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Using the Freshwater Health Index to Assess Hydropower Development Scenarios in the Sesan, Srepok and Sekong River Basin

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Abstract: Sustainable water resource management is a wicked problem, fraught with uncertainties, an indeterminate scope, and divergent social values and interests among stakeholders. To facilitate better management of Southeast Asia's transboundary Sesan, Sekong and Srepok (3S) River basin, we used the Freshwater Health Index (FHI) to diagnose the basin's current and likely future level of freshwater health. We used the conditions for December 2016 as a baseline, where Ecosystem Vitality and Ecosystem Services scored 66 and 80, respectively, out of a possible 100, whilst Governance & Stakeholders scored 43. Thus, the 3S provided a range of desired ecosystem services, but there were signs of environmental stress as well as undeveloped water governance systems and limited stakeholder engagement. We also modelled four hydropower development scenarios and found that increasing development reduced the scores of a subset of indicators. This compromised the future ability of the 3S basin's ecosystem to provide its current range of services. The FHI helped identify data deficiencies, illuminated important social dynamics, made ecosystem–human–water dynamics more understandable to stakeholders, and examined the long-term dynamics of the basin.

Keywords: freshwater ecosystems; ecosystem services; water governance; Freshwater Health Index; lower Mekong; hydropower

1. Introduction

There are fewer problems more wicked than maintaining a healthy environment whilst providing our planet's growing human population with fresh water. This arises from the inherent uncertainties, manifold risks, and the diversity of social values placed on water [1–3]. Indeed, the environmental values of freshwater systems have long been neglected in favour of managing water as a physical resource [4]. As a result, current approaches to water resources management seldom provide sustainable solutions [5]. A change is needed; in particular, the recognition that people are central to water systems [6,7], and that healthy freshwater systems deliver important ecosystem services [8]. In redefining our approach to managing water, we must also forsake traditional risk and optimization approaches that consider single issues and adopt exploratory analysis of complex trade-offs and real-world systems [1,7].

In tackling the problem of water resource management, we present an application of the Freshwater Health Index (FHI) to Southeast Asia's transboundary Sekong, Sesan and Srepok (3S) River basin. The FHI is a socio- and eco-centric indicator framework that views the sustainable management of freshwater ecosystems and the services they support as central to water resources management [8]. It is a nested, quantitative indicator system that assesses three interrelated components of freshwater health: Ecosystem Vitality, the health of freshwater ecosystems; Ecosystem Services, water-associated provisioning, regulating and cultural services; and Stakeholders and Governance, the people who have an interest in, or influence over, freshwater ecosystems and the rules, regulations and institutions that regulate the way in which stakeholders engage with freshwater ecosystems. The FHI aggregates data and knowledge from the social and natural sciences under a social-ecological framework to holistically characterize the health of a freshwater system on a scale of 0–100. We are developing the FHI to assist stakeholders in understanding freshwater ecosystem dynamics, how they are manipulated to affect water-related services, and how the governance regime manages these dynamics. The FHI also organizes relevant data, provides quantitative information about social dynamics, and creates a platform for exploring future scenarios.

Scenario analysis is an important part of the FHI framework [8]. Scenarios help explore options and can assist planning when faced with irreducible uncertainty [9]. When developing FHI scenarios, we aim to depict plausible future states under different climate projections, or proposed management or development plans. We also make use of possible, but unlikely, scenarios, against which we may assess the more plausible options. We also recognise that some indicators are more amenable to quantitative scenario analysis, whilst for others, qualitative results, such as identifying the direction of change, may only be possible.

The 78,650 km^2 3S basin comprises three rivers: the Sekong, which originates in Lao PDR; and the Srepok and Sesan Rivers, which rise in Vietnam (Figure 1; [10]). All three flow into Cambodia and merge shortly before joining the Mekong River. The 3S rivers provide almost a quarter of the Mekong River's total discharge [11,12] and nearly 15% of the rivers suspended sediment [13]. These sediments provide nutrients to both the Tonle Sap Lake, driving the great inland fishery [14], and the Mekong Delta, Vietnam's rice bowl [15,16]. The 3S is also the Mekong's most important catchment for maintaining migrating fish populations [17]. Around 3.4 million people live in the 3S basin [18]. Of the 3 million who live in the Central Highlands of Vietnam, almost one quarter, most of whom are minority groups living on marginal land, live in poverty [19]. In Cambodia and Lao PDR, most people live close to rivers and are highly dependent upon natural resources [18], especially fish [20]. Malnutrition is rife throughout the basin, as in Cambodia's Stung Treng province, where 40% of children have stunted growth [20].

Rising regional energy demand and irrigation development are driving extensive dam construction throughout the Mekong River basin [21,22]. In the 3S, there are already 66 operational hydropower and irrigation dams, eight more are under construction and another 37 potential sites are under consideration. Extensive dam development could increase dry season flows by 63% and reduce wet season flows by 22% [23], while dams could trap 80–97% of sediment yielded by the catchment [24–26]. These dams would also have negative impacts on fish migration and diversity [17,27]. Moreover, the basin is experiencing extensive deforestation [28] from illegal activity and industrial agriculture, which is likely to alter the provisioning services of water catchment and sediment transport, the latter potentially compensating for sediment trapped by dams [29].

Development of the 3S River Basin has come at a social cost, affecting local inhabitants' livelihoods, health and food security [30,31]. Ethnic minorities remain exposed to economic and environmental vulnerabilities that undermine their livelihoods, health and general well-being. The costs have been both local—the Lower Sesan II dam likely will have displaced around 3000 people [31]—and transboundary—Vietnam's Yali dam negatively impacts Cambodians living downstream [30–32]. As more dams are built, new tensions could arise, as seven of the eight dams currently under construction are in the Sekong River catchment in Lao PDR, upstream of Cambodia. Indeed, on 23 July 2018, an auxiliary dam at the Xepian Xenamnoy hydropower project collapsed, and the subsequent flooding killed 34 people (with 100 missing) and destroyed the homes and livelihoods of thousands of downstream villagers [33]. Impacts are also likely to travel downstream to the populous Tonle Sap Lake and Mekong Delta in Vietnam, as exported ecosystem services—migratory fish and sediment—decline [17,24–26].

Governance of this rapidly changing region is complex, as the 3S traverses three nations and stakeholders include numerous ethnic groups, priorities and languages. The need for transboundary governance of the basin was advocated more than a decade ago [32], but sub-basin management is not covered under the 1995 Mekong River Agreement or the Mekong River Commission's (MRC) mandate. However, new initiatives to improve water management include the IUCN BRIDGE Program [34], the MRC's Sesan and Srepok River Basins Water Resources Management Project [35], and the development of decision-support systems for the Sesan and Srepok Rivers funded by the World Bank.

Our first objective in applying the FHI to the 3S basin was to produce a timely summary of the basin's freshwater health, comprising consolidated scores for Ecosystem Vitality, Ecosystem Services and Governance & Stakeholders. Then, in collaboration with a diverse group of stakeholders, we developed and assessed the impact that a range of hydropower development scenarios might have on a subset of Ecosystem Vitality and Ecosystem Services indicators.

2. Materials and Methods

2.1. Application of the Freshwater Health Index

In applying the FHI to assess the ecological health, ecosystem service delivery, and resource governance in the 3S River basin, we calculated metrics for all 11 major indicators and 29 of the 31 sub-indicators (Table 1).

We calculated FHI indicators using empirical and modelled data in conjunction with stakeholder surveys. All indicator scores were calculated on a scale of 0–100. For Ecosystem Vitality, a score of 0 represented a complete change from natural conditions, whilst 100 was an entirely natural system. For Ecosystem Services, 0 represented the service not being provided, whilst 100 was complete provision. For Governance & Stakeholders, 0 meant the function or role was completely absent, whilst 100 indicated that it was being implemented in its entirety. As engagement with decision-makers and stakeholders is an integral component of the FHI, we engaged government officials and staff from non-government organizations from Cambodia, Lao PDR and Vietnam through the IUCN BRIDGE network and the 3S Nexus regional technical advisory group [36]. Stakeholders participated in a series of workshops and completed the Governance & Stakeholders survey along with a weighting exercise that described the importance of each Ecosystem Service and Governance & Stakeholders indicator and sub-indicator.

Table 1. Freshwater Health Index components and indicators. Bold sub-indicators were assessed for the hydropower development scenarios. Sub-indicators in italics were not assessed.

Components/Major Indicators	Sub-Indicators
ECOSYSTEM VITALITY	
Water Quantity	Deviation from Natural Flow Regime
	Groundwater Storage Depletion
Water Quality	Suspended Solids in Surface Water
	Total Nitrogen in Surface and Groundwater
	Total Phosphorous in Surface and Groundwater
	Indicators of Major Concern
Drainage-Basin Condition	Bank Modification
	Flow Connectivity
	Land Cover Naturalness
Biodiversity	Changes in Number (i.e., species number) and Population Size of Species of Concern
	Changes in Number and Population Size of Invasive and Nuisance Species
ECOSYSTEM SERVICES	
Provisioning	Water Supply Reliability Relative to Demand
	Biomass for Consumption
Regulation and Support	Sediment Regulation
	Deviation of Water Quality Metrics from Benchmarks
	Flood Regulation
	Exposure to Water-Associated Diseases
Cultural/Aesthetic	Conservation/Cultural Heritage Sites
	Recreation
GOVERNANCE & STAKEHOLDERS	
Enabling Environment	Water Resource Management
	Rights to Resource Use
	Incentives and Regulations
	Technical Capacity
	Financial Capacity
Stakeholder Engagement	Information Access and Knowledge
	Engagement in Decision-Making Processes
Vision and Adaptive Governance	Strategic Planning and Adaptive Governance
	Monitoring and Learning Mechanisms
Effectiveness	Enforcement and Compliance
	Distribution of Benefits from Ecosystem Services
	Water-Related Conflict

In testing the utility of the FHI for assessing scenarios, we focused on hydropower development, which is one of the major drivers of change in the basin. We assessed five scenarios based on known and potential dam construction (Table 2) by re-calculating four of the Ecosystem Vitality and Ecosystem Services sub-indicators (Table 1). The remaining Ecosystem Vitality and Ecosystem Services indicators were only calculated for scenario 1 (December 2016). In aggregating sub-indicators, we used the scenario 1 values for these 12 indicators across the other four scenarios. This was a conservative approach that assumed that the indicator scores did not change with hydropower development.

Table 2. Five hydropower development scenarios based on known and potential dam construction in the 3S basin. Full details of each dam can be found in Table S1.

Scenario	Number of Dams	Description
1. December 2016	65	The 65 dams operating as of 31 December 2016.
2. Lower Sesan II	66	The 65 scenario 1 dams plus the Lower Sesan II dam which was commissioned on 25 September 2017.
3. Under construction	74	The 66 dams in scenario 2, plus eight dams under construction.
4. Lower Sekong	75	The 74 dams in scenario 3 plus the prospective Lower Sekong dam in Cambodia.
5. Full development	111	The 75 dams in scenario 4 plus the remaining 37 licensed and potential dams. This scenario presents an extreme end point upon which we assessed the other scenarios.

