



FRESHWATER HEALTH INDEX

**Sekong, Sesan and Srepok Basin:
An assessment of freshwater
ecosystem health in the Lower Mekong**

December 2016

Version 1.0

ACKNOWLEDGMENTS

We would like to thank all of the participants in our stakeholder forums for their time and insightful feedback in this testbed application of the Freshwater Health Index. Many thanks to the BRIDGE 3S project, facilitated by IUCN, which helped convene stakeholders, and BRIDGE 3S Champions, who were involved in the consultation process. We are grateful to the numerous people and organisations, such as the Mekong River Commission and University of Canterbury, who provided us with data and models. Additionally, we benefitted from being included in the meetings of the “Measuring, Understanding and Adapting to Nexus trade-offs in the 3S River Basins” project, co-led by IUCN, IWMI and ICEM. Staff at the Mekong River Commission helped review preliminary results during a meeting in Vientiane.

We would also like to acknowledge the contributions of our Science Working Group (www.freshwaterhealthindex.org/science-working-group), which provided the initial conceptual and technical guidance to develop the Freshwater Health Index.

Finally, we are immensely grateful to our dedicated financial supporters, without whom we could not have realized the success of the Freshwater Health Index. Thank you to the Victor and William Fung Foundation Limited, Borrego Foundation, Flora Family Foundation, Betty and Gordon Moore, and Starwood Foundation.

Recommended citation:

Freshwater Health Index (2018) Sekong, Sesan and Srepok Basin: An assessment of freshwater ecosystem health in the Lower Mekong, December 2016. Version 1.0. Available from <http://www.freshwaterhealthindex.org/sites/default/files/3S%20Basin%20Technical%20Report.pdf>.

TABLE OF CONTENTS

Executive Summary	5
1. Background	8
2. Ecosystem Vitality: Indicator and Sub-Indicator Results	8
2.1. Water Quantity	9
2.1.1. Deviation from Natural Flow	9
2.1.2. Groundwater Storage Depletion	11
2.2. Water Quality	11
2.3. Basin Condition	11
2.3.1. Bank Modification	12
2.3.2. Flow Connectivity	12
2.3.3. Land Cover Naturalness	13
2.4. Biodiversity	13
2.4.1. Species of Concern	14
2.4.2. Invasive & Nuisance Species	14
3. Ecosystem Services: Indicator and Sub-Indicator Results	14
3.1. Provisioning	14
3.1.1. Water Supply Reliability	15
3.1.2. Biomass for Consumption	15
3.2. Regulation & Support	15
3.2.1. Sediment Regulation	15
3.2.2. Water Quality Regulation	16
3.2.3. Flood Regulation	16
3.2.4. Disease Regulation	16
3.3. Cultural	17
3.3.1. Conservation Areas	17
3.3.2. Recreation	18
4. Governance & Stakeholders: Indicator and Sub-Indicator Results	19
4.1. Enabling Environment	20
4.1.1. Water Resources Management	20
4.1.2. Rights to Resource Use	20
4.1.3. Incentives & Regulations	21
4.1.4. Financial Capacity	21
4.1.5. Technical Capacity	21
4.2. Stakeholder Management	22
4.2.1. Information Access	22
4.2.2. Engagement in Decision-making Process	22
4.3. Vision & Adaptive Governance	22
4.3.1. Strategic Planning & Adaptive Governance	23
4.3.2. Monitoring & Learning Mechanisms	23
4.4. Effectiveness	23
4.4.1. Enforcement & Compliance	23
4.4.2. Distribution of Benefits	24
4.4.3. Water-related Conflict	24
5. Conclusion	24
Endnotes	26
Appendix	27

SEKONG, SESAN & SREPOK BASIN



EXECUTIVE SUMMARY

SEKONG, SESAN & SREPOK BASIN

Supporting a population of about 3.4 million people, the Sekong, Sesan and Srepok (3S) Rivers form an important sub-catchment of the lower Mekong and represent a microcosm of the challenges faced by the entire Mekong River basin. Covering just 10% of the Mekong Basin, the 3S rivers provide almost a quarter of the Mekong's total discharge and nearly 15% of the river's suspended sediment — which, in turn, provides nutrients to the Tonle Sap Lake and inland fishery as well as the Mekong Delta, Vietnam's rice bowl. More than 65 dams, most used to generate electricity, are currently operational in the 3S system, impacting seasonal flows, sediment transport and fish migration. Expansion of the agriculture sector in the 3S has the potential to increase water demand for irrigation, particularly in the dry season, placing additional pressure on water resources.

To help decision-makers assess trade-offs and set priorities for the 3S basin's future, a consortium led by Conservation International applied the Freshwater Health Index (FHI), a pioneering tool for assessing basin health in three components: ecosystems, water services and governance. Working in collaboration with government officials and non-profits from Lao PDR, Cambodia and Vietnam in partnership with the IUCN BRIDGE network, a team of experts measured 11 key indicators, with 25 sub-indicators, all scaled from 0-100 for ease of interpretation. Stakeholders representing ministries, national Mekong committees, academia and civil society provided input into the process and helped identify top priorities. This first ever comprehensive look at freshwater health in the 3S basin provides several insights for further analysis or possible policy action.

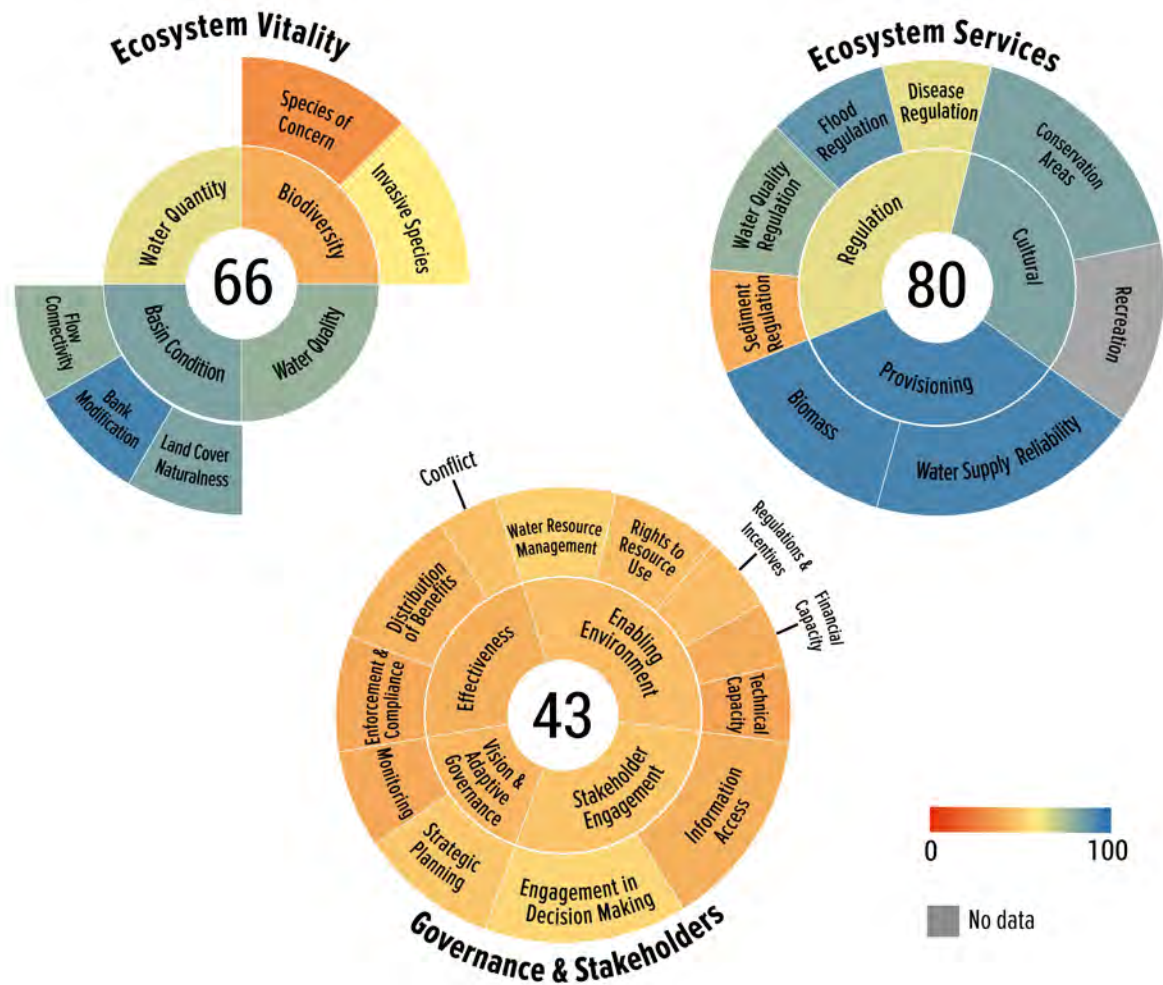
KEY RESULTS

- The 3S basin received a score of 66 for Ecosystem Vitality, indicating that the ecosystem itself is moderately healthy. Looking more closely, however, shows that, while Land Cover Naturalness and Water Quality scored relatively high, signs of stress are revealed by the high number of threatened and invasive aquatic species.
- The score of 80 for Ecosystem Services suggests that the basin is generally meeting the needs of the people who depend on it, though there is some variation among the types of services — provision of water and biomass scored highly, but regulating services scored considerably lower.
- The overall score for the Governance & Stakeholders component was 43, with little variation among the major indicators that fall within it. This is the lowest performing component for the basin, and improving this score should be a top priority for decision-makers in all three countries.
- The major current pressure on the ecosystem is dam operation, which substantially modifies the natural water flow and decreases sediment flows. Water is retained in the wet season and released during the dry season, and significant amounts of sediment that naturally nourish agricultural land and fisheries downstream are instead being retained within reservoirs.

