation of Innovative Management

Strategies to Mitigate the Risk: A Retrospective Survey of Rural Punjab, Pakistan. *Technovation* **2022**, *117*, 102255, doi:10.1016/j.technovation.2021.102255.
132. Elahi, E.; Khalid, Z.; Zhang, Z. Understanding Farmers' Intention and Willingness to Install Renewable Energy Technology: A Solution to Reduce the Environmental Emissions of Agriculture. *Appl. Energy* **2022**, *309*, 118459, doi:10.1016/j.apenergy.2021.118459.
133. Rama, H.-O.; Roberts, D.; Tignor, M.; Poloczanska, E.S.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. *Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; 2022;
134. Shepherd, A.; Wu, L.; Chadwick, D.; Bol, R. A Review of Quantitative Tools for Assessing the Diffuse Pollution Response to Farmer Adaptations and Mitigation Methods Under Climate Change. In *Advances in Agronomy*; Elsevier, 2011; Vol. 112, pp. 1–54 ISBN 978-0-12-385538-1.
135. UNFCCC Report of the Conference of Parties on Its Thirteenth Session, Bali, Indonesia. 2007.
136. Khorchani, M.; Nadal-Romero, E.; Lasanta, T.; Tague, C. Carbon Sequestration and Water Yield Tradeoffs Following Restoration of Abandoned Agricultural Lands in Mediterranean Mountains. *Environ. Res.* **2022**, *207*, 112203, doi:10.1016/j.envres.2021.112203.
137. Hairiah, K. *Measuring Carbon Stocks: Across Land Use Systems: A Manual*; Published in close cooperation with Brawijaya University and ICALRRD (Indonesian Center for Agricultural Land Resources Research and Development): Malang, Indonesia, 2011; ISBN 978-979-3198-55-2.
138. Pereira, P. Ecosystem Services in a Changing Environment. *Sci. Total Environ.* **2020**, *702*, 135008, doi:10.1016/j.scitotenv.2019.135008.
139. Chen, L.; Wang, L.; Ma, Y.; Liu, P. Overview of Ecohydrological Models and Systems at the Watershed Scale. *IEEE Syst. J.* **2015**, *9*, 1091–1099, doi:10.1109/JSYST.2013.2296979.
140. Cramer, W.; Kicklighter, D.W.; Bondeau, A.; Iii, B.M.; Churkina, G.; Nemry, B.; Ruimy, A.; Schloss, A.L. Comparing Global Models of Terrestrial Net Primary Productivity (NPP): Overview and Key Results. *Glob. Change Biol.* **1999**, *5*, 1–15, doi:10.1046/j.1365-2486.1999.00009.x.
141. Field, C.B.; Randerson, J.T.; Malmström, C.M. Global Net Primary Production: Combining Ecology and Remote Sensing. *Remote Sens. Environ.* **1995**, *51*, 74–88, doi:10.1016/0034-4257(94)00066-V.
142. Eggleston, H. S, Buendia, L, Miwa, K, Ngara, T.; Tanabe, K. 2006 IPCC Guidelines for National Greenhouse Gas Inventories 2006.
143. Nayak, A.K.; Rahman, M.M.; Naidu, R.; Dhal, B.; Swain, C.K.; Nayak, A.D.; Tripathi, R.; Shahid, M.; Islam, M.R.; Pathak, H. Current and Emerging Methodologies for Estimating Carbon Sequestration in Agricultural Soils: A

Review. *Sci. Total Environ.* **2019**, *665*, 890–912, doi:10.1016/j.scitotenv.2019.02.125.
144. Sun, J.; Yue, Y.; Niu, H. Evaluation of NPP Using Three Models Compared with MODIS-NPP Data over China. *PLOS ONE* **2021**, *16*, e0252149, doi:10.1371/journal.pone.0252149.
145. Dickinson, R.E.; Cicerone, R.J. Future Global Warming from Atmospheric Trace Gases. *Nature* **1986**, *319*, 109–115, doi:10.1038/319109a0.
146. Ramanathan, V.; Cicerone, R.J.; Singh, H.B.; Kiehl, J.T. Trace Gas Trends and Their Potential Role in Climate Change. *J. Geophys. Res.* **1985**, *90*, 5547, doi:10.1029/JD090iD03p05547.
147. Mondal, B.; Bauddh, K.; Kumar, A.; Bordoloi, N. India’s Contribution to Greenhouse Gas Emission from Freshwater Ecosystems: A Comprehensive Review. *Water* **2022**, *14*, 2965, doi:10.3390/w14192965.
148. Cicerone, R.J.; Shetter, J.D. Sources of Atmospheric Methane: Measurements in Rice Paddies and a Discussion. *J. Geophys. Res.* **1981**, *86*, 7203, doi:10.1029/JC086iC08p07203.
149. Tian, H.; Xu, X.; Liu, M.; Ren, W.; Zhang, C.; Chen, G.; Lu, C. Spatial and Temporal Patterns of CH and N2O Fluxes in Terrestrial Ecosystems of North America during 1979–2008: Application of a Global Biogeochemistry Model. *Biogeosciences* **2010**, *7*, 2673–2694, doi:10.5194/bg-7-2673-2010.
150. Huang, R.; Huang, J.; Zhang, C.; Ma, H.; Zhuo, W.; Chen, Y.; Zhu, D.; Wu, Q.; Mansaray, L.R. Soil Temperature Estimation at Different Depths, Using Remotely-Sensed Data. *J. Integr. Agric.* **2020**, *19*, 277–290, doi:10.1016/S2095-3119(19)62657-2.
151. Xu, C.; Qu, J.J.; Hao, X.; Zhu, Z.; Gutenberg, L. Surface Soil Temperature Seasonal Variation Estimation in a Forested Area Using Combined Satellite Observations and In-Situ Measurements. *Int. J. Appl. Earth Obs. Geoinformation* **2020**, *91*, 102156, doi:10.1016/j.jag.2020.102156.
152. Van Woesik, F.; Steenbergen, F. van; Sambalino, F.; Jan de Boer, H.; Ricci, J.M.P.; Bastiaanssen, W. *Managing the Local Climate: How to Positively Affect the Local Climate and Agrecological Conditions with Local Interventions*; Practical Action Publishing: Rugby, United Kingdom, 2023; ISBN 978-1-78853-224-2.
153. Osann Jochum, M.A. Operational Space-Assisted Irrigation Advisory Services: Overview Of And Lessons Learned From The Project DEMETER. In Proceedings of the AIP Conference Proceedings; AIP: Naples (Italy), 2006; Vol. 852, pp. 3–13.
154. Dörnhöfer, K.; Klinger, P.; Heege, T.; Oppelt, N. Multi-Sensor Satellite and in Situ Monitoring of Phytoplankton Development in a Eutrophic-Mesotrophic Lake. *Sci. Total Environ.* **2018**, *612*, 1200–1214, doi:10.1016/j.scitotenv.2017.08.219.

