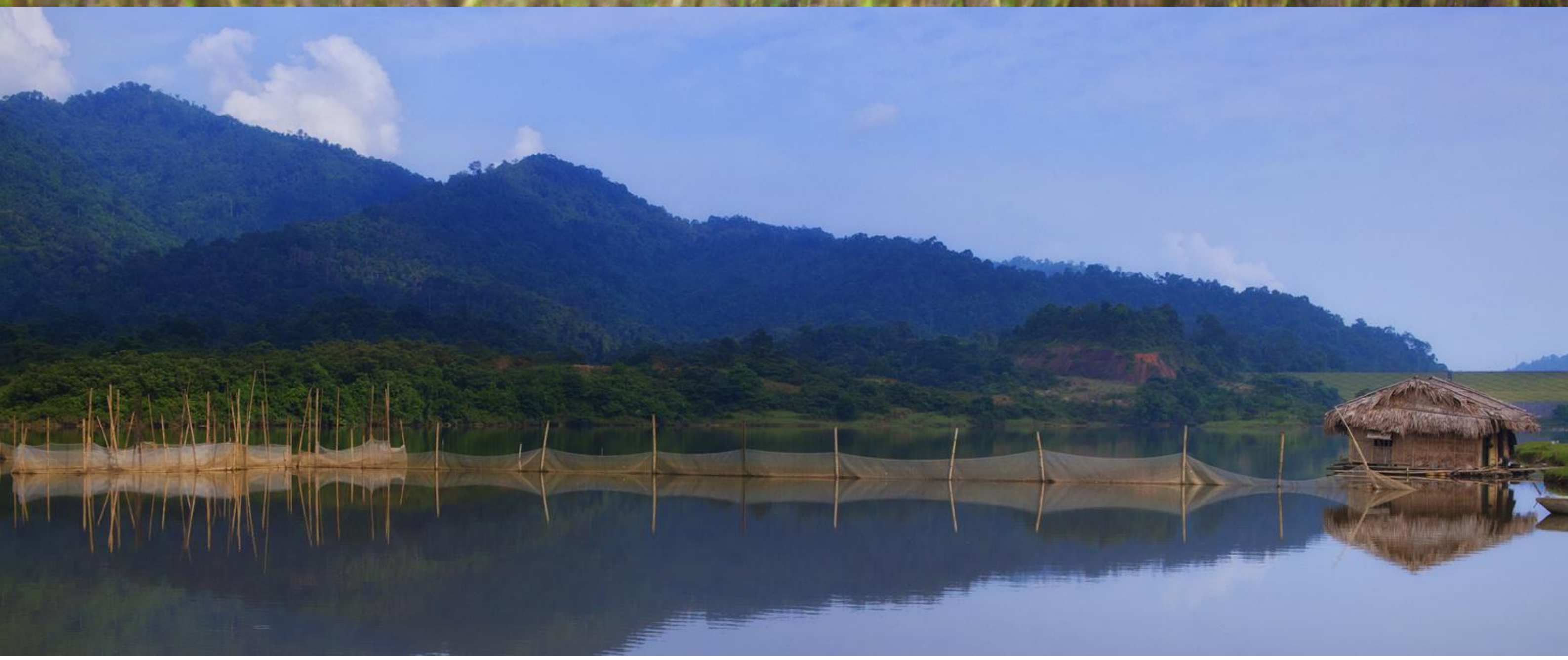
On Spatially Distributed Hydrological Ecosystem Services

Bridging the Quantitative Information Gap using Remote Sensing and Hydrological Models



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On Spatially Distributed Hydrological Ecosystem Services

Bridging the Quantitative Information Gap using Remote Sensing and Hydrological Models

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Foreword

One of the ways in which the CGIAR Research Program on Water, Land and Ecosystems (WLE) addresses the challenge of achieving sustainable growth is by improving our understanding of tradeoffs and synergies related to water, food, environment and energy. Essential to the success of these efforts is the availability of quantitative data on these tradeoffs and synergies, and how they vary across space and time.

Specifically for the countries sharing the Mekong River, WLE Greater Mekong seeks to drive and inform research and dialogue around the rivers of the region. Hydrological EcoSystem Services (HESS) are heavily affected by intensive development across the region, such as the construction of hydropower dams and land use changes - in particular deforestation, urbanization and agricultural intensification. The full extent of such changes in the agro-ecological system is often unknown, and it is a challenge to account for tradeoffs in HESS in policy processes.

As in many other areas of the world, improving governance and management of water resources and associated land and ecosystems in the Greater Mekong region is not only a matter of generating more data. Sharing of knowledge and practices is a key focus of WLE Greater Mekong, which we strive to promote by enhancing the accessibility of valuable information to a wide diversity of regional stakeholders, and promoting dialogue by facilitating the creation of communities of practice.

This white paper demonstrates state-of-the-art methods for assessing different HESS and their tradeoffs under different development scenarios. It explores opportunities for spatial monitoring of HESS and predicting changes under different future scenarios, information that is essential for achieving a balanced and healthy agro-ecological system. By relying on tools in the public domain and leveraging the resulting HESS data through online information platforms, this white paper is an excellent example of current efforts supported by WLE Greater Mekong to stimulate uptake of ecosystem services assessments in decision-making processes.

Kim Geheb
Regional Coordinator – Greater Mekong
CGIAR Research Program on Water, Land and Ecosystems
June, 2017

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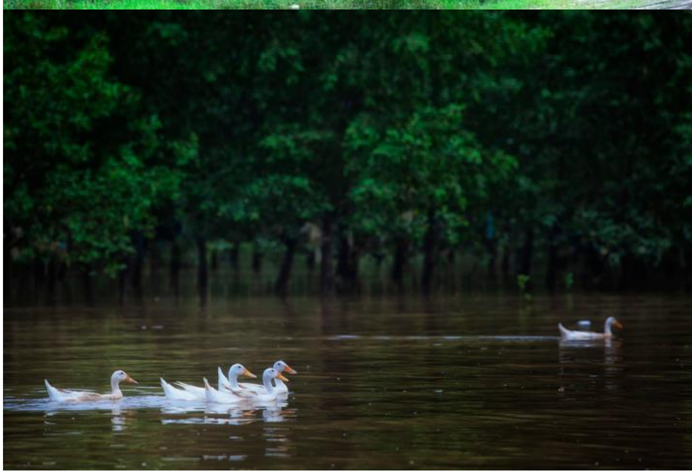
1. Hydrological Ecosystem Services: an introduction

1.1 Introduction to ecosystem services

Ecosystems provide a wide range of benefits to humans, but these **ecosystem services** (ESS) are rarely accounted for in any proactive way by decision makers. More typically, ecosystem benefits are ignored until it is too late, at which point expensive and reactive interventions are required to address the loss of ecosystem benefits. Different frameworks based on the general concept of ecosystem services to humans were developed over the past two decades, aiming to mainstream the proactive consideration of ecosystem benefits in planning and policy decisions.

Application of ESS frameworks is most fundamentally about the quantification of tradeoffs. When ecosystems are affected by economic development, the benefits that the ecosystem once provided may be compromised or eliminated. Some such services, such as the regulation of water flows, can be replaced via engineered solutions but the cost of this replacement can be significant. In contrast, many cultural services such as the aesthetic or spiritual value of nature are often irreplaceable. **Quantification** of these opportunity costs can be compared to the economic benefits of the development, allowing for a more holistic view of costs and benefits. ESS frameworks are used not only to look at the loss in services from development, but also at the gain in services achieved through effective ecosystem restoration and its impact on people's livelihoods.

Despite the emergence of several classification schemes, there is still debate about how ecosystem services should be defined and categorized. One of the most common systems of categorization is from the **Millennium Assessment** (MA, 2005). It splits up all ecosystem services into four overarching functional categories.



Application of ecosystem services frameworks is most fundamentally about the quantification of tradeoffs

Ecosystem services are typically classified in Provisioning, Cultural, Regulating, and Supporting services

Provisioning services

Goods directly gathered from nature, such as food, fresh water, fiber, firewood and building materials

Cultural services

Those services that are based on human preference, like recreational opportunities, aesthetic views, education, and far more intangible services like spiritual value and existence value, or finding value in knowing that something simply exists.

Regulating services

Processes where nature regulates and mitigates the flow of both positive and negative processes that are essential to human survival, such as fresh water supply regulation and flood mitigation, respectively. Often a regulating service reduces the cost of production of a market good, such as in the case of pollination, where natural pollinators help increase crop yields.

Supporting services

These services do not directly benefit humans, but support the production of other services that do provide direct benefits. The distinction between some regulating and supporting services is often ambiguous, as the extent to which some regulating functions are seen as providing direct benefits depends on temporal and spatial scale. For instance, waste treatment is usually classed as a regulating service because it is short term and has a direct link to human welfare, while nutrient cycling is generally considered a supporting service with its long-term cycles and an indirect link to human utility.

After the Millennium Assessment, one of the most significant attempts at categorizing ecosystem services came out the Economic of Ecosystems and Biodiversity (TEEB) project, which proposed a variant on the MA framework. This variant keeps two of four primary categories, slightly alters the cultural category and replaces the Supporting Services category with “Habitat Services”. TEEB's strong focus on habitat and biodiversity is based on the contention that these two things underpin almost all other services. The **Ecosystem Services and Resilience Framework (ESR)** of the CGIAR Research Program on Water, Land and Ecosystems (CGIAR, 2014) builds on the TEEB concept, and emphasizes the interplay between agricultural systems and ecosystems. In this concept of integrated *agricultural landscapes*, communities are supported by stocks and flows of ecosystem services that they are able to manage at different scales, in order to ultimately improve human well-being and alleviate poverty.

An extensive discussion of different ESS frameworks goes beyond the scope of this white paper. Excellent resources on ESS and their classification are found at:

- *wle.cgiar.org/research/themes/ecosystem-services-and-resilience*
- *www.teebweb.org/resources/ecosystem-services*
- *biodiversity.europa.eu/topics/ecosystem-services*

For more in-depth literature including many case studies, debates and proposed nuances, the reader is referred to papers by Costanza *et al.* (1998), Wallace (2007), Farber *et al.*, 2006, Boyd & Banzhaf (2007), De Groot *et al.* (2010), Fisher & Kerry Turner (2008), Fisher, Turner, & Morling (2009), and Fisher *et al.* (2009).

Some types of ecosystem services are impossible to value or quantify. For instance, spiritual, religious, educational, or bequest values (feeling of value associated with providing for future generations) are of great importance for ecosystems across the world, but they do not lend themselves to quantification in most circumstances. Nor do non-use values, such as existence or option value, which is the value that people ascribe to a place for its mere existence, or for the fact that it may be useful at some time in the future. Even habitat value is not generally considered quantifiable as it is not a service that is directly consumed by human beneficiaries, but rather supports the creation of other services that humans consume.

> *Many services can be quantified and even monetized by using state-of-the-art tools*

Nonetheless, many other services—particularly those that involve the need to engineer replacements—can be **quantified** and even **monetized**. Many services that involve water fall under this category: water supply regulation, nutrient and sediment regulation, waste assimilation, flood regulation, and carbon sequestration can all be quantified by using state-of-the-art tools. A value can subsequently be ascribed to them when there are human beneficiaries downstream. All of these services depend on healthy upstream ecosystems and we can evaluate the extent to which land change will compromise the flow of these services which, in turn, will require expenditures to engineer replacements to maintain a certain level of well-being among downstream beneficiaries.

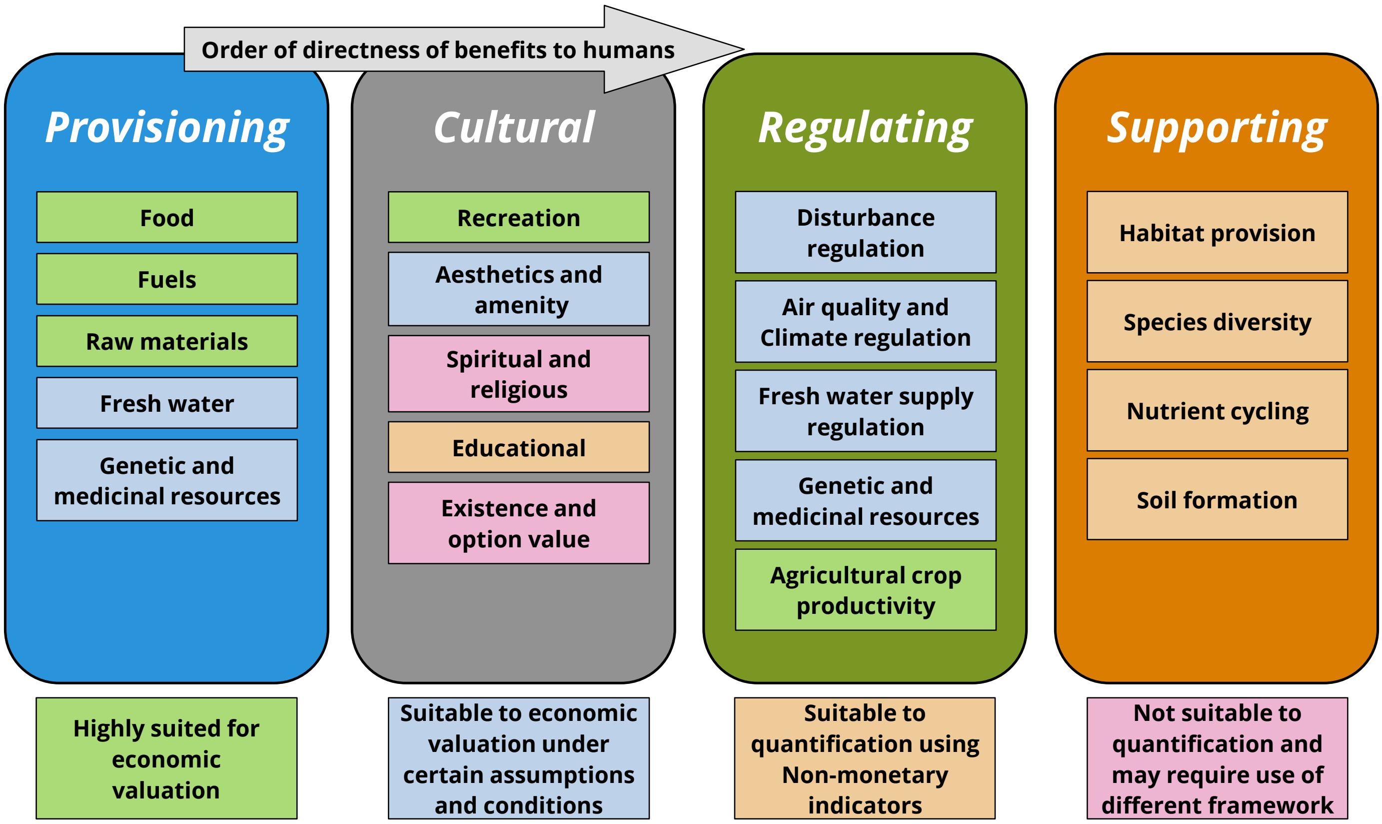


Figure 1: Ecosystem service classification system, color-coded by suitability for quantification (based on Saah and Troy, 2016).

1.2 Hydrological Ecosystem Services: the link to water

Water underpins many of the services that ecosystems provide and is a critical component in maintaining ecosystem functions. **Hydrological EcoSystem Services (HESS),** also known as Water-related Ecosystem Services, comprise those ESS that explicitly describe the services rendered from water resources.

The water cycle at the river basin scale in relation to ecosystem services is illustrated in Figure 2. For a clear accounting of water flows, it is recommended to distinguish between the vertical and horizontal components of water flow and fluxes. The soil water balance describes the essentially vertical flows and the interaction between land and atmosphere, as well as the moisture exchange between unsaturated and saturated soil. The regional water balance describes horizontal flows that convey water through streams, rivers and aquifers. Information on horizontal flows can be derived from adding together all spatially distributed vertical soil water flows across a certain spatial domain. A domain can be a single catchment (e.g. the catchment of a reservoir) and should always be studied in the context of the river basin for having access to an estimation of the lateral flows from the upstream part.

The benefits associated with HESS are not only determined by the spatial distribution of volumes of water, but is equally dependent on timing of water flows. In case the volume of water supplied is too large to be put to beneficial use at a certain point in time, the extent to which certain HESS can be provided will depend on the presence of natural or artificial storage mechanisms.