- Stakeholder Engagement in the 3S basin received a score of 46 and was weighted highest (along with Enabling Environment) by stakeholders. Information Access scored particularly low here (41), and stakeholders noted a lack of access among different agencies within the same country as well as across countries.

CONCLUSIONS & NEXT STEPS

Overall, the results for the 3S basin assessment matched expectations of a basin meeting present needs but showing signs of ecological stress, and with a governance system in place that will need to substantially improve to ensure that further economic development does not undermine the basin’s sustainability. This first Freshwater Health Index assessment provides the basin’s river managers and stakeholders with a set of transparent and justifiable metrics that can be used to develop a shared vision of water resource management. As the 3S basin is rapidly developing, with numerous





FISHERMAN, CAMBODIA © JEREMY HOLDEN

hydropower dams being constructed in Lao PDR and Cambodia, frequent updates to the FHI metrics will be required to track the inevitable changes in basin health. The Index can provide guidance on future basin development by applying a range of scenarios; for example, the impact of selected dam cascades and re-calculating relevant metrics.

We identified some data gaps that should be addressed prior to a subsequent assessment. Although the basin is generally water-rich, and scarcity is not a concern, sectoral and spatial data on withdrawals should be collected to better understand seasonal supply reliability, and environmental flow requirements for each river should be established and included in subsequent assessments. Because of the importance of freshwater fisheries in the region, standardized data on fish catches would be useful as well. Similarly, the Mekong basin is one of the world's biodiversity hotspots, and so more frequent regional assessments of aquatic species are needed to track population changes. Recreation services were not measured in this assessment due to a lack of data, but stakeholders noted the potential for developing water-based recreation in parts of the 3S, so it is recommended that this be tracked in future assessments. Finally, as this was the first attempt to assess governance in the 3S basin, we focused on the governance situation in each of the three countries. However, because the 3S is a trans-boundary basin, it will also be useful to develop further insights into how well trans-boundary governance is performing.

With the large number of additional dams in various stages of planning in the 3S, an immediate next step is to continue working with stakeholders to create scenarios for dam development and model their impacts using a sub-set of the FHI indicators. Additional scenario options could consider land-use change (e.g., plantation agriculture development, or reforestation and rehabilitation) as well as potential climate change impacts. All of these will help stakeholders identify undesirable trade-offs and possible synergies, and begin setting quantitative targets for safeguarding the 3S's health.

1. BACKGROUND

Home to 65 million people in six riparian countries, the Mekong River Basin (MRB) has provided food and water to its inhabitants for thousands of years. The Mekong River's inland fishery, second only to the Amazon in freshwater fish biodiversity, is the world's largest. The value of the Lower Mekong fisheries is worth around US\$ 17 billion per year¹. Two-thirds of the basin population rely on subsistence fisheries for their survival², but population growth and rapid development are increasing pressure on the Mekong. The 3S river basin, a sub-catchment of the Mekong River Basin, represents a microcosm of the management challenges faced in the MRB and other rapidly developing parts of the world.

Southeast Asia's 3S basin comprises the catchments of three rivers, the Sekong, Sesan and Srepok. The Sekong River originates in Laos, and the Srepok and Sesan Rivers rise in Vietnam. The three merge just before joining the Mekong River in Cambodia. While the 3S rivers cover just 10% of the Mekong Basin, they account for nearly a quarter of the Mekong's total discharge and support a population of approximately 3.4 million people. Sixty-five dams have been constructed in the 3S to provide water for irrigation and hydropower. And many more are under construction or being planned.

The increasing number of hydropower dams combined with ever greater pressure on water resources from the agricultural sector are likely to further impact seasonal flows (which affect timing and amount of rice production), sediment transport (which affects the amount of nutrients delivered to fields and fisheries downstream) and fish migration (which affects productivity of the region's fisheries). Changes in river flow likely will have negative impacts on the riverine ecosystem, while sediment from the 3S is an important source of nutrients that drives the Tonle Sap fishery and replenishes the important rice growing Mekong delta in Vietnam. The 3S is an important site for migratory fish, which form an important part of the world's largest inland fishery. The 3S's trans-boundary nature makes resource management an even greater challenge, and the basin provides an opportunity to improve regional dialogue between intergovernmental management agencies and civil society stakeholders.

By providing a scientifically derived set of metrics, the FHI provides a focal point for developing and enacting a shared vision of the 3S basin's water resources; and progress in strengthening trans-boundary management of the 3S and safeguarding its health will provide a strong, regional example to transfer to the Greater Mekong region. To help stakeholders in the 3S basin assess current conditions and begin planning for the future, we applied the Freshwater Health Index to measure health along three dimensions: Ecosystem Vitality, Ecosystem Services, and Governance & Stakeholders.

2. ECOSYSTEM VITALITY: INDICATOR AND SUB-INDICATOR RESULTS

The Ecosystem Vitality component of the Freshwater Health Index measures the integrity and functioning of the ecosystems — streams, rivers, wetlands and forests — within the basin. Healthy ecosystems are fundamental to providing clean water, fish, protection from floods and a variety of other benefits that people rely on in the basin. The four major indicators within the Ecosystem Vitality component measure: water quantity, water quality, basin condition, and biodiversity. Data come primarily from official government sources and are presented at the sub-basin or municipality scale, where possible, to show how and where the indicator scores vary within different parts of the basin.



When combining the four major indicators, the 3S basin receives an overall score of 66. This suggests moderate ecosystem health, but as the detailed results below indicate, there is substantial variation among the individual indicator scores, where some are performing well and others poorly. Specifically, the health of the ecosystems (in terms of natural land cover and water condition) is relatively good, whereas the health of species is comparatively poor. Therefore, **emphasis should be placed on ensuring these scores do not decline as well as analyzing how improvements in the ecosystem vitality metrics could also benefit ecosystem service delivery.** Stakeholders did not weight the Ecosystem Vitality indicators, so each indicator is given an equal weight by default, and it is not possible to infer particular preferences, as can be done for the Ecosystem Services and Governance & Stakeholders indicators.

2.1 Water Quantity

Water Quantity measures the amount and flow of water through the basin, including surface and groundwater. Ecosystems depend on seasonal patterns of water in the basin, and in regions like the Lower Mekong, human communities have also come to depend on these seasonal fluctuations in water quantity. Changing this natural pattern is often a consequence of modern development (e.g., building dams to regulate periods of flooding and drought), so it represents a trade-off with meeting human needs. However, these alterations can also have negative consequences for aquatic biodiversity and human communities who are accustomed to a natural flow pattern. **The 3S basin received a Water Quantity score of 66, but this is based solely on the score for Deviation from Natural Flow, since groundwater storage data were not available.**

2.1.1 Deviation from Natural Flow

Deviation from Natural Flow measures the degree to which current surface water flows have shifted from historic, natural flows (that is, pre-development). Reservoirs, agriculture and land-use change affect the timing and volume of surface water flows, which in turn, affect aquatic life and the availability of freshwater services downstream. Water resources traditionally have been managed to smooth out seasonal variability — reducing flood damages and/or

Table 1. Freshwater Health Index Indicators

Major indicators	Sub-indicators
ECOSYSTEM VITALITY	
Water Quantity	Deviation from Natural Flow Groundwater Storage Depletion
Water Quality	Suspended solids in surface water Total nitrogen in surface and groundwater Total phosphorous in surface and groundwater
Basin Condition	Indicators of major concern Bank Modification Flow Connectivity Land Cover Naturalness
Biodiversity	Species of Concern Invasive & Nuisance Species
ECOSYSTEM SERVICES	
Provisioning	Water Supply Reliability (relative to demand) Biomass for Consumption
Regulation & Support	Sediment Regulation Water Quality Regulation Flood Regulation Disease Regulation
Cultural & Aesthetic	Conservation & Cultural Heritage Recreation
GOVERNANCE & STAKEHOLDERS	
Enabling Environment	Water Resource Management Rights to Resource Use Incentives & Regulations Financial Capacity Technical Capacity
Stakeholder Engagement	Information Access Engagement in Decision-making Process
Vision & Adaptive Governance	Strategic Planning & Adaptive Governance Monitoring & Learning Mechanisms
Effectiveness	Enforcement & Compliance Distribution of Benefits Water-related Conflict

ensuring adequate supplies — so some deviation from natural conditions may be necessary to continue meeting human demands. **The 3S basin received a score of 66 for Deviation from Natural Flow, signifying a sizable departure from baseline natural conditions, with the maximum modification of flow occurring on the Sesan River at the Cambodia-Vietnam border.** Concentration of dams on the main stem of the Sesan, combined with few major undammed tributaries to offset these flow modifications, contributed to the low score. Improving the scores for this indicator would be difficult without substantially altering the operational rules or removing existing dams, so emphasis should be placed on minimizing further decreases in the score. This is of particular concern when considering the ongoing and proposed development of 42 dams within the 3S basin.