155. Poddar, S.; Chacko, N.; Swain, D. Estimation of Chlorophyll-a in Northern Coastal Bay of Bengal Using Landsat-8 OLI and Sentinel-2 MSI Sensors. *Front. Mar. Sci.* **2019**, *6*, 598, doi:10.3389/fmars.2019.00598.
156. Ma, J.; Jin, S.; Li, J.; He, Y.; Shang, W. Spatio-Temporal Variations and Driving Forces of Harmful Algal Blooms in Chaohu Lake: A Multi-Source Remote Sensing Approach. *Remote Sens.* **2021**, *13*, 427, doi:10.3390/rs13030427.
157. Peppa, M.; Vasilakos, C.; Kavroudakis, D. Eutrophication Monitoring for Lake Pamvotis, Greece, Using Sentinel-2 Data. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 143, doi:10.3390/ijgi9030143.
158. Sharifi, A. Using Sentinel-2 Data to Predict Nitrogen Uptake in Maize Crop. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2020**, *13*, 2656–2662, doi:10.1109/JSTARS.2020.2998638.
159. Kanke, Y.; Tubaña, B.; Dalen, M.; Harrell, D. Evaluation of Red and Red-Edge Reflectance-Based Vegetation Indices for Rice Biomass and Grain Yield Prediction Models in Paddy Fields. *Precis. Agric.* **2016**, *17*, 507–530, doi:10.1007/s11119-016-9433-1.
160. Zhang, K.; Ge, X.; Shen, P.; Li, W.; Liu, X.; Cao, Q.; Zhu, Y.; Cao, W.; Tian, Y. Predicting Rice Grain Yield Based on Dynamic Changes in Vegetation Indexes during Early to Mid-Growth Stages. *Remote Sens.* **2019**, *11*, 387, doi:10.3390/rs11040387.
161. Pereira, P.; Bogunovic, I.; Muñoz-Rojas, M.; Brevik, E.C. Soil Ecosystem Services, Sustainability, Valuation and Management. *Curr. Opin. Environ. Sci. Health* **2018**, *5*, 7–13, doi:10.1016/j.coesh.2017.12.003.
162. Dang, Y.; Ren, W.; Tao, B.; Chen, G.; Lu, C.; Yang, J.; Pan, S.; Wang, G.; Li, S.; Tian, H. Climate and Land Use Controls on Soil Organic Carbon in the Loess Plateau Region of China. *PLoS ONE* **2014**, *9*, e95548, doi:10.1371/journal.pone.0095548.
163. Williams, J.R.; others The EPIC Model. *Comput. Models Watershed Hydrol.* **1995**, 909–1000.
164. Schaake, J.C.; Koren, V.I.; Duan, Q.-Y.; Mitchell, K.; Chen, F. Simple Water Balance Model for Estimating Runoff at Different Spatial and Temporal Scales. *J. Geophys. Res. Atmospheres* **1996**, *101*, 7461–7475, doi:10.1029/95JD02892.
165. Xue, J.; Gui, D.; Zhao, Y.; Lei, J.; Feng, X.; Zeng, F.; Zhou, J.; Mao, D. Quantification of Environmental Flow Requirements to Support Ecosystem Services of Oasis Areas: A Case Study in Tarim Basin, Northwest China. *Water* **2015**, *7*, 5657–5675, doi:10.3390/w7105657.
166. Smakhtin, V.; Revenga, C.; Döll, P. A Pilot Global Assessment of Environmental Water Requirements and Scarcity. *Water Int.* **2004**, *29*, 307–317, doi:10.1080/02508060408691785.
167. Winsemius, H.C.; Schaefli, B.; Montanari, A.; Savenije, H.H.G. On the Calibration of Hydrological Models in Ungauged Basins: A Framework for Integrating Hard and Soft Hydrological Information: Integrating Hard and Soft Information. *Water Resour. Res.* **2009**, *45*, doi:10.1029/2009WR007706.

168. Vereecken, H.; Schnepf, A.; Hopmans, J.W.; Javaux, M.; Or, D.; Roose, T.; Vanderborght, J.; Young, M.H.; Amelung, W.; Aitkenhead, M.; et al. Modeling Soil Processes: Review, Key Challenges, and New Perspectives. *Vadose Zone J.* **2016**, *15*, vzj2015.09.0131, doi:10.2136/vzj2015.09.0131.
169. Schoups, G.; Nasseri, M. GRACEfully Closing the Water Balance: A Data-Driven Probabilistic Approach Applied to River Basins in Iran. *Water Resour. Res.* **2021**, *57*, doi:10.1029/2020WR029071.
170. Molden, D. Accounting for Water Use and Productivity.; SWIM Report 1: Colombo, Sri Lanka, 1997.
171. Salvadore, E.; Michailovsky, C.; Coerver, B.; Bastiaanssen, W.G.M. *Water Accounting in Selected Asian River, Basins: Pilot Study in Cambodia*; Asian Development Bank: Manila, Philippines, 2016; p. 66;.
172. Vardon, M.; Lenzen, M.; Peevor, S.; Creaser, M. Water Accounting in Australia. *Ecol. Econ.* **2007**, *61*, 650–659, doi:10.1016/j.ecolecon.2006.07.033.
173. Molden, D.; Frenken, K.; Barker, R.; Svendsen, M.; Sadoff, C.; Max, C.; Contributing, F.; Giordano, M.; Inocencio, A.; Lannerstad, M.; et al. Trends in Water and Agricultural Development. In; 2007.
174. Simons, G.; Bastiaanssen, W.; Ngô, L.; Hain, C.; Anderson, M.; Senay, G. Integrating Global Satellite-Derived Data Products as a Pre-Analysis for Hydrological Modelling Studies: A Case Study for the Red River Basin. *Remote Sens.* **2016**, *8*, 279, doi:10.3390/rs8040279.
175. Vigerstol, K.L.; Aukema, J.E. A Comparison of Tools for Modeling Freshwater Ecosystem Services. *J. Environ. Manage.* **2011**, *92*, 2403–2409, doi:10.1016/j.jenvman.2011.06.040.
176. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large Area Hydrologic Modeling and Assessment Part I: Model Development. *J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89, doi:10.1111/j.1752-1688.1998.tb05961.x.
177. Liang, X.; Lettenmaier, D.P.; Wood, E.F.; Burges, S.J. A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models. *J. Geophys. Res.* **1994**, *99*, 14415, doi:10.1029/94JD00483.
178. Francesconi, W.; Srinivasan, R.; Pérez-Miñana, E.; Willcock, S.P.; Quintero, M. Using the Soil and Water Assessment Tool (SWAT) to Model Ecosystem Services: A Systematic Review. *J. Hydrol.* **2016**, *535*, 625–636, doi:10.1016/j.jhydrol.2016.01.034.
179. Dechmi, F.; Burguete, J.; Skhiri, A. SWAT Application in Intensive Irrigation Systems: Model Modification, Calibration and Validation. *J. Hydrol.* **2012**, *470–471*, 227–238, doi:10.1016/j.jhydrol.2012.08.055.
180. Gitau, M.W.; Chaubey, I. Regionalization of SWAT Model Parameters for Use in Ungauged Watersheds. *Water* **2010**, *2*, 849–871, doi:10.3390/w2040849.
181. Srinivasan, R.; Zhang, X.; Arnold, J. SWAT Ungauged: Hydrological Budget and Crop Yield Predictions in the Upper Mississippi River Basin. *Trans. ASABE* **2010**, *53*, 1533–1546.