2.2. *Common Data Sets*

We developed three common datasets (the 3S Basin Network, 3S River Network and the 3S Dam Dataset) which were used in the calculation of several FHI indicators. To generate the 3S Basin Network, we divided the 3S basin into 111 sub-basins based on the level 8 HydroBasins classification [37]. This involved combining eight very small sub-basins with larger adjacent basins.

The 3S River Network was derived from the HydroSHEDS 15 arc-second resolution drainage direction map [38]. The 3S dams dataset (Table S1) was derived from three sources: the Mekong River Commission hydropower database [39]; the WLE Mekong dams dataset [40] and Open Development Cambodia [41]. The first two sources covered the entire 3S basin; the third, Cambodia only. The three datasets were reconciled, and the locations of existing dams and dams under construction were checked using Google Earth and local knowledge. Subsets of these dams were used to determine various metrics due to differences in available data and models (Table S1).

2.3. *Calculation of Ecosystem Vitality Indicators*

2.3.1. Water Quantity

The Water Quantity indicator comprised two sub-indicators: Deviation from Natural Flow Regime and Groundwater Storage Depletion. Due to a lack of data, we could not calculate Groundwater Storage Depletion. Thus, the Deviation from Natural Flow Regime score became the Water Quantity index.

We used Piman et al.'s [23] hydrological model of the 3S system to determine Deviation from Natural Flow Regime. This model simulates the effect of 42 existing, under construction and planned hydropower dams on the flow regime of the Srepok, Sesan and Sekong Rivers (Table S1). The hydrological model only considers a subset of the basin's largest existing dams and those thought most likely to be constructed in the future. The full suite of dams was not modelled due to a lack of information on their dimensions and capacity, and because many are believed to have a minimal effect on flow.

As hydropower dam operational policies in the 3S were not publicly available [23], we assumed the dams were operated to maximize seasonal energy production. The seasonal variation rule is a set of seasonal reservoir water release targets and is normally used in dam feasibility studies. All other model parameters followed Piman et al. [23].

The modelled flow regimes for the various hydropower dam scenarios were compared against modelled unregulated natural flow using the Amended Annual Proportion of Flow Deviation indicator [42,43], which provides a score. This score increases with the level of alteration and was assigned an Ecosystem Health Score (EHS), which ranges from 0 to 100, with 100 being no deviation from the natural flow regime. We assessed four locations (Figure 1):

(P1) the 3S outlet to the Mekong;
(P2) the Sekong at the Cambodian/Lao PDR border;

(P3) the Sesan at the Vietnam/Cambodia border; and
(P4) the Srepok at the Vietnam/Cambodia border.

The basin-wide deviation from natural flow regime score was the weighted arithmetic mean of EHS scores from the four locations, with EHS scores weighted by mean annual discharge at each location.

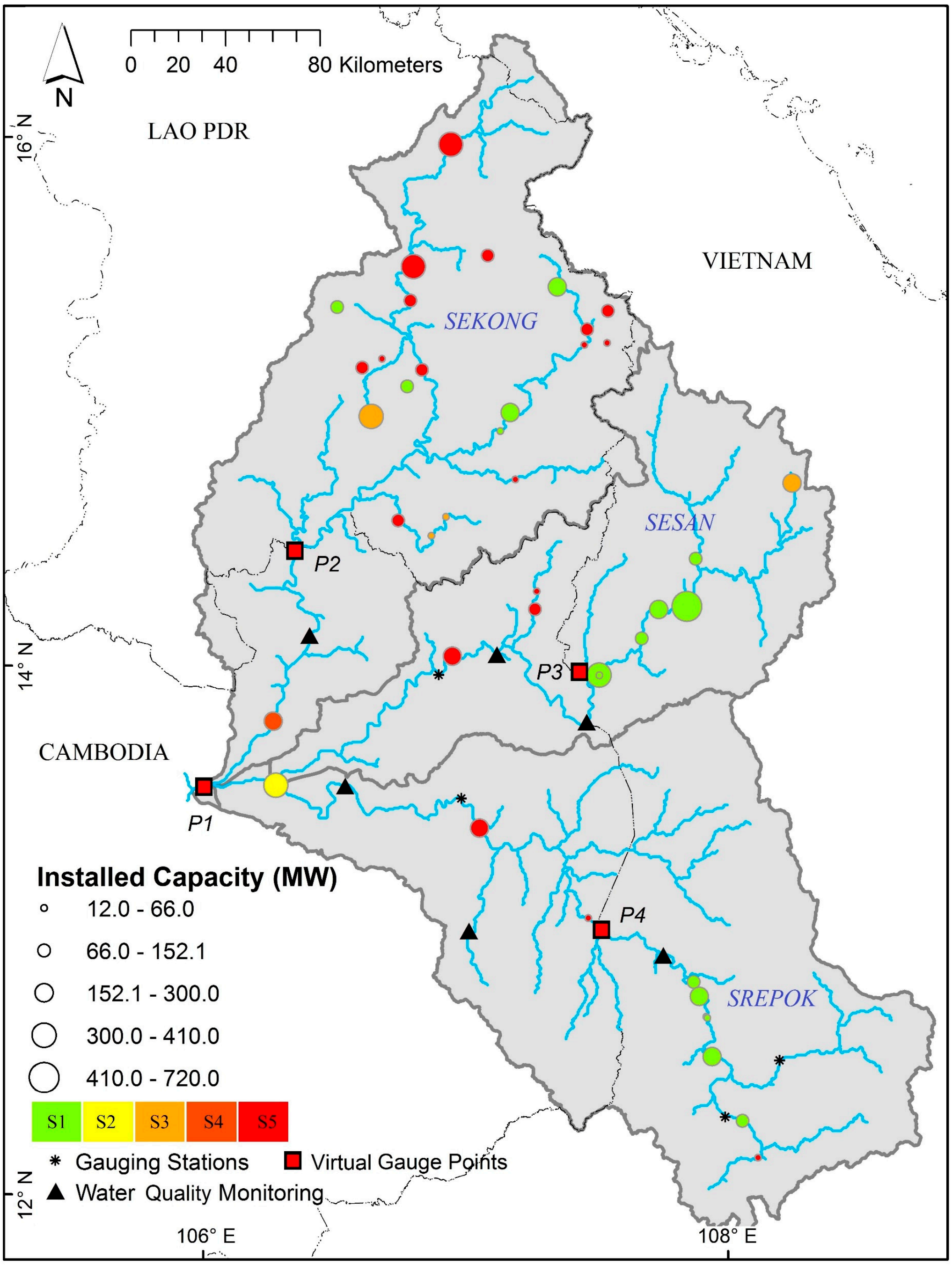

Figure 1. The Sesan, Srepok and Sekong basins showing deviation from natural flow assessment locations, flow gauging stations, water quality monitoring stations and the location and capacity of the main dams considered in the five hydropower development scenarios.

2.3.2. Water Quality

We assessed four surface water quality parameters: Total Suspended Solids (TSS), Total Phosphorous (TP), Total Nitrogen (TN) and pH. These parameters were collected from six Mekong

River Commission monitoring stations. Stations were located on the Sekong (one site in Cambodia), the Sesan (two in Cambodia, one in Vietnam) and the Srepok (one station each in Cambodia and Vietnam) Rivers (Figure 1). In total, 658 samples were collected between 2004 and 2014, monthly in most years and bimonthly in others.

Published threshold values were available for all parameters except TSS, which we derived using actual data. The TP (< 0.13 mg/L) and pH (6–9) thresholds are for the protection of aquatic ecosystems in the entire lower Mekong basin [44], whilst the lowland rivers threshold was used for TN (<1.6 mg\L) [45]. Water quality data for the last five years of sampling (2010–2014) were compared against these benchmarks. We established monthly TSS thresholds by calculating the minimum and maximum TSS values for each calendar month from 2004 to 2009. We used these values as baseline thresholds, against which we assessed monthly data from 2010 to 2014.

Our Ecosystem Vitality Water Quality Index (EVWQI) is a modified version of the CCMW Water Quality Index (CCMW WQI [46]). The CCMW WQI is made up of three factors: F_1—scope the percentage of water quality parameters that failed their objectives at least once;

$$F_1 = \left(\frac{Number\ of\ failed\ variabes}{Total\ number\ of\ variables}\right) \times 100 \tag{1}$$

F_2—frequency, the percentage of tests that did not meet objectives;

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) \times 100 \tag{2}$$

and F_3—amplitude, the amount by which failed tests did not meet their objectives. To calculate F_3, first the magnitude of failure was determined by calculating excursions using Equations (3) and (4) for parameters that must not exceed or fall below, the threshold values, respectively.

$$Ex_i = \left(\frac{Failed\ test\ value_i}{Threshold_i}\right) - 1 \tag{3}$$

$$Ex_i = \left(\frac{Threshold_i}{Failed\ test\ value_i}\right) - 1 \tag{4}$$

These values were used to calculate the normalized sum of excursions (Equation (5)), which was then scaled to yield the F_3 value which ranges between 0–100 (Equation (6)).

$$nse = \frac{\sum_{i=0}^{n} Ex_i}{Total\ number\ of\ tests} \tag{5}$$

$$F_3 = \left(\frac{nse}{nse + 1}\right) \times 100 \tag{6}$$

As factor F_3 is a weighted version of F_2—the number of failed tests in Equation (2) being replaced by the sum of excursions in Equation (5)—we omit F_2 from our Ecosystem Vitality Water Quality Index ($EVWQI$):

$$EVWQI = 100 - \sqrt{F_1 \times F_3} \tag{7}$$

to produce a number between 0, indicating the lowest water quality and 100, indicating the highest water quality.

2.3.3. Drainage Basin Condition

Drainage Basin Condition was calculated as the geometric mean of three sub-indicators: Bank Modification, Flow Connectivity and Land Cover Naturalness.

Bank Modification. Bank Modification measures the extent of unmodified river channel in the 3S basin. The river channel can be modified by various means, including engineering work such as channelization and bank stabilization, which are minor in the 3S system, or inundation by reservoirs. We determined the extent of reservoir inundation using maps generated by the SERVIR Mekong dam inundation mapping tool [47] and Landsat Imagery [48] for a subset of dams (Table S1) for the December 2018 and Lower Sesan II scenarios. and the 3S River Network dataset. The Bank Modification statistic is:

$$CN = 100 - \left(\frac{rL}{L} \times 100\right) \tag{8}$$

where rL is the total length of inundated rivers and L is the total length of rivers in the 3S basin.