2.1.2 Groundwater Storage Depletion

Groundwater Storage Depletion is a measure of the changes in the availability of water stored in aquifers. **Currently, however, the data required to estimate the scope of groundwater extraction and use is unavailable. This is identified as an important knowledge gap.**

2.2 Water Quality

Water Quality refers to concentrations of selected water quality parameters compared to thresholds needed to sustain biodiverse aquatic ecosystems. Independent of the direct impacts on human health and safety, poor water quality can harm aquatic life directly and also upset ecological balance by, for example, triggering harmful algal blooms. **Water Quality for the 3S basin received a score of 81, indicating good overall health.** Four surface water quality indicators were assessed: Total Suspended Solids, Total Phosphorous and Total Nitrogen, along with pH as another parameter of major concern. The high score was a result of low frequency and magnitude of failed water quality tests. However, water quality variables were only collected from six sites and localized areas of poor water quality may occur, particularly downstream of hydropower dams³. As more dams are constructed, declines in water quality may become more common and widespread.

2.3 Basin Condition

Basin Condition measures the extent of physical modifications to both land cover (e.g., forests converted to agriculture) and stream/river channels (e.g., building dams or widening channels), all of which can impact the flow and quality of water as well as habitat for aquatic life. **Combining Bank Modification, Flow Connectivity and Land Cover Naturalness gave the 3S basin a Basin Condition score of 85, indicating good overall health.** A lower score for flow connectivity was offset by a very high score for bank modification.

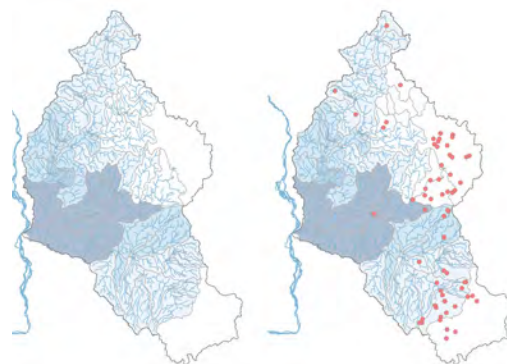
2.3.1 Bank Modification

Bank Modification measures what is known as floodplain (lateral) connectivity. Lateral connectivity affects how the streams reach land and thus how materials such as nutrients and sediments are exchanged. Changes to this pattern, either through channelization or inundation through impoundments, affect the suitability for native vegetation and wildlife (including spawning fish and water birds), the biogeochemistry of the streams, as well as the extent of floodplains. **The 3S basin received a score of 98 for Bank Modification, a near perfect score reflecting that almost none of the main stream channels have been modified through engineering works (channelization, artificial stabilization, or inundation through reservoir development).** This score will decline in the future as additional dams are constructed and upstream channels are flooded to create reservoirs.

2.3.2 Flow Connectivity

Longitudinal connectivity is particularly important to the movement of aquatic life, such as fish, but also affects the flow of materials. It is affected by natural obstructions such as waterfalls and engineered structures such as dams and weirs. Decreased longitudinal connectivity can negatively impact fish migration and reproduction and may prevent sediment and other nutrients from being delivered downstream to the delta. **The Flow Connectivity score for the 3S basin overall is 71, signifying moderate health.** This score is influenced by the number of dams within the basin, but also their “passability” for fish. Thus, the score may be improved by constructing fish ladders or other means to increase their passability. Connectivity is one of the most important drivers of fish biodiversity in the 3S and Lower Mekong basins. This sub-indicator is also the most sensitive to future dam development and will see steep declines in the future as dams under construction are completed and even more so if dams are developed in the lowest reaches of the 3S.

Figure 1. Flow Connectivity in the 3S Basin

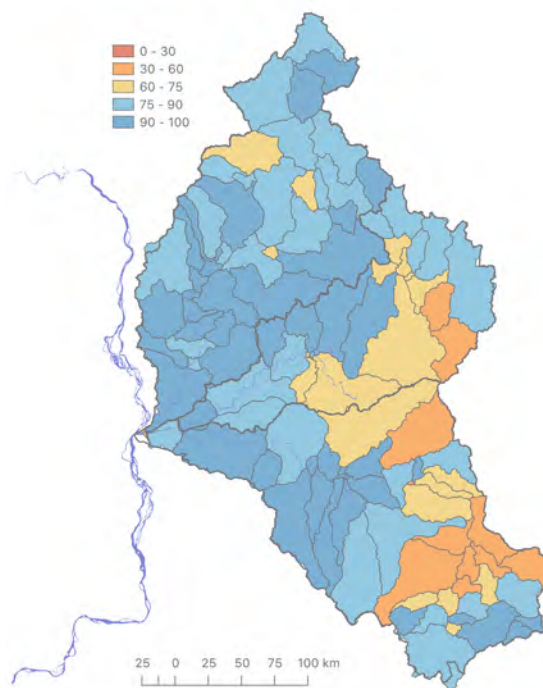


Left, natural conditions; Right includes existing dams (in red). Darker shades of blue signify more important areas for migratory fish spawning.

2.3.3 Land Cover Naturalness

Land Cover Naturalness measures how much the land has been changed from its natural, undisturbed state. Forests and wetlands are natural buffers that regulate the flow and quality of water. When they become degraded or are converted to agricultural or urban use, it changes the landscape's ability to regulate the water cycle. **The 3S basin has a Land Cover Naturalness score of 82, signifying good health.** 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 score down. The disaggregated values reveal that much of the land cover modification has occurred in Vietnam, particularly the corridor extending southwest from Buon Ma Thuot, provincial capital of Dak Lak (Figure 2), which is dominated by plantations of coffee, pepper and soy bean, and seasonal rice cultivation.

Figure 2. Land Cover Naturalness in the 3S Basin



2.4 Biodiversity

Biodiversity refers to the population status and trends of animal and plant species that live directly in or adjacent to waterways. Declines in native species, or increases in non-native “invasive” species, both are used as indicators of a deteriorating ecosystem. Moreover, aquatic biodiversity is often positively associated with productive fisheries and cultural services such as recreation. The Biodiversity indicator is divided into two

components: Species of Concern, which focuses on threatened or otherwise locally important species, and Invasive & Nuisance species. **When combined, the 3S basin overall has a Biodiversity score of 43, suggesting poor health.** This low score was driven by the basin's high number of threatened species (90), which were mostly fish.

2.4.1 Species of Concern

Species of Concern measures threatened aquatic or riparian species in the basin — their proportion relative to the total species diversity, as well as population trends. Increasing numbers of threatened species is an early warning sign for ecosystem deterioration and can correspond to declines in human benefits, such as fishing. **The 3S basin has a score of 31 for Species of Concern, which is the lowest of all sub-indicator scores.** Fish, which represented more than 40% of the assessed species in the 3S, accounted for over half of the threatened species and included eight listed as Critically Endangered. As many of these threatened fish species are migratory, continued development of hydropower within the system may lead to regional extinctions, further reducing the score.

2.4.2 Invasive & Nuisance Species

Invasive Species refers to alien (non-native) species introduced into the ecosystem (intentionally or accidentally), which are then able to out compete or pose a threat to native species. Increasing populations of invasive species place added pressure on native species, degrade ecosystems and can damage economic and human health. **The 3S basin's Invasive Species sub-indicator was assessed at 59.** This assessment focused exclusively on invasive aquatic species, of which eight have been documented, seven of them fish. Once established, invasive aquatic species can be challenging to eradicate, so future improvements likely will be based on controlling existing populations and preventing introductions of new invasive species.

3. ECOSYSTEM SERVICES: INDICATOR AND SUB-INDICATOR RESULTS

The Ecosystem Services component of the Freshwater Health Index measures the range of water-related benefits — from drinking water to hydroelectric power to protection from floods — provided by a freshwater ecosystem. These benefits, often provided in place of or as a complement to human-made infrastructure, are a way of connecting people to the natural ecosystems that they depend on. Ecosystem services are often classified according to how people experience them, and this is reflected in our three major indicators: Provisioning (goods taken from ecosystem), Regulation & Support ('background' processes that occur in ecosystems) and Cultural (experiences people 'take' from ecosystems). **When combining these indicators, the 3S basin received an Ecosystem Services component score of 80, signifying good health.** This indicates that, at present, the basin is generally capable of fulfilling residents' well-being needs, though there is variation among the specific services.