182. Abbaspour, K.C.; Rouholahnejad, E.; Vaghefi, S.; Srinivasan, R.; Yang, H.; Kløve, B. A Continental-Scale Hydrology and Water Quality Model for Europe: Calibration and Uncertainty of a High-Resolution Large-Scale SWAT Model. *J. Hydrol.* **2015**, *524*, 733–752, doi:10.1016/j.jhydrol.2015.03.027.
183. Raghavan, S.V.; Tue, V.M.; Shie-Yui, L. Impact of Climate Change on Future Stream Flow in the Dakbla River Basin. *J. Hydroinformatics* **2014**, *16*, 231, doi:10.2166/hydro.2013.165.
184. Schneider, K.; Ketzer, B.; Breuer, L.; Vaché, K.B.; Bernhofer, C.; Frede, H.-G. Evaluation of Evapotranspiration Methods for Model Validation in a Semi-Arid Watershed in Northern China. *Adv. Geosci.* **2007**, *11*, 37–42.
185. Shrestha, B.; Babel, M.S.; Maskey, S.; van Griensven, A.; Uhlenbrook, S.; Green, A.; Akkharath, I. 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.* **2013**, *17*, 1–20, doi:10.5194/hess-17-1-2013.
186. van Griensven, A.; Ndomba, P.; Yalew, S.; Kilonzo, F. Critical Review of SWAT Applications in the Upper Nile Basin Countries. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 3371–3381, doi:10.5194/hess-16-3371-2012.
187. Bitew, M.M.; Gebremichael, M. Assessment of Satellite Rainfall Products for Streamflow Simulation in Medium Watersheds of the Ethiopian Highlands. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1147–1155, doi:10.5194/hess-15-1147-2011.
188. Abbaspour, K.C.; Vejdani, M.; Haghighat, S. SWAT-CUP Calibration and Uncertainty Programs for SWAT. In Proceedings of the MODSIM07 - Land, water and environmental management: integrated systems for sustainability in L. Oxley & D. Kulasiri (Eds.); Modelling and Simulation Society of Australia and New Zealand., 2007; pp. 1596–1602.
189. *Remote Sensing and Hydrology: Proceedings of a Symposium Organized by the International Commission on Remote Sensing of IAHS, Held at Jackson Hole, Wyoming, USA, 27 - 30 September 2010*; Neale, C.M.U., International Association of Hydrological Sciences, International Association of Hydrological Sciences, Eds.; IAHS publication; IAHS Press: Wallingford, 2012; ISBN 978-1-907161-27-8.
190. Pietroniro, A.; Leconte, R. A Review of Canadian Remote Sensing and Hydrology, 1999–2003. *Hydrol. Process.* **2005**, *19*, 285–301, doi:10.1002/hyp.5771.
191. Bastiaanssen, W.G.M.; Harshadeep, N.R. Managing Scarce Water Resources in Asia: The Nature of the Problem and Can Remote Sensing Help? *Irrig. Drain. Syst.* **2005**, *19*, 269–284, doi:10.1007/s10795-005-5188-y.
192. Melesse, A.M.; Weng, Q.; Thenkabail, P.S.; Senay, G.B. Remote Sensing Sensors and Applications in Environmental Resources Mapping and Modelling. *Sensors* **2007**, *7*, 3209–3241, doi:10.3390/s7123209.
193. Dembélé, M.; Zwart, S.J. Evaluation and Comparison of Satellite-Based Rainfall Products in Burkina Faso, West Africa. *Int. J. Remote Sens.* **2016**, *37*, 3995–4014, doi:10.1080/01431161.2016.1207258.

194. Serrat-Capdevila, A.; Valdes, J.B.; Stakhiv, E.Z. Water Management Applications for Satellite Precipitation Products: Synthesis and Recommendations. *JAWRA J. Am. Water Resour. Assoc.* **2014**, *50*, 509–525, doi:10.1111/jawr.12140.
195. Templeton, R.C.; Vivoni, E.R.; Méndez-Barroso, L.A.; Pierini, N.A.; Anderson, C.A.; Rango, A.; Laliberte, A.S.; Scott, R.L. High-Resolution Characterization of a Semiarid Watershed: Implications on Evapotranspiration Estimates. *J. Hydrol.* **2014**, *509*, 306–319, doi:10.1016/j.jhydrol.2013.11.047.
196. Kalma, J.D.; McVicar, T.R.; McCabe, M.F. Estimating Land Surface Evaporation: A Review of Methods Using Remotely Sensed Surface Temperature Data. *Surv. Geophys.* **2008**, *29*, 421–469, doi:10.1007/s10712-008-9037-z.
197. Karimi, P.; Bastiaanssen, W.G.M. Spatial Evapotranspiration, Rainfall and Land Use Data in Water Accounting – Part 1: Review of the Accuracy of the Remote Sensing Data. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 507–532, doi:10.5194/hess-19-507-2015.
198. Li, Z.-L.; Tang, R.; Wan, Z.; Bi, Y.; Zhou, C.; Tang, B.; Yan, G.; Zhang, X. A Review of Current Methodologies for Regional Evapotranspiration Estimation from Remotely Sensed Data. *Sensors* **2009**, *9*, 3801–3853, doi:10.3390/s90503801.
199. Senay, G.B.; Leake, S.; Nagler, P.L.; Artan, G.; Dickinson, J.; Cordova, J.T.; Glenn, E.P. Estimating Basin Scale Evapotranspiration (ET) by Water Balance and Remote Sensing Methods. *Hydrol. Process.* **2011**, *25*, 4037–4049, doi:10.1002/hyp.8379.
200. Carlson, T.N.; Ripley, D.A. On the Relation between NDVI, Fractional Vegetation Cover, and Leaf Area Index. *Remote Sens. Environ.* **1997**, *62*, 241–252, doi:10.1016/S0034-4257(97)00104-1.
201. Droogers, P.; Bastiaanssen, W. Irrigation Performance Using Hydrological and Remote Sensing Modeling. *J. Irrig. Drain. Eng.* **2002**, *128*, 11–18.
202. Githui, F.; Selle, B.; Thayalakumaran, T. Recharge Estimation Using Remotely Sensed Evapotranspiration in an Irrigated Catchment in Southeast Australia. *Hydrol. Process.* **2012**, *26*, 1379–1389, doi:10.1002/hyp.8274.
203. Jhorar, R.K.; Smit, A.A.M.F.R.; Bastiaanssen, W.G.M.; Roest, C.W.J. Calibration of a Distributed Irrigation Water Management Model Using Remotely Sensed Evapotranspiration Rates and Groundwater Heads. *Irrig. Drain.* **2011**, *60*, 57–69, doi:10.1002/ird.541.
204. Schuurmans, J.M.; Troch, P.A.; Veldhuizen, A.A.; Bastiaanssen, W.G.M.; Bierkens, M.F.P. Assimilation of Remotely Sensed Latent Heat Flux in a Distributed Hydrological Model. *Adv. Water Resour.* **2003**, *26*, 151–159.
205. Vazifedoust, M.; Van Dam, J.C.; Feddes, R.A.; Feizi, M. Increasing Water Productivity of Irrigated Crops under Limited Water Supply at Field Scale. *Agric. Water Manag.* **2008**, *95*, 89–102, doi:10.1016/j.agwat.2007.09.007.