Water plays an important role in ecosystem service valuation

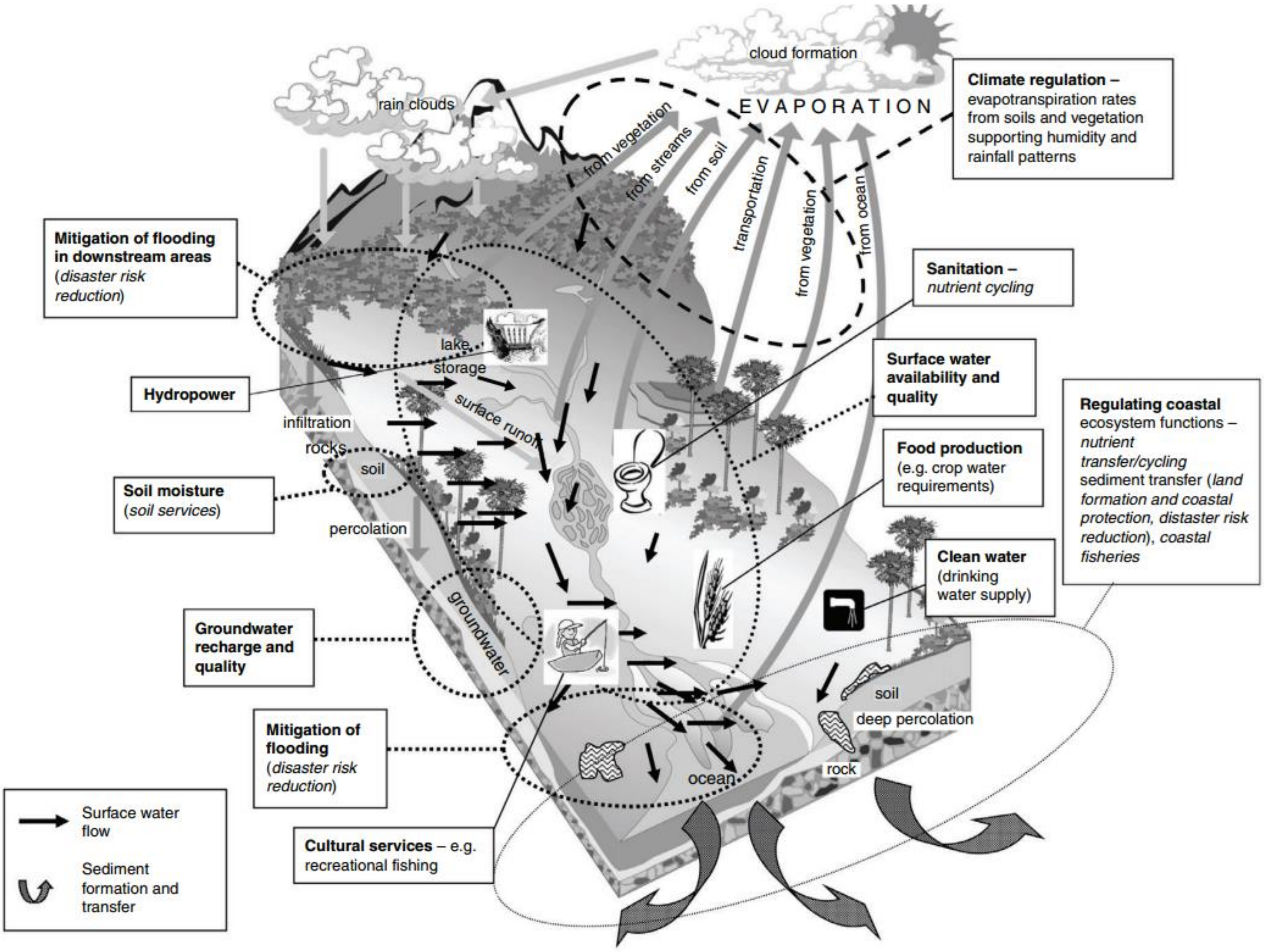


Figure 2: Hydrological and water management processes in relation to their ecosystem services (after Coates *et al.*, 2013).

Many ecosystem services relate to the **consumptive use** of water. Water resources are consumed when traversing from the point of entry in the river basin – usually through rainfall or interbasin flow – towards the downstream end of the river system. Water is considered to be consumed when it is **no longer available** to downstream users. The most common process of consumption is actual evapotranspiration, where water moves from liquid to vapor phase. The water is literally disappearing and cannot be conveyed to water user groups, unless it is returned by local rainfall. Another example of water becoming a sink term of the water balance, is when it is part of products (e.g. inside banana or bottled water) or cannot be economically exploited because it flows through faults and cracks into very deep layers. When water gets very polluted by wastewater discharge or non-sources pollutants from agriculture, the quality can reach deterioration levels that no longer meet minimum quality standards. Under such situation we also refer to water as being consumed.

The process of water consumption provides several benefits and services, and its irreversible character prompts humans to acquire maximum benefits from it. The transpiration of trees will provide timber products because carbon is taken up when water vapor flows out of the stomata. Simultaneously, sap flow will transport the required minerals for sustaining tree health. Transpiration from vegetation provides biomass production, both above and below ground. The biomass accumulation is a result of Net Primary Production (NPP)[1] which is the basis for food, feed and fiber; the intended primary and economic benefit which links to the provisioning category of ecosystem services.

> *The process of water consumption provides many primary and secondary benefits and services*

Ecological production also has several secondary benefits that provide a pleasant living environment. Evapotranspiration requires large amounts of energy and this energy is no longer available for heating of the atmosphere. Therefore, air temperature over evaporating land surfaces is often several degrees lower than over moderately moist surfaces. This physical process is exploited, among others, by creating green parks, city ponds and roof gardens in urban areas to reduce the impact of urban heat islands. Further to atmospheric cooling, the process of evapotranspiration sustains rainfall and sequesters atmospheric carbon. Healthy vegetation supports biodiversity and conserves land and soil resources by reducing erosion.

Figure 3: A wide range of economic and ecological benefits are a result of consumptive water use and the total services can be improved through proper planning of land use in relation to the green and blue water resources in river basins.

Unfortunately, however, a large fraction of consumptive use is **non-beneficial.** This relates mainly to the evaporation from wet leaves – interception – and wet soils. While they indirectly contribute to micro-climatic cooling and sustaining rainfall, the direct benefits are little. It is therefore important to prevent water logging by introducing proper drainage technologies.

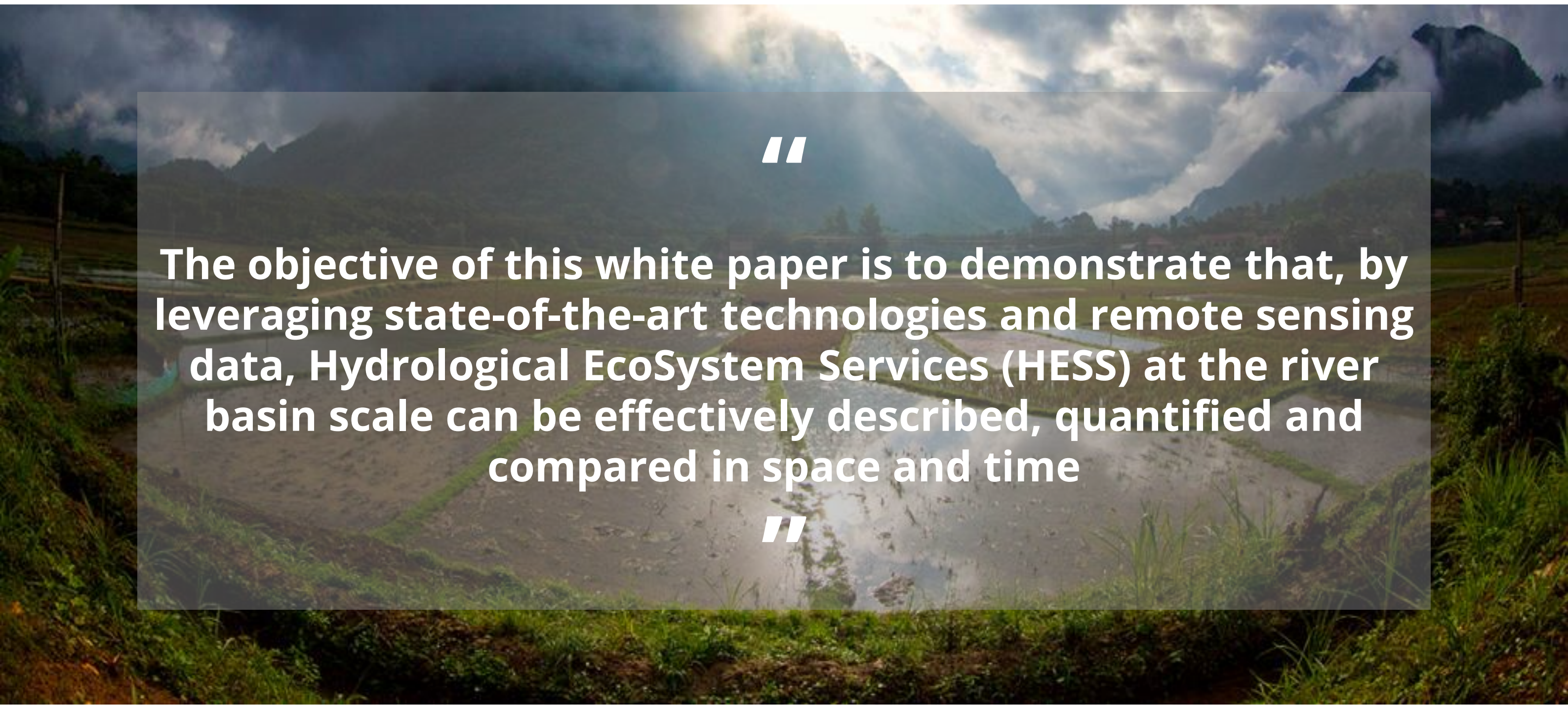
[1]NPP is defined as Gross Primary Production (GPP), the total amount of chemical energy produced by the plant, minus the energy used for respiration

1.3 Objectives of this white paper

A global revolution in the planning of scarce water resources to secure food production and economic growth without degradation in biodiversity is urgently required. Hence, efforts to realize green growth must be well-managed to avoid unintended social, economic and ecosystem consequences across landscapes. This requires a thorough understanding of water flow paths and associated hydrological ecosystem services.

The objective of this white paper is to demonstrate that, **by leveraging state-of-the-art technologies and remote sensing data, HESS at the river basin scale can be effectively described, quantified and compared in space and time**. While discussions on the theoretical framework are infinite, it is urgently needed to develop procedures to quantify HESS and make them accessible to a large audience. Such efforts are undertaken, for example, in the **CGIAR WLE Greater Mekong**[1] and **SERVIR-Mekong** programs[2]. This white paper demonstrates collaborative efforts that draw from state-of-the-art technologies to achieve this vision of enhanced quality and accessibility of spatially explicit HESS information.

An operational reporting system is a prerequisite for managing scarce water resources wisely. Responsible authorities can make better plans if they have a measurement and monitoring system in place. The link to water resources is inevitable and this white paper defines a number of key HESS indicators as recognized by the WLE program. We showcase a set of open-access data and hydrological modelling tools which help to produce spatial, quantitative datasets on HESS to bridge existing knowledge gaps. These datasets should be distributed through online information platforms such as the SERVIR global and regional websites, which will serve to increase the use of HESS-related information by planners, policy makers, and other decision makers. Readily available information on HESS is expected to foster the implementation of this concept in longer term water resources management plans.



[1]wle.cgiar.org, [2]servir.adpc.net

2. Defining the knowledge gap

2.1 Shortlist of Hydrological Ecosystem Services

Within the CGIAR WLE program, efforts are undertaken to improve the livelihoods and ecological benefits derived from reservoirs and their catchments without impairing the economic and social gains of development. WLE promotes an approach to sustainable agricultural intensification that recognizes the fundamental role that healthy ecosystems play in sustainable natural resource management, human well-being and resilient food system. Together with experts active in the WLE program, a **shortlist of key HESS indicators** has been developed in 2015-2016 during workshops in Vientiane and Hanoi (see Figure 4). This table can be considered a minimum list of 17 HESS indicators on which consensus was achieved during expert consultations. The link of these HESS indicators to agro-ecological processes is described in this section.

> *A list of 17 important indicators of Hydrological Ecosystem Services was established*

The total availability of blue water resources in rivers, lakes, streams and aquifers is a result of fast surface and slow groundwater runoff. Runoff arises when the soil has insufficient capacity to retain the rainfall locally. During these moments, excess water flows to streams and aquifers that represent the renewable water resources that can be explored for utilization. The same water flow provides also habitats to flora and fauna and it is relevant to maintain certain historic flow regimes – or a portion of it – for spawning and migration of fish, among others. The total water stock is important for survival during elongated periods of drought. The vertical soil water balance is land use dependent. Ecosystems with a good aeration will infiltrate more water and forests will have deep rooting systems that can store large amounts of water in the vadose zone. For these reasons, forests will have the ability to attenuate peak flow for safeguarding flooding in downstream areas, a rather direct impact on the livelihood of people living in deltas.

Many of these water systems are natural (lakes, rivers, mangroves) and can be a source of water during the dry season. Net Primary Production from natural pastures, alpine pastures, wetlands and other classes provides livestock feed. For more woody types of vegetation (e.g. forests and savannah), accumulated biomass can be used for firewood and woody vegetation sequesters more carbon in the trunk and branches. The underground dry matter production of these ecosystems contributes to carbon fixation in soils.

The exchanges between landscapes – and especially green landscapes - with the atmosphere have, next to constituting a net carbon sink, also a positive impact on a reduction of the near-surface air temperature and generation of rainfall. A higher density of atmospheric water vapor will increase the likelihood of rainfall, which typically increases towards mountainous areas. In case of larger river basins, this atmospheric moisture recycling will feed the upstream rivers at their source areas and enhance their discharge rates.

Large amounts of fertile soil are potentially eroded through surface runoff or by wind gusts. Soil conservation can be achieved by contour management and covering the soil with vegetation, reducing erosion and sedimentation. These potential extra benefits of food production are often not recognized.

	Category		Service
Provisioning	**Fresh water**	1	Total runoff
Provisioning	**Food**	2	Inland capture fishery
Provisioning	**Food**	3	Natural livestock feed production
Provisioning	**Fuel**	4	Fuelwood from natural forests
Cultural	**Recreation**	5	Leisure
Regulating	**Fresh water supply**	6	Dry season base flow
Regulating	**Fresh water supply**	7	Groundwater recharge
Regulating	**Fresh water supply**	8	Water storage in lakes
Regulating	**Fresh water supply**	9	Meeting environmental flow requirements
Regulating	**Fresh water supply**	10	Sustaining rainfall
Regulating	**Air quality and climate**	11	Carbon sequestration
Regulating	**Air quality and climate**	12	Reduce greenhouse gas emissions
Regulating	**Air quality and climate**	13	Microclimate cooling
Regulating	**Disturbance regulation**	14	Peak flow attenuation
Regulating	**Water quality**	15	Reduction of eutrophication in water
Regulating	**Water quality**	16	Reduction of soil erosion
Supporting	**Habitat provision**	17	Aquatic connectivity (fragmentations)

Figure 4: Shortlist of 17 indicators of Hydrological EcoSystem Services.

2.2 Existing frameworks demanding HESS data

As the concept of ecosystem services evolved during the past two decades, attempts have been made to link academic assessments of ecosystem services to decision making processes. These frameworks / concepts / methods all **demand input data** on hydrological ecosystem services, varying in space and time. A few examples are given below to demonstrate the need for HESS information. Given the multitude of perspectives and institutions involved in this field of work, this is by no means an exhaustive list.

1 Water Accounting Plus (WA+)

The long-term planning process for water and environmental resources in river basins requires a system for measurement, reporting and monitoring. The Partnership for Water Accounting (IHE-Delft, IWMI and FAO) works jointly on the development of an accounting system that provides monthly standard reports on rivr 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. Software tools are being prepared that link open-access input data to reporting sheets. WA+ can be used to evaluate and plan water resources management, to monitor changes in water resources and to assess the impacts of future interventions, ensuring a sustainable water balance.

www.wateraccounting.org

WA+ improves understanding of the current state of water resources in a river basin, development opportunities and future challenges

As part of the CGIAR WLE program, WA+ has been implemented in the Nile, Greater Mekong and Volta basins, as well as in smaller basins such as the Red River basin. This work has involved the development of an indicator framework for HESS which has been incorporated into the WA+ approach. Here, quantified HESS (mainly provisioning & regulating) are related to consumptive and non-consumptive water use by different categories of land use classes, corresponding with land use - specific water management options. A publically available sheet generator converts HESS data into the reporting sheet presented in Figure 5.