Flow Connectivity. We used the Dendritic Connectivity Index (DCI) [49] to assess disruption in connectivity caused by dams using the method described by Shaad et al. [50]. With one exception, none of the dams in the 3S system were constructed to facilitate fish passage. Whilst the Lower Sesan II dam has been retrofitted with a fish passage, its effectiveness is unknown. Thus, we assumed the passability of all dams in the 3S basin for fish in either direction to be zero. DCI evaluates both the loss of connectivity between the 3S basin and the Mekong River (*DCId*), which affects migratory fish, and between the various segments created within the 3S basin due to the dams (*DCIp*), which affects non-migratory fish. We calculated a combined index (*cDCI*) by combining these two values, weighted by the proportion of migratory vs. non-migratory fish. A total of 329 species of fish have been recorded from the 3S system, of which 89 are migratory [51,52]. Thus,

$$cDCI = (0.27 \times DCId + 0.73 \times DCIp) \times 100 \tag{9}$$

Whilst this formula gave a score between 0 and 100, we normalized it using the value of 71.7, which is the *cDCI* value for natural connectivity. Two natural waterfalls in Vietnam, Yali on the Sesan River and Dray Nur on the Srepok, are natural barriers to fish movement and the baseline *cDCI* was determined with these barriers in place.

Land Cover Naturalness. Land Cover Naturalness exists on a gradient of natural to artificial [52]. Human conversion of land and waterways are associated with increases in pollutant loads (non-point source from agriculture, point-source from urban and industrial), changes to infiltration and run-off regimes, and losses of regulating services (flood mitigation, erosion prevention, water purification). Land Cover Naturalness is a proxy indicator for the degree to which these naturally occurring functions are preserved within the basin. It is based on similar efforts to categorize and quantify this gradient over landscapes [53,54].

We used land cover data from the Mekong River Commission (MRC) as the classification categories and temporal coverage were consistent across the 3S basin. The MRC has two datasets for 2010, comprising the wet and dry seasons [55,56]. The 2010 dry season dataset was used to calculate Land Cover Naturalness as it captured additional agricultural and other non-natural (though seasonal) land use that was classified as water bodies in the wet season data. This provided a more conservative estimate of natural land cover.

Land cover types were assigned scores based on the following criteria: degree of naturalness, degree of human management of the water cycle to maintain this land cover, degree of pollution emissions, and vegetation characteristics (Table 3).

As the MRC land cover dataset is a polygon (i.e., contiguous parcels of the same Land use/Land Cover (LULC) are grouped together), we assigned naturalness scores to each polygon, which were then converted into a raster dataset of 30 m resolution. Finally, zonal statistics were calculated for the entire 3S basin, the three main rivers' sub-basins, and for the 3S Basin Network, to depict intra-basin variation.

Table 3. Land Use/Land Cover (LULC) types classified by degree of naturalness.

LULC Type from MRC Data	Score	Degree of Naturalness	Water Cycle Modification	Pollution Emissions	Vegetation Characteristics
Natural water body	100	Natural and semi-natural	None	None to Low	Native
Marshes/swamps	100				
Mangrove	100				
Coniferous forest	100				
Bamboo forest	100				
Broadleaved evergreen forest	100				
Broadleaved deciduous forest	100				
Flooded forest	100				
Shrubland	60	Cultural assisted system	Low	Low	Mixed, high diversity
Shifting cultivation	60				
Forest plantation	50	Transformed system	Low to Moderate		Permanent cover with atypical species
Industrial plantation	50				
Orchard	50				
Grassland	40		Moderate to High	Moderate to High	Seasonal cover with atypical species
Paddy rice	30				
Reservoirs	30				
Annual crop	20				
Bare soil	10	Completely artificial	High		Sparse to no cover
Urban area	1			High	

2.3.4. Biodiversity

The status and trends of a basin's freshwater biodiversity signify ecosystem health, with declining populations of native species (which includes increasing numbers of threatened species) and increasing populations of invasive and nuisance species indicating deteriorating conditions or ecosystem degradation. We calculated the Biodiversity indicator as the geometric mean of two sub-indicators: Changes in Number (i.e., species number) and Population Size of Species of Concern (Species of Concern), and Changes in Number and Population Size of Invasive and Nuisance Species (Invasive and Nuisance Species). Species of Concern (ISC_i) has three components: (1) the proportion of threatened freshwater species ($I_{TE,i}$), (2) change in the number of species of concern (ΔSC_i), and (3) average population trend across all species of concern (PT_i). These three parameters are combined to give an overall index for the status and change in Species of Concern.

$$ISC_i = min\left\{ISC_{i-1}\ \sqrt[3]{I_{TE,i} \times \Delta SC_i \times PT_i},\ 100\right\} \tag{10}$$

For the first assessment of the basin at time = 1, $ISC_0 = 100$.

We could only calculate $I_{TE,i}$ as the data needed for ΔSC_i or PT_i were unavailable, in which case both parameters were set to equal 1 for the calculation of ISC_i.

Species of Concern. For Species of Concern, we calculated the proportion of threatened freshwater species ($I_{TE,i}$) by determining the weighted proportion of freshwater species listed on the IUCN Red List as critically endangered (CR), endangered (EN), or vulnerable (VU) against the total number of species assessed [57] as:

$$I_{TE,i} = \frac{w_{CR} n_{CR,i} + w_{EN} n_{EN,i} + w_{VU} n_{VU,i}}{(w_{CR} + w_{EN} + w_{VU})} \times \frac{1}{n_{Total,i}} \tag{11}$$

where $n_{CR,i}$, $n_{EN,i}$, and $n_{VU,i}$ are the number of species listed as CR, EN, or VU under the IUCN Red List categories and criteria at time t = i, respectively, w_{CR}, w_{EN} and w_{VU} are weights applied to the number of CR, EN, and VU species, respectively, and $n_{Total,\ i}$ is the total number of freshwater species assessed in the basin under the IUCN Red List criteria. Weights were assigned as $w_{CR} = 1.0$, $w_{EN} = 0.75$, and $w_{VU} = 0.5$.

We used IUCN Red List spatial data [58] for amphibians, terrestrial mammals, reptiles and the freshwater polygon groups for fish, molluscs, plants, odonates, shrimps, crayfish and crabs, delimited to the 3S catchment boundary. We obtained water bird data from Birdlife International [59]. We included all listed aquatic species except those classified as possibly extant, due to a lack of confirmed records.

Invasive and Nuisance Species. Invasive and Nuisance Species (INS_i) also has three components: (1) invasive and nuisance species richness ($I_{IN,i}$), (2) change in invasive and nuisance species richness ($\Delta n_{IN,i}$), and (3) the average population trend across all invasive and nuisance species (IPT_i). These three parameters were then combined to give an overall index for Invasive and Nuisance Species.

$$INS_i = min\left\{INS_{i-1}\ \sqrt[3]{I_{IN,i} \times \Delta n_{IN,i} \times IPT_i},\ 100\right\} \tag{12}$$

For the first assessment of the basin at time $= 1$, $INS_0 = 100$.

We could only calculate $I_{IN,i}$ as the data needed for $\Delta n_{IN,i}$ or IPT_i were unavailable, in which case both parameters were set to equal 1 for the calculation of INS_i.

The Invasive and Nuisance Species index is calculated as:

$$I_{IN,i} = \begin{cases} 1 - \frac{n_{IN,i}}{10}, & \text{for } 0 \le n_{IN,i} \le 8 \\ 0.1, \ \text{for } n_{IN,i} \ge 9 & \end{cases} \tag{13}$$

where $n_{IN,i}$ is the number of invasive and nuisance species in the basin at time t = i.

The number of invasive and nuisance species in the 3S basin was determined through a literature review and interviews with regional experts.

2.4. Calculation of Ecosystem Services Indicators

The Ecosystem Services metrics comprises three major indicators with eight sub-indicators. The three major indicators (Provisioning, Regulation and Support, and Cultural) are based on the categories from the Millennium Ecosystem Assessment [60] for quantifying human direct use, indirect use, and experiential use of ecosystems. For the Provisioning and Regulation and Support indicators, we calculated an index with spatial, temporal and magnitude factors, building on the approach used in the Canadian Water Quality Index [46]. We attempted to calculate all three factors for each indicator, depending on the data available. F_1 measured the spatial scope of the system to provide the ecosystem service:

$$F_1 = \left(\frac{Number\ of\ spatial\ units\ that\ did\ not\ meet\ demand\ at\ least\ once}{Total\ number\ of\ spatial\ units}\right) \times 100 \tag{14}$$

F_2 introduced a temporal dimension measuring how frequently the system fails to provide the ecosystem service;

$$F_2 = \left(\frac{Number\ of\ instances\ where\ demand\ was\ not\ met}{Total\ number\ of\ instances\ monitored}\right) \times 100 \tag{15}$$

and F_3 measured the magnitude of the deviation when the service is for parameters that must not exceed (Equation (16)) or fall below (Equation (17)), the threshold values.

$$Ex_i = \left(\frac{Failed\ test\ value_i}{Threshold_i}\right) - 1 \tag{16}$$

$$Ex_i = \left(\frac{Threshold_i}{Failed\ test\ value_i}\right) - 1 \tag{17}$$

These values were used to calculate the normalized sum of excursions (Equation (18)), which was then scaled to yield the F_3 value, which ranged between 0 and 100 (Equation (19)).

$$nse = \frac{\sum_{i=0}^{n} Ex_i}{Total\ number\ of\ tests} \tag{18}$$

$$F_3 = \left(\frac{nse}{nse+1}\right) \times 100 \tag{19}$$

We used the geometric mean to aggregate the scores to give the Ecosystem Service Indicator (*ESI*) score according to the following rules:

If only able to determine F_1 (low evidence);

$$ESI_1 = 100 - F_1 \tag{20}$$

Otherwise, if able to determine both F_1 and F_2 (medium evidence);

$$ESI_2 = 100 - \sqrt{F_1 \times F_2} \tag{21}$$

Otherwise, if able to determine all three (high evidence);

$$ESI_3 = 100 - \sqrt{F_1 \times F_3} \tag{22}$$

2.4.1. Provisioning

The Provisioning indicator is the geometric mean of two components: Water Supply Reliability Relative to Demand and Biomass for Consumption.

Water Supply Reliability Relative to Demand. We calculated Water Supply Reliability Relative to Demand using the global 0.5 resolution self-calibrated Palmer Drought Severity Index [61,62]. Monthly mean values of the Index for the period 2011–2015 were compared with the full range (1901–2015) to derive a change in the spatial scope (F_1) and frequency (F_2) of water availability. The main limitation of using a Drought Severity Index is that it does not explicitly account for demand from individual sectors and we used the change from the long-term mean as a proxy for inability to meet water demand.