206. Cheema, M.J.M.; Immerzeel, W.W.; Bastiaanssen, W.G.M. Spatial Quantification of Groundwater Abstraction in the Irrigated Indus Basin. *Groundwater* **2014**, *52*, 25–36, doi:10.1111/gwat.12027.
207. Immerzeel, W.W.; Gaur, A.; Zwart, S.J. Integrating Remote Sensing and a Process-Based Hydrological Model to Evaluate Water Use and Productivity in a South Indian Catchment. *Agric. Water Manag.* **2008**, *95*, 11–24, doi:10.1016/j.agwat.2007.08.006.
208. Immerzeel, W.W.; Droogers, P. Calibration of a Distributed Hydrological Model Based on Satellite Evapotranspiration. *J. Hydrol.* **2008**, *349*, 411–424, doi:10.1016/j.jhydrol.2007.11.017.
209. Sousa, A.M.L.D.; Vitorino, M.I.; Castro, N.M.D.R.; Botelho, M.D.N.; Souza, P.J.O.P.D. Evapotranspiration from Remote Sensing to Improve the Swat Model in Eastern Amazonia. *Floresta E Ambiente* **2015**, *22*, 456–464, doi:10.1590/2179-8087.083814.
210. Sun, C.; Jiang, D.; Wang, J.; Zhu, Y. Validating Remote Sensing Derived Evapotranspiration with the Soil and Water Assessment Tool (SWAT) Model: A Case Study in Zhelin Basin, China. *Afr. J. Agric. Res.* **2013**, *8*, 2090–2098.
211. Breda, N.J.J. Ground-Based Measurements of Leaf Area Index: A Review of Methods, Instruments and Current Controversies. *J. Exp. Bot.* **2003**, *54*, 2403–2417, doi:10.1093/jxb/erg263.
212. Van Griensven, A.; Maskey, S.; Stefanova, A. The Use of Satellite Images for Evaluating a SWAT Model: Application on the Vit Basin, Bulgaria. In Proceedings of the iEMSs 2012 - Managing Resources of a Limited Planet; December 1 2012; pp. 3030–3037.
213. Giuliani, M.; Anghileri, D.; Castelletti, A.; Vu, P.N.; Soncini-Sessa, R. Large Storage Operations under Climate Change: Expanding Uncertainties and Evolving Tradeoffs. *Environ. Res. Lett.* **2016**, *11*, 035009, doi:10.1088/1748-9326/11/3/035009.
214. Luu, T.N.M.; Garnier, J.; Billen, G.; Orange, D.; Némery, J.; Le, T.P.Q.; Tran, H.T.; Le, L.A. Hydrological Regime and Water Budget of the Red River Delta (Northern Vietnam). *J. Asian Earth Sci.* **2010**, *37*, 219–228, doi:10.1016/j.jseaes.2009.08.004.
215. Quynh, L.T.P.; Billen, G.; Garnier, J.; Théry, S.; Fézard, C.; Minh, C.V. Nutrient (N, P) Budgets for the Red River Basin (Vietnam and China): Red River Nutrient Budget. *Glob. Biogeochem. Cycles* **2005**, *19*, n/a-n/a, doi:10.1029/2004GB002405.
216. Arnold, J.G.; Moriasi, D.N.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, R.D.; Van Griensven, A.; Van Liew, M.W.; et al. SWAT: Model Use, Calibration, and Validation. *Trans. ASABE* **2012**, *55*, 1491–1508.
217. Cibin, R.; Sudheer, K.P.; Chaubey, I. Sensitivity and Identifiability of Stream Flow Generation Parameters of the SWAT Model. *Hydrol. Process.* **2010**, *24*, 1133–1148, doi:10.1002/hyp.7568.

218. Hargreaves, G.L.; Hargreaves, G.H.; Riley, J.P. Agricultural Benefits for Senegal River Basin. *J. Irrig. Drain. Eng.* **1985**, *111*, 113–124, doi:10.1061/(ASCE)0733-9437(1985)111:2(113).
219. Priestley, C.H.B.; Taylor, R.J. On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. *Mon. Weather Rev.* **1972**, *100*, 81–92, doi:10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2.
220. Abbaspour, K.C.; Van Genuchten, M.T.; Schulin, R.; Schläppi, E. A Sequential Uncertainty Domain Inverse Procedure for Estimating Subsurface Flow and Transport Parameters. *Water Resour. Res.* **1997**, *33*, 1879–1892.
221. Abbaspour, K.C. *SWAT-Calibration and Uncertainty Programs (CUP)—A User Manual*; Swiss Federal Institute of Aquatic Science and Technology: Eawag, Duebendorf, 2015; pp. 1–100;.
222. Strauch, M.; Volk, M. SWAT Plant Growth Modification for Improved Modeling of Perennial Vegetation in the Tropics. *Ecol. Model.* **2013**, *269*, 98–112, doi:10.1016/j.ecolmodel.2013.08.013.
223. Bontemps, S.; Defourny, P.; van Bogaert, E.; Herold, M.; Kooistra, L.; Kalogirou, V.; Arino, O. Producing Global Land Cover Maps Consistent over Time to Respond the Needs of the Climate Modelling Community. *6th Int. Workshop Anal. Multitemporal Remote Sens. Images MultiTemp Trento Italy* **2011**, 161–164.
224. 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.; et al. SoilGrids1km — Global Soil Information Based on Automated Mapping. *PLoS ONE* **2014**, *9*, e105992, doi:10.1371/journal.pone.0105992.
225. Food and Agriculture Organization of the United Nations Digital Soil Map of the World and Derived Soil Properties 2003.
226. Meng, J.; Li, L.; Hao, Z.; Wang, J.; Shao, Q. Suitability of TRMM Satellite Rainfall in Driving a Distributed Hydrological Model in the Source Region of Yellow River. *J. Hydrol.* **2014**, *509*, 320–332, doi:10.1016/j.jhydrol.2013.11.049.
227. Li, Z.; Yang, D.; Gao, B.; Jiao, Y.; Hong, Y.; Xu, T. Multiscale Hydrologic Applications of the Latest Satellite Precipitation Products in the Yangtze River Basin Using a Distributed Hydrologic Model. *J. Hydrometeorol.* **2015**, *16*, 407–426, doi:10.1175/JHM-D-14-0105.1.
228. Peña-Arancibia, J.L.; van Dijk, A.I.J.M.; Renzullo, L.J.; Mulligan, M. Evaluation of Precipitation Estimation Accuracy in Reanalyses, Satellite Products, and an Ensemble Method for Regions in Australia and South and East Asia. *J. Hydrometeorol.* **2013**, *14*, 1323–1333, doi:10.1175/JHM-D-12-0132.1.
229. 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. *A Quasi-Global Precipitation Time Series for Drought Monitoring*; Data Series; Reston, VA, 2014; p. 12;.

230. Toté, C.; Patricio, D.; Boogaard, H.; van der Wijngaart, R.; Tarnavsky, E.; Funk, C. Evaluation of Satellite Rainfall Estimates for Drought and Flood Monitoring in Mozambique. *Remote Sens.* **2015**, *7*, 1758–1776, doi:10.3390/rs70201758.
231. Rodell, M.; Houser, P.R.; Jambor, U.; Gottschalck, J.; Mitchell, K.; Meng, C.-J.; Arsenault, K.; Cosgrove, B.; Radakovich, J.; Bosilovich, M.; et al. The Global Land Data Assimilation System. *Bull. Am. Meteorol. Soc.* **2004**, *85*, 381–394, doi:10.1175/BAMS-85-3-381.
232. Mu, Q.; Heinsch, F.A.; Zhao, M.; Running, S.W. Development of a Global Evapotranspiration Algorithm Based on MODIS and Global Meteorology Data. *Remote Sens. Environ.* **2007**, *111*, 519–536.
233. Hu, G.; Jia, L.; Menenti, M. Comparison of MOD16 and LSA-SAF MSG Evapotranspiration Products over Europe for 2011. *Remote Sens. Environ.* **2015**, *156*, 510–526, doi:10.1016/j.rse.2014.10.017.
234. Ramoelo, A.; Majozi, N.; Mathieu, R.; Jovanovic, N.; Nickless, A.; Dzikiti, S. Validation of Global Evapotranspiration Product (MOD16) Using Flux Tower Data in the African Savanna, South Africa. *Remote Sens.* **2014**, *6*, 7406–7423, doi:10.3390/rs6087406.
235. Knipper, K.R.; Kinoshita, A.M.; Hogue, T.S. Evaluation of a Moderate Resolution Imaging Spectroradiometer Triangle-Based Algorithm for Evapotranspiration Estimates in Subalpine Regions. *J. Appl. Remote Sens.* **2016**, *10*, 016002, doi:10.1117/1.JRS.10.016002.
236. Trambauer, P.; Dutra, E.; Maskey, S.; Werner, M.; Pappenberger, F.; van Beek, L.P.H.; Uhlenbrook, S. Comparison of Different Evaporation Estimates over the African Continent. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 193–212, doi:10.5194/hess-18-193-2014.
237. Chen, X.; Su, Z.; Ma, Y.; Yang, K.; Wen, J.; Zhang, Y. An Improvement of Roughness Height Parameterization of the Surface Energy Balance System (SEBS) over the Tibetan Plateau. *J. Appl. Meteorol. Climatol.* **2013**, *52*, 607–622, doi:10.1175/JAMC-D-12-056.1.
238. Su, Z. The Surface Energy Balance System (SEBS) for Estimation of Turbulent Heat Fluxes. *Hydrol. Earth Syst. Sci. Discuss.* **2002**, *6*, 85–100.
239. Guerschman, J.P.; Van Dijk, A.I.J.M.; Mattersdorf, G.; Beringer, J.; Hutley, L.B.; Leuning, R.; Pipunic, R.C.; Sherman, B.S. Scaling of Potential Evapotranspiration with MODIS Data Reproduces Flux Observations and Catchment Water Balance Observations across Australia. *J. Hydrol.* **2009**, *369*, 107–119, doi:10.1016/j.jhydrol.2009.02.013.
240. Senay, G.B.; Bohms, S.; Singh, R.K.; Gowda, P.H.; Velpuri, N.M.; Alemu, H.; Verdin, J.P. Operational Evapotranspiration Mapping Using Remote Sensing and Weather Datasets: A New Parameterization for the SSEB Approach. *JAWRA J. Am. Water Resour. Assoc.* **2013**, *49*, 577–591, doi:10.1111/jawr.12057.
241. Senay, G.B.; Budde, M.; Verdin, J.P.; Melesse, A.M. A Coupled Remote Sensing and Simplified Surface Energy Balance Approach to Estimate Actual Evapotranspiration from Irrigated Fields. *Sensors* **2007**, *7*, 979–1000.