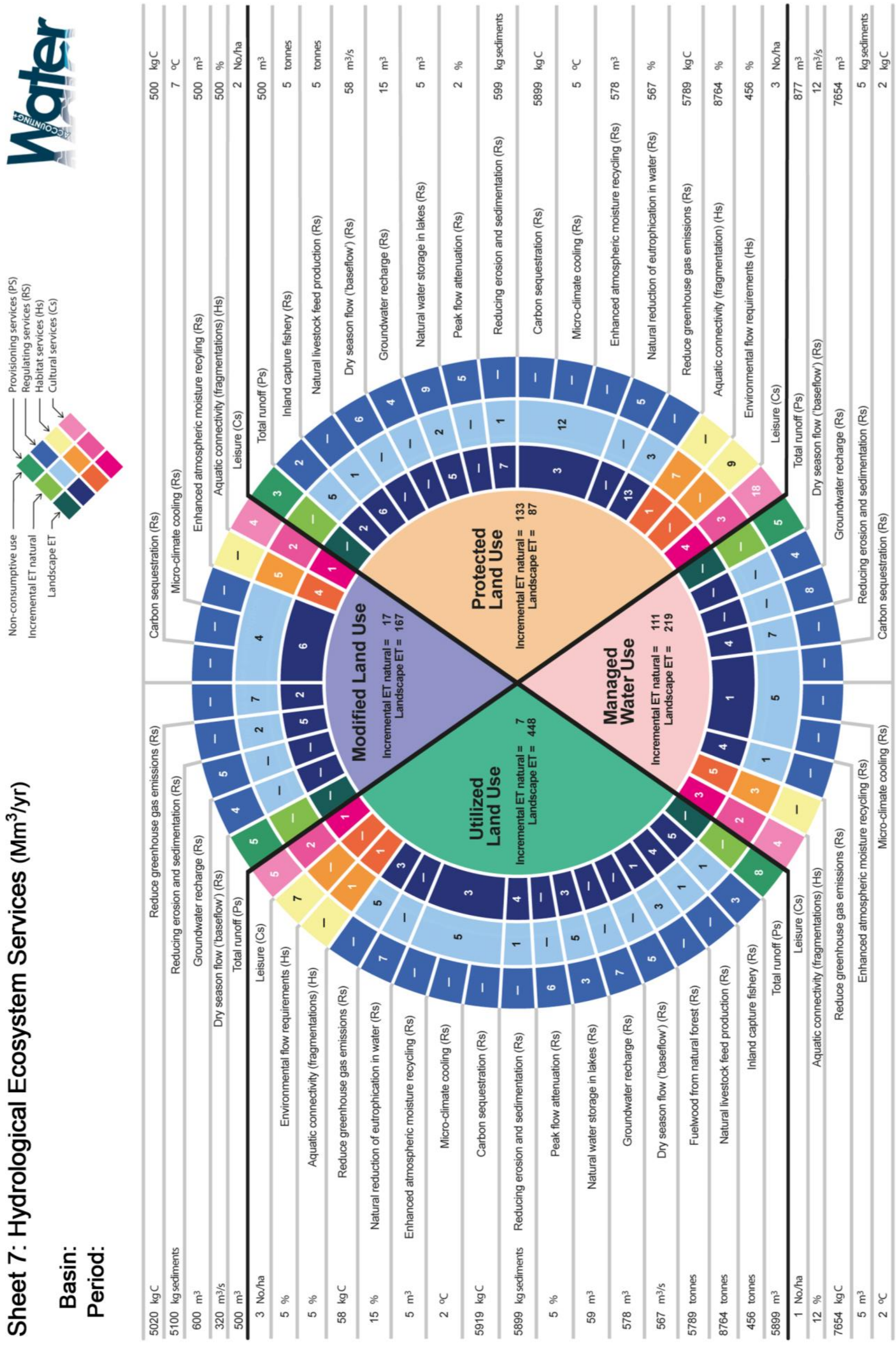


Figure 5: HESS reporting sheet as developed for Water Accounting Plus (WA+) within the CGIAR WLE Greater Mekong program.

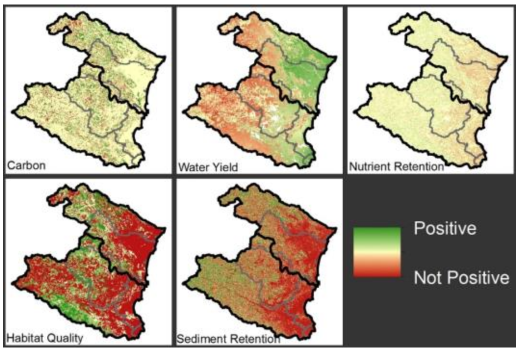
2 InVEST

InVEST from the Natural Capital Project, is an exploratory tool that models how changes in ecosystems may lead to changes in benefits that flow to people. Its models employ a production function approach that predicts the output of ecosystem services based on environmental input conditions and processes. Once a biophysical output is predicted, InVEST allows users to estimate valuations (provided that the required valuation input data are available). InVEST has been used in several dozen contexts around the world in support of spatial planning, payment for ecosystem services schemes, climate adaptation planning, development impacts analysis, restoration planning and corporate risk management. InVEST has 18 modules, each of which is designed to model a different ecosystem service. In terms of non-coastal hydrology, there are the following: water purification, nutrient retention, sediment retention and delivery, water yield for hydropower production, and marine water quality (which accounts for transport of pollution through surface waters). Interestingly, there is no avoided flood model and no water supply timing model.

InVEST

integrated valuation of ecosystem services and tradeoffs

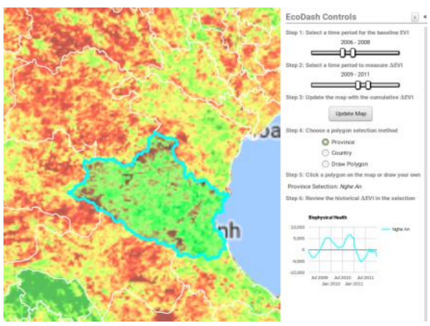
www.naturalcapitalproject.org/invest



InVEST’s hydrology models are data intensive. In particular they require detailed data on soils and temporally disaggregated precipitation patterns. As an example, the water yield for hydropower model requires input data on precipitation, transpiration, evaporation, water availability, root depth, vegetation type and groundwater recharge rate. This is a challenge in locations where data are scarce.

3 EcoDash

The **EcoDash** tool was developed by a team supported by the SERVIR-Mekong project, a collaboration of USAID and NASA. This online tool enables policy makers, funders, project evaluation teams and consultants to evaluate the biophysical impact of a development project in a fast and cost-effective manner. An intuitive user interface allows the user to investigate changing conditions within and/or between one or more explicit areas using basic calculations performed on gridded datasets of interest.



ecodash-servir.adpc.net

The current implementation leverages Google Earth Engine's state-of-the-art cloud-based GIS technologies consisting of unparalleled co-located data and computing power. The tool enables users to compare the biophysical conditions of an area with historical baseline conditions and/or with other sites. Currently the focus of the tool is on the Enhanced Vegetation Index derived from NASA's MODIS Earth observation mission. However, additional HESS indicators will be accessible via the tool in the near future and it is seen as an important development milestone in the process of creating a broad and robust platform to support the general access to and use of HESS and related data.

4 ARIES (ARtificial Intelligence for Ecosystem Services)

aries.integratedmodelling.org

ARIES "strives to quantify the benefits that nature provides to society in a manner that accounts for dynamic complexity and its consequences, but keeps models clear enough to users to remain understandable, usable, and adaptable to conditions of varying data availability". ARIES is essentially an integrated modelling framework that aims to serve and connect modelers, institutions, researchers and decision makers. Its focus is on modeling the spatial connection between service producing ecosystems, flow paths of services, and the beneficiaries who consume those services. Information from earth observing satellites, airborne, land and water-based sensor networks, and crowdsourced observations are combined in order to enhance collaboration and communication among stakeholders.

Potential uses of ARIES include spatial economic valuation of ecosystem services, natural capital accounting, optimization of payment schemes for Ecosystem Services, and forecasting of future changes in ecosystem service provisioning, all of which demand spatial quantification of hydrological ecosystem services.

3. A toolbox for assessing Hydrological Ecosystem Services

3.1 Remote sensing data

Recent international scientific developments in remote sensing are rapid and significant, leading to the distribution of spatial, quantitative data on relevant eco-hydrological parameters for the entire globe. Data Active Archives provide thematic satellite data, free of charge and 24/7. Many datasets are distributed for land and water management applications, such as global land cover, Leaf Area Index (LAI), rainfall, evapotranspiration, soil moisture, and water levels. Several companies, universities and NGO's have made their own added value products based on publicly available raw satellite data provided by space agencies.

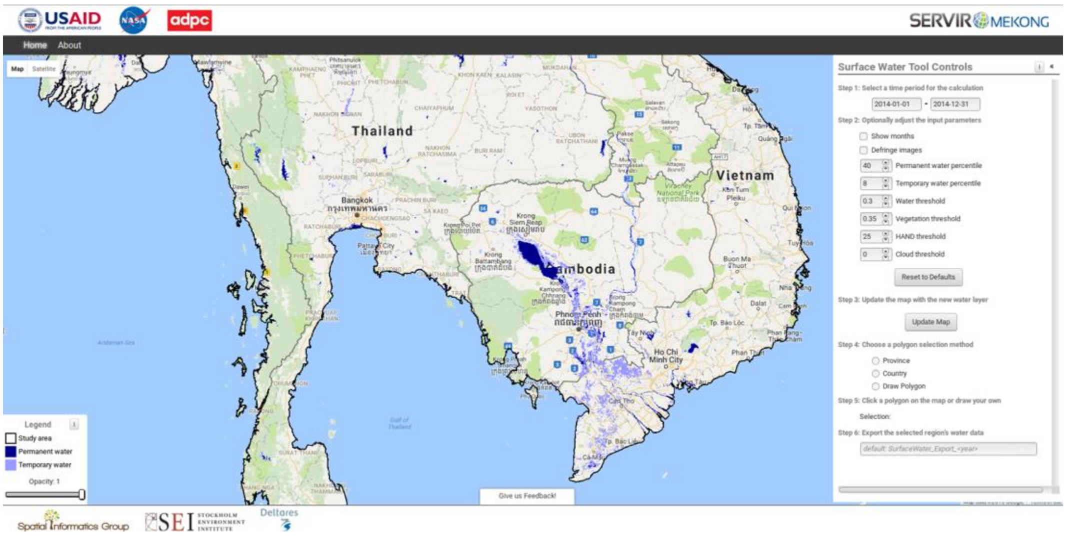


Figure 6: The surface water tool developed by the USAID-funded SERVIR-Mekong program. The tool calculates past patterns of surface water extent from multiple layers of Landsat imagery (surface-water-servir.adpc.net/).

Examples of water-related applications are the SERVIR-Mekong surface water tool (Figure 6), the Dartmouth Flood Observatory for flooded areas[1] and the DAHITI database of water levels in lakes, reservoirs, rivers and wetlands[2]. If specific datasets are not directly available, then own remote sensing algorithms have to be applied or developed. The latter is typically the case with evapotranspiration, biomass production, and local water resource availability. Hence, in the context of HESS mapping, four categories of remote sensing input data can be distinguished:

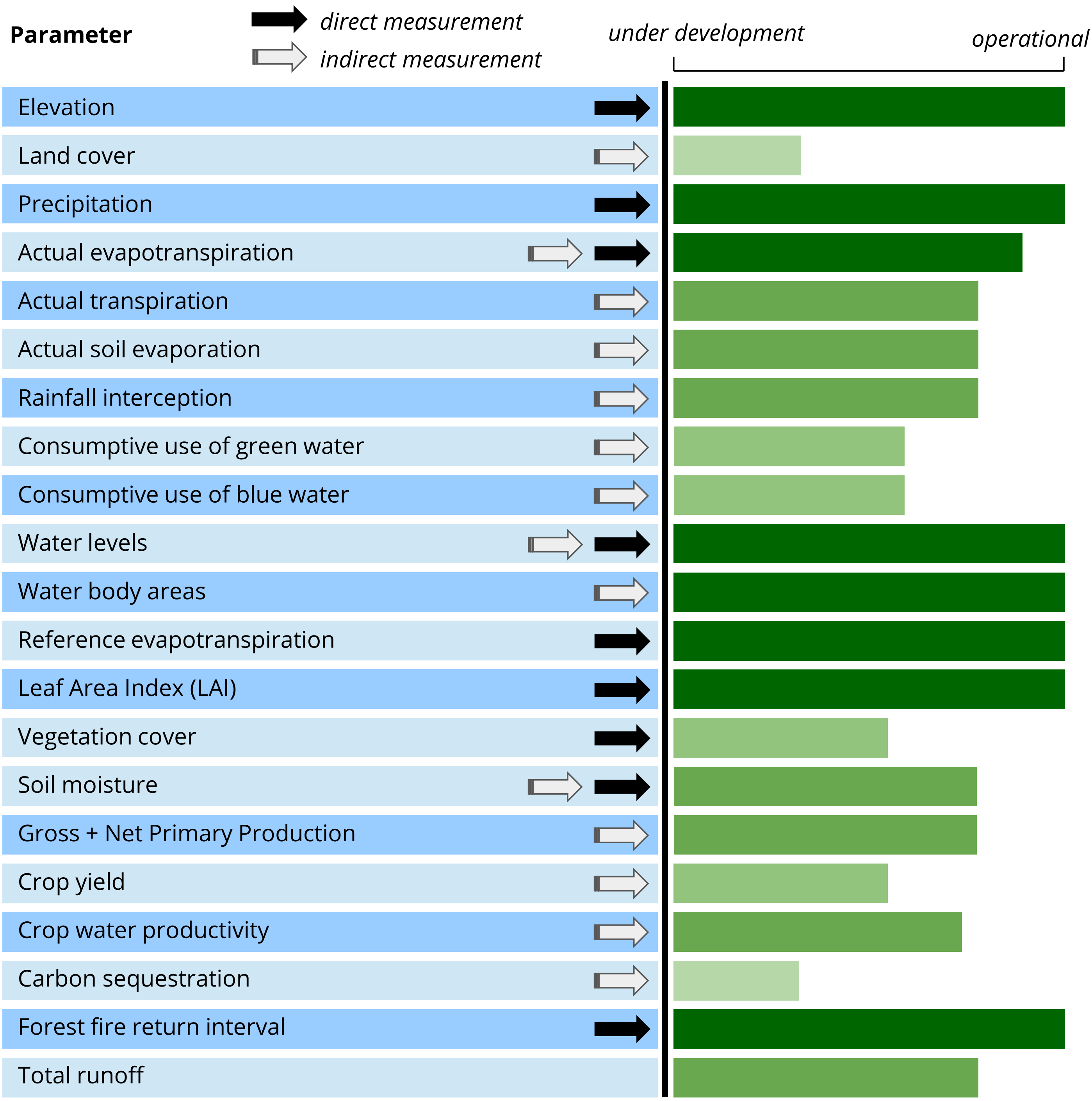
- Original satellite radiance measurements (i.e. raw data)
- Standardized land and water management data provided by space agencies.
- Added value products provided by knowledge centers (i.e. directly available)
- Additional data needed specifically for HESS analysis (i.e. indirectly available)

> *Recent international scientific developments in remote sensing are rapid and significant, leading to the distribution of spatial, quantitative data on relevant eco-hydrological parameters for the entire globe*

[1]floodobservatory.colorado.edu, [2]dahiti.dgfi.tum.de

It is possible to obtain or produce most of these data at a spatial resolution of 1 km x 1 km at the daily scale, following the typical moderate resolution satellite images from MODIS and related earth observing systems. VIIRS is the successor of MODIS, and it provides grids with cells of 375 m x 375 m, every day. Certain products can also be created at 100 m x 100 m data using PROBA-V satellite measurements[1].

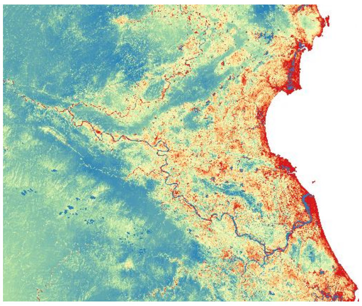
The available set of spatially variable remote sensing data is presented below, with the corresponding level of maturity. The latter is essential to distinguish between standard datasets with a high accuracy, and other datasets that require more scientific attention. These assessments are based on the expert judgements of the authors.



[1]proba-v.vgt.vito.be

Rainfall

For **rainfall**, it is customary to consider global satellite-derived products such as those derived from the GPM mission[1] or CHIRPS[2]. CHIRPS is global gridded rainfall product with over 30 years of data at a 5 km spatial resolution.

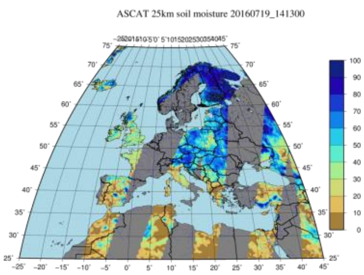


Evapotranspiration

IHE-Delft is currently preparing an ensemble product using 7 different global energy balance models for **evapotranspiration** (ET) at the global scale with 250 m spatial resolution and monthly time steps. The global direct products for ET that are downloadable are MOD16[3] and GLEAM[4]. The datasets of SEBS can be obtained after sending a message to the developers. The same holds more or less true for SSEBop, CMRSET and ALEXI. ETMonitor is under development by the Chinese Academy of Sciences and has a global coverage as well.