3.1 Provisioning

Provisioning services refer to the physical outputs (primarily water and fish/biomass) that people are taking from freshwater ecosystems. These ecosystem outputs are critical inputs into economic development and are fundamental to food and water security. The Provisioning indicator comprises two sub-indicators: Water Supply

Reliability (relative to demand) and Biomass for Consumption. When combined, **Provisioning had a score of 94, indicating a sound ability to currently meet demand for water supply as well as fish.** Stakeholders assigned a higher weight (~30% higher) to water supply compared to biomass, indicating that they place a greater importance on securing water supply.

3.1.1 Water Supply Reliability

Water Supply Reliability measures the current ability of the basin to meet demand for various uses, at all locations, despite seasonal variability. This includes minimum amounts of water for ecological maintenance, known as environmental flows. Decreases in reliability correspond to water insecurity, ecological degradation or unsustainable consumption of groundwater to compensate for surface water shortages. **The 3S basin received a score of 95, though this was calculated without local information on sectoral demand or the inclusion of environmental flows, since the rivers do not currently have environmental flow provisions.** Although water supply is not presently considered a problem area, confidence in this score can be improved by assembling sectoral data and developing environmental flow requirements for each of the three rivers.

3.1.2 Biomass for Consumption

Biomass for Consumption refers to the fish, wild food and other materials that people harvest from freshwater ecosystems. These resources provide economic and food security, particularly in regions such as the Lower Mekong, and so declines in biomass availability can have direct and serious impacts on human well-being. **Biomass received a score of 94, but this initial calculation was based on a proxy measure of migratory fish habitat rather than actual catch data. This score does not take into account the contribution of non-migratory fish to biomass for consumption, although they make a greater proportion of species in the basin.** Improvements in fish catch data will increase confidence in this score.

3.2 Regulation & Support

Regulation refers to the natural processes that support water supply and fisheries (e.g., by keeping water clean and flowing) and offer protection from floods and other hazards. Water resource development decisions frequently overlook the natural processes that help regulate water in an ecosystem, but replacing these “free” services with built infrastructure can be expensive. The Regulation & Support indicator comprises four sub-indicators: Sediment Regulation, Water Quality Regulation, Flood Regulation and Disease Regulation. **Regulation & Support received a score of 66, with substantial variation among the sub-indicator scores.** Stakeholders assigned the highest weight to this major indicator among Ecosystem Services, indicating that they attach great importance to regulating services.

3.2.1 Sediment Regulation

Sediment Regulation measures the ability of the ecosystem to moderate the flow of sediments from land to streams and deposit it in floodplains or outlets downstream. Too much sediment flowing downstream can compromise reservoirs' ability to retain sufficient quantity of water, or degrade water quality, while too little sediment delivered downstream deprives aquatic life and agricultural lands of critical nutrients. **Sediment Regulation received a score of 39, which is the lowest score for any of the sub-indicators within Ecosystem Services.** None

of the reservoirs within the 3S have the ability to pass sediment, thus trapping large amounts of sediment that would otherwise flow downstream to the Tonle Sap Lake and Mekong Delta. **Future dam development needs to consider further sediment impacts and plan to reduce sediment capture behind newly constructed dams. Options for flushing sediment from pre-existing dams should also be considered to improve this score.**

3.2.2 Water Quality Regulation

Water Quality Regulation refers to the ecosystem's ability to moderate concentrations of water quality parameters relative to human health standards. Ecosystems naturally filter and break down many water pollutants, but their capacity can easily be outstripped by the volume of pollutants released by human activity. **The 3S basin received a Water Quality Regulation score of 81, indicating good health.** Although this is the same score as the Water Quality indicator under Ecosystem Vitality, Water Quality Regulation measures more parameters/pollutants (20). Total Suspended Solids values exceeded the maximum threshold most often during the dry season, likely due to dam releases, while they fell below the threshold during the wet season, likely a result of dams holding water and trapping sediment. This pattern was not observed for Total Phosphorous, where the highest incidences of threshold exceedance were lower values in the late wet season. This is early evidence of dams having a wider impact on water quality. **Stakeholders assigned this sub-indicator the highest weight among the Regulation & Support group, signaling its importance regardless of presently good health.**

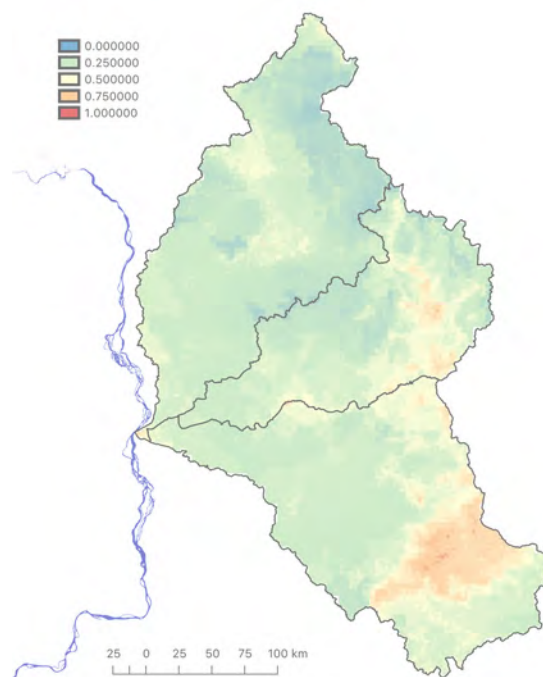
3.2.3 Flood Regulation

Flood Regulation measures the ability of the ecosystem to reduce the volume of flood runoff by slowing the timing of peak flows downstream and/or absorbing flood waters (e.g., in wetlands). Floods are one of the costliest natural disasters, and intact forests and wetlands can help reduce the level of this hazard and keep people and property out of harm's way. **The 3S basin received a Flood Regulation score of 88, indicating good health.** All of the 3S basin is at risk of flooding, according to the Mekong River Commission (MRC), but in the period analyzed, the floods that did occur were of brief duration and magnitude. **Climate change and uncoordinated dam releases could both present challenges to flooding in the 3S basin in the future, and thus, this issue should be investigated further to ensure that the ecosystems can continue to provide the required flood regulating service.**

3.2.4 Disease Regulation

Disease Regulation measures the prevalence of major water-associated diseases, such as dengue, malaria, *Cryptosporidium* and schistosomiasis. These diseases are a leading cause of hospitalizations worldwide, and their risk to people increases with human modifications to freshwater ecosystems (dam construction, pollution, etc.). **Disease Regulation was assessed with a score of 67, indicating moderate health.** Two water-associated diseases present in the 3S — dengue and schistosomiasis — were assessed. Of the two, dengue is more widespread (particularly during the wet season) and therefore brings the overall score down, while Mekong schistosomiasis is presently confined to a smaller region, mostly near the confluence of the 3S rivers.

Figure 3. Dengue Exposure in the 3S Basin



Exposure is shown for the wet season, and is measured on a scale of 0-1.

3.3 Cultural & Aesthetic

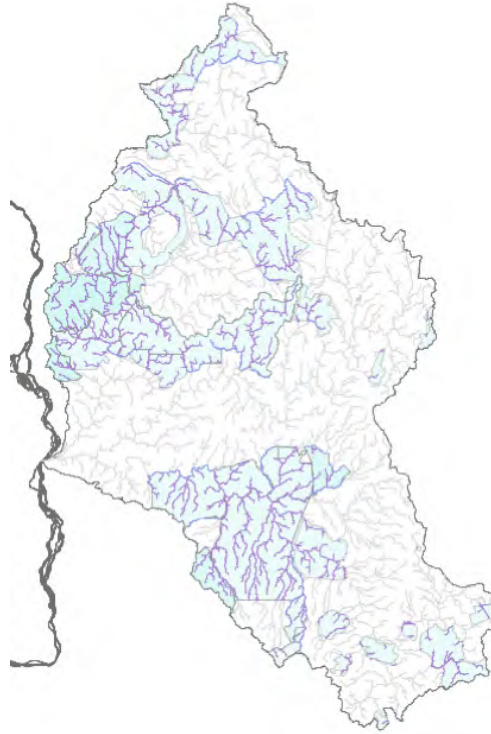
Cultural services refer to the non-material benefits people experience from freshwater ecosystems, such as their aesthetic beauty, recreational opportunities and cultural or spiritual fulfillment. These cultural services are linked to physical, emotional and mental health benefits as well as economic development opportunities (such as eco-tourism) — and freshwater ecosystems in particular are often associated with a society’s cultural identity. **The 3S basin received a score of 83 for Cultural Services, indicating good health, though data on water-related recreation were not available, and so this score is based on the Conservation & Cultural Heritage sub-indicator.** It is also worth noting that stakeholders assigned a weight nearly equivalent to that assigned for Provisioning Services, suggesting that the importance of maintaining these cultural services is almost on par with the 3S’s continued provision of water and biomass.