242. Kim, H.W.; Hwang, K.; Mu, Q.; Lee, S.O.; Choi, M. Validation of MODIS 16 Global Terrestrial Evapotranspiration Products in Various Climates and Land Cover Types in Asia. *KSCE J. Civ. Eng.* **2012**, *16*, 229–238, doi:10.1007/s12205-012-0006-1.
243. Westerhoff, R.S. Using Uncertainty of Penman and Penman–Monteith Methods in Combined Satellite and Ground-Based Evapotranspiration Estimates. *Remote Sens. Environ.* **2015**, *169*, 102–112, doi:10.1016/j.rse.2015.07.021.
244. Bastiaanssen, W.G.M.; Pelgrum, H.; Soppe, R.W.O.; Allen, R.G.; Thoreson, B.P.; De C. Teixeira, A.H. Thermal-Infrared Technology for Local and Regional Scale Irrigation Analyses in Horticultural Systems. *Acta Hortic.* **2008**, 33–46, doi:10.17660/ActaHortic.2008.792.2.
245. Bastiaanssen, W.G.M.; Hoekman, D.H.; Roebeling, R. A Methodology for the Assessment of Surface Resistance and Soil Water Storage Variability at Mesoscale Based on Remote Sensing Measurements. A Case Study with HAPEX-EFEDA Data. *Rapp 38 Vakgr. Watershuishouding Landbouwuniv. Wagenineng* **1993**, 71.
246. Ferguson, C.R.; Sheffield, J.; Wood, E.F.; Gao, H. Quantifying Uncertainty in a Remote Sensing-Based Estimate of Evapotranspiration over Continental USA. *Int. J. Remote Sens.* **2010**, *31*, 3821–3865, doi:10.1080/01431161.2010.483490.
247. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. FAO Irrigation and Drainage Paper No. 56. *Rome Food Agric. Organ. U. N.* **1998**, 26–40.
248. Mohan, S.; Arumugam, N. Irrigation Crop Coefficients for Lowland Rice. *Irrig. Drain. Syst.* **1994**, *8*, 159–176, doi:10.1007/BF00881016.
249. Tyagi, N.K.; Sharma, D.K.; Luthra, S.K. Determination of Evapotranspiration and Crop Coefficients of Rice and Sunflower with Lysimeter. *Agric. Water Manag.* **2000**, *45*, 41–54, doi:10.1016/S0378-3774(99)00071-2.
250. Vu, S.H.; Watanabe, H.; Takagi, K. Application of FAO-56 for Evaluating Evapotranspiration in Simulation of Pollutant Runoff from Paddy Rice Field in Japan. *Agric. Water Manag.* **2005**, *76*, 195–210, doi:10.1016/j.agwat.2005.01.012.
251. Abdullahi, A.S.; Soom, M.; Ahmad, D.; Shariff, R. Characterization of Rice (Oryza Sativa) Evapotranspiration Using Micro Paddy Lysimeter and Class “A” Pan in Tropical Environments. *Aust. J. Crop Sci.* **2013**, *7*, 650–658.
252. Stisen, S.; Jensen, K.H.; Sandholt, I.; Grimes, D.I.F. A Remote Sensing Driven Distributed Hydrological Model of the Senegal River Basin. *J. Hydrol.* **2008**, *354*, 131–148, doi:10.1016/j.jhydrol.2008.03.006.
253. Chapin, F.S.; Matson, P.A.; Mooney, H.A. *Principles of Terrestrial Ecosystem Ecology*; Springer: New York, 2002; ISBN 978-0-387-95439-4.
254. Holland, R.A.; Darwall, W.R.T.; Smith, K.G. Conservation Priorities for Freshwater Biodiversity: The Key Biodiversity Area Approach Refined and Tested for Continental Africa. *Biol. Conserv.* **2012**, *148*, 167–179, doi:10.1016/j.biocon.2012.01.016.

255. Harrison-Atlas, D.; Theobald, D.M.; Goldstein, J.H. A Systematic Review of Approaches to Quantify Hydrologic Ecosystem Services to Inform Decision-Making. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2016**, *12*, 160–171, doi:10.1080/21513732.2016.1181105.
256. Ha, L.T.; Bastiaanssen, W.G.M.; Simons, G.W.H.; Poortinga, A. A New Framework of 17 Hydrological Ecosystem Services (HESS17) for Supporting River Basin Planning and Environmental Monitoring. *Sustainability* **2023**, *15*, 6182, doi:10.3390/su15076182.
257. Eigenbrod, F.; Armsworth, P.R.; Anderson, B.J.; Heinemeyer, A.; Gillings, S.; Roy, D.B.; Thomas, C.D.; Gaston, K.J. The Impact of Proxy-Based Methods on Mapping the Distribution of Ecosystem Services. *J. Appl. Ecol.* **2010**, *47*, 377–385, doi:10.1111/j.1365-2664.2010.01777.x.
258. European Commission. Directorate General for the Environment. *Mapping and Assessment of Ecosystems and Their Services: Indicators for Ecosystem Assessments under Action 5 of the EU Biodiversity Strategy to 2020 : 2nd Report – Final, February 2014.*; Publications Office: Luxembourg, 2014;
259. Le Maitre, D.C.; Milton, S.J.; Jarmain, C.; Colvin, C.A.; Saayman, I.; Vlok, J.H. Linking Ecosystem Services and Water Resources: Landscape-Scale Hydrology of the Little Karoo. *Front. Ecol. Environ.* **2007**, *5*, 261–270, doi:10.1890/1540-9295(2007)5[261:LESAWR]2.0.CO;2.
260. Pearson, T.R.H.; Brown, S.L.; Birdsey, R.A. *Measurement Guidelines for the Sequestration of Forest Carbon*; U.S. Department of Agriculture, Forest Service, Northern Research Station: Newtown Square, PA, 2007; p. NRS-GTR-18;
261. Saatchi, S.S.; Harris, N.L.; Brown, S.; Lefsky, M.; Mitchard, E.T.A.; Salas, W.; Zutta, B.R.; Buermann, W.; Lewis, S.L.; Hagen, S.; et al. Benchmark Map of Forest Carbon Stocks in Tropical Regions across Three Continents. *Proc. Natl. Acad. Sci.* **2011**, *108*, 9899–9904, doi:10.1073/pnas.1019576108.
262. Skidmore, A.K.; Pettorelli, N.; Coops, N.C.; Geller, G.N.; Hansen, M.; Lucas, R.; Mücher, C.A.; O'Connor, B.; Paganini, M.; Pereira, H.M.; et al. Environmental Science: Agree on Biodiversity Metrics to Track from Space. *Nature* **2015**, *523*, 403–405, doi:10.1038/523403a.
263. Saad, R.; Koellner, T.; Margni, M. Land Use Impacts on Freshwater Regulation, Erosion Regulation, and Water Purification: A Spatial Approach for a Global Scale Level. *Int. J. Life Cycle Assess.* **2013**, *18*, 1253–1264, doi:10.1007/s11367-013-0577-1.
264. Milne, R.; Brown, T.A. Carbon in the Vegetation and Soils of Great Britain. *J. Environ. Manage.* **1997**, *49*, 413–433, doi:10.1006/jema.1995.0118.
265. McGuire, A.D.; Christensen, T.R.; Hayes, D.; Heroult, A.; Euskirchen, E.; Kimball, J.S.; Koven, C.; Lafleur, P.; Miller, P.A.; Oechel, W.; et al. An Assessment of the Carbon Balance of Arctic Tundra: Comparisons among Observations, Process Models, and Atmospheric Inversions. *Biogeosciences* **2012**, *9*, 3185–3204, doi:10.5194/bg-9-3185-2012.