Biomass for Consumption. As a surrogate measure of Biomass for Consumption, we assessed the availability of migratory fish habitat in the 3S basin. We determined migratory freshwater fish distribution in the 3S using the IUCN RedList/Integrated Biodiversity Assessment Tool datasets. Of the 89 identified migratory species [51] in the 3S basin, suitable distribution data were only available for 25. We generated a combined assessment of migratory fish habitat for each of the 111 3S Basin Network sub-basins (Figure 2). By blocking fish passage, dams deny access to sub-basins, the importance of which for migratory fish was weighted by migratory fish richness, with sub-basins that supported a higher number of migratory fish receiving a higher weight. Each sub-basin was given a category ranging from 1 to 6 based on the number of migratory fish found within it:

- 0 migratory fish species;
- 4–7 migratory fish species (if migratory species were present the minimum number present was 4);
- 8–11 migratory fish species;
- 12–15 migratory fish species;
- 16–20 migratory fish species; and
- 21–25 migratory fish species.

We assigned a score of 100 to a fully connected river network where migratory fish had access to all sub-basins.

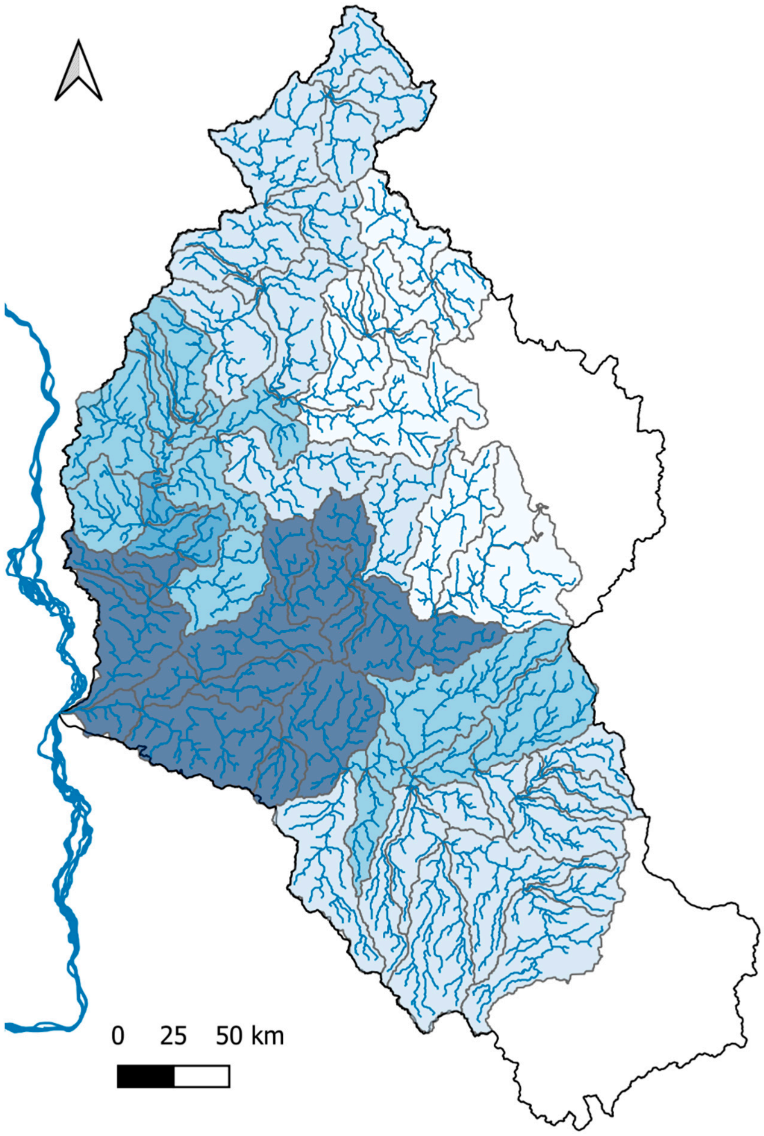

Figure 2. Migratory fish distribution in the 3S basin. Darker colours represent higher sub-basin migratory fish richness. The white portions showing no river system are areas that naturally were unavailable to migratory fish due to waterfalls.

Thus, F_1 equalled the number of sub-basins that were disconnected from migratory fish due to downstream dams. F_3 was calculated by Equations (23) and (24):

$$nse_{F3} = \frac{\sum^{n_c}\left(\frac{\sum^{n_{sb}} MFH \times TCL}{\sum^{n_{sb}} MFH \times ACL}\right) - 1}{n_c} \quad (23)$$

$$F_3 = \left(\frac{nse_{F3}}{nse_{F3} + 1}\right) \times 100 \quad (24)$$

where *MFH* is migratory fish habitat; *ACL* is the length of river channel available to migratory fish; *nse* is the number of level 8 HydroBasins; *TCL* is the total length of the river channel; and n_c is the number of river basins. In this case, n_c = 3 as calculations were made for the Srepok, Sesan and Sekong River basins.

As with the calculation of the DCI, we assumed that all dams completely blocked fish passage. Our analysis excluded fish resident in the 3S which are less likely to be affected by hydropower development than migratory fish. Due to a lack of information, we did not assess the proportion of non-migratory fish that are harvested for consumption, nor did we consider the potential for these species to fill niches made vacant by the absence of migratory species.

2.4.2. Regulation and Support

The Regulation and Support indicator comprised four sub-indicators: Sediment Regulation, Deviation of Water Quality Metrics from Benchmarks, Flood Regulation and Exposure to Water-Associated Diseases. In aggregating sub-indicators for the hydropower development scenarios, scenario 4 (Lower Sekong) used the scenario 3 (under construction) Sediment Regulation score as the Lower Sekong dam was not included in the 3S SedSim model.

Sediment Regulation. Sediment Regulation was determined using Wild and Loucks' [25] 3S basin SedSim simulation model. SedSim applies seasonal supply dam operation rules for up to 41 reservoirs (Table S1) to calculate the indicator. We used the seasonal supply operational regime described in the Deviation from Natural Flow section. SedSim applies null routing for the river reaches and, thus, primarily estimates the trapping of sediment by the reservoirs. To compensate for this limitation, the calculation process considers the full potential for dam construction (from Scenario 5) as the spatial unit over which F_1 and F_3 were calculated. As SedSim did not contain the Lower Sekong dam, this scenario could not be calculated.

Deviation of Water Quality Metrics from Benchmarks. Twenty surface water quality parameters were assessed as a part of the Deviation of Water Quality Metrics from Benchmarks indicator: TSS, TP, TN, pH, Electrical Conductivity (EC), Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), Total Nitrite and Nitrate (NO_2 + NO_3), Ammonia (NH3), Ammonium (NH4), Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Alkalinity, Chloride (Cl), Sulphate (SO4), Ca/Mg, Na/Cl, Na/K, Ca/SO.

Samples were obtained at the same time and from the same sites as those assessed for the Water Quality major indicator. Specific lower Mekong basin benchmark values for the protection of human health were used to assess pH, 6–9; DO, 4 mg/L; COD, 5 mg/L; NO_2 + NO_3; 5 mg/L and NH_3, 0.5 mg/L. The agriculture value was adopted for EC, 700 mS/m [44] and the lowland rivers threshold was used for TN (<1.6 mg\L) [45]. Water quality data for the last five available years of sampling (2010–2014) were compared against these benchmarks. For the other parameters, we followed the protocol used to establish monthly minimum and maximum TSS thresholds for the Water Quality major indicator.

For each parameter a Deviation from Water Quality (DvWQ) indicator score was determined by calculating and aggregating the F_1 and F_3 components to produce a number between 0, indicating the lowest water quality, and 100, indicating the highest water quality. The DvWQ value for each parameter was combined into a Deviation of Water Quality Metrics from Benchmarks score by taking the geometric mean.

Flood Regulation. We calculated the Flood Regulation indicator using the four gauged stations along the Sesan and Srepok Rivers with defined flood levels (450101, Lumphat, Srepok, Cambodia; 440102 Voeun Sai, Sesan, Cambodia; 450502 Giang Son, Krong Ana (Srepok), Vietnam; 450701 Duc Xuyen, Krong Kno (Srepok), Vietnam). The indicator was calculated using the gauging stations water level time series from 2010–2015.

Exposure to Water Associated Diseases. We assessed two water-associated diseases present in the 3S: Mekong schistosomiasis and dengue fever. A composite Exposure to Water-Associated Diseases indicator was generated by weighting both diseases and determining the arithmetic mean. As it is closely associated with the surface water system, Mekong schistosomiasis received a weighting of 0.8, whilst dengue received a weighting of 0.2, as the mosquito larvae habitat, which is often small isolated rainfed pools of water, is less closely associated with the basin's water system.

Mekong schistosomiasis (*Schistosoma mekongi*) is a parasitic blood fluke endemic to the Sesan and Sekong Rivers in Cambodia's Stung Treng province [63,64]. People are exposed to infection by bathing, swimming, washing clothes and dishes, fishing and obtaining water [64]. The fluke's aquatic host snails, *Neotricula aperta,* are present in these endemic areas as well as on the Srepok River further upstream in Cambodia's Ratanakiri province and the Sekong and XeKaman Rivers near Attapeu in Lao PDR. Snails near Jua Talai in Ratanakiri on the Srepok River were infected by the *S. mekongi* parasite, whilst snails found in Lao PDR were not [65]. We used this information to calculate F_1 using the 3S Basin Network. Sub-basins within Stung Treng province that were traversed by either the Sekong, Sesan or Srepok Rivers were counted along with the sub-basin in Ratanakiri from where the infected snail was found. The transmission of Mekong schistosomiasis to humans occurs during the dry season from February or March to April [63,64]. This allows for an estimate of frequency (2.5 months out of 12).

Dengue fever is a water-related disease transmitted by the mosquito *Aedes aegypti*, an insect vector with an aquatic phase in its lifecycle. We used the exposure indicator of the Water Associated Disease Index (WADI) [66] to calculate our metric for Dengue. The WADI exposure indicator is a composite indicator that 'represents conditions conducive to the presence and transmission of the pathogen within the environment' [66]. Although the WADI also measures the susceptibility of the resident population to the pathogen, we did not measure this aspect as exposure is a sufficient measure of this ecosystem service. Dickin et al. [66] used three components to create their exposure indicator: climate, land environment and human environment. These were divided into four Dengue WADI factors (Table 4) from which the indicator was developed.

Table 4. Dengue WADI exposure indicator components and factors for the 3S.

Component	Dengue WADI Factor	Data Source
Climate	Maximum temperature; precipitation	WorldClim version 2 global climate surfaces [67].
Land environment	Types of land use	MRC 2010 dry and wet season land cover [55,56].
Human environment	Population density	FAO Global population density estimates 2015 [68].

In developing the index, each exposure indicator factor was converted to an exposure value of between 0 and 1 (Table 5), following the values used by Dickin et al. [66,69]. These values were applied to the datasets in the open source Geographical Information System—Quantum GIS [70]. Each dataset was processed as a raster with pixels containing values between 0 and 1 as per the exposure value (Table 5). Temperature and precipitation rasters were developed for each month and two land use rasters where generated, one each for the wet and dry seasons. The mean exposure values (Table 6) of each raster were calculated to give 12 exposure indicator raster layers. A threshold of 0.25 for the exposure indicator was set, and the mean value was calculated for each sub-basin for each of the 12 months. This information allowed the calculation of F_1, and F_3 for dengue.