3.3.1 Conservation & Cultural Heritage

Conservation & Cultural Heritage measures the degree to which freshwater ecosystems are being preserved for their cultural significance. Areas may be conserved to maintain ecological integrity and biodiversity or because of more direct ties to regional cultural heritage (e.g., river fish sanctuaries at some Thai Buddhist temples). **Conservation & Cultural Heritage received a score of 83, indicating good health.** This score is based on the amount of the river network that is contained within some form of protected area. While this is a proxy for the actual conservation of the rivers for cultural heritage preservation, it does signal

that the 3S is far exceeding a global target (set by the Convention on Biological Diversity) of protecting a minimum of 17% of wetlands and waterways. Future assessments for this sub-indicator could consider the quality of this protection, to help identify geographic priority areas for future inclusion or improvement in the protected area network.

Figure 4. Conservation of Cultural Heritage in the 3S Basin



Stream network segments within areas having some form of protected area designation.

3.3.2 Recreation

Recreation refers to the time that people spend engaging in water-related recreational activities, such as fishing, hiking, boating or enjoying waterfront scenery. These recreational activities provide important physical, emotional and mental health benefits but can also provide economic development opportunities, particularly if they draw tourism from outside of the basin. **Recreation was not assessed due to a lack of suitable data.** However, stakeholders did assign it a weight slightly below Conservation & Cultural Heritage, indicating that it is still a valued potential service in the basin.



CAMBODIA © CONSERVATION INTERNATIONAL/PHOTO BY TANGKOR DONG

4. GOVERNANCE & STAKEHOLDERS: INDICATOR AND SUB-INDICATOR RESULTS

The Governance & Stakeholders component of the Freshwater Health Index evaluates the structures (such as regulations) and processes by which people make decisions related to water resources. In contrast to Ecosystem Vitality and Ecosystem Services indicators, where data are routinely collected and measurement methods are commonplace, measuring governance is an emerging area without standardized approaches. The issues are also more subjective, meaning that peoples' perception is a valid source of information. To collect this information, we administered a survey to a large group of government and non-government stakeholders from the 3S basin, with assistance from the IUCN BRIDGE network. While we obtained participation from all three countries and multiple sectors, the results could be improved by incorporating responses from more stakeholders involved in water governance in the 3S, and by including additional information (possibly new sub-indicators) dedicated to trans-boundary issues. It should also be noted that the stakeholders who participated strongly recommended that this survey be extended, in a simplified form, to a wider cross-section of the residents living in the 3S basin, to better reflect their perception and provide more useful information on current conditions related to water governance.

When combining the current survey results, the 3S basin has a score of 43 for Governance & Stakeholders, with little variation among the major indicators.

A robust cross-country comparison is not advisable due to the small number of responses, but in general scores from Vietnam were lower, higher from Lao P.D.R., with Cambodia in between. And there was a generally similar pattern when comparing sub-indicators (for example, all countries gave lower scores to Information & Knowledge versus Engagement in Decision-making). Overall, Governance & Stakeholders is the lowest performing component for the basin, which is consistent with Freshwater Health Index assessments in other basins around the world. **Improving this score should be a top priority for decision makers in the basin, particularly given the expected future increases in dam development and climate change-induced variability, all of which will require nimble governance to avoid negative consequences.** Fortunately, the detailed assessments below provide insight into where and how such improvements could be made.



CARDAMOMS, CAMBODIA © ALLAN MICHAUD

4.1 Enabling Environment

The enabling environment refers to the policies, regulations, market mechanisms, and social norms that are in place to help govern and manage freshwater resources. Collectively, these determine what rights and assets are protected within a basin, as well as how they are managed in the face of competition and conflict. When combining the five sub-indicators below, **the 3S basin has a score of 42 for Enabling Environment, with substantial agreement among the three countries in terms of their scores (ranging from 42-44).**

4.1.1 Water Resource Management

Water Resource Management measures the degree to which institutions are responsible for performing functions such as inter-basin coordination, planning and development of infrastructure, mobilizing financial resources, and protecting ecosystems. Water resource management is a complex set of tasks, typically involving multiple public agencies and other stakeholders. Weak coordination among these groups can lead to inefficient, inequitable, or ineffective outcomes. **The 3S basin received a score of 50 for Water Resource Management.** Water resource development policy coordination received the highest marks, while ecosystem conservation policies received the lowest marks. It was also the highest weighted sub-indicator within Enabling Environment, indicating its perceived importance among stakeholders. Scores by country varied considerably (44 for Lao P.D.R., 48 for Vietnam, 59 for Cambodia).

4.1.2 Rights to Resource Use

Rights to Resource Use measures the clarity of rights to water and water-related resources. Clear and enforceable rights, whether they are formal or informal (e.g., communal rights), are important for the efficient use of resources such as freshwater and for their equitable distribution throughout the basin. **The 3S basin received a score of 45 for Rights to Resource Use, with a range for 44 to 47 by country.** Quality and clarity of rules for freshwater fisheries received the highest marks, whereas rules for groundwater abstraction received the lowest marks, highlighting it as a high priority for improvement.

4.1.3 Incentives & Regulations

Incentives & Regulations refers specifically to the availability of different management instruments, such as impact assessments or financial incentives, that can be applied to encourage human activity with minimal negative impact on water and related environmental resources. In principle, a greater diversity of effective management instruments means more flexibility to devise solutions and, in turn, produce efficient responses. **The 3S basin received a score of 45 for Incentives & Regulations, with lower scores from Cambodia (42) and Vietnam (43) offsetting the higher score from Lao P.D.R. (53).** This reflects the present emphasis on command and control regulatory approaches to water resource management in the basin (environmental and social impact assessments garnered the highest marks among issues surveyed) and early stage or no development of additional tools (market-based initiatives received the lowest marks). **As stakeholders noted, improving this score should be contingent on ensuring that capacity is in place to enforce existing and any new regulatory tools (see section 4.4.1).**

4.1.4 Financial Capacity

Financial Capacity attempts to measure the extent to which necessary investments are being made to support water resource development and protection. Water resource development has high costs, and while economic instruments such as water pricing or pollution charges can be applied so that consumers or users (including individuals and corporations) help offset these costs or fund additional measures, public investment may be necessary to ensure adequate financing for safeguards, ecosystem protection, and remediation. **Financial Capacity received a score of 36, which was the lowest performing sub-indicator within the Governance & Stakeholder component.** Country-level scores ranged from 33 (Cambodia) to 40 (Lao P.D.R.), with Vietnam near the upper end of the range (39). Detailed data on budgets were not easily obtained but could provide useful complementary information to this sub-indicator. Investments in water supply development and service delivery systems (e.g., wastewater handling and treatment, and water distribution networks) received comparatively high marks, while investments in ecosystem conservation and rehabilitation received the lowest individual marks. Greater investment in these activities among governments will be needed to increase these scores over time and may require development aid and multilateral development bank support, particularly in the near term, to help governments close this critical gap between financial needs and current capacity.

4.1.5 Technical Capacity

Technical Capacity refers to the adequacy of the workforce, in terms of number, skill level, and training opportunities, to fulfill technical functions related to water resource management, not necessarily the level of technology that is in use. Even with sufficient financial capacity, a shortage of technical skills such as environmental engineering can hinder the effective and sustainable development of water resources. **Technical Capacity received a score of 42, with lower individual marks for staff expertise compared to number of staff and opportunities for professional training.** Improving training opportunities may also become more important as technical staff address emerging issues such as climate change.

4.2 Stakeholder Engagement

Stakeholder Engagement refers to the ways that stakeholders interact with one another within the basin, and the degree of transparency and accountability surrounding these interactions. While stakeholder engagement is carried out in different ways around the world, it is generally regarded as a key principle of good water governance, to ensure that the full range of concerns are considered before major decisions are taken, to avoid potential conflicts, and ensure equitable distribution of benefits from water resource development. The Stakeholder Engagement indicator is subdivided into sub-indicators on Information Access and Engagement in Decision-making Processes, which stakeholders assigned equal weights. **Stakeholder Engagement in the 3S basin received a score of 46, and was weighted highest (along with Enabling Environment) by stakeholders.** There is a substantial variation in this indicator among the three countries, with Vietnam assessing Stakeholder Engagement at 37, Cambodia just above the mean (48), and Lao P.D.R. at the top of the range (57).

4.2.1 Information Access

Information access measures the accessibility of data on water quantity, quality, resource management and development. Even in cases where data are routinely being collected, if they are not available to interested stakeholders for their own research or analysis, decisions may be considered less transparent. Access to data also helps stakeholders hold decision-makers accountable, e.g., to determine that a policy or project is delivering the intended benefits. Information access received a score of 41 for the 3S basin. Information accessibility scored the lowest, while information quality, transparency, and application to decisions all scored higher. Again, Vietnam scored lowest (34), followed by Cambodia (43) and Lao P.D.R. (53).