266. Coughenour, M.B.; Makkar, H.P.S. *Conducting National Feed Assessments*; FAO animal production and health manual; FAO: Rome, 2012; ISBN 978-92-5-107332-2.
267. Awan, U.K.; Ismaeel, A. A New Technique to Map Groundwater Recharge in Irrigated Areas Using a SWAT Model under Changing Climate. *J. Hydrol.* **2014**, *519*, 1368–1382, doi:10.1016/j.jhydrol.2014.08.049.
268. Jayakrishnan, R.; Srinivasan, R.; Santhi, C.; Arnold, J.G. Advances in the Application of the SWAT Model for Water Resources Management. *Hydrol. Process.* **2005**, *19*, 749–762, doi:10.1002/hyp.5624.
269. Luo, Y.; He, C.; Sophocleous, M.; Yin, Z.; Hongrui, R.; Ouyang, Z. Assessment of Crop Growth and Soil Water Modules in SWAT2000 Using Extensive Field Experiment Data in an Irrigation District of the Yellow River Basin. *J. Hydrol.* **2008**, *352*, 139–156, doi:10.1016/j.jhydrol.2008.01.003.
270. Yang, Q.; Zhang, X. Improving SWAT for Simulating Water and Carbon Fluxes of Forest Ecosystems. *Sci. Total Environ.* **2016**, *569–570*, 1478–1488, doi:10.1016/j.scitotenv.2016.06.238.
271. Krysanova, V.; White, M. Advances in Water Resources Assessment with SWAT—an Overview. *Hydrol. Sci. J.* **2015**, 1–13, doi:10.1080/02626667.2015.1029482.
272. Radcliffe, D.E.; Reid, D.K.; Blombäck, K.; Bolster, C.H.; Collick, A.S.; Easton, Z.M.; Francesconi, W.; Fuka, D.R.; Johnsson, H.; King, K.; et al. Applicability of Models to Predict Phosphorus Losses in Drained Fields: A Review. *J. Environ. Qual.* **2015**, *44*, 614–628, doi:10.2134/jeq2014.05.0220.
273. Farr, T.G.; Rosen, P.A.; Caro, E.; Crippen, R.; Duren, R.; Hensley, S.; Kobrick, M.; Paller, M.; Rodriguez, E.; Roth, L.; et al. The Shuttle Radar Topography Mission. *Rev. Geophys.* **2007**, *45*, 2005RG000183, doi:10.1029/2005RG000183.
274. Myneni, Ranga; Knyazikhin, Yuri; Park, Taejin MODIS/Terra+Aqua Leaf Area Index/FPAR 8-Day L4 Global 500m SIN Grid V061 2021.
275. Soil Conservation Service, U.S.S.C. *SCS National Engineering Handbook, Section 4: Hydrology*; SCS National Engineering Handbook, Section 4: Hydrology; The Service, 1972;
276. Herrero, M.; Havlik, P.; Valin, H.; Notenbaert, A.; Rufino, M.C.; Thornton, P.K.; Blummel, M.; Weiss, F.; Grace, D.; Obersteiner, M. Biomass Use, Production, Feed Efficiencies, and Greenhouse Gas Emissions from Global Livestock Systems. *Proc. Natl. Acad. Sci.* **2013**, *110*, 20888–20893, doi:10.1073/pnas.1308149110.
277. Sassen, M.; Sheil, D.; Giller, K.E. Fuelwood Collection and Its Impacts on a Protected Tropical Mountain Forest in Uganda. *For. Ecol. Manag.* **2015**, *354*, 56–67, doi:10.1016/j.foreco.2015.06.037.
278. Ponce-Hernandez, R.; Koohafkan, P.; Antoine, J. Assessing Carbon Stocks and Modelling Win-Win Scenarios of Carbon Sequestration through Land-Use Changes.; 2004.

279. Ahmad, M.-D.; Bastiaanssen, W.G.M. Retrieving Soil Moisture Storage in the Unsaturated Zone Using Satellite Imagery and Bi-Annual Phreatic Surface Fluctuations. *Irrig. Drain. Syst.* **2003**, *17*, 141–161, doi:10.1023/A:1025101217521.
280. Savenije, H.H.G. The Runoff Coefficient as the Key to Moisture Recycling. *J. Hydrol.* **1996**, *176*, 219–225, doi:10.1016/0022-1694(95)02776-9.
281. Keys, P.W.; Wang-Erlandsson, L.; Gordon, L.J. Revealing Invisible Water: Moisture Recycling as an Ecosystem Service. *PLOS ONE* **2016**, *11*, e0151993, doi:10.1371/journal.pone.0151993.
282. Coerver, B. Regional Precipitation and Evaporation Patterns in South East Asia Based on ERA5 Data (Internal Note) 2007.
283. Vleeshouwers, L.M.; Verhagen, A. Carbon Emission and Sequestration by Agricultural Land Use: A Model Study for Europe. *Glob. Change Biol.* **2002**, *8*, 519–530, doi:10.1046/j.1365-2486.2002.00485.x.
284. Yoshida, S. *Fundamentals of Rice Crop Science*; International Rice Research Institute (IRRI): Laguna, Philippines, 1981; pp. 195–211;.
285. Klok, L.; Zwart, S.; Verhagen, H.; Mauri, E. The Surface Heat Island of Rotterdam and Its Relationship with Urban Surface Characteristics. *Resour. Conserv. Recycl.* **2012**, *64*, 23–29, doi:10.1016/j.resconrec.2012.01.009.
286. Mohamed, Y.A.; Bastiaanssen, W.G.M.; Savenije, H.H.G. Spatial Variability of Evaporation and Moisture Storage in the Swamps of the Upper Nile Studied by Remote Sensing Techniques. *J. Hydrol.* **2004**, *289*, 145–164, doi:10.1016/j.jhydrol.2003.11.038.
287. Smakhtin, V.; Eriyagama, N. Developing a Software Package for Global Desktop Assessment of Environmental Flows. *Environ. Model. Softw.* **2008**, *23*, 1396–1406, doi:10.1016/j.envsoft.2008.04.002.
288. Tuinenburg, O.A.; Hutjes, R.W.A.; Stacke, T.; Wiltshire, A.; Lucas-Picher, P. Effects of Irrigation in India on the Atmospheric Water Budget. *J. Hydrometeorol.* **2014**, *15*, 1028–1050, doi:10.1175/JHM-D-13-078.1.
289. Iroumé, A.; Mayen, O.; Huber, A. Runoff and Peak Flow Responses to Timber Harvest and Forest Age in Southern Chile. *Hydrol. Process.* **2006**, *20*, 37–50, doi:10.1002/hyp.5897.
290. Gaur, S.; Singh, B.; Bandyopadhyay, A.; Stisen, S.; Singh, R. Spatial Pattern-based Performance Evaluation and Uncertainty Analysis of a Distributed Hydrological Model. *Hydrol. Process.* **2022**, *36*, doi:10.1002/hyp.14586.
291. Gaur, Srishti Distributed Hydrological Modelling Under Climate Change: A Way-Forward For Accounting, Planning and Management of Water Resources, IIT Kharagpur, 2022.
292. Molden, D.; Sakthivadivel, R. Water Accounting to Assess Use and Productivity of Water. *Int. J. Water Resour. Dev.* **1999**, *15*, 55–71, doi:10.1080/07900629948934.