Soil moisture

Top-soil moisture can be best acquired from ASCAT[5] (12.5 km), but it needs to be complemented with the newest products from ESA and NASA for downscaling to 1 km. Top-soil moisture can be used to infer surface runoff and help to determine **sub-soil moisture** (being more important for resilience to drought and storage changes). Sub-soil moisture can be acquired from thermal remote sensing products, and should therefore be MODIS- or VIIRS-based. Under clouded conditions, shifting to micro-wave based sub-soil moisture estimation needs to be considered. The change of storage, which is essential for estimating the carrying-over of water from wet to dry periods, can be derived from time series of sub-soil moisture.



Floods

Flooded areas can be identified on the basis of optical images such as Landsat and PROBA-V and VIIRS. However, the flood season typically has overcast skies, causing microwave-based detection of open water to be necessary. This can be accomplished with the SENTINEL 1A radar, and other freely available radar imagery (e.g. ALOS, Tandem-X).

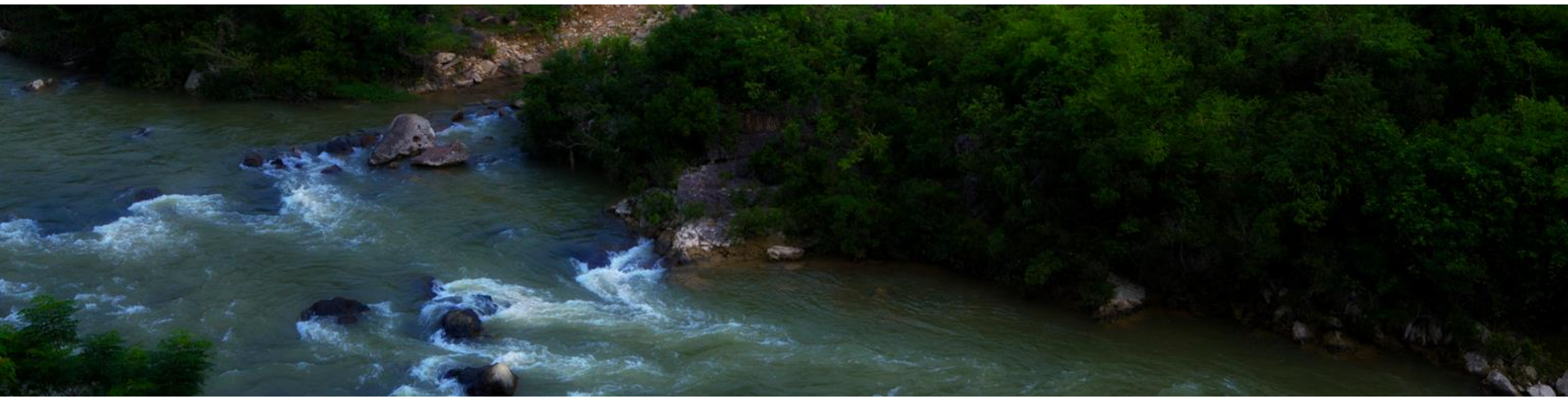
Biomass

The combination of **Net Primary Production** (NPP) and **land cover** is attractive for the separation into crop yield, feed, fruits & vegetables, fiber, oil and timber. Crop residues can be used for livestock feed. The **accumulated biomass** is also a measure for fuelwood in electricity scarce environments. NPP can be computed from the radiation and surface energy balance which are available through the ET technologies described before. The level of detail in the legend of land cover maps is often a limiting factor. Reliable maps of crop types are rarely available, and they often need to be made manually.

[1]pmm.nasa.gov/gpm, [2]chg.geog.ucsb.edu/data/chirps, [3]www.ntsg.umt.edu/project/mod16, [4]www.gleam.eu, [5]manati.star.nesdis.noaa.gov/datasets/ASCATData.php

3.2 Hydrological models

As discussed in the previous section, remote sensing provides important information for quantifying eco-hydrological processes at the land surface. However, by solely using earth observation techniques it is not possible to address all relevant hydrological processes. The lateral flow arising from surface runoff, drainage, floods, groundwater recharge and groundwater seepage must be computed with hydrological models. In addition, satellites by definition provide a view on the past, whereas decision makers need to know HESS under current and especially future conditions. Such **scenario thinking** allows for the evaluation of potential impacts of policy interventions.



Simulation models are an ideal tool for providing an outlook on different possible futures, dependent on factors both within and outside control of the decision maker. They can also provide information on subsurface processes, something which satellites cannot do (or only very limited). Models can be calibrated and validated for current conditions using data from observations and remote sensing. Once a satisfactory model performance has been established, model inputs can be varied to simulate different future scenarios. Analysis of the outcomes of these models allows for anticipation on e.g. future shifts in climate patterns and evaluation of the effect of different policies.

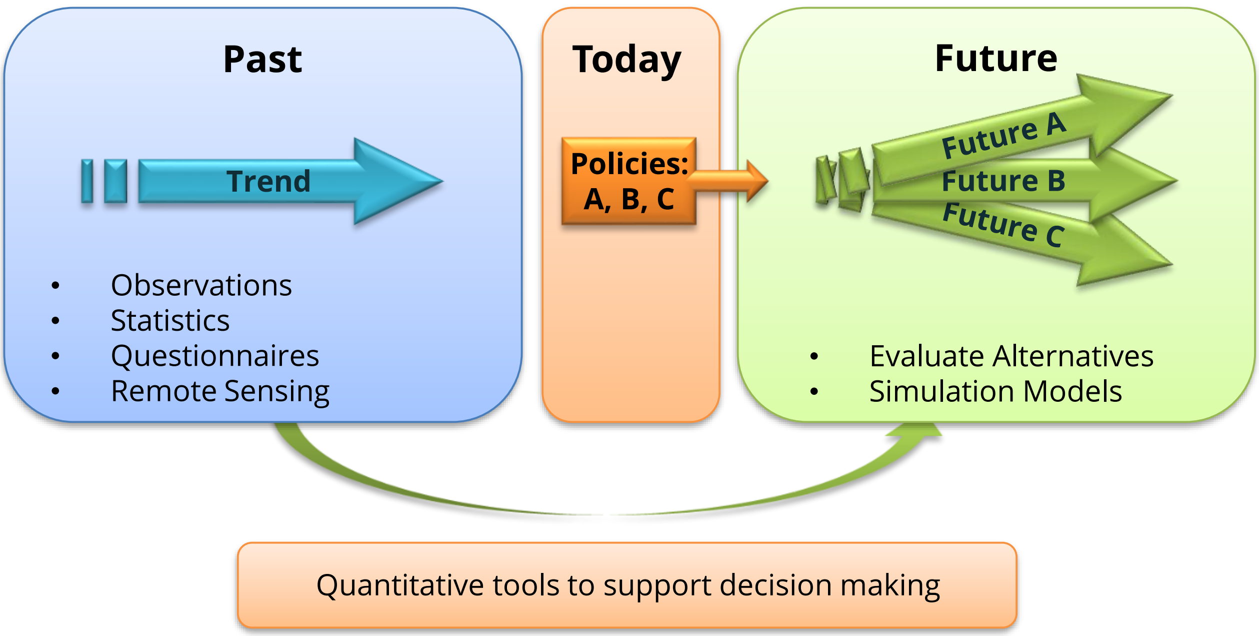


Figure 7: Why models are needed to support decision makers.

Many hydrological models are available, each with their own strengths and weaknesses. Selecting the right model for the right application is often the most difficult task. For bridging the HESS knowledge gap, it is important that the selected model provides quantitative information on the hydrological processes that govern the majority of the shortlisted HESS indicators. Furthermore, the model should be applicable at the river basin scale, contain sufficient biophysical detail, and ideally be available in the public domain (to facilitate easy uptake around the world). Two examples of such hydrological models that have proven their use in ecosystem services assessments are Soil and Water Assessment Tool (**SWAT**) and Spatial Processes in Hydrology (**SPHY)**. In this white paper we propose the use of SPHY due to its pixel-based nature that allows for easy integration with remote sensing data.

> *Simulation models are an ideal tool for providing an outlook on different possible futures, dependent on factors both within and outside control of the decision maker*

SPHY (Terink *et al.* 2015) is an **eco-hydrological modeling tool** suitable and applied for a wide range of water resource management applications. It is a state-of-the-art, easy to use, robust tool, that can be applied for operational as well as strategic decision support. SPHY was developed by FutureWater in cooperation with national and international clients and partners and is meant to close the gap between the more complex hydrological models and the steady-state approaches. It is open-source and in the public domain, thus freely available for download and application by everyone.

SPHY has been successfully applied in various studies ranging from real-time soil moisture predictions in flat lands, to operational reservoir inflow forecasting applications in mountainous catchments, solutions to water scarcity in the Middle East, and detailed climate change impact studies in the snow- and glacier-melt dominated the Himalayan region. SPHY was developed with the explicit aim to simulate terrestrial hydrology at flexible scales, under various land use and climate conditions. The main terrestrial hydrological processes are described in a physically consistent way so that changes in storages and fluxes can be assessed adequately over time and space. Different modules are available, including an erosion and a reservoir module, which can be switched on and off depending on the specific task.

[1]swat.tamu.edu, [2]www.sphy.nl, [3]www.sphy.nl/applications

An overview of the SPHY model concepts is shown in Figure 8. SPHY is grid-based and local values thus represent averages over a cell, but sub-grid variability is taken into account. The land compartment is divided in two upper soil stores and a third groundwater store, with their corresponding drainage components: surface runoff, lateral flow and base flow. Any precipitation that falls on land surface can be intercepted by vegetation and in part or in whole evaporated. The snow storage is updated with snow accumulation and/or snow melt. A part of the liquid precipitation is transformed in surface runoff, whereas the remainder infiltrates into the soil. The resulting soil moisture is subject to evapotranspiration, depending on the soil properties and fractional vegetation cover, while the remainder contributes on the long-term to river discharge by means of lateral flow from the first soil layer, and base flow from the groundwater reservoir.

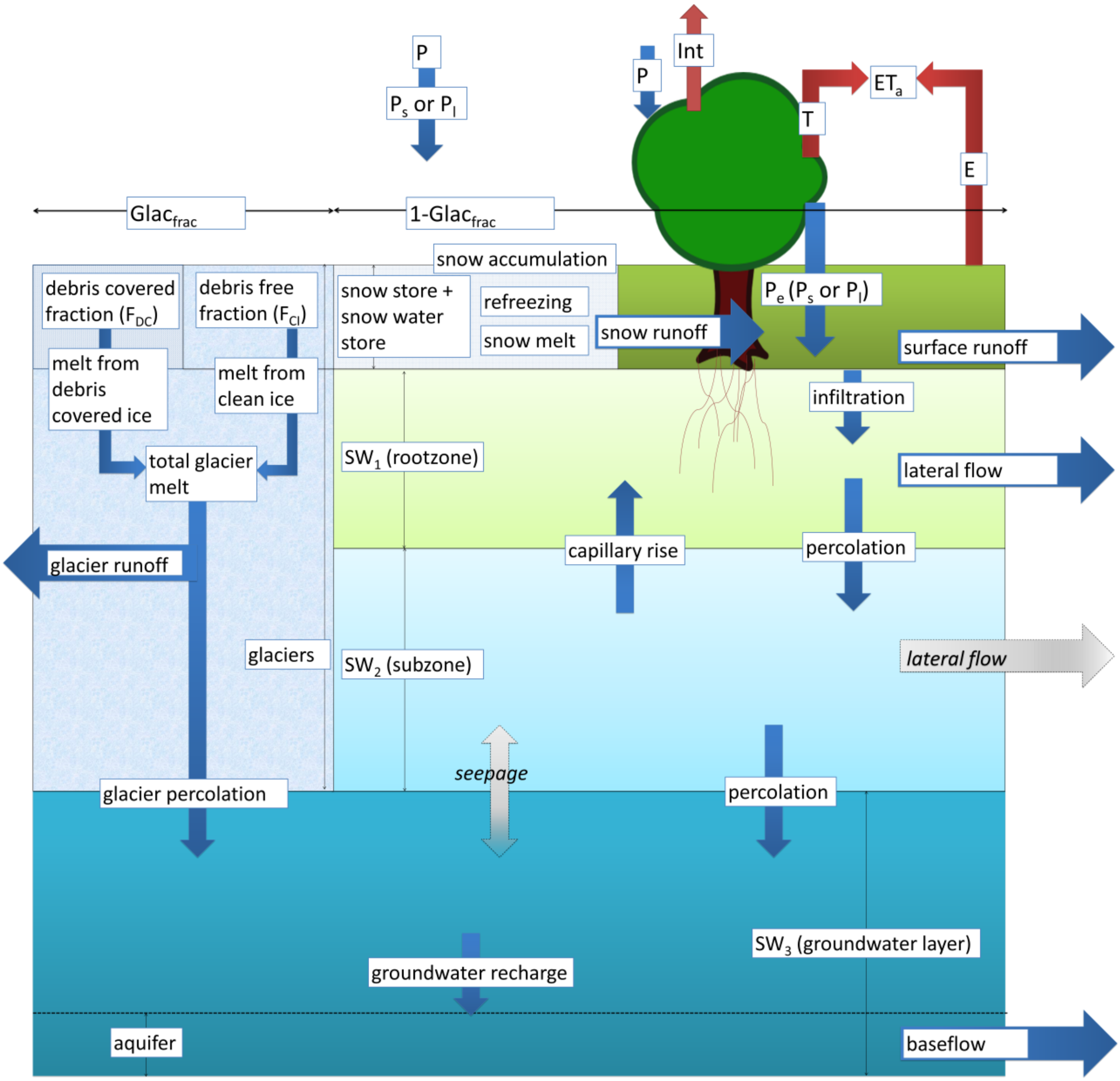


Figure 8: SPHY model concepts.

As input, SPHY requires data on state variables as well as dynamic variables. For the state variables the most relevant are Digital Elevation Model (DEM), land use type, glacier cover, reservoirs and soil characteristics. The main dynamic variables are climate data such as precipitation, temperature, reference evapotranspiration. In addition, very relevant for HESS applications, the dynamic vegetation module relies on satellite-based vegetation data in order to simulate the temporal variability of soil-water-vegetation-atmosphere interactions.

3.3 Towards an operational information system

An **operational processing system** is required for downloading all required data, coupling remote sensing and models, and disseminating the output of these models to stakeholders through an online platform. SERVIR is an example of such a platform that distributes open geospatial data, in partnership with leading regional organizations. Google Earth Engine is another example where various HESS-related parameters can be found or can be computed tailor made using the available spatial data sets as input. Figure 9 illustrates how HESS data derived from the integrated remote sensing and modeling toolbox is distributed through a platform like SERVIR, allowing end users to tap into this information pool with their own specific applications and frameworks (such as those discussed in Section 2.2).

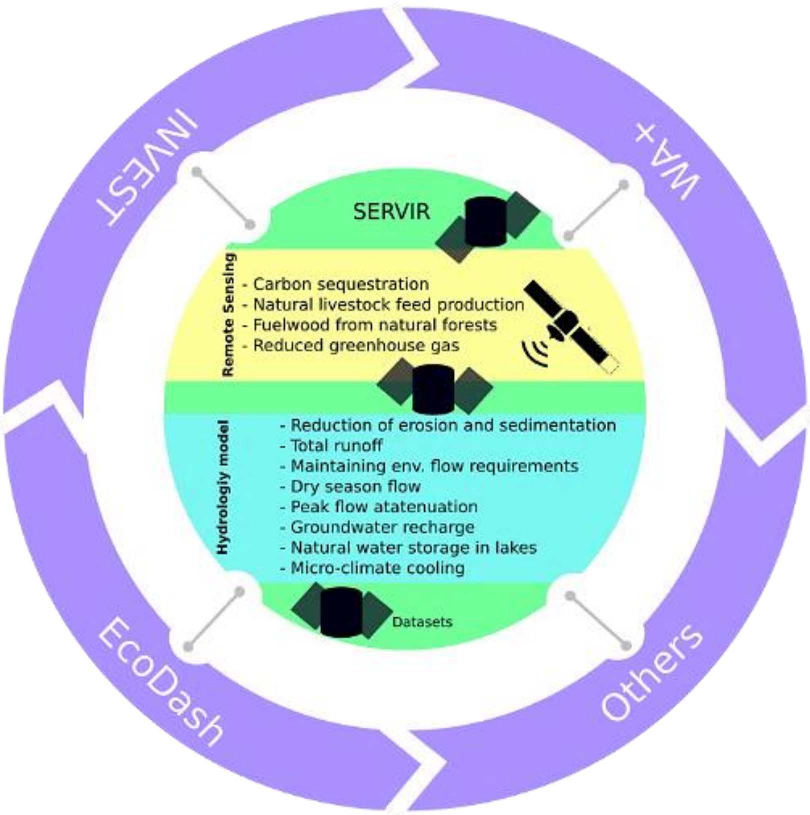


Figure 9: Conceptual framework of an operational data platform on HESS indicators derived from remote sensing and hydrological modeling.