4.2.2 Engagement in Decision-making Process

This sub-indicator measures the scope of stakeholders' involvement in some aspect of decision-making processes, and the degree to which they have a voice in the cycle of policy and planning. While there are different levels of "suitable" engagement, increased participation is generally associated with improved information transfer, more targeted and equitable plans and policies, improved transparency and accountability, and reduced conflict. **Engagement in Decision-Making Processes received a score of 51, with similar variation among the countries (Vietnam: 40, Cambodia: 54, Lao P.D.R.: 63).** Marks were comparatively high for stakeholder notification, and lowest for decision-makers' responsiveness to stakeholders' participation. Respondents noted that consultation periods for major development projects such as dams were more comparable to lobbying sessions, which fail to meet the expectations of the public.

4.3 Vision & Adaptive Governance

This indicator measures the capacity to apply information to set policies and develop plans for the basin. Effective water resource management requires flexible yet integrated forms of governance to deal with the sometimes rapidly changing conditions in a basin, and the uncertainty associated with climate change and other challenges. Therefore, strategic planning is a sub-indicator, along with monitoring and learning mechanisms, which allow strategic plans to be updated and adapted as circumstances change. **The 3S basin received a score of 43 for Vision & Adaptive Governance; Vietnam scored 34, Cambodia 47, and Lao P.D.R. 51.**

4.3.1 Strategic Planning & Adaptive Management

This sub-indicator measures the degree to which comprehensive strategic planning (i.e., accounting for land and water use and infrastructure development) occurs within the basin. Having comprehensive plans, with well-defined objectives and long-term resource development priorities, can help establish a vision for sustainably meeting freshwater needs. But importantly, these plans need to be adjusted as circumstances change, or as new information becomes available.

Strategic Planning & Adaptive Management received a score of 47, but variation among countries was the highest of any sub-indicator, with Vietnam scoring 34, Cambodia 54, and Lao P.D.R. at 64. The comparatively high score from Lao P.D.R. stakeholders reflects the fact that the National Water Law was being drafted and provides an opportunity to strengthen comprehensive strategic planning through the country's watersheds.

4.3.2 Monitoring & Learning Mechanisms

This sub-indicator refers to the quality and use of physical, chemical, and biological monitoring of water resources in the basin, to guide policy and planning. Ideally, decisions about water resource management are based on sound data and information, but this data needs to have been collected (which entails costs) and making this information understandable to decision-makers. **The 3S basin received a score of 39 for this sub-indicator, with Vietnam assessed at 33, and both Cambodia and Lao P.D.R. at 41.** Biological & ecological monitoring received the lowest score, with Cambodia receiving a higher score than the other two countries. This was also reflected in the need to rely on global data for the Biodiversity indicator under Ecosystem Vitality, in the absence of long term official, locally collected data pertaining to biodiversity in the 3S basin.

4.4 Effectiveness

Effectiveness refers to the outcomes from water-related policies and investment decisions — are they in fact achieving what they were intended to do? Around the world, there is often a gap between policy and practice, between what is expected based on a complex decision and what actually occurs. This major indicator and its sub-indicators attempt to evaluate whether decisions are having the intended effects. **The 3S basin received a score of 43 for this indicator, suggesting room for improvement in closing this gap between policy and practice.** Country values ranged from 40 (Cambodia) to 45 (Lao P.D.R. and Vietnam).

4.4.1 Enforcement & Compliance

This sub-indicator measures the degree to which laws are upheld and agreements are enforced. An “enforcement gap” can reflect either insufficient regulatory capacity or a lack of accountability, both of which undermine the effectiveness of laws and policies. **The 3S basin received a score of 37 for this sub-indicator, the lowest among sub-indicators in this group.** Cambodia received the lowest country score (29), followed by Lao P.D.R. (37) and Vietnam (45). Among the specific topics, enforcement of groundwater abstraction guidelines received the lowest marks, whereas enforcement of land use as it impacts waterways received the highest marks.

4.4.2 Distribution of Benefits

Distribution of Benefits refers to the impacts of decisions about water resource management, with special attention to different segments of society: economically vulnerable populations, indigenous communities, women, and those employed in resource-dependent sectors such as fishermen. Water-related ecosystem services are, by their nature, unevenly distributed across a basin, and so actions must be taken (such as when developing infrastructure) to ensure that the resources are equitably distributed. **The 3S basin received a score of 42 for this sub-indicator with a narrow range among countries (Cambodia: 41, Lao P.D.R.: 42, Vietnam: 45).** This sub-indicator received the highest weighting from stakeholders, 10-15% higher than the other two sub-indicators suggesting it is of high importance. **Therefore, the high level of discontent with benefit distribution deserves more attention from decision-makers.** At the basin level, marks were roughly equal among all segments of society, but Lao P.D.R. gave lowest marks for distribution of benefits to economically vulnerable populations. This sub-indicator could be improved by more detailed information, including a wider public survey administered throughout the basin, to help prioritize policy responses.

4.4.3 Water-related Conflict

Tensions among stakeholders are expected when there is competition for scarce resources such as water. Tension that escalates into legal battles or even violent conflict prevents agreement and can delay or undermine decisions taken within the basin. Here, we restrict the consideration to conflicts over water allocation, access, pollution, diversion, or infrastructure development. **Water-related Conflict in the 3S basin received a score of 45, with the lowest score coming from Vietnam (39) and higher scores from Cambodia (49) and Lao P.D.R. (50).** Marks for specific sources of conflict varied slightly, with lowest marks being given to issues of overlapping jurisdictions (country versus country, national versus provincial/local) and water quality impacts and other negative downstream impacts. Despite high marks for water quality overall, it is apparent that declining water quality is a potential source for local conflicts, though this may also be capturing concerns about downstream flow impacts of dams.

5. CONCLUSION

The three FHI component scores reveal that the 3S basin is showing signs of ecosystem stress (Ecosystem Vitality 66); it is providing a range of ecosystem services (Ecosystem Services 80); and governance and stakeholder involvement in decision making are poor (Governance & Stakeholders, 43). We may infer that the current level of ecosystem services is not sustainable, and that the present governance system will not be able to manage any future ecosystem degradation and declines in services.

Ecosystem Vitality was most compromised by a low biodiversity score, which itself was influenced by an abundance of threatened aquatic species. This has wider implications as high biodiversity is central to the productivity of the lower Mekong fishery. Thus, threatened biodiversity is a risk to the ecosystem service indicator, biomass for consumption. Water quantity (measured as deviation from natural flow) was affected by hydropower dam operations, with reduced wet season flow, and increases in dry season flow. This may be desirable from a human-use perspective, but it has implications for downstream ecosystems and communities who have developed

agricultural practices based on the seasonal flow patterns. Both water quality and drainage basin condition have high scores, showing that factors such as land clearance and hydropower dam operations have had little impact on water quality — at least at the stations monitored. The existing dam's smaller size and location high in the catchment (predominantly Vietnam) have reduced their impact on channel modification and riverine connectivity.

The high Ecosystem Services score was driven by high scores for provisioning and cultural services. However, regulation and support services (which underpin provisioning and cultural services) were showing signs of stress, with sediment regulation receiving a very low score. This is a result of hydropower dams blocking sediment that has traditionally been a source of nutrients to downstream agricultural land and fisheries. While deviation of water quality metrics from benchmarks received a high score there were signs of impact with high values of Total Suspended Solids appearing to increase in the dry season, as the dams release water, and falling below their wet season thresholds as the dams store water.

The low FHI Governance & Stakeholders score highlights underdeveloped management systems, which may hinder the ability to influence and respond to further development and its likely consequence — environmental degradation. Financial capacity, information accessibility, biological and ecological monitoring, and rules for groundwater abstraction had the among the lowest scores. The lack of financial capacity was expected, particularly in underdeveloped Lao PDR and Cambodia. Low levels of investment in ecosystem conservation and rehabilitation were reported. This is a concern given that the ecosystem vitality scores revealed increasing levels of ecosystem stress. The lack of rules for groundwater abstraction linked with our inability to calculate a change in groundwater due to a lack of data. Our stakeholders group identified uncontrolled groundwater extraction as an emerging issue in Vietnam, particularly during the 2015 El Niño dry season. A lack of shared vision for development was also reported. This is not surprising as development in the three countries has been driven by national policies and the lack of an official trans-boundary governance mechanism.