Table 5. Thresholds used to create the exposure indicator components.

Exposure Indicator Factor	Dimension	Exposure Value
Population density (people/sq. km)	<10	0
	10–49	0.25
	50–99	0.5
	100–199	0.75
	≥200	1
Land cover component	Urban areas	1
	Annual crop	0.5
	Paddy rice	0.5
	Orchard	0.5
	Industrial Plantation	0.5
	Marshes swamp area	0.5
	Shifting cultivation	0.25
	Grassland	0.25
	Bare soil	0.25
	Shrubland	0
	Broadleaved deciduous forest	0
	Broadleaved evergreen forest	0
	Bamboo forest	0
	Coniferous forest	0
	Water body	0
Temperature	Maximum monthly temperature, lag of 2 months	20 °C and ≤34 °C: linear increase in exposure up to 1; ≤2 0 °C and >34 °C: 0 exposure
Precipitation	Monthly cumulative precipitation, lag of 2 months	<300 mm precipitation: linear increase in exposure up to 1; >300 mm monthly precipitation: 0 exposure

Table 6. Combinations of exposure indicator factors used to derive monthly dengue exposure indicator values.

Assessment Month	Temperature/Precipitation	Land Use
January	November	Dry season
February	December	Dry season
March	January	Dry season
April	February	Dry season
May	March	Dry season
June	April	Wet season
July	May	Wet season
August	June	Wet season
September	July	Wet season
October	August	Wet season
November	September	Wet season
December	October	Dry Season

2.4.3. Cultural and Aesthetic

The Cultural/Aesthetic indicator comprises two sub-indicators: Conservation/Cultural Heritage Sites and Recreation. As use of water in the 3S as a recreational resource was not identified, the Conservation/Cultural Heritage indicator was used as the Cultural/Aesthetic indicator. We calculated the Cultural/Aesthetic indicator using a protected areas map derived from Open Development Cambodia [71] and IUCN and UNEP-WCMC [72]. The river length within the protected areas system and length of streams that formed protected area boundaries were determined from the 3S River Network dataset. These were compared against the total river length within the 3S using equation 25:

$$PoR = \frac{0.5 \times BL + IL}{RL} \times 100 \quad (25)$$

where PoR is the percentage of river length protected; BL is the length of rivers bordering protected areas; IL is the length of rivers within protected areas; and RL is the total length of rivers within the 3S.

With the global target of minimum wetlands and waterways under protected areas set at 17% under the Convention on Biological Diversity Aichi Biodiversity Target 11 [73], we scaled the value using an asymptotic function:

$$Cultural\ Indicator = 1.17 \frac{PoR}{PoR + 17} \quad (26)$$

2.5. Calculation of the Governance & Stakeholders Indicators

Governance & Stakeholders comprises four major indicators—Enabling Environment, Stakeholder Engagement, Vision and Adaptive Governance, and Effectiveness—within which are 12 sub-indicators. The Governance & Stakeholders indicators are based on stakeholders' perceptions and were assessed using a questionnaire (Appendix S1) comprising 12 modules corresponding to each sub-indicator with 3–6 questions per module. Fifty-one questions were asked, each using a 1–5 Likert-type scale to quantify the qualitative responses. The questionnaire was administered in English, both online (www.typeform.com) and through guided exercises at stakeholder workshops held in each country. Survey responses were anonymous and targeted towards people with specific knowledge of the 3S and its governance system. Survey responses were transformed from the 1–5 to a 1–100 scale, and the mean value for each response was used to calculate the final indicator and sub-indicator scores, and responses were also presented according to country affiliations.

2.6. Stakeholder Weighting Exercise

To ensure that the aggregated indicator values for both Ecosystem Services and Governance & Stakeholders reflected stakeholders' preference, we asked the same set of stakeholders to complete a weighting exercise based on the Analytic Hierarchy Process [74]. A hierarchy was created so that stakeholders made a total of 34 pairwise comparisons, first amongst major indicators in each component, and then amongst sub-indicators within a major indicator category. Eighteen stakeholders completed the exercise, first selecting the indicator or sub-indicator they considered more important, and then rating how much more important using a 1–9 intensity scale (where 1 was used to indicate "no preference" between the two objects being compared). These numeric scores were translated into a reciprocal matrix and the principal right eigenvector was calculated to derive weights between 0 and 1. We used the BPMSG AHP Online System [75] to design, administer (in English), and process the exercise. The mean group value was used for weighting aggregated indicators, though we also evaluated individuals' consistency ratios (CR) and the strength of consensus for each choice task.

3. Results

Given the available data, we completed an FHI assessment of the 3S basin as of December 2016 (Figure 3). We also calculated a smaller set of sub-indicators for the four other hydropower development scenarios.

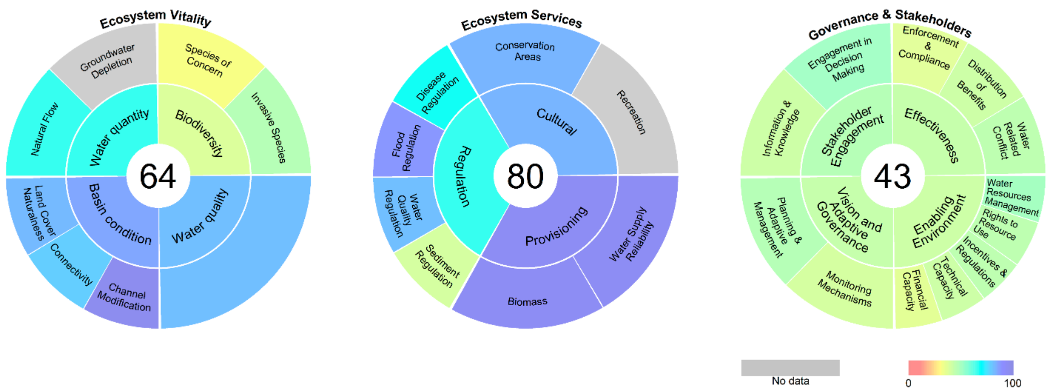

Figure 3. Summary December 2016 Freshwater Health Index scores for the 3S basin.

3.1. *Ecosystem Vitality*

For the December 2016 assessment, the Ecosystem Vitality score was a mid-range value of 64 (Table 7). Whilst the scores for Water Quality and Drainage Basin Condition were both above 80, the mid-range score for Water Quantity, and very low score for Biodiversity, reduced the total. Indicator scores for both Water Quantity and Drainage Basin Condition, and consequently Ecosystem Vitality, declined with increasing hydropower dam development, with all three showing major declines under the full development scenario (Table 7).

Table 7. Ecosystem Vitality major and sub-indicator scores. Dashes ("-") denote that the same (sub-) indicator value was used as for the December 2016 scenario.

Ecosystem Vitality Major and Sub-Indicators (Italics)	December 2016	Lower Sesan II	Under Construction	Lower Sekong	Full Development
Aggregate score	64	61	59	57	40
Water Quantity	66	66	61	61	22
Water Quality	81	-	-	-	-
Drainage-Basin Condition	85	67	66	58	36
Bank Modification	96	95	-	-	-
Flow Connectivity	78	38	36	25	6
Land Cover Naturalness	82	-	-	-	-
Biodiversity	38	-	-	-	-
Species of Concern	31				
Invasive and Nuisance Species	46				

3.1.1. Deviation from Natural Flow Regime

With the absence of an indicator for Groundwater Storage, the Deviation from Natural Flow Regime indicator was the only Water Quantity indicator. The December 2016 scenario's score of 66.0 shows that a sizable shift from the natural flow regime occurred, with maximum modification of flow on the Sesan River (P3, Table 8). The concentration of dams on the Sesan's main stem with few major tributaries contributes to the low score. Planned construction in the Sekong system contributes to the low score seen in the full development scenario, projected to decline to 20.1 at P1. This implies a dampening of the seasonal flow pattern to the same order of magnitude as mean flow, i.e., during the dry season, there may be more than twice the unregulated natural flow, while mean monthly flow during the wet season will drop by a similar magnitude.

Table 8. Deviation from Natural Flow Regime scores for the five hydropower development scenarios in the 3S basin (P1-4 are points on the river network located in Figure 1).

Scenario	Basin Outlet (P1)	Sekong, Lao-Cambodia Border (P2)	Sesan, Vietnam-Cambodia Border (P3)	Srepok, Vietnam-Cambodia Border (P4)	Basin Score
December 2016	68.6	69.7	42.1	53.9	66.0
Lower Sesan II	68.0	69.7	42.1	53.9	65.6
Under construction	64.4	58.7	41.4	53.9	60.8
Sekong dam	64.0	58.7	41.4	53.9	60.6
Full development	20.1	14.6	41.4	42.9	21.9

3.1.2. Water Quality

The EVWQI score for the period of 2010–2014 was 80.6, which was derived from an F_1 of 100 and F_3 of 3.8. Thus, all water quality parameters failed their threshold values at least once. However, both the frequency (8.3% of tests) and magnitude of failure were consistently low.

3.1.3. Drainage Basin Condition

Drainage Basin Condition scored 85 for the December 2016 scenario. Bank Modification was minor for December 2016 (96) but decreased by 1% with the construction of the Lower Sesan II dam (Table 7). The Flow Connectivity score ranged from 76 for December 2016 to 6 under the full dam development scenario (Table 9). The decrease was due to the dams progressively reducing connectivity and reservoirs inundating increasingly more river channels (Table 9). The entire 3S basin had a mean Land Cover Naturalness value of 82. The three river sub-basins' scores showed that the Sekong was in a comparatively natural state (90) while the Sesan (79) and Srepok (78) brought the overall mean down. The disaggregated values (Figure 4) reveal that much of the land cover modification has occurred in Vietnam, particularly the corridor extending southwest from Buon Ma Thuot, the provincial capital of Dak Lak. Land cover in this region and Vietnam's Central Highlands more generally is dominated by industrial plantations such as coffee, pepper and soybean, as well as seasonal rice [76,77].

Table 9. Combined Dendritic Connectivity Index (*cDCI*) and normalized *cDCI* metrics for a range of scenarios in the 3S catchment.