293. Hellegers, P.J.G.J.; Soppe, R.; Perry, C.J.; Bastiaanssen, W.G.M. Combining Remote Sensing and Economic Analysis to Support Decisions That Affect Water Productivity. *Irrig. Sci.* **2009**, *27*, 243–251, doi:10.1007/s00271-008-0139-7.
294. Choudhury, B.J.; DiGirolamo, N.E. A Biophysical Process-Based Estimate of Global Land Surface Evaporation Using Satellite and Ancillary Data I. Model Description and Comparison with Observations. *J. Hydrol.* **1998**, *205*, 164–185, doi:10.1016/S0022-1694(97)00147-9.
295. *Drainage Principles and Applications*; Ritzema, H.P., Ed.; ILRI publication; 2. ed. (completely rev.).; ILRI: Wageningen, 1994; ISBN 978-90-70754-33-4.
296. Doorenbos, J.; Pruitt, W.O. *Guidelines for Predicting Crop Water Requirements*; FAO irrigation and drainage paper ; 24; Rev.; Food and Agriculture Organization of the United Nations: Rome, 1977; ISBN 978-92-5-100279-7.
297. Malhi, Y.; Franklin, J.; Seddon, N.; Solan, M.; Turner, M.G.; Field, C.B.; Knowlton, N. Climate Change and Ecosystems: Threats, Opportunities and Solutions. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190104, doi:10.1098/rstb.2019.0104.
298. Dunlop, T.; Khojasteh, D.; Cohen-Shacham, E.; Glamore, W.; Haghani, M.; Van Den Bosch, M.; Rizzi, D.; Greve, P.; Felder, S. The Evolution and Future of Research on Nature-Based Solutions to Address Societal Challenges. *Commun. Earth Environ.* **2024**, *5*, 132, doi:10.1038/s43247-024-01308-8.
299. Xu, K.; Chen, J.; Feng, Y.; Wang, J.; Bai, Z. How Are Nature-Based Solutions Contributing to the Improvement of Ecosystem Quality in China: A Systematic Review. *Ecol. Indic.* **2023**, *155*, 110985, doi:10.1016/j.ecolind.2023.110985.
300. Fu, B.; Liu, Y.; Lü, Y.; He, C.; Zeng, Y.; Wu, B. Assessing the Soil Erosion Control Service of Ecosystems Change in the Loess Plateau of China. *Ecol. Complex.* **2011**, *8*, 284–293, doi:10.1016/j.ecocom.2011.07.003.
301. Seddon, N.; Chausson, A.; Berry, P.; Girardin, C.A.J.; Smith, A.; Turner, B. Understanding the Value and Limits of Nature-Based Solutions to Climate Change and Other Global Challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190120, doi:10.1098/rstb.2019.0120.
302. Liu, J.; Yang, H.; Gosling, S.N.; Kummu, M.; Flörke, M.; Pfister, S.; Hanasaki, N.; Wada, Y.; Zhang, X.; Zheng, C.; et al. Water Scarcity Assessments in the Past, Present, and Future. *Earths Future* **2017**, *5*, 545–559, doi:10.1002/2016EF000518.
303. Fu, B.; Wang, S.; Liu, Y.; Liu, J.; Liang, W.; Miao, C. Hydrogeomorphic Ecosystem Responses to Natural and Anthropogenic Changes in the Loess Plateau of China. *Annu. Rev. Earth Planet. Sci.* **2017**, *45*, 223–243, doi:10.1146/annurev-earth-063016-020552.
304. Apurv, T.; Cai, X. Impact of Droughts on Water Supply in U.S. Watersheds: The Role of Renewable Surface and Groundwater Resources. *Earths Future* **2020**, *8*, e2020EF001648, doi:10.1029/2020EF001648.
305. Sood, A.; Smakhtin, V.; Eriyagama, N.; Villholth, K.G.; Liyanage, N.; Wada, Y.; Ebrahim, G.; Dickens, C. *Global Environmental Flow Information for the*

Sustainable Development Goals; International Water Management Institute (IWMI), 2017;
306. Rau, M.I.; Julzarika, A.; Yoshikawa, N.; Nagano, T.; Kimura, M.; Setiawan, B.I.; Ha, L.T. Application of Topographic Elevation Data Generated by Remote Sensing Approaches to Flood Inundation Analysis Model. *Paddy Water Environ.* **2024**, *22*, 285–299, doi:10.1007/s10333-023-00967-1.
307. Andreadis, K.M.; Das, N.; Stampoulis, D.; Ines, A.; Fisher, J.B.; Granger, S.; Kawata, J.; Han, E.; Behrangi, A. The Regional Hydrologic Extremes Assessment System: A Software Framework for Hydrologic Modeling and Data Assimilation. *PLOS ONE* **2017**, *12*, e0176506, doi:10.1371/journal.pone.0176506.
308. Ha, L.T.; Bastiaanssen, W.G.M. Determination of Spatially-Distributed Hydrological Ecosystem Services (HESS) in the Red River Delta Using a Calibrated SWAT Model. *Sustainability* **2023**, *15*, 6247, doi:https://doi.org/10.3390/su15076247.
309. *WaPOR Database Methodology*; FAO, 2020; ISBN 978-92-5-132981-8.
310. Bastiaanssen, W.G.M.; Cheema, M.J.M.; Immerzeel, W.W.; Miltenburg, I.J.; Pelgrum, H. Surface Energy Balance and Actual Evapotranspiration of the Transboundary Indus Basin Estimated from Satellite Measurements and the ETLook Model. *Water Resour. Res.* **2012**, *48*, 2011WR010482, doi:10.1029/2011WR010482.
311. Penman, H. Natural Evaporation from Open Water, Bare Soil and Grass. *Proc. R. Soc. Lond. Ser. Math. Phys. Sci.* **1948**, *193*, 120–145, doi:10.1098/rspa.1948.0037.
312. Das, N.N.; Entekhabi, D.; Dunbar, R.S.; Colliander, A.; Chen, F.; Crow, W.; Jackson, T.J.; Berg, A.; Bosch, D.D.; Caldwell, T.; et al. The SMAP Mission Combined Active-Passive Soil Moisture Product at 9 Km and 3 Km Spatial Resolutions. *Remote Sens. Environ.* **2018**, *211*, 204–217, doi:10.1016/j.rse.2018.04.011.
313. Singh, G.; Das, N.N. A Data-Driven Approach Using the Remotely Sensed Soil Moisture Product to Identify Water-Demand in Agricultural Regions. *Sci. Total Environ.* **2022**, *837*, 155893, doi:10.1016/j.scitotenv.2022.155893.
314. Anav, A.; Proietti, C.; Menut, L.; Carnicelli, S.; De Marco, A.; Paoletti, E. Sensitivity of Stomatal Conductance to Soil Moisture: Implications for Tropospheric Ozone. *Atmospheric Chem. Phys.* **2018**, *18*, 5747–5763, doi:10.5194/acp-18-5747-2018.
315. Bontemps, S.; Defourny, P.; Radoux, J.; Van Bogaert, E.; Lamarche, C.; Achard, F.; Mayaux, P.; Boettcher, M.; Brockmann, C.; Kirches, G.; et al. Consistent Global Land Cover Maps For Climate Modelling Communities: Current Achievements Of The ESA' Land Cover CCI. In Proceedings of the ESA Living Planet Symposium; December 2013; Vol. 722, p. 62.
316. Blatchford, M.L.; Mannaerts, C.M.; Njuki, S.M.; Nouri, H.; Zeng, Y.; Pelgrum, H.; Wonink, S.; Karimi, P. Evaluation of WAPOR V2 Evapotranspiration