Multiple agencies in each country are involved in land and water management, at national, regional and local levels, and as such, sufficient coordination to make decisions about development does not often take place within the three country borders. Between the countries there is no formal basin management agency or structure for the 3S. As a tributary system, the 3S is not covered under the 1995 Mekong River Agreement and its management is not covered by the Mekong River Commission's mandate. Indeed, parties only need to notify others of their intention to build tributary dams - consultation is not required. While the need for trans-boundary governance was realized over a decade ago⁴, cross border water management is still informal and under development through the IUCN Bridge Program. Water related conflict scores rated low, and stakeholders suggested that conflict takes different forms in the basin—at present, it arises most frequently as an unwillingness to cooperate (e.g., on sharing information, or jointly deciding on dam operational rules). However, there is a potential for such issues to escalate if disagreements compromise state security⁵. That the low Governance & Stakeholders score was a self-assessment is encouraging, as there is self-awareness among the 3S decision makers that the governance system is weak. Quantifying these deficiencies and putting them into some order of priority can be a catalyst for improvement.

ENDNOTES

1. Nam, S. et al. (2016) Lower Mekong fisheries estimated to be worth around \$17 billion a year. *Catch and Culture*, 21(3), 4-7.
2. Dugan, P.J., et al. (2010) Fish Migration, Dams, and Loss of Ecosystem Services in the Mekong Basin. *Ambio*, 39, 344–348. Doi: 10.1007/s13280-010-0036-1.
3. Wyatt, A. B., and I. G. Baird (2007) Trans-boundary Impact Assessment in the Sesan River Basin: the Case of the Yali Falls Dam. *International Journal of Water Resources Development*, 23(3), 427–442, doi:10.1080/07900620701400443.
4. Hirsch, P., and A. Wyatt (2004) Negotiating local livelihoods: scales of conflict in the Se San River Basin. *Asia Pacific Viewpoint*, 45(1), 51–68, doi:http://dx.doi.org/10.1111/j.1467-8376.2004.00227.x.
5. Sithirith, M. (2016) Dams and state security: Damming the 3S rivers as a threat to Cambodian state security. *Asia Pacific Viewpoint*, 57(1), 60–75, doi:10.1111/apv.12108.

APPENDIX A: Methodology for select indicator calculations

Full documentation of the Freshwater Health Index methods is available in the FHI User Manual, which can be accessed through the website (www.freshwaterhealthindex.org). Below, we provide details on how the methods were applied and the data sources used to produce the 3S basin assessment.

ECOSYSTEM VITALITY

Deviation from Natural Flow

We used Piman et al's (2013) 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. The hydrological model only considers a subset of the basin's largest existing dams and those thought most likely to be constructed in future. The full suite of dams was not modelled due to lack of information on their dimensions and capacity and as many are believed to have a minimal effect on flow. We compare modeled regulated flow against modeled unregulated flow using the Amended Annual Proportion of Flow Deviation indicator (AAPFD) (Gehrke et al., 1995; Gippel et al., 2011). The AAPFD gives a score, whereby the higher the number, the greater the alteration. This score was transformed and normalized to a 0-100 range, with 100 being no deviation from the natural flow regime. The basin-wide deviation from natural flow regime score was the weighted (by mean annual discharge) arithmetic mean of the scores from four locations: (1) the 3S outlet to the Mekong; (2) the Sekong at the Cambodian/Lao PDR border; (3) the Sesan at the Vietnam/Cambodia border; and (4) the Srepok at the Vietnam/Cambodia border.

Water Quality

Water Quality was assessed based on monitored levels of four water quality parameters considered crucial for "good" ecological health of freshwater ecosystems: Total Suspended Solids (TSS), Total Phosphorous (TS) and Total Nitrogen (TN), with pH as an indicator of major concern. The Mekong River Commission (MRC) maintains six water quality monitoring stations in the 3S basin. One site in Cambodia was sampled on the Sekong River, three sites from the Sesan River (two in Cambodia, one in Vietnam) and two sites on the Srepok River (one each in Cambodia and Vietnam). We accessed data from 2004-2014. Samples were collected monthly in most years and bimonthly in others, giving a total of 647 samples.

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 Lower Mekong Basin (Ly and Larsen, 2016). The lowland rivers threshold was used for TN (<1.6 mg/L) (Hart et al., 1999). Water quality data for the last five years of sampling (2010-2014) were compared against these benchmarks. We determined the monthly minimum and maximum TSS values recorded for each calendar month from 2004-2009. These baseline threshold values were then compared to the most recent five years of data from 2010-2014, using a modification of the CCMW Water Quality Index method (Canadian Council of Ministers of the Environment, 2001). The Index incorporates three elements: scope (the number of variables not meeting water quality objectives); frequency (the number of times these objectives are not met); and amplitude (the amount by which the objectives are not met). The index produces a number between 0 (worst water quality) and 100 (best water quality), which we use as the FHI score.

Bank Modification

We determined the extent of reservoir inundation, a proxy for the loss of natural riparian area and thus bank modification, using maps generated by the SERVIR Mekong dam inundation mapping tool (<https://servir.adpc.net/tools/dam-inundation-mapping-tool>) for the 41 existing dams and the river network dataset.

The extent of channel modification statistic is:

$$CN = 100 - \left(\frac{rL}{L} \times 100 \right) \quad (1)$$

Where rL is the total length of inundated rivers; L is the total length of rivers in the 3S basin.

Flow Connectivity

The Dendritic Connectivity Index (DCI) (Cote et al., 2009) was used to determine the level of river channel fragmentation caused by all existing dams in the 3S basin. We assumed the 'passability' of all dams in the 3S basin for fish in either direction to be zero. This is reasonable as no dams are known to have been constructed to facilitate fish passage. 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 3S due to the dams (DCIp), which affects non-migratory fish. A combined index (cDCI) is calculated 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 (Baran et al., 2014).

Land Cover Naturalness

We used land cover data from the Mekong River Commission (2015a,b) 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. 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 provides a more conservative estimate of natural land cover. Land cover types were assigned scores ranging from 0-100 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. The MRC land cover dataset is a polygon dataset (i.e., contiguous parcels of the same land use are grouped together) and naturalness scores were assigned to each polygon. The polygons were then converted into a raster dataset of 30 m resolution. Naturalness was then calculated on a per pixel (30 m resolution) basis, and then the mean value is the basin score. Zonal statistics were then calculated for sub-basins.

Species of Concern

For Species of Concern, we calculated the proportion of threatened freshwater species by determining the weighted proportion of freshwater species listed on the IUCN Red List as critically endangered, endangered, or vulnerable against the total number of species assessed (IUCN, 2012). We used IUCN Red List spatial data (<http://www.iucnredlist.org/technical-documents/spatial-data>) for amphibians, terrestrial mammals, reptiles and the freshwater polygon groups for fish, mollusks, plants, Odonata, shrimps, crayfish and crabs, delimited to the 3S catchment boundary. We obtained water bird data from Birdlife International (<http://datazone.birdlife.org/home>). We included all listed aquatic species except those classified as possibly extant, due to a lack of confirmed records.

Invasive & Nuisance Species

The number of invasive and nuisance species index is calculated as:

$$I_{IN,i} = \begin{cases} 1 - \frac{n_{IN,i}}{10}, & \text{for } 0 \leq n_{IN,i} \leq 8 \\ 0.1, & \text{for } n_{IN,i} \geq 9 \end{cases} \quad (2)$$

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.

For Provisioning and Regulation & Support indicators, we calculate an index with spatial, temporal and magnitude factors, building on the approach used in the Canadian Water Quality Index (Canadian Council of Ministers of the Environment, 2001). We attempted to calculate all three factors for each indicator depending on the data available.

F_1 measures the spatial scope of the system to provide the ecosystem service:

$$F_1 = \left(\frac{\text{Number of spatial units that did not meet demand at least once}}{\text{Total number of spatial units}} \right) \times 100 \quad (3)$$

F_2 introduces a temporal dimension measuring how frequently the system failed to provide the ecosystem service;

$$F_2 = \left(\frac{\text{Number of instances where demand was not met}}{\text{Total number of instances monitored}} \right) \times 100 \quad (4)$$

and F_3 measures the magnitude of the deviation when the service is not met. To calculate F_3 first the magnitude of failure was determined by calculating excursions using equations 5 and 6 for parameters that must not exceed or fall below, the threshold values respectively.

$$EX_i = \left(\frac{\text{Failed test value}_i}{\text{Threshold}_i} \right) - 1 \quad (5)$$

$$EX_i = \left(\frac{\text{Threshold}_i}{\text{Failed test value}_i} \right) - 1 \quad (6)$$

These values were used to calculate the normalized sum of excursions (Equation 7) which was then scaled to yield the F_3 value which ranges between 0-100 (Equation 8).

$$nse = \frac{\sum_{i=0}^n EX_i}{\text{Total number of tests}} \quad (7)$$

$$F_3 = \left(\frac{nse}{nse+1} \right) \times 100 \quad (8)$$

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

1. If only able to determine F_1 (low evidence):

$$ESI_1 = 100 - F_1 \quad (9)$$

2. Else, if able to determine both F_1 and F_2 (medium evidence):

$$ESI_2 = 100 - \sqrt{F_1 \times F_2} \quad (10)$$

3. Else, if able to determine all three (high evidence):

$$ESI_3 = 100 - \sqrt{F_1 \times F_3} \quad (11)$$

Water Supply Reliability

We calculated Water Supply Reliability using the global 0.5° resolution self-calibrated Palmer Drought Severity Index (van der Schrier et al., 2013; Osborn et al., 2016). Monthly mean values of the Index for the period 2011-2015 were compared with the full range (1901-2015) to derive shift in spatial scope (F_1) and frequency (F_2) of water availability. The main limitation of using a Drought Severity Index as a metric is that it does not explicitly account for demand from individual sectors, whereby, shift from a long-term mean acts 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 obtained the freshwater IUCN RedList/IBAT dataset migratory fish distribution maps generated as a part of the Measuring, Understanding and Adapting to Nexus trade-offs in the 3S River Basins project and combined these with each of Lehner and Grill's (2013) Level 08 HydroBasins. By blocking fish passage, dams deny access to sub-basins, the importance of which for migratory fish were weighted by the presence of migratory fish, with basins that supported a higher number of migratory fish receiving a higher weight. We assigned a score of 100 to a fully connected river network where migratory fish had access to all sub-basins.