4. Example applications

4.1 Case study 1: Ecosystem services tradeoffs in the international Da River Basin

This project site was part of a project within the CGIAR-WLE Greater Mekong program on healthy rivers, known as MK27 (wle-mekong.cgiar.org/projects/mk27)

The Da River is one of the three main branches of the Red River system, with its drainage area located in both China and Vietnam (and a minor part in Lao PDR). Its outflow ends up in the Hoa Binh reservoir, the largest reservoir in Vietnam, and a major source of water to the extensive agricultural and economic activity occurring in the densely populated Red River Delta. Over the past decades, changes in land use and in storage capacity have altered the hydrological ecosystem services provided by the Da River basin. The full impact of these changes however remains unclear, and quantification of HESS would enable their accounting in policy making. This is especially relevant in the light of climate change, which is expected to affect water availability through both altered precipitation patterns and increased evaporation rates.

The transboundary Da River basin is important for a safe and secure water supply in the Red River delta

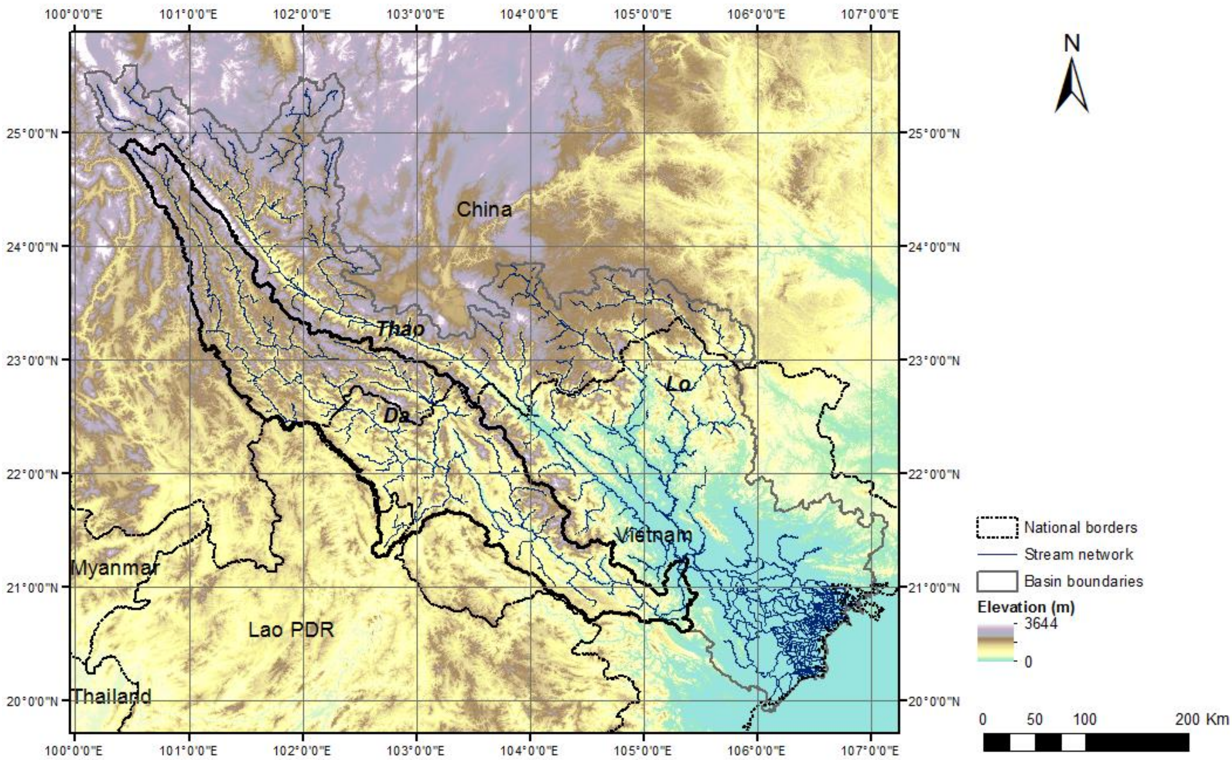


Figure 10: The transboundary Da Basin, a sub-catchment of the Red River Basin.

The SPHY model was set up at a 500 x 500 m resolution with daily time steps for a period of 11 years (1 January 2000 - 31 December 2010), in order to simulate baseline conditions in Da River Basin. The satellite-based MODIS Normalized Difference Vegetation Index (NDVI) product was used to implement temporal vegetation dynamics. The spatially explicit nature of the SPHY model allows for the **identification of locations** with particularly high or low values for a certain HESS indicator. FIgures 12 and 13 demonstrate two of the resulting maps, for the HESS microclimate cooling and natural fuelwood production respectively.

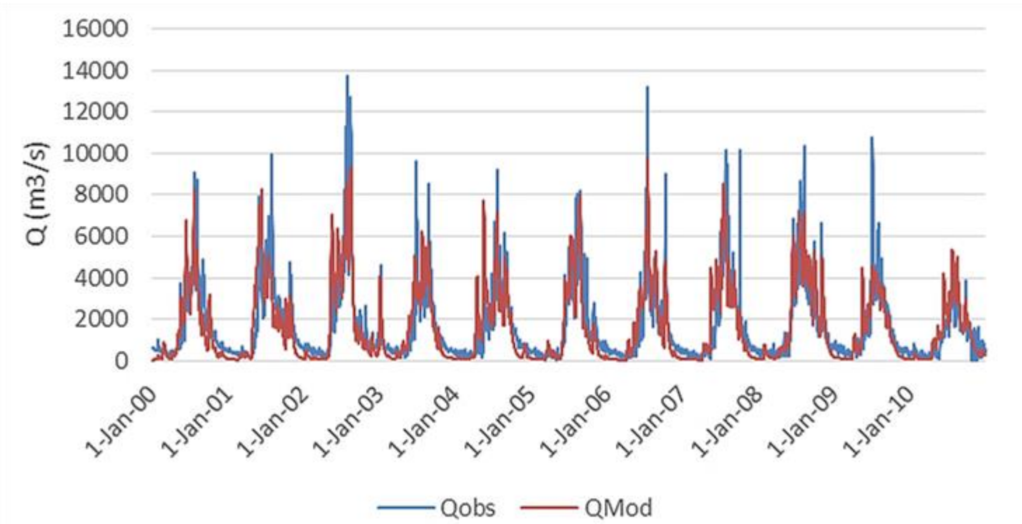


Figure 11: Performance of the SPHY model in predicting streamflow at the downstream end of Da River Basin (inflow into Hoa Binh reservoir). *Qobs* represents measured values, *Qmod* depicts model results.

In addition to an assessment of the current situation, the SPHY model was used for **simulating different future scenarios**. The objective of this assessment is to provide regional policy makers with spatial, quantitative information on HESS under different future scenarios, thus supporting the definition of policies which can increase total HESS. The following page lists all scenarios that were evaluated. Scenarios A to E essentially amount to changes in land cover parameters, in order to use analyze the impact of different management interventions that regional planning agencies may consider. Scenarios F1 and F2 serve to investigate the impact of predicted changes in climate. In these scenarios, precipitation and temperature forcing was altered with delta change factors obtained from running the online climate modeling tool Climate Explorer.

[1]climexp.knmi.nl

Eight different scenarios were evaluated for Da River Basin

- **0** Baseline conditions (2000-2010)
- **A1** Deforestation within existing forested areas (5%) and conversion into rainfed cropland
- **A2** Deforestation by thinning of existing forests
- **B** Reforestation (10%)
- **C** Urban expansion (500 m buffer around urban centers)
- **D** Increase irrigated acreage (10%)
- **E** More surface water storage – addition of a new hydropower reservoir
- **F1** Projected climate in 2050s (1.5 °C temperature rise)
- **F2** Projected climate in 2090s (1.5 °C temperature rise and 6% rainfall increase)

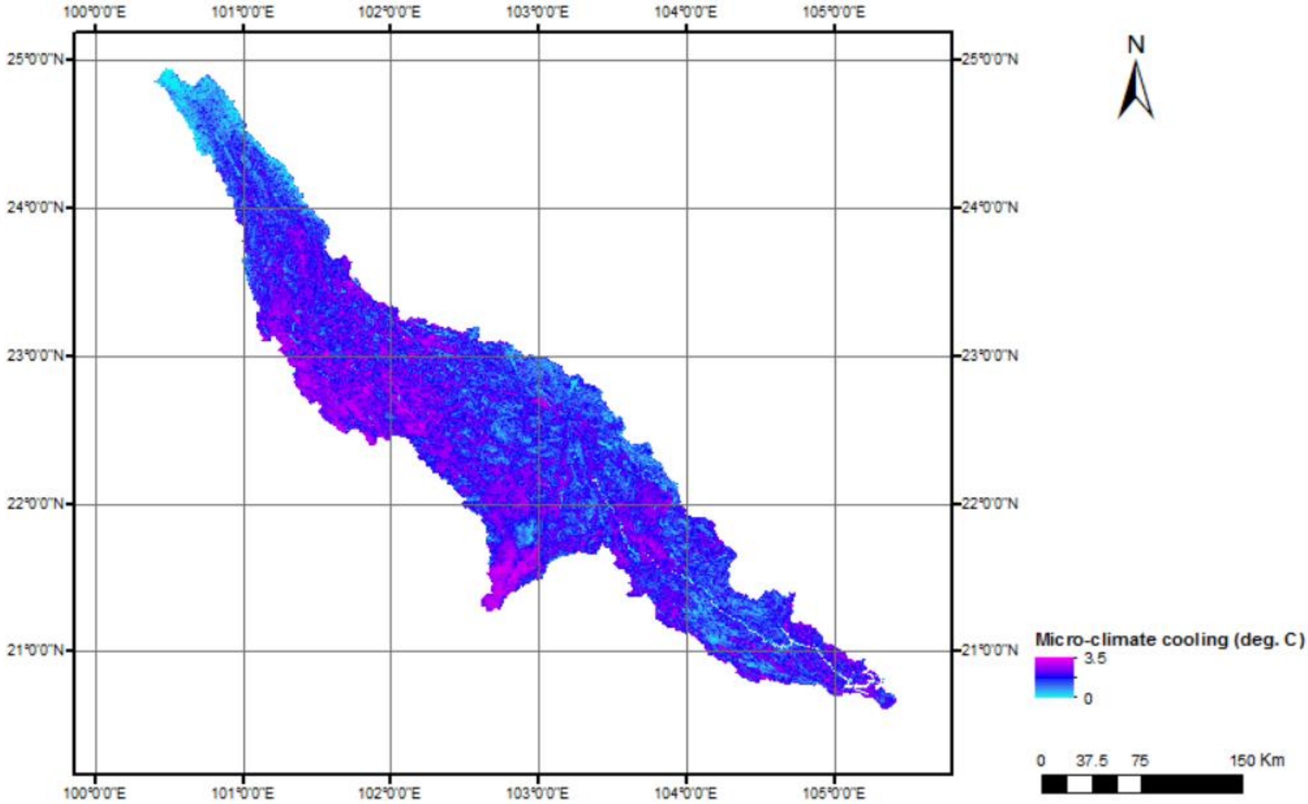


Figure 12: Micro-climate cooling in Da River Basin under baseline conditions.

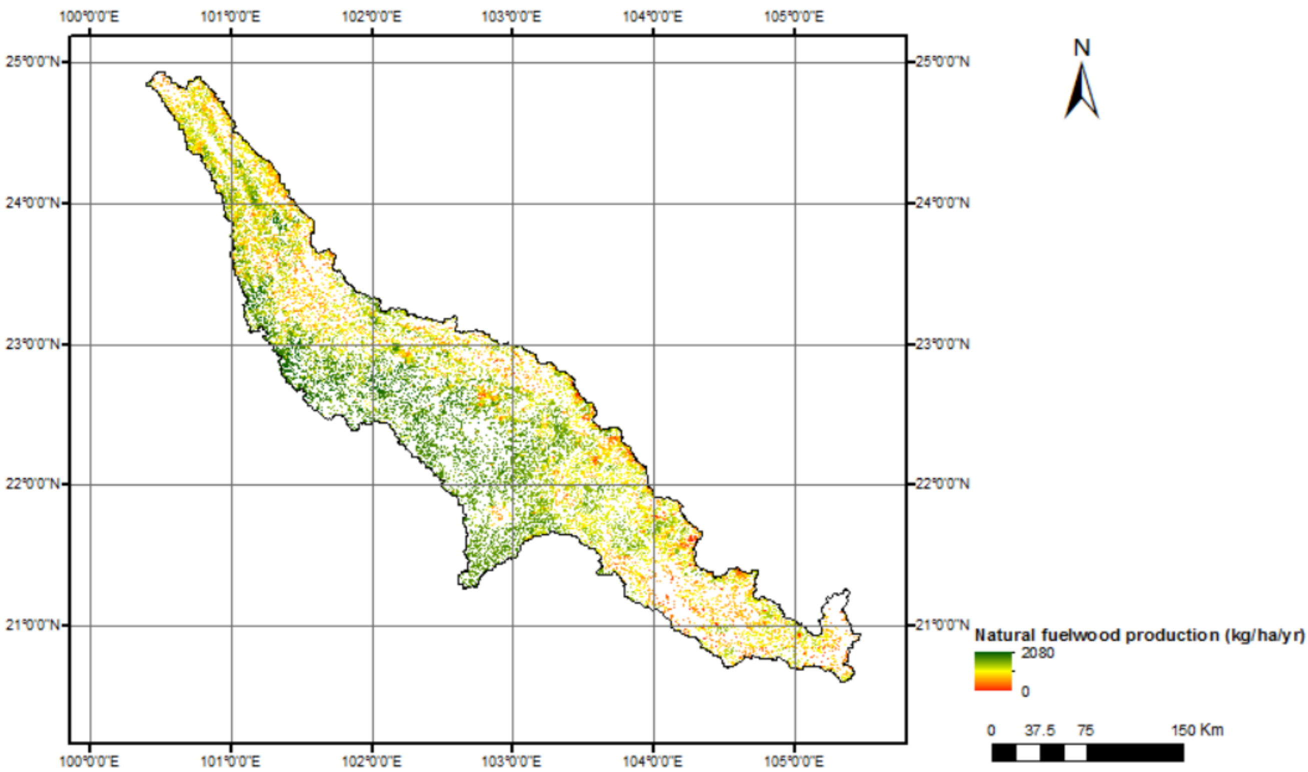


Figure 13: Natural fuelwood production in Da River Basin under baseline conditions.

For each of the HESS, baseline maps were compared to expected changes in the different future scenarios, to assess tradeoffs in a spatially explicit manner. Figure 14 depicts how the expected temperature increase due to climate change is expected to lead to reduced groundwater recharge in the 2050s. As the evaporative demand of the atmosphere will increase, partitioning between evapotranspiration and runoff will shift and less water will percolate to replenish the aquifers, leading to a reduction of this particular HESS.