Scenario	*cDCI*	Normalized *cDCI*
Natural	71.7	100
December 2016	55.6	77.5
Lower Sesan II	27.3	38.0
Under construction	25.9	36.1
Sekong dam	17.8	24.7
Full development	4.3	6.0

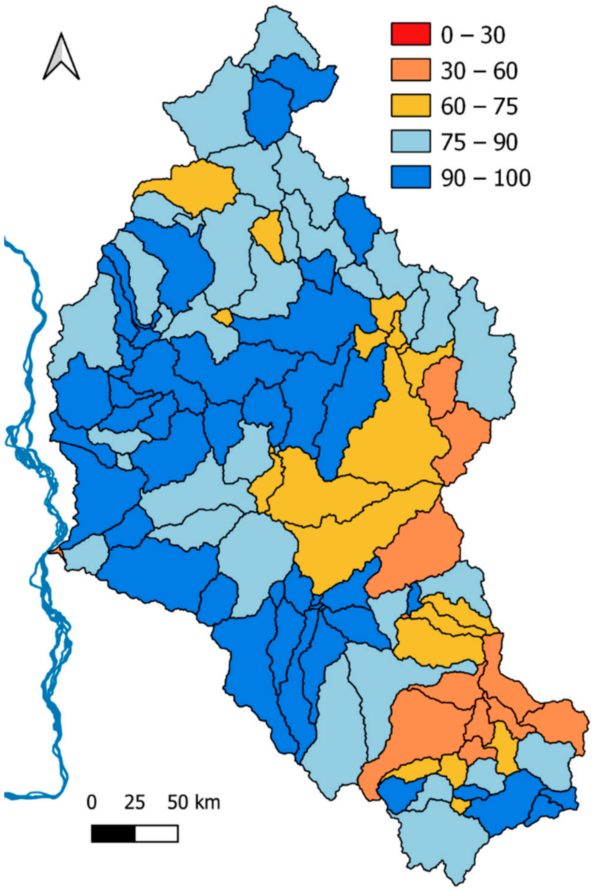

Figure 4. Land Cover Naturalness based on the Mekong River Commission 2010 land use map. The legend depicts land cover naturalness scores, as per Table 3.

3.1.4. Biodiversity

The December 2016 Biodiversity score was 38. This comprised a Species of Concern score of 31, and an Invasive and Nuisance Species score of 46. We recorded 90 threatened species out of a total of 862 assessed by the IUCN. This gave an $I_{TE,i}$ score of 0.03. Most threatened species were fish (Actinopterygii), which also contained the most Critically Endangered species. Fish were also the most species-rich group assessed under the Red List criteria (Table 10). Nine invasive species were identified from the 3S basin, which gave an $I_{IN,i}$ score of 0.1 (Table 11).

Table 10. The number of IUCN Red List species present in the 3S basin categorized by higher taxonomic groups. CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern.

Red List Category	Actinopterygii	Aves	Reptilia	Amphibia	Mollusca	Mammalia	Odonata	Plantae	Decapoda	Total
CR	8	3	1	-	-	-	-	-	-	12
EN	19	4	-	9	-	-	-	-	-	32
VU	19	4	-	7	14	2	-	-	-	46
NT	13	12	-	11	33	1	-	-	-	70
LC	295	72	5	79	100	-	127	7	17	702
Total	354	95	6	106	147	3	127	7	17	862

Table 11. Invasive species present in the 3S system.

Invasive Species	Reference
Common Tilapia (*Oreochromis mossambicus*)	[51,77]
Nile Tilapia (*Oreochromis niloticus*)	[51,78]
Silver Carp (*Hypophthalmichthys molitrix*)	[51,79]
Bighead Carp (*Hypophthalmichthys nobilis*)	[51]
Rohu (*Labeo rohita*)	[51,79]
Common Carp (*Cyprinus carpio*)	[51,79]
African walking catfish (*Clarias gariepinus*)	[51]
Golden Apple Snail (*Pomacea canaliculate*)	[77]; Jeremy Carew-Reid, pers. comm.
Giant mimosa (*Mimosa pigra*)	Peter John Meynell, personal observation.

3.2. Ecosystem Services

The December 2016 Ecosystem Services score of 80.1 was high (Table 12). The major indicator scores for both Provisioning and Cultural/Aesthetic were high, with Regulation and Support much lower due to the low Sediment Regulation score (Table 12). The indicator scores for both Provisioning and Regulation and Support, and thus Ecosystem Services, declined with increasing dam development (Table 12).

Stakeholders did not exhibit strong preferences amongst Provisioning, Regulation and Support, and Cultural/Aesthetic services, as evidenced by the small range of weights (0.31–0.35) compared to the default weight of 0.33 (Table 12). Within sub-indicators, there was a more pronounced preference for Water Supply to Biomass for Consumption, and for Deviation of Water Quality Metrics from Benchmarks (0.32) compared to other Regulation services.

Table 12. Weighted ecosystem service indicators for the five hydropower development scenarios. Dashes ("-") denote that the same (sub-) indicator was used as for the December 2016 scenario.

Ecosystem Service Major and Sub-Indicators (Italics), [Stakeholder Weightings]	December 2016	Lower Sesan II	Under Construction	Lower Sekong	Full Development
Aggregate score	80	65	63	17	16
Provisioning [0.34]	94	50	49	1	1
Water Supply Relative to Demand [0.57]	95	-	-	-	-
Biomass for Consumption [0.43]	94	26	26	0.01	0.01
Regulation and Support [0.35]	66	66	61	61	54
Sediment Regulation [0.21]	39	39	29	-	17
Deviation from Water Quality Metrics from Benchmarks [0.32]	81	-	-	-	-
Flood Regulation [0.25]	88	-	-	-	-
Exposure to Water associated Diseases [0.22]	67	-	-	-	-
Cultural/Aesthetic [0.31]	83	-	-	-	-

3.2.1. Provisioning

Water Supply Relative to Demand. In comparison with the long-term mean, only a few months reported a lower Palmer Drought Severity Index, giving this indicator a high score (94.9) in December 2016, suggesting an abundance of water in the system. However, with the rise of cash crops in the region, stakeholders reported localized water scarcity, and recommended tracking water demand and usage.

Biomass for Consumption. The construction of both the Lower Sesan II and Lower Sekong dams had the greatest impact on migratory fish access to the 3S basin (Table 13; Figure 5) and thus, on Biomass for Consumption. The near-zero values for the Sekong dam and full development scenarios are a result of migratory fish being unable to access almost all of their 3S habitat.

Table 13. Biomass for Consumption F_1, F_3 and indicator scores for the five hydropower scenarios.

Scenario	F_1	F_3	Biomass for Consumption Score
December 2016	13.9	2.63	93.9
Lower Sesan II	54.2	100	26.4
Under construction	55.6	100	25.5
Sekong dam	100	100	0.01
Full development	100	100	0.01

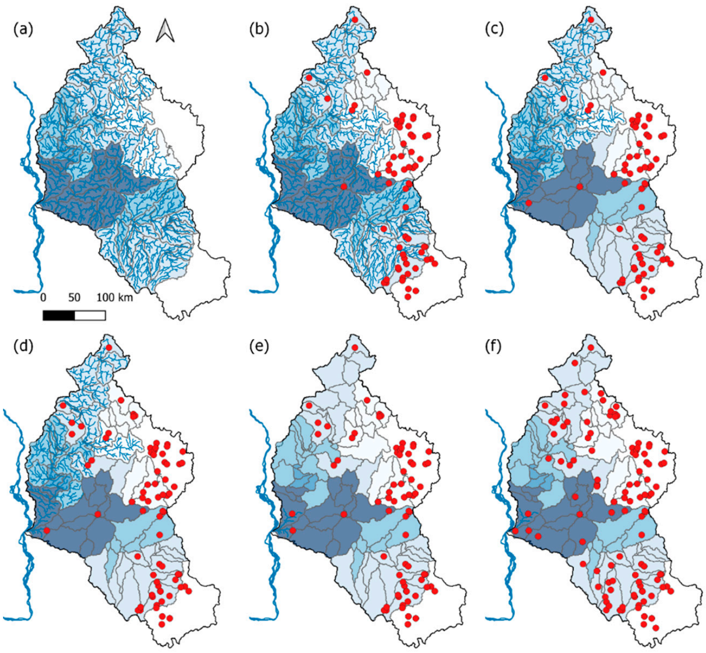

Figure 5. Maps of the 3S river basin for each hydropower development scenario: (**a**) natural; (**b**) December 2016; (**c**) Lower Sesan II; (**d**) under construction; (**e**) Sekong dam; (**f**) full development. Grey lines demarcate the sub-basins. Darker shading represents sub-basins with higher migratory fish richness. The red dots are the locations of the hydropower dams and the blue lines represent the river network available to migratory fish under each development scenario. The river to the left of the basin is the Mekong.

3.2.2. Regulation and Support

Sediment Regulation. Sediment Regulation was one of most impacted services in December 2016, achieving a mid to low score of 38.7 (Table 14). With increasing dam development, more sediment was blocked from passing downstream, further reducing the score.

Table 14. Sediment Regulation F_1, F_3 and indicator scores for the five hydropower development scenarios. No score could be given for the Sekong dam scenario as that dam was not included in the SedSim model.

Scenario	F1	F3	SR
December 2016	51.2	73.6	38.7
Lower Sesan II	51.2	73.9	38.6
Under construction	61.0	83.7	28.6
Sekong dam	-	-	-
Full development	80.1	85.6	17.2

Deviation of Water Quality Metrics from Benchmarks. The December 2016 DvWQ scores ranged from 57.6 for TP to 100 for EC, NO_2 + NO_3, and NH_3 (Table 15). Eleven parameters had an F_1 score of 100, which meant that they exceeded threshold values at every site at least once. However, for these parameters, the F_3 values were much lower, showing that threshold breaches were generally infrequent and of a small magnitude. These results give a sub-indicator score of 81.3.

Table 15. Deviation of water quality (DvWQ) F_1, F_3 and indicator scores for 21 water quality parameters for the period of 2010–2014.

Water Quality Parameter	F_1	F_3	DvWQ Score
TSS	100.0	4.6	78.6
TP	100.0	17.9	57.6
TN	33.3	0.4	96.4
pH	66.7	0.1	97.6
EC	0.0	0.0	100
DO	50.0	0.4	95.6
COD	66.7	1.0	91.9
$NO_2 + NO_3$	0.0	0.0	100
NH_3	0.0	0.0	100
NH_4	100.0	12.9	64.1
Ca	100.0	6.1	75.2
Mg	100.0	3.1	82.4
Na	66.7	2.9	86.1
K	100.0	16.2	59.8
Alkalinity	100.0	4.8	78.1
Cl	33.3	0.3	96.8
SO_4	100.0	8.2	71.4
Ca/Mg	66.7	3.6	84.5
Na/Cl	100.0	2.6	83.9
Na/K	100.0	13.6	63.1
Ca/SO_4	100.0	10.8	67.1

The minimum and maximum TSS values ranged from 0.7 mg/L in April at the end of the dry season to 566 mg/L in July at the start of the wet season (Table 16). TSS was lowest in the late dry season (February–April) and highest at the start and middle of the wet season (May–September). TSS values exceeded the maximum threshold most often during the dry season (February–April), likely due to dam releases, whilst they fell below the threshold during the wet season, likely a result of dams holding water and trapping sediment (Table 16). This pattern was not observed for TP, where the highest incidences of threshold exceedance were lower values in the late wet season (Table 17).