Products across Africa. *Hydrol. Process.* **2020**, *34*, 3200–3221, doi:10.1002/hyp.13791.
317. Dhonthi, A.; Fonseca Aponte, F.H.; Nemer, Z.; Hadj Ali, C.; Tebbouche, M.Y.; Van Der Kwast, H. Advancing Water Productivity Monitoring: WaPLUGIN for the Analysis and Validation of FAO WaPOR Data in QGIS. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *XLVIII-4/W12-2024*, 35–41, doi:10.5194/isprs-archives-XLVIII-4-W12-2024-35-2024.
318. Mul Marloes; Bastiaanssen W.G.M. WaPOR Quality Assessment. Technical Report on the Data Quality of the WaPOR FAO Database Version 1.0. 2019.
319. Weerasinghe, I.; Bastiaanssen, W.; Mul, M.; Jia, L.; Van Griensven, A. Can We Trust Remote Sensing Evapotranspiration Products over Africa? *Hydrol. Earth Syst. Sci.* **2020**, *24*, 1565–1586, doi:10.5194/hess-24-1565-2020.
320. Geneletti, D. Assessing the Impact of Alternative Land-Use Zoning Policies on Future Ecosystem Services. *Environ. Impact Assess. Rev.* **2013**, *40*, 25–35, doi:10.1016/j.eiar.2012.12.003.
321. Lu, C.; Sidai, G.; Yangli, L. Discerning Changes and Drivers of Water Yield Ecosystem Service: A Case Study of Chongqing-Chengdu District, Southwest China. *Ecol. Indic.* **2024**, *160*, 111767, doi:10.1016/j.ecolind.2024.111767.
322. Zhou, Y.; Huang, Q.; Wu, P.; Hou, Y.; Zhou, Y.; Chen, P.; Duan, X. Seasonal Variations in Ecosystem Service Supply and Demand Based on the SWAT Model: A Case Study in the Guanting Reservoir Basin, China. *Ecol. Indic.* **2024**, *158*, 111552, doi:10.1016/j.ecolind.2024.111552.
323. Shrestha, S.; Bae, D.-H.; Hok, P.; Ghimire, S.; Pokhrel, Y. Future Hydrology and Hydrological Extremes under Climate Change in Asian River Basins. *Sci. Rep.* **2021**, *11*, 17089, doi:10.1038/s41598-021-96656-2.

Acknowledgement

I would like to express my deepest gratitude to my promotor, Prof.Dr. Wim Bastiaanssen, who provided me with great guidance, support, and continuous inspiration. Without Wim's dedicated supervision and shared wisdom, I would not be able to complete this dissertation. I also want extend my heartfelt gratitude to the copromotor, Dr. Gerrit Schoups, for his unwavering support during the times when it was most needed to complete this dissertation.

My gratitude also go to my colleagues at the Institute of Water Resources Planning and the Ministry of Agriculture and Rural Development. Their full support and encouragement have greatly assisted me throughout my doctoral journey in The Netherlands and also in the office.

I truly cherish the precious time spent during my intermittent visits in Delft and Wageningen. My heartfelt gratitude goes to Tim Hessels, Jonna van Opstal, Claire Michailovsky, Bert Coerver, Marloes Mul, Martine Rutten, Marjan Kreijns, Elga Salvadore, Gonzalo Espinosa Dávalos, Xueliang Cai, Gijs Simons and many others really amazed me with their vast knowledge and a wealth of food for thought whenever I came to their desks.

A workshop with international scientists was undertaken as part of the MK27 project on "Inclusive development paths for healthy Red River landscapes based on ecosystem services" organized as part of a CGIAR Water, Land and Ecosystems program where many aspects of HESS were discussed. My thanks went to CGIAR specialists Matthew McCartney, Lisa-Maria Rebelo, Natalia Carmona who were there and being a source of inspiration about HESS.

My gratitude also extends to colleagues at USAID's Vietnam Forests and Deltas Programme, Mark Fenn and Ate Poortinga, who opened my eyes to the world of remote sensing and to my own Vietnamese terrestrial and hydrologic ecosystems.

Finally, I am deeply grateful to my family and friends for their unconditional care and support throughout this wonderful journey.

Curriculum Vitae

Education

2025	**Doctor of Philosophy**, Delft University of Technology (TU Delft), The Netherlands.
2010	**Master of Science in Hydro-Informatics and Water Management (EUROAQUAE)**, University of Côte d'Azur (formerly University of Nice Sophia-Antipolis), Nice, France**.** Intermittent exchanges at Polytechnic University of Catalonia (UPC), Barcelona, Spain and University of Newcastle, Newcastle upon Tyne, United Kingdom.
2007	**Bachelor of Engineering**, Thuy loi University, Hanoi, Vietnam. Major: Water infrastructure.

Employment record

2012-present	**Water resources engineer/Head of Department,** Department of Training and International Cooperation, Institute of Water Resources Planning (IWRP), Hanoi, Vietnam.
2010-2012	**Researcher/Modeller,** DHI-NTU Research Center, DHI Water & Environment, Singapore.
2007-2008	**Water resources engineer/Modeller,** Egis BCEOM Project Office, Hanoi, Vietnam.

List of publications

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

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. Determination of Spatially-Distributed Hydrological Ecosystem Services (HESS) in the Red River Delta Using a Calibrated SWAT Model. Sustainability 2023, 15, 6247. https://doi.org/10.3390/su15076247

Ha, L.T., Bastiaanssen, W.G.M., Das, N., Hessels, T., 2024. Mapping of Hydrological Ecosystem Services (HESS) of all major river basins in Vietnam using remote sensing and hydrological modelling to promote Nature-based Solutions and sustainable water management. Journal of Hydrology: Regional Studies. *Under review*.

Simons, G.; Poortinga, A.; Bastiaanssen, W.G.M.; Saah, D.S.; Troy, D.; Hunink, J.E.; Klerk, M. de; Rutten, M.; Cutter, P.; Rebelo, L.-M.; et al. On Spatially Distributed Hydrological Ecosystem Services: Bridging the Quantitative Information Gap Using Remote Sensing and Hydrological Models; 2017.

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

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