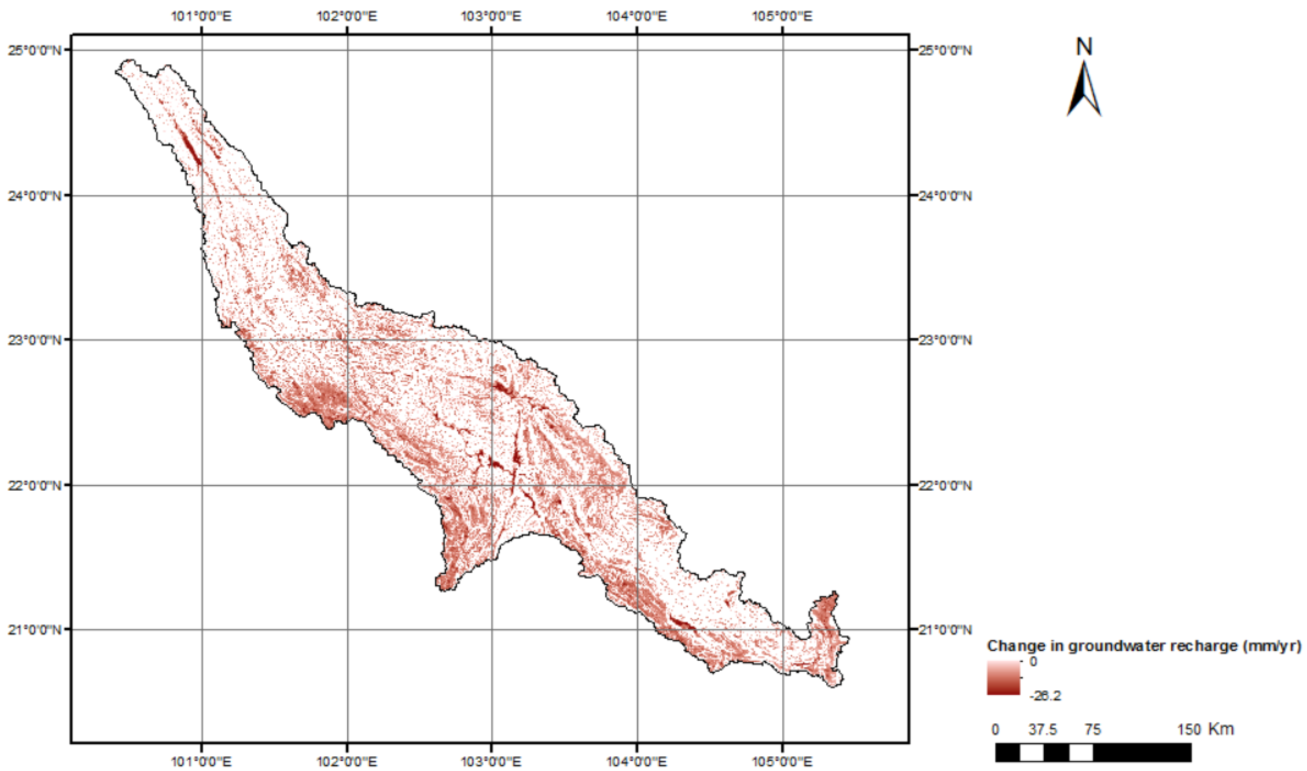


Figure 14: Predicted changes in groundwater recharge in the 2050s as compared to baseline conditions.

Table 1 summarizes all evaluated HESS provided by Da River Basin under baseline conditions, as well as three selected scenarios. The table clearly shows how **tradeoffs in HESS** can occur due to shifts in land management or climate patterns. Even deforestation leads to improved values of certain HESS, such as streamflow in the dry season and environmental flow. Naturally, however, sediment yield from the basin will increase substantially with the removal of forest, as well as peak flows and corresponding flood risk. **Climate change** also has an ambiguous effect on the general state of HESS provided by the basin. Da River Basin is clearly not a water-limited system, as the predicted temperature rise in the 2050s (F1) is expected to lead to increased plant transpiration and enhanced provisioning services from biomass, such as crop production and fuelwood. As precipitation amounts change further into the future (F2), these provisioning services will improve even further, although at the cost of higher erosion and peak flows. It is interesting to observe that 7 out of the 11 HESS values will increase with climate change. Focusing on a single HESS value thus provides an incomplete picture.

For the sake of brevity, Table 1 only shows annual averages and therefore relates to long-term trends under the different scenarios. However, as the SPHY model is run with daily time steps and input data from remote sensing is frequently updated, also the **timing** of HESS provision can be evaluated and the impact of temporal shifts (e.g. of water availability) can be evaluated.

Thanks to spatial, quantitative information on HESS under different future scenarios, regional policy makers can account for the complexities of tradeoffs

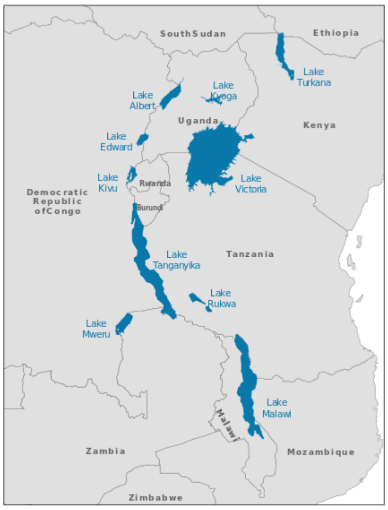
Table 1: Average annual HESS provided by the Da River Basin in the current situation (scenario 0) and their tradeoffs under different future scenarios (see page 27 for scenario descriptions). Colors indicate whether future changes can generally be considered desirable (green) or undesirable (red).

HESS indicator	Unit	0	A2	F1	F2
Total runoff	km^3	52.8	58.1	51.9	57.2
Environmental flow	km^3	15.8	17.4	15.6	17.2
Natural livestock feed production	tonnes	1.34E+07	1.34E+07	1.38E+07	1.39E+07
Fuelwood from natural forests	tonnes	3.19E+06	3.09E+06	3.28E+06	3.32E+06
Dry season flow	m^3/s	282	347	272	305
Groundwater recharge	km^3	3.3	4.1	3.2	3.5
Peak flow	m^3/s	9832	10487	9772	10572
Carbon sequestration	tonnes	378	364	388	393
Microclimate cooling	deg. C	2.5	2.4	2.6	2.6
Atmospheric moisture recycling	km^3	8.6	7.7	8.9	9.0
Sediment yield*	tonnes	13.4	14.9	13.1	14.6

**Sediment yield was not calculated at the most downstream point of the basin, but instead at the Lai Chau station, approximately 60% downstream.*

4.2 Case study 2: Erosion and sedimentation near Lake Tanganyika

The world's longest lake, Lake Tanganyika, holds 17 percent of our planet's fresh surface water and boasts more than 300 fish species. The Greater Mahale Ecosystem encompasses 4.8 million acres of mostly forested landscape and is home to approximately 93 percent of Tanzania's 2,800 endangered chimpanzees. Local communities of small-scale farmers and fishers still live close to the land, and their lives and livelihoods are dependent upon the area's rich natural resources. The Lake Tanganyika basin is shared by four countries: Rwanda, D.R. of Congo, Zambia and Tanzania.



The health of this diverse natural environment and the well-being of its people are threatened by extreme poverty compounded by a rapidly growing human population. A key threat is erosion which in this area is linked to uncontrolled dry season fire activity, the use of fire in land clearance and the usage of fire for cooking and charcoal production. These sediments flow into the Lake Tanganyika and have a severe impact on the fish habitat. Increased sediment loads entering the Lake are likely the principal causes of the declined fishery-related HESS in the coastal zones with its negative consequences on the local communities.

To tackle this downward spiral, The Nature Conservancy (TNC) looks for integrated solutions by engaging stakeholders and communities. For this engagement process, quantitative information on the link between upstream land management and the aquatic diversity of the Tanganyika Lake system is crucial. Remote sensing information in combination with hydrological modeling provides an efficient and science-based solution to this need. These tools were applied to the Mahale region, one of the hotspots regions around the Lake.

A standard satellite product from the MODIS platform[1] was used to map the spatial distribution and number of annual fire events. The MODIS algorithm detects the approximate date of burning (at 500 m resolution) by locating the occurrence of rapid changes in daily surface reflectance time series data. Both the dry season and wet season fires were used to calculate the fire return interval. Dry season fires cause reduced soil cover from which vegetation is likely to recover very slowly, thus contributing to the erosion hazard during less frequent rainfall events in or just after the dry period. Fires in the wet season may cause more immediate erosion due to imminent rainfall.

[1]modis-fire.umd.edu/pages/BurnedArea.php

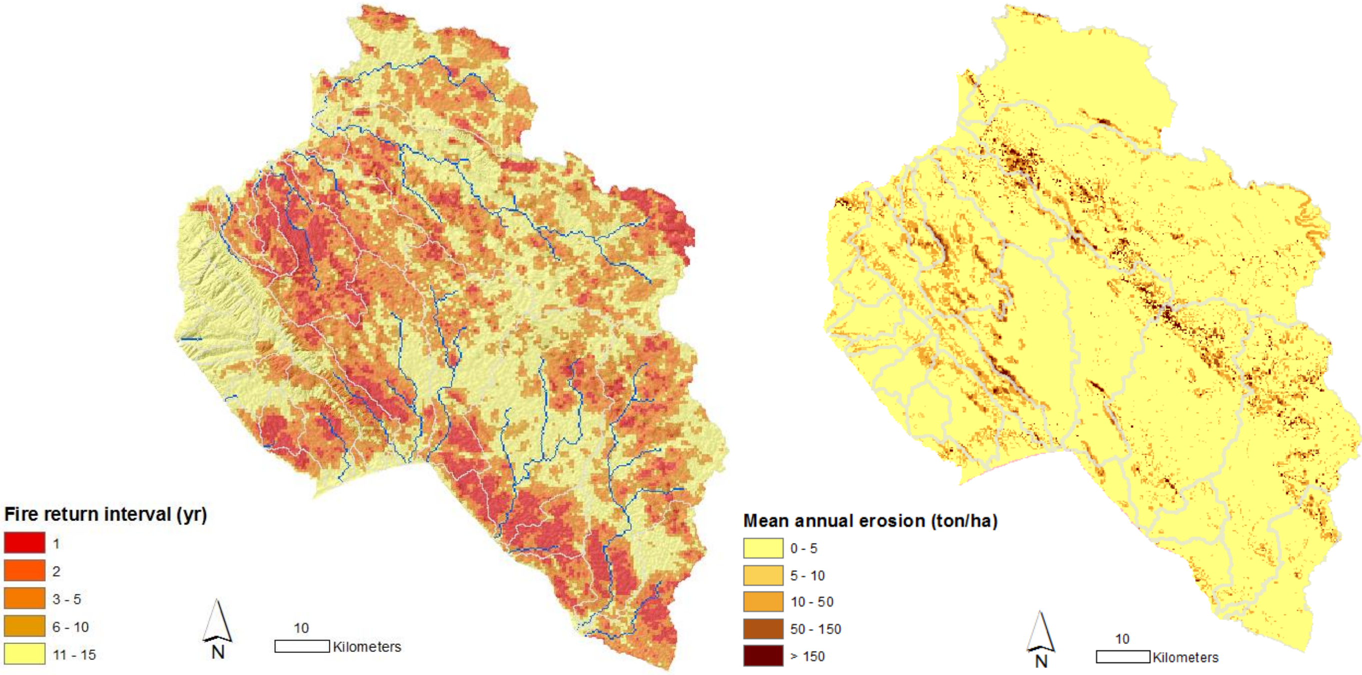


Figure 15: Fire return interval (left) and mean annual erosion rate (right).

The satellite-derived fire return interval for each location was related to the hydrological and erosion parameters in the hydrological model SPHY. Figure 15 shows that patterns of fire return interval and erosion are linked to some extent, but in some areas with steep slopes combined with dense vegetation show substantially lower erosion rates. Other areas are relatively prone to erosion due to wildfires and lower vegetation cover. For the northern and southern parts of the study area, runoff and erosion is relatively low: these areas have a relatively low slope, and only minor cultivated areas. The combination of remote sensing information and hydrological modeling was used to obtain quantitative insight in how the interplay between hydrology and erosion processes determine HESS provision for different land use types.

> *The combination of remote sensing information and hydrological modeling was used to quantify how the interplay between hydrology and erosion processes determines HESS provision for different land use types.*

TNC is using this spatially explicit information to target certain priority areas and focal issues. These results showed that especially wildfires in the bamboo zone contribute significantly to the total sediment load entering the Lake. Another critical land use is the Miombo woodland, which is by far the principal land cover (>60%) in the region, and contributes considerably to the erosion hazard (27%). Another important outcome of the analysis is the influence of newly cultivated area, which has increased by more than 50% over the last 10 years. The analysis shows that the newly cultivated areas contribute an additional 14% of sediment to the total sediment yield of the area.

Figure 16 shows mean annual sediment yield entering the lake for different sub-catchments. This information allows TNC to start working with the local communities to improve local governance, strengthen forest management and enhance fisheries management. This should lead to an integrated solution addressing the pressures on people and nature simultaneously.

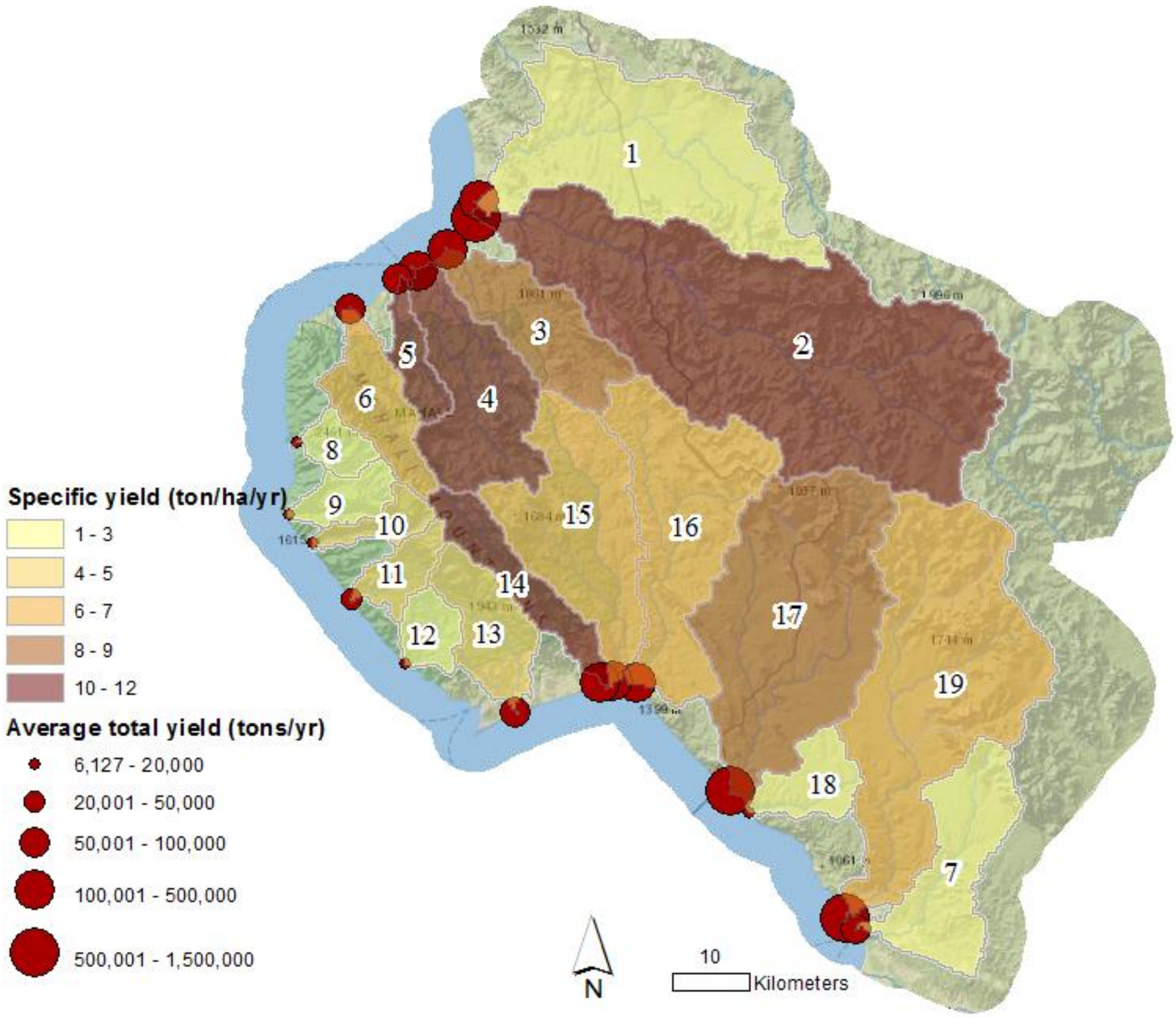


Figure 16: Mean annual sediment yield (tons/yr) and specific yield (total yield divided by area) for each catchment in the area. The size of the dots indicates the relative contribution to the total sediment input of the area.

4.3 Case study 3: Estimating carbon stocks in the Greater Mekong region

Remote sensing offers exciting opportunities to compare the conditions of a landscape in a standardized and reproducible manner. However, to obtain, process and interpret satellite data requires technical expertise and is a time and resource consuming endeavor. Recent technological advances such as **Google Earth Engine** platform allow natural resources managers to investigate natural capital in a fast and cost effective manner. Readily available satellite-derived products (such as those related to vegetation health, the leaf area of trees, temperature, carbon, etc.) provide valuable direct or indirect information on the ecosystem services delivered by the landscape.

Satellite-derived information on ecosystem services allow countries to monetize natural capital and estimate net benefits of environmental protection

In this section we demonstrate how MODIS products that estimate Gross and Net primary Production (NPP & GPP)[1] can be used to estimate the value of carbon gained or lost by vegetation on a country scale. Based on these data products, changes in the estimated net carbon stored for the period 2011 - 2014 are compared with a baseline period (2001 - 2010). Cumulative changes in net carbon storage are **monetized** using a value of $15 per ton of CO_2.