Table 16. Mean, minimum and maximum Total Suspended Solids (TSS) values recorded for each calendar month across the six sampling sites in the 3S basin from 2004–2009. Numbers in braces are the frequency of the samples (as a percent) that fell below and above the minimum and maximum values during the period of 2010–2014.

Month	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)
January	26.3	2.0 {4.5}	131.0
February	18.1	2.0	47.0 {23.3}
March	17.1	1.0	42.5 {18.2}
April	15.8	0.7	53.0 {13.8}
May	63.2	8.0 {13.6}	354.0
June	68.7	10.0 {3.3}	166.0 {3.3}
July	97.9	20.5 {4.5}	566.0
August	107.4	25.0 {10.0}	381.0
September	105.6	22.5 {4.5}	347.0
October	43.4	13.0	118.0 {10.0}
November	40.3	6.0	128.0
December	25.8	2.5	102.0 {3.3}

Table 17. Mean, minimum and maximum Total Phosphorous (TP) values recorded for each calendar month across the six sampling sites in the 3S basin from 2004 to 2009. Numbers in braces are the frequency of the samples {as a percent} that fell below and above the minimum and maximum values during the period of 2010–2014.

Month	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)
January	0.06	0.01 {9.1}	0.30 {4.5}
February	0.04	0.02	0.08
March	0.03	0.001 {9.1}	0.18 {9.1}
April	0.06	0.01	0.19
May	0.08	0.02	0.21
June	0.13	0.03	0.47 {3.3}
July	0.12	0.04	0.43 {9.1}
August	0.14	0.07	0.25
September	0.10	0.03	0.18
October	0.11	0.001 {16.7}	0.24
November	0.07	0.005 {18.2}	0.18
December	0.08	0.01	0.23

Flood Regulation. In December 2016, Flood Regulation scored 88.2. Floods occurred at all four gauging stations (F1 = 100). However, they were generally low in intensity and duration, which gave the score a high value.

Exposure to Water Associated Diseases. In December 2016, 11 sub-basins were identified to be endemic areas for Mekong schistosomiasis (Figure 6), with a transmission period of 2.5 months, giving a score of 83.4 (Table 18). Dengue fever was widespread throughout the 3S basin with more favourable conditions for the disease in the wet than the dry season (Table 18; Figure 6). The combined Exposure to Water Associated Diseases score was 67.0.

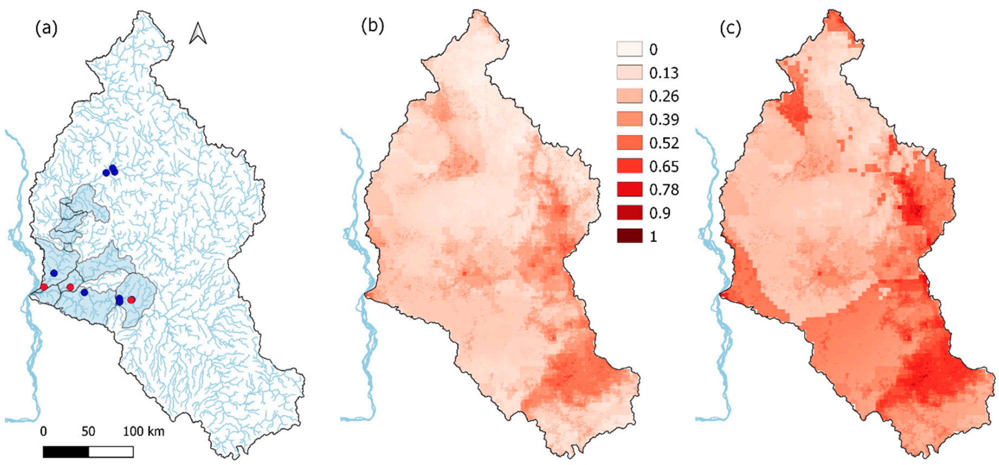

Figure 6. Mekong schistosomiasis (**a**) red dots, host snails and parasite present; blue dots, host snails present, but no parasites; light blue sub-basins, endemic areas. Dengue fever (**b**) dry season, (**c**) wet season exposure indicator.

Table 18. Mekong schistosomiasis and dengue fever F_1, F_2 an F_3 values and Water Associated Disease Index (WADI) scores.

Water Associated Disease	F_1	F_2	F_3	WADI Score
Mekong schistosomiasis	11	20.8	-	83.4
Dengue fever	100	-	97.1	1.5

3.2.3. Cultural and Aesthetic

Seven-hundred-and-three kilometres of river bordered protected areas and 5651 km of river were contained within protected areas (Figure 7). This gave a percentage of river length protected score of 42 and a Cultural/Aesthetic indicator score of 83.0.

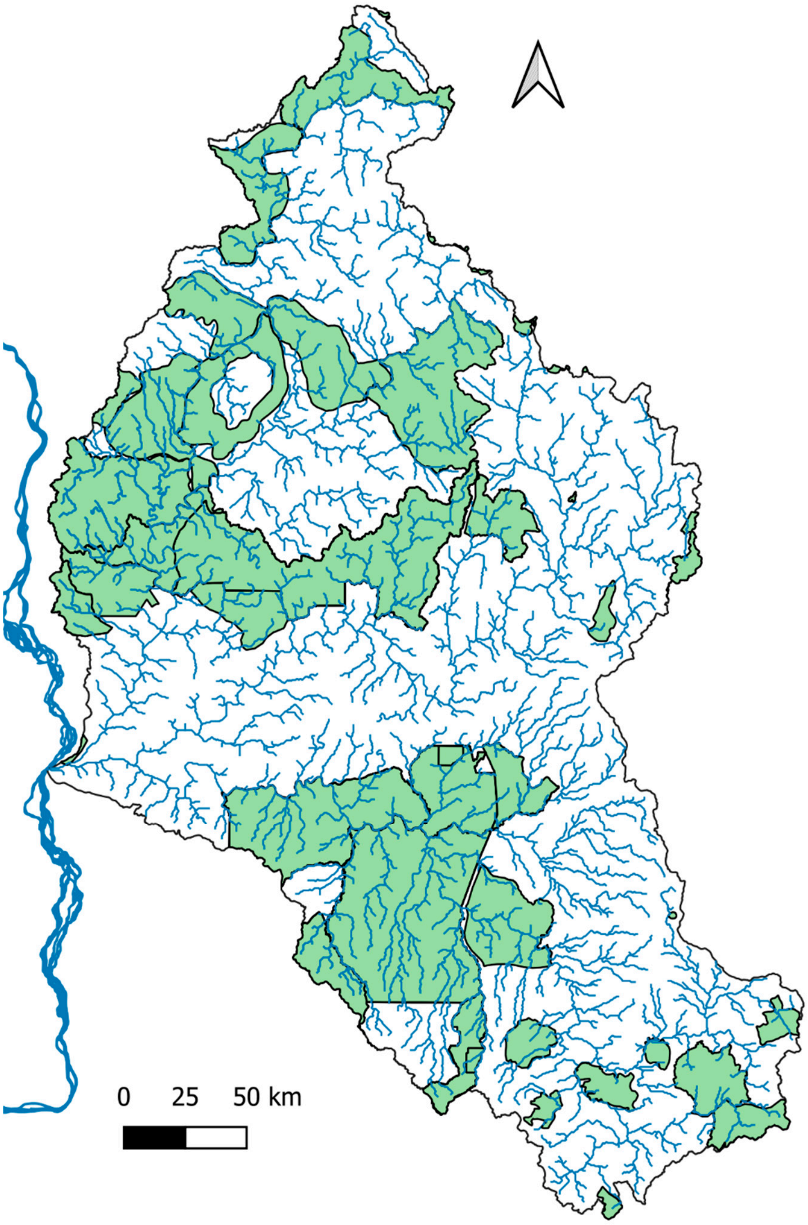

Figure 7. Protected areas in the 3S basin (green polygons).

3.3. Governance & Stakeholders

The Governance & Stakeholders survey was completed by 26 representative stakeholders with knowledge of the 3S's governance system. Respondents came from each of the three riparian nations and several foreign countries. Whilst their perceptions were their own, they were employed by government agencies, non-government organizations, academia and consultancies.

Governance & Stakeholders received a weighted score of 43, with limited variation among the four major indicators (Table 19). Among sub-indicators, Financial Capacity (36) and Enforcement and Compliance (37) received the lowest scores. Since stakeholders each represented one of the three countries and were asked to provide their responses based on baseline governance within their country (and part of the basin), we also analysed scores according to respondents' home country, with two international representatives excluded (Table 19). Except for the Effectiveness indicators, Vietnam and Lao P.D.R. consistently gave the lowest and highest scores, respectively. The Stakeholder Engagement and Vision and Adaptive Governance indicators showed the starkest contrasts between the countries. Nevertheless, the patterns amongst sub-indicators within a major indicator group were generally similar across countries.

Table 19. Summary of weighted scores for Governance & Stakeholders indicators.

Governance & Stakeholders Major and Sub-Indicators (Italics), [Stakeholder Weightings]	Scores			
	Overall (N = 26)	Cambodia (N = 8)	Lao P.D.R (N = 6)	Vietnam (N = 10)
Aggregate score	43			
Enabling Environment [0.27]	42	42	44	42
Water Resources Management [0.23]	50	59	44	48
Rights to Resource Use [0.19]	45	44	47	46
Incentives and Regulations [0.18]	45	42	53	43
Technical Capacity [0.20]	42	40	50	42
Financial Capacity [0.19]	36	33	40	39
Stakeholder Engagement [0.27]	46	48	57	37
Information and Knowledge [0.50]	41	43	53	34
Engagement in Decision-Making [0.50]	51	54	63	40
Vision and Adaptive Governance [0.24]	43	47	51	34
Monitoring and Learning Mechanisms [0.51]	39	41	41	33
Strategic Planning and Adaptive Governance [0.49]	47	54	64	34
Effectiveness [0.22]	43	40	45	45
Enforcement and Compliance [0.33]	37	29	37	45
Distribution of Benefits from Ecosystem Services [0.36]	42	41	42	45
Water-Related Conflict [0.31]	45	49	50	39

Stakeholder preferences, as revealed by the weights, show a small range for the four major indicators (0.22–0.27 compared to default of 0.25). Weights for the sub-indicators similarly exhibit a small range, although individual respondents had higher inconsistencies (Consistency Ratios (CR) > 0.10), suggesting difficulty in evaluating options and discerning clear preferences.