Figure 17 shows that all countries in the Greater Mekong region experience a decline in net carbon storage in 2011 - 2014 when compared to the period 2000 - 2010. Numbers add up to over 16 billion dollar for Myanmar and Thailand, but Vietnam and Cambodia have losses of 6 and 10 billion dollar respectively. Moreover, losses are in the same order of magnitude for all years and do not seem to stabilize. Environmental protection programs may improve carbon storage capacity of the countries.

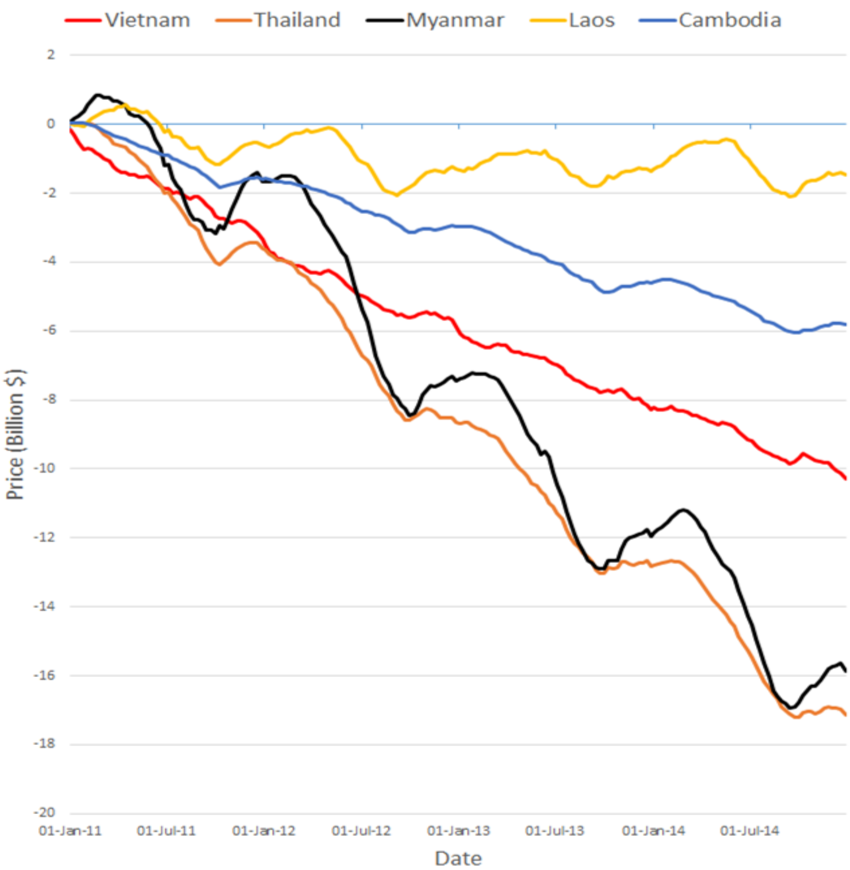


Figure 17: Estimated market value of carbon stocks in the Greater Mekong Subregion at the country level.

[1]www.ntsg.umt.edu/project/MOD17

High resolution satellite data also allow to map the areas with the highest gain or loss in net carbon. These spatial maps allow policy makers to quickly and intuitively identify regions undergoing environmental degradation and/or areas with the best return on investment for various types of intervention.

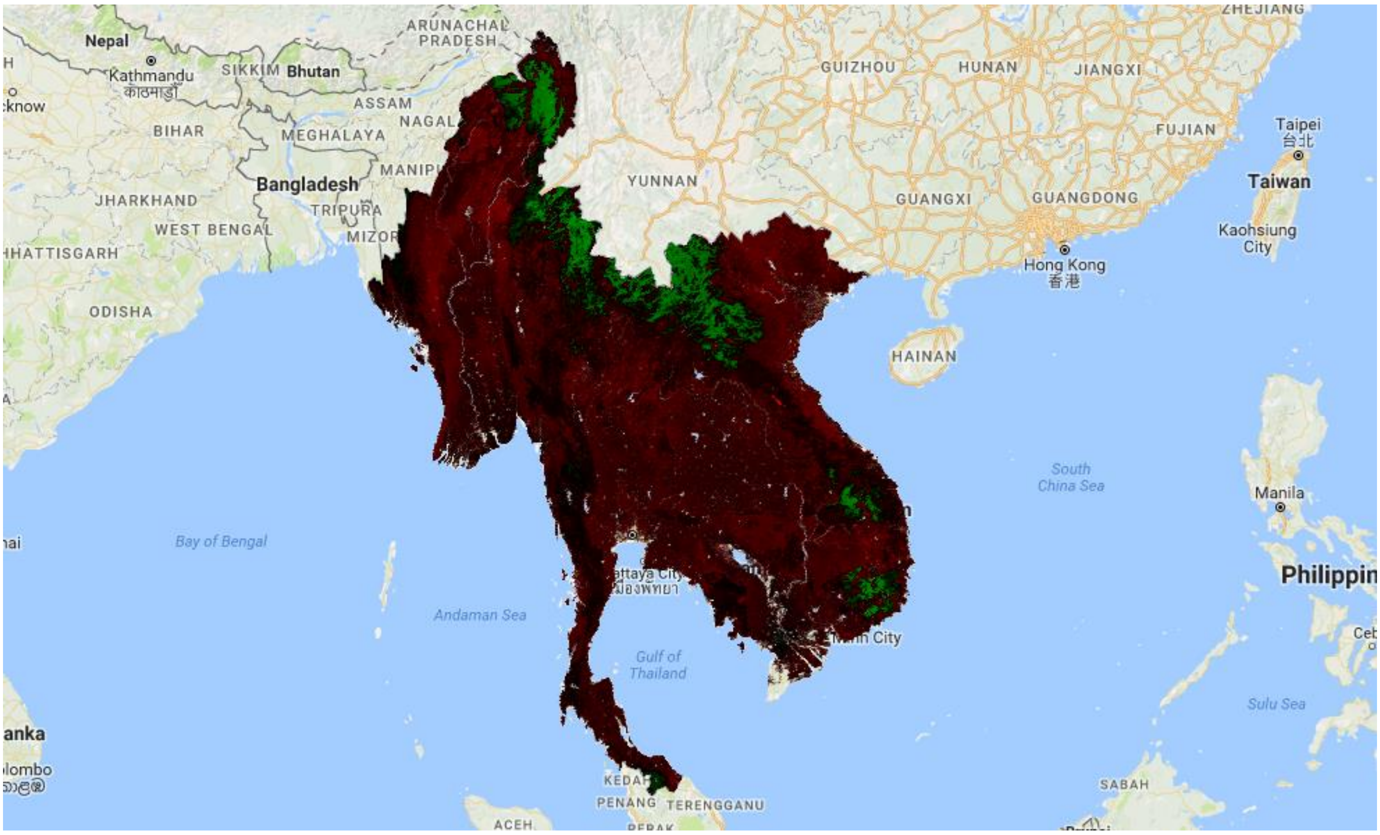


Figure 18: Carbon storage measured from space. The years 2013 - 2014 were compared to the baseline period 2001 - 2012. Green colors indicate an increase in storage, red colors a decrease (Map data ©2017 Google, SK telecom, ZENRIN).

4.4 Case study 4: Quantifying HESS on the global scale

Recent progress in the field of remote sensing, storing capacity and computational power allow to estimate hydrological ecosystem services on a planetary scale (Simons et al., 2016). Complete archives on rainfall products such as CHIRPS and GPM are readily available and can be used to estimate water inflow into river basins. Although more global products on evapotranspiration (ET) such as MOD16, EEflux[1], SSEBop[2] and the Surface Surface Energy Balance Algorithm for Land (SEBAL) will gradually become available on the Earth Engine, they are not fully operational yet. Meanwhile, the archives of the IHE-Delft ET Ensemble product will be uploaded to the cloud and can be accessed for high performance parallel computing architecture.

For most basins, estimates of ET are specifically important, as ET is not measured in a routine manner while it accounts for a large portion of the water balance. Sophisticated calculations using the energy balance fill this gap and provide water resource managers with valuable information. An example is shown in Figure 19. It shows monthly ET on a 30 meter spatial resolution for the Ca river basin in Vietnam. It illustrates that remote sensing has reduced the need for extensive field campaigns and elaborate sensor networks, as satellites measures large areas in a standardized and routinely manner.

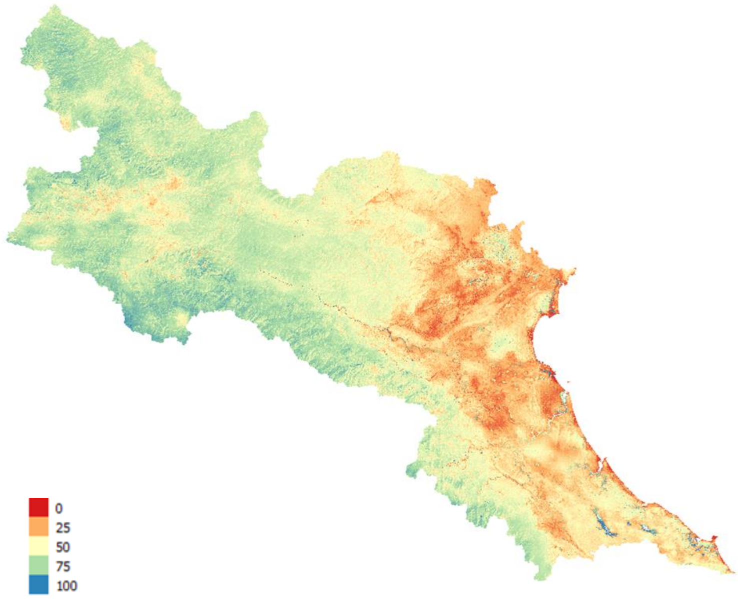


Figure 19: Downscaled ET for the Ca river basin in Vietnam (values in mm/month).

With no limitations on storage space and computational demand, we can apply a simple water balance equation of Precipitation (P) minus ET at the global scale (Figure 20). Where procedures to estimate yearly runoff from satellite imagery were time and resource consuming in the past, **total annual runoff** can now be calculated easily for any location with unprecedented precision.

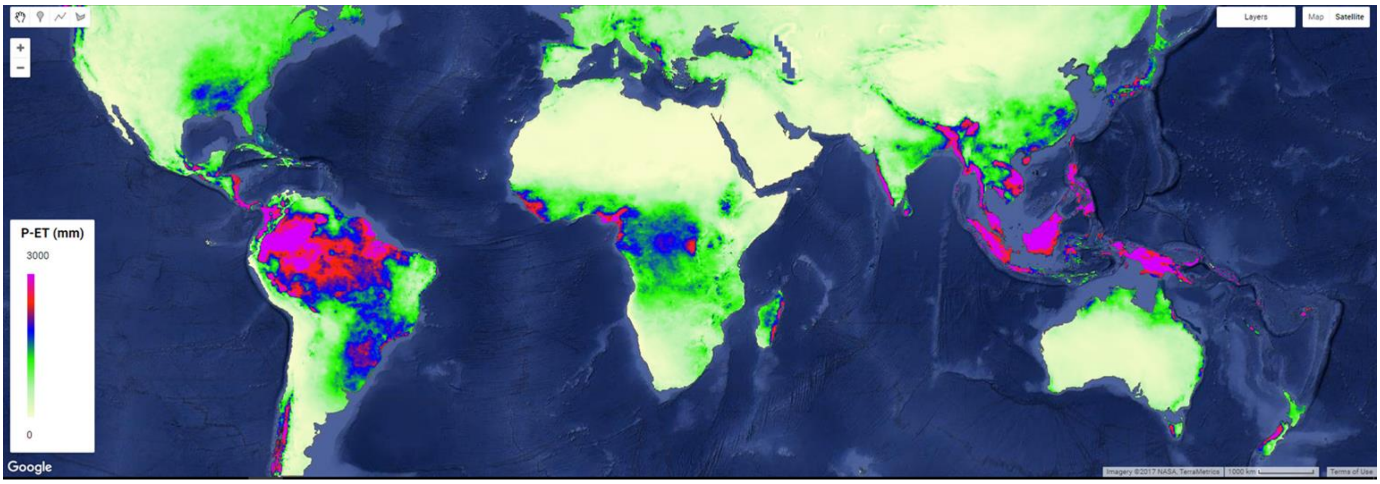
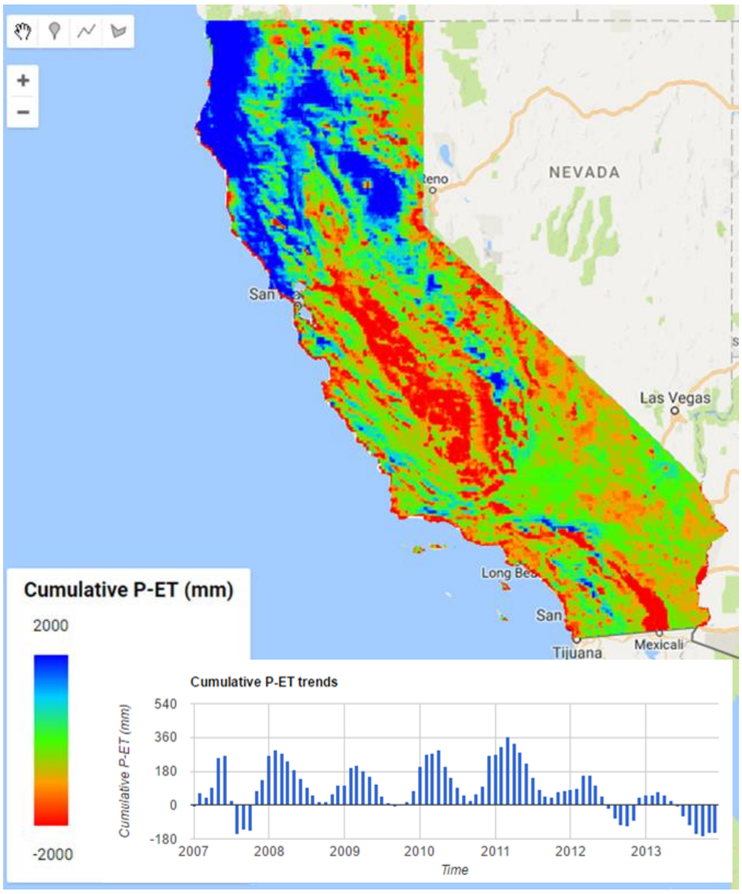


Figure 20: A global map of precipitation (P) minus Evapotranspiration (ET) for the year 2009. CHIRPS is used for P and MOD16 is used for ET.

[1]eeflux-level1.appspot.com, [2]earlywarning.usgs.gov/docs/SSEBopETreadme.pdf



California has been challenged by drought and groundwater depletion in the recent past. We investigated water resources in California for the period 2007-2013. Figure 21 shows cumulative P-ET in this period. The areas with higher ET than rainfall are indicated with a red color. These are mostly irrigated agricultural areas. The net water consumption areas are indicated with a red color. These are mostly irrigated areas or areas with Groundwater Dependent Ecosystems (GDE). The graph in Figure 21 shows the evolution of the cumulative P-ET trend for the entire state. It can be seen that 2007, 2012 and 2013 were dry years with a negative water balance, while the other years have a positive water balance. Maps on the overexploitation of water are useful to investigate viable mitigation measures, as they provide quantitative insights on the problems at hand.

Figure 21: Cumulative P-ET (precipitation - evapotranspiration) in California (2007-2013).

A recent publication of Poortinga *et al.* (2017) presents a novel way to partition maps of P-ET into **surface runoff** and **groundwater recharge**. The method makes use of satellite-derived estimates of precipitation, evapotranspiration, soil moisture and Leaf Area Index to separate runoff and storage changes. This method is specifically suitable for cloud-based computational platforms in ungauged river basins. The empirical formula of the Soil Conservation Service to calculate runoff from rainfall, soil moisture and interception was used, after an innovative self-calibration method, to calculate the runoff anomaly for El Nino event in 2009 - 2010 for the months December - January (Figure 22). It can be seen that large parts of South-East Asia and northern Latin America experience a severe runoff deficit, whereas runoff in parts of North America and Argentina is significantly higher compared to average years.

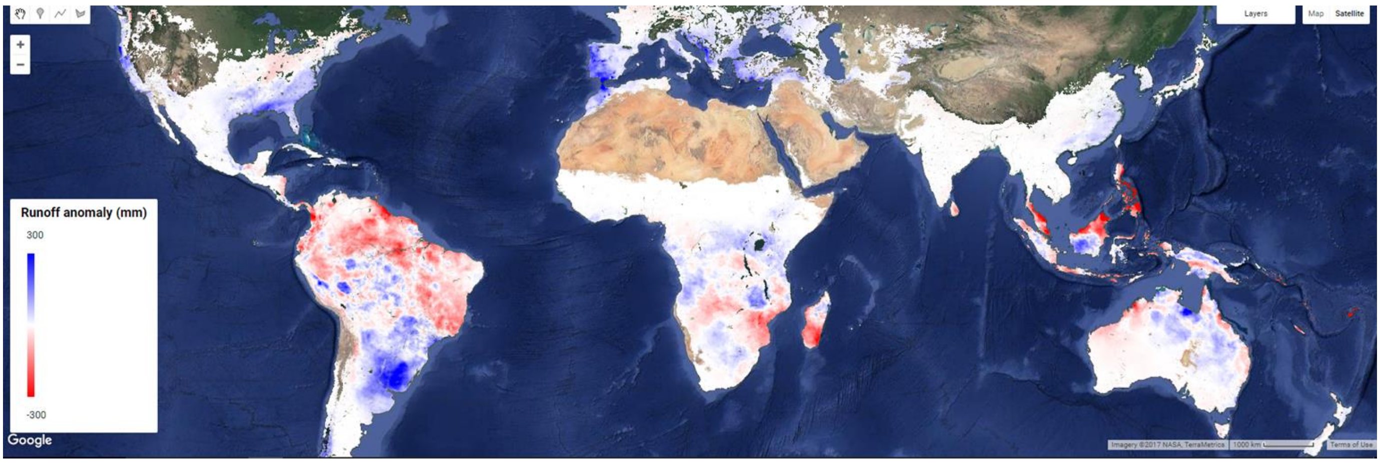


Figure 22: Global runoff anomaly in the El Nino year 2009 - 2010 for December until February computed with a preliminary version of the WaterPix model (Poortinga *et al.*, 2017).

Global maps on environmental indicators help to identify areas under stress, as a first step to investigating underlying causes and proposing feasible solutions to reduce the stress. Decades of earth observation data allow to investigate the health of earth's ecosystems over long time series. For example, the Global Inventory Modeling and Mapping Studies (GIMMS) data collection provides bi-monthly images on vegetation health (NDVI) since 1981 until 2013. In Figure 22, relative global environmental stress is presented with respect to a 1983 - 1990 baseline period. Green colors indicate areas where vegetation has become more abundant, whereas red areas have been exposed to some form of land degradation. It can be seen that the tropics and North America have experienced more environmental stress, while stress has reduced in large parts of Europe and Russia.

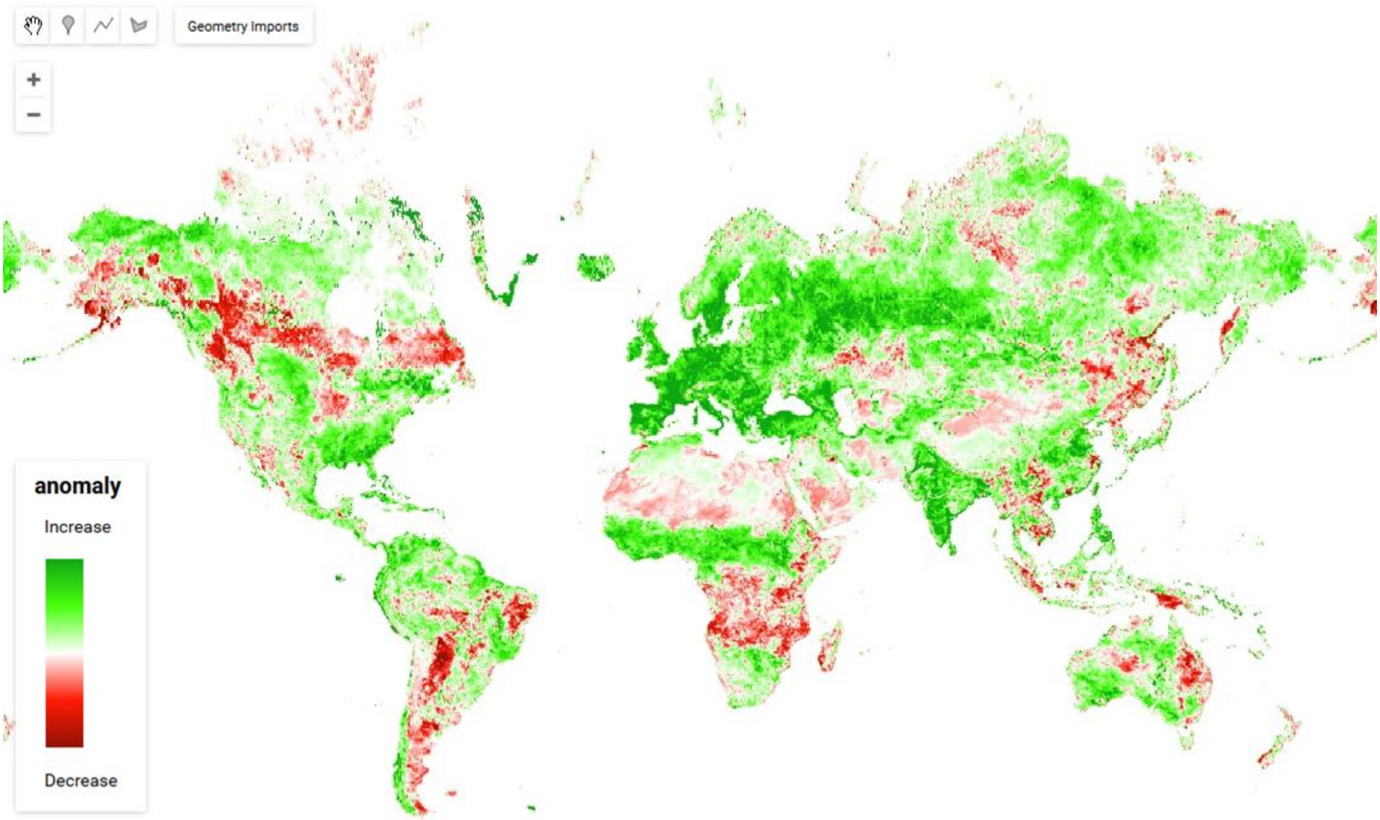


Figure 23: Environmental stress between 1990 and 2013 (calculated from GIMMS-based NDVI values).

Production of carbon per mm of water consumed is the biophysical basis of **Water Productivity** (WP). WP is one of the Sustainable Development Goals (SDG's) of the United Nations and is promoted and supported by several international organizations and countries to convert the agricultural sector to become more efficient with water. WP can be calculated from satellite-derived products on NPP and evapotranspiration. Figure 24 presents a global map with regions where little carbon is produced in red and areas with high carbon production in green. The map presents the year 2012. It can be seen that large amount of water are need for carbon production in the Sahel, large parts of India and northern Australia. Relatively large amounts of carbon are produced per unit of water in Europe and North America.

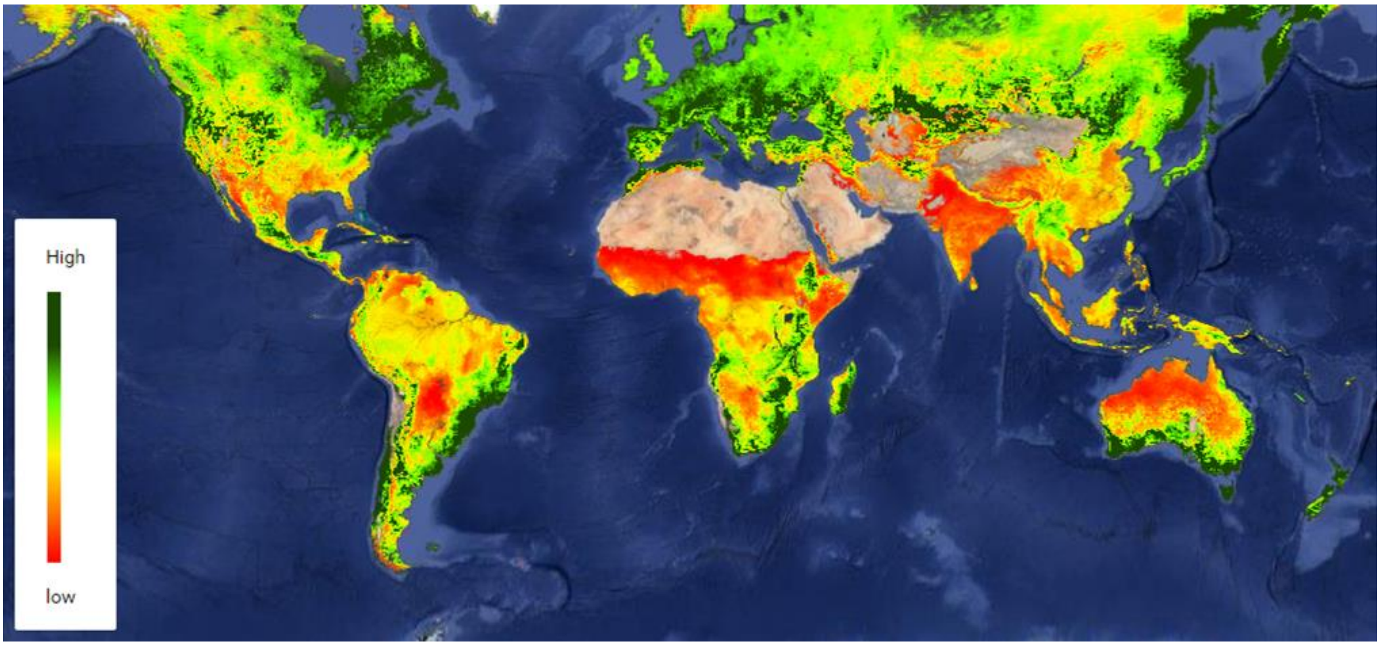


Figure 24: Amount of carbon produced per mm of water in the year 2012.

5. Concluding remarks: mainstreaming assessments of hydrological ecosystem services into decision making

Sustainable planning of scarce water resources to secure food production and economic growth without further environmental degradation is urgently needed. Most ecosystem services, and certainly those related to the water cycle, have long been under-acknowledged and undervalued. Two main causes for the lack of explicit uptake of Hydrological EcoSystem Services (HESS) in policy frameworks can be identified:

1. Assessing and modeling the status and change of natural capital is challenging. This is the case all over the world, including relatively data-rich areas.
2. Even in areas with responsive and responsible environmental policy frameworks, policy processes are not designed to respond to new information about ecosystem management tradeoffs

In this white paper, we present the **definition of a standard set of HESS indicators** and demonstrate how an integrated toolset of state-of-the-art **remote sensing** and **hydrological models** can be put to use to quantify and value them. Thanks to earth-observing satellites, spatial data and long time series of important indicators of ecosystem health and hydrological processes are available irrespective of political borders and terrain accessibility. Information that cannot be directly distilled from remote sensing can be obtained by running hydrological models, which are fed and calibrated by satellite data. Next to completing the outlook on the eco-hydrological system, these models offer the chance to look into the future and evaluate different scenarios, as demonstrated in Section 4.1 of this white paper.

Coupled with powerful new geospatial information technologies, the integration of remote sensing and simulation models sets the stage for an **operational system** that can provide geospatial data on hydrological ecosystem services in data-scarce areas. By combining this information with simulation models, scenario analyses can be performed which allow policy makers to evaluate the **expected impacts** of different land and water management policies and anticipate on changing conditions under **climate change**. As explained in this white paper, it is important to examine ecosystem services of both consumptive and non-consumptive water use, and maximize the benefits associated with water consumption: the water that truly disappears from the watershed.

Although this is an important step towards addressing the first challenge identified above, **actual uptake** of this information in policy frameworks remains a prerequisite for truly altering management of water resources. How easily decision makers can acquire the information they need, in the form they need it, and when they need it, will determine its use. SERVIR and other initiatives that base their work on the needs of end users can be key agents for operationalizing systems to **enhance access to information** and **increase transparency.** As such systems become more common and prove their worth in environmental management, it is expected that decision-making processes will benefit from (and maybe even adapt to) this new pool of valuable and timely information.

This white paper puts in evidence that nowadays, the technology and science is 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 (Figure 25) that are already being used for policy change as demonstrated in the case studies (Section 4). As the digital information age advances, future progress is expected to enable further upscaling and standardization of operational monitoring of Hydrological Ecosystem Services.

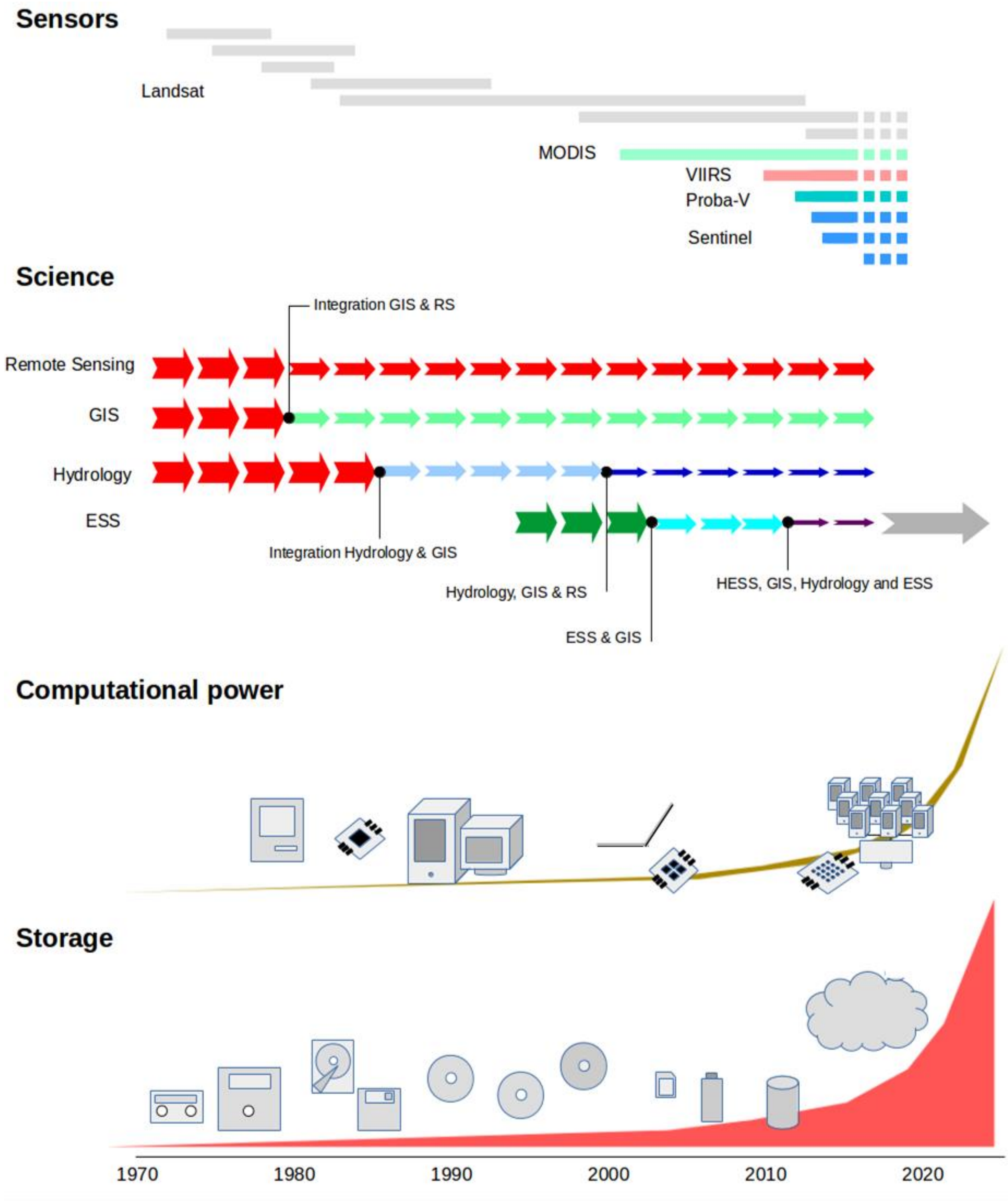


Figure 25: Historical development and future outlook regarding satellite-based sensors, scientific advances, computational power and storage capacity.

Further reading

The list of literature below contains the sources referenced in this white paper, as well as additional recommended literature on Hydrological Ecosystem Services; their background and classification as well as the existing technologies for quantifying them using satellite-derived data products and hydrological models.

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The objective of this white paper is to demonstrate that, **by leveraging state-of-the-art technologies and remote sensing data, Hydrological EcoSystem Services (HESS) at the river basin scale can be effectively described, quantified and compared in space and time**. While discussions on the theoretical framework are infinite, it is urgently needed to develop procedures to quantify HESS and make them accessible to a large audience. Such efforts are undertaken, for example, in the **CGIAR WLE Greater Mekong** and **SERVIR-Mekong** programs. This white paper demonstrates collaborative efforts that draw from state-of-the-art technologies to achieve this vision of enhanced quality and accessibility of spatially explicit HESS information.