4. Discussion

4.1. Baseline Assessment for Freshwater Health

The December 2016 Freshwater Health Index assessment revealed that although the 3S basin was showing signs of ecosystem stress (indicated by an Ecosystem Vitality score of 64, Table 7), it continued to provide a range of ecosystem services (Ecosystem Services score of 80, Table 12). However, the water governance system in the three countries was weak (Governance & Stakeholders score of 43, Table 19; Figure 3). This describes an unsustainable level of ecosystem service provision and a governance system that may not respond effectively to continued ecosystem degradation and declines in services revealed by the four hydropower development scenarios. Ecosystem Vitality was most influenced by a low Biodiversity score of 38, the result of numerous threatened aquatic species. Water Quantity (with a score of 66) was affected by existing hydropower dam operations which, as modelled, cause reduced wet season flow and increased dry season flow. This has implications downstream where the river ecology and agricultural ecosystems are adapted to seasonal flow patterns. Indeed, the changes to the 3S rivers' flow regime have reportedly reduced the seasonality of the fish assemblage and led to generalist species becoming more dominant [27]. Water Quality had a high score of 81, suggesting that factors such as land clearance and dam operations have had little impact on water quality as it affects ecosystem health and function, at least at the six stations monitored. A high score of 85 for Drainage-Basin Condition indicates that the smaller size of existing dams and their location upstream in the catchment (predominantly in Vietnam) had minimal impacts on Bank Modification and Flow Connectivity throughout the basin.

The high Ecosystem Services score (80) was driven by scores of 95 for Provisioning and 83 for Cultural services (Table 12). Regulation and Support services show signs of deterioration, with Sediment Regulation receiving a low score of 39, as a result of hydropower dams blocking sediment flow. Whilst the sub-indicator Deviation of Water Quality Metrics from Benchmarks received a high score of 81, there were suspected signs of impact with extremely high values of Total Suspended Solids appearing to increase in the dry season and falling below their wet season thresholds. High dry season values for the Deviation of Water Quality Metrics from Benchmarks may be explained by dams releasing water, whilst low wet season values may be due to water storage.

The low Governance & Stakeholders score of 43 highlights underdeveloped management systems, which may hinder the ability of stakeholders to influence and respond to further development or adverse environmental conditions (Table 19). Financial Capacity, Enforcement and Compliance, and Monitoring and Learning Mechanisms had the lowest scores of 36, 37 and 39, respectively. The low Financial Capacity score reflected scant investment in ecosystem conservation and rehabilitation, particularly in underdeveloped Lao PDR and Cambodia. This is notable as the Ecosystem Vitality score revealed signs of stress. Rights to Resource Use received a low score of 45, largely driven by lack of rules for groundwater extraction. This was consistent with our inability to calculate changes in groundwater due to the lack of data from Cambodia and Lao PDR, and inability to access data from Vietnam. Stakeholders identified uncontrolled groundwater extraction as an emerging issue in Vietnam, particularly during the 2015 El Niño, which brought extreme dry conditions to the region. The low Monitoring and Learning Mechanisms score reflected insufficient ecological and biological monitoring to collect baseline data or detect changes in the system. This was consistent with our use of a modelling approach to assess Biomass for Consumption rather than field data. A low score of 47 for Strategic Planning and Adaptive Governance was largely due to a lack of shared vision for development. This was not surprising, as development in the three countries has occurred in the absence of official transboundary governance mechanisms.

Multiple agencies in each country are involved in land and water management at national, regional and local levels, and there is insufficient coordination in development decisions across the three countries' borders. The low Water-Related Conflict score (45) indicates a high level of conflict, which, according to our stakeholders, arises most frequently as a lack of cooperation (e.g., in sharing information or jointly deciding on dam operational rules). The potential exists for such issues to escalate if disagreements compromise state security [31]. That the low Governance & Stakeholders score was a self-assessment is encouraging, as it indicates an awareness amongst basin stakeholders that the governance system needs strengthening. Quantifying these deficiencies and putting them into some order of priority could be a catalyst for improvement.

Data availability was the greatest problem in assessing the Ecosystem Vitality and Ecosystem Services indicators. Often, data were not available (e.g., groundwater), spatially sparse (e.g., flooding) or temporally limited (e.g., a lack of water quality data before dam construction). These problems were particularly apparent in Lao PDR for which there was no water quality or flooding data. The FHI methods proved robust enough to calculate metrics for most parameters and highlighted the need for more data collection. One solution to our data problems was to develop proxy indicators, such as for Biomass for Consumption. A lack of detailed data on the cultural importance of water within the 3S led us to make a simple assessment of the proportion of the river system under formal protection. However, this is an oversimplification, as water is culturally important to the indigenous people of the 3S [31] and we learnt through our stakeholders that changes to river flow in Vietnam had compromised some indigenous groups' access to water for cultural purposes. Unfortunately, turning this information into an indicator would require considerable effort, beyond that which our resources allowed.

4.2. Development in the Basin: Insights from Scenarios

The four hydropower development scenarios provided insights into possible trajectories of change in the 3S basin and implications for ecosystems and service provision under different hydropower development plans. The indicators calculated for the Lower Sesan II Dam scenario, commissioned in September 2017, represent the basin's current status. The major impact of the dam is a reduction in system connectivity, as the Flow Connectivity sub-indicator score declines from 78 to 38 (Table 9 and [51]). We assessed the dam as completely blocking migratory fish passage to and from the Sesan and Srepok Rivers, resulting in substantial declines in the Biomass for Consumption score, from 94 to 26 (Table 13). The Biodiversity score may also decline as threatened migratory fish are unable to access upstream spawning habitat. The commissioning of a fish pass for the Lower Sesan II dam may alleviate some of these problems. However, as the effectiveness of the fish pass is yet to be assessed, we did not assign the Lower Sesan II dam a passability value. Instead, we assessed the worst-case scenario of complete blockage. Also, land cover will have changed as terrestrial habitats have been inundated by the reservoir. Indeed, the filling of the reservoir reduced the Bank Modification score by 1%.

Construction of the eight additional dams in the under-construction scenario will have the greatest impact on Water Quantity (down from a score of 66 to 61) and Sediment Regulation (down from 39 to 29), with a further reduction in Flow Connectivity to 36.

The Lower Sekong scenario is speculative—but plausible—as the feasibility of this dam is currently being assessed. Construction of the Lower Sekong dam, without fish passage, would further reduce Flow Connectivity to 25 (Table 9). This would almost certainly eliminate migratory fish from the 3S basin and see a large decline in the Biodiversity score. Even if all of the under-construction dams and the Lower Sekong dam were built with highly-efficient fish passes, their cumulative effect would still have a large negative impact on system connectivity [50]. Although the full development scenario is unlikely, it provides an upper boundary against which to compare the previous scenarios. Full development of the basin's hydropower resources reduces Ecosystem Vitality to 41 and Ecosystem Services to 16, which we consider unsustainable. Under this scenario, the scores for all assessed indicators were reduced to very low values. Hydropower development is likely to affect a range of other indicators that we were unable to model. As discussed above, there are indications that water quality is changing due to dam operations. If this is the case, the addition of more dams could see widespread declines in water quality, such as those that have been reported downstream of the Yali dam [30]. Hydrological changes have already altered the three rivers' fish communities [27]. With full development, the historic freshwater ecosystems supported by the 3S basin would almost certainly cease to exist, replaced by a simplified and fragmented novel ecosystem. It is highly unlikely that such a system could provide the ecosystem services that the basin currently enjoys. Under the full development scenario, the multiple ecosystem services provided by the 3S basin would be traded off for electricity. This would likely have severe social impacts to both the inhabitants of the basin as well as people downstream who rely upon the exported ecosystem services.

By demonstrating the continuing reduction in a sub-set of Ecosystem Vitality and Ecosystem Services indicators with increasing hydropower development, our results support calls to diversify regional energy generation to include a greater use of solar, wind and storage technologies and develop integrated planning for any future hydropower dams [80]. Our Deviation from Natural Flow Regime results for the December 2016, Lower Sesan II and under construction scenarios, when viewed in light of Ngor et al.'s [27] findings, recommend the need to provide the 3S Rivers with environmental flows, returning the regime to a more natural state. There is legislative support for this, along with headwater re-forestation, providing fish passage and improving protection of biodiversity [81].

4.3. Linking the Social, Ecological and Hydrological Systems in Practice

Translating this freshwater social-ecological framework into a set of decision-relevant indicators provided insights into both the opportunities and challenges of promoting systems-based thinking for water resource management. The indicators provide stakeholders from different sectors with a common language and a basis for comparison. By starting a process of quantifying and communicating Ecosystem Vitality, Ecosystem Services, and Governance & Stakeholders, the FHI provides a foundation for discussion among stakeholders about future sustainable development in the 3S. The 3S BRIDGE stakeholder group have reviewed our results and agreed to adopt the FHI as their common indicator framework and would like to see further development of the indicators and improved data sharing. A next step is to work with this group to mutually agree upon indicator targets and limits of acceptable change, frame their development activities within these targets, and monitor progress. Modelling these future trajectories could yield additional insights or surprises, which would allow stakeholders to evaluate more (or less) suitable development pathways and help them meet targets that enhance river basin health.

Data availability and accessibility challenges were anticipated, but they were particularly acute in Lao PDR, which is in an early stage of developing its water resource monitoring systems. The Mekong is the most widely studied river in Southeast Asia, receiving significant international investment in data collection and management. However, certain crucial datasets were either not comprehensively or consistently collected (fisheries) or not available (groundwater) for all countries in the basin. Our quantitative methods were all documented in reports and in an online User Manual [82], along with guidelines for addressing uncertainty and data availability. Nevertheless, a critical threshold of information is needed for the FHI to be meaningful and useful to stakeholders for decision-making.

Scenarios showing how the freshwater social-ecological system will change over time allows for a more effective exchange of knowledge between technical experts and other stakeholders. Given the scale of hydropower dam development considered in this set of scenarios, the general trend of progressively lower FHI indicators scores was not surprising. While simplified, these scenarios also give insight into how the governance system may shape future hydrological changes, and how these may affect the resident human population. A next step will be to incorporate more models such as for land-use change [29,83] and climate change [83,84] and collect further information on stakeholder perceptions and the factors influencing decision-making, as well as to continue to improve the collection and accessibility of relevant datasets in the 3S River basin. This would allow both a better assessment of current conditions in the 3S and calculation of additional indicators for future scenarios, providing decision-makers with more detail upon which to contemplate.

5. Conclusions

In using the FHI to examine the freshwater health of 3S, we revealed current and potentially future sources of stress to the basin's ecosystems, its ability to provide ecosystem services and its governance system. This information has formed the basis of much needed dialogue between water managers across the basin's international borders. The likely impact of further hydropower development in the 3S revealed wicked water resource management problems. A lack of data leads to uncertainty in prediction; the risks to both ecosystem services and vitality are extensive; and competing needs—electricity generation versus local reliance on ecosystem services, coupled with weak governance—complicates decision-making. By helping to diagnose these wicked problems, the FHI facilitates dialogue amongst stakeholders, hopefully leading to context-appropriate solutions.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/3/788/s1, Table S1: 3S dams dataset, Appendix S1: Freshwater Health Index 3S Governance & Stakeholders Survey.

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