Thus, F_1 equals the number of sub-basins that were disconnected from migratory fish due to downstream dams. F_3 was calculated by formulas 12 and 13:

$$nse_{F_3} = \frac{\sum^{n_c} \left(\frac{\sum^{n_{sb}} MFH \times TCL}{\sum^{n_{sb}} MFH \times ACL} \right) - 1}{n_c} \quad (12)$$

$$F_3 = \left(\frac{nse_{F_3}}{nse_{F_3} + 1} \right) \times 100 \quad (13)$$

Where MFH is migratory fish habitat; ACL, the length of river channel available to migratory fish; nse, the number of level 08 HydroBasins; TCL, total length of river channel; n_c , number of river basins. In this case, $n_c = 3$ as calculations were made for the Srepok, Sesan and Sekong River basins.

Sediment Regulation

Soil erosion and sediment transport are processes regulated by rainfall runoff and stream flow. Currently, estimates of sediment trapped by the reservoirs as well as in-channel erosion, extraction (by mining/dredging) and deposition are not available. Sediment Regulation was determined using Wild and Loucks' (2014) 3S basin SedSim model. The model simulates seasonal supply operational rules for up to 41 reservoirs, identical to ones used in our hydrological modelling for determining Deviation from Natural Flow. 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 as the spatial unit over which F_1 and F_3 were calculated.

Water Quality Regulation

Twenty surface water quality parameters were assessed as a part of the Water Quality Regulation sub-indicator, including the four parameters assessed for Water Quality under Ecosystem Vitality. Data were obtained at the same temporal frequency and from the same stations as those assessed for Ecosystem Vitality.

Specific Lower Mekong Basin benchmark values were used to assess pH (6-9), Dissolved Oxygen (DO, 4 mg/L), Chemical Oxygen Demand (COD, 5 mg/L), Total Nitrite and Nitrate ($\text{NO}_2 + \text{NO}_3$, 5 mg/L), Ammonia (NH_3 , 0.5 mg/L) (protection of human health) and Electrical Conductivity (EC, 700 mS/m) (agriculture) (Ly and Larsen, 2016). The lowland rivers threshold was used for TN (<1.6 mg/L) (Hart et al., 1999). Water quality data for the last five years of sampling (2010-2014) were compared against these benchmarks. For the other parameters (TSS, Total Phosphorous, Ammonia (NH_3), Ammonium (NH_4), Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Alkalinity, Chloride (Cl), Sulphate (SO_4), Ca/Mg, Na/Cl, Na/K, Ca/ SO_4), we followed the protocol used to establish monthly minimum and maximum TSS thresholds as was done for Ecosystem Vitality.

The sub-indicator score was determined by calculating and aggregating the F_1 and F_3 components to produce a number between 0, lowest water quality, and 100, highest water quality.

Flood Regulation

We calculated the Flood Regulation indicator using the four gauged stations along the Sesan and Srepok Rivers with defined flood levels (Lumphat, Srepok, Cambodia; Voeun Sai, Sesan, Cambodia; Giang Son, Krong Ana (Srepok), Vietnam; Duc Xuyen, Krong Kno (Srepok), Vietnam), using the gauging stations water level time series from 2010-2015. F_1 measured the presence of flooding using the pre-defined flood levels, while F_3 measured the magnitude of the floods based on their exceedance of the levels.

Disease Regulation

We assessed two water associated diseases present in the 3S, Mekong schistosomiasis and Dengue fever. We used information on the presence of aquatic snails infected with Mekong schistosomiasis to calculate F_1 . We included sub-basins within Stung Treng province that were traversed by either the Sekong, Sesan or Srepok Rivers, along with the sub-basin in Ratanakiri where the infected snail species has been found. F_2 for Mekong schistosomiasis was then calculated based on its transmission period (the dry season).

To calculate exposure to Dengue fever, we used the Water Associated Disease Index exposure indicator, which 'represents conditions conducive to the presence and transmission of the pathogen within the environment' (Dickin et al. 2013). Using geospatial data on four factors (maximum temperature, precipitation, land use, and population density) and a table of exposure values based on Dickin & Schuster-Wallace (2014), we calculated F_1 and F_3 for Dengue fever.

We then combined the scores for the two diseases using a weighted arithmetic mean. As it is closely associated with the surface water system, Mekong schistosomiasis received a weighting of 0.8, while Dengue received a weighting of 0.2, as the mosquito larvae habitat, which is often small isolated rain-fed pools of water, is less closely associated with the basin's water system.

Conservation & Cultural Heritage

We calculated the cultural/aesthetic indicator using a protected areas map derived from Open Development Cambodia (2016) and IUCN and UNEP-WCMC (2017). The river length within the protected areas system and length of streams that formed protected area boundaries was determined from the river network dataset. These were compared against the total river length within the 3S using the following formula:

$$PoR = \frac{0.5*BL+IL}{RL} * 100 \quad (14)$$

PoR is the percent river length protected; BL, the length of rivers bordering protected areas; IL, 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 (<https://www.cbd.int/sp/targets/>), the value is scaled using an asymptotic function:

$$CS = 1.17 \frac{PoS}{PoS+17} \quad (15)$$

GOVERNANCE & STAKEHOLDERS

Values for Governance & Stakeholders indicators were determined qualitatively and were elicited via survey methods. A 49-question survey using a Likert-type 5-point scale was administered in English to participants through guided exercises at workshops in each country in April and May 2017. Twenty-six stakeholders with knowledge of the governance system of the 3S took part, representing national governments, research and academia, and civil society organizations. Scores were averaged within "modules" where each module related to a sub-indicator and included 3-6 questions. These averages (on

the 1-5 scale) were then normalized to a 0-100 scale, but responses were also analyzed according to sectoral and country affiliations.

WEIGHTING

Major and sub-indicator weights for the Ecosystem Services and Governance & Stakeholders components were elicited from stakeholders using a two-level Analytic Hierarchy Process. Workshop participants were asked to make a series of pairwise comparisons (e.g., do you consider “Water Provision” or “Biomass such as fish” to be more important?) and then rate the strength of their preferences. Numeric weights were then calculated using a balanced scale in the BPMSG AHP online system (<http://bpmsg.com/academic/ahp.php>), and the mean value of the group was used as the final weight. These weights were applied when combining sub-indicators into major indicator scores and when combining major indicators into component scores.

REFERENCES

Baran, E., S. Saray, S.J. Teoh and T.C. Tran (2014) Fish and fisheries in the Sesan, Sekong and Srepok River basins (Mekong watershed), In: On optimizing the management of cascades or system of reservoirs at catchment level, ICEM, Hanoi, Vietnam.

Canadian Council of Ministers of the Environment (2001) Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User’s Manual. In: Canadian Environmental Quality Guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg, Canada.

Cote, D., D.G. Kehler, C. Bourne and Y.F. Wiersma (2009) A new measure of longitudinal connectivity for stream networks. *Landscape Ecology*, 24(1), 101-113.

Dickin, S.K. and C.J. Schuster-Wallace (2014) Assessing changing vulnerability to dengue in northeastern Brazil using a water-associated disease index approach. *Global Environmental Change*, 29 (November), 155–164, doi:10.1016/j.gloenvcha.2014.09.007.

Dickin, S.K., C.J. Schuster-Wallace and S.J. Elliott (2013) Developing a vulnerability mapping methodology: applying the water-associated disease index to dengue in Malaysia. *PLoS One* 8(5), doi: 10.1371/journal.pone.0063584.

Gehrke, P., P. Brown, C.B. Schiller, D.B. Moffatt and A. Bruce (1995) River regulation and fish communities in the Murray–Darling river system, Australia. *Regulated Rivers: Research and Management*, 15,181–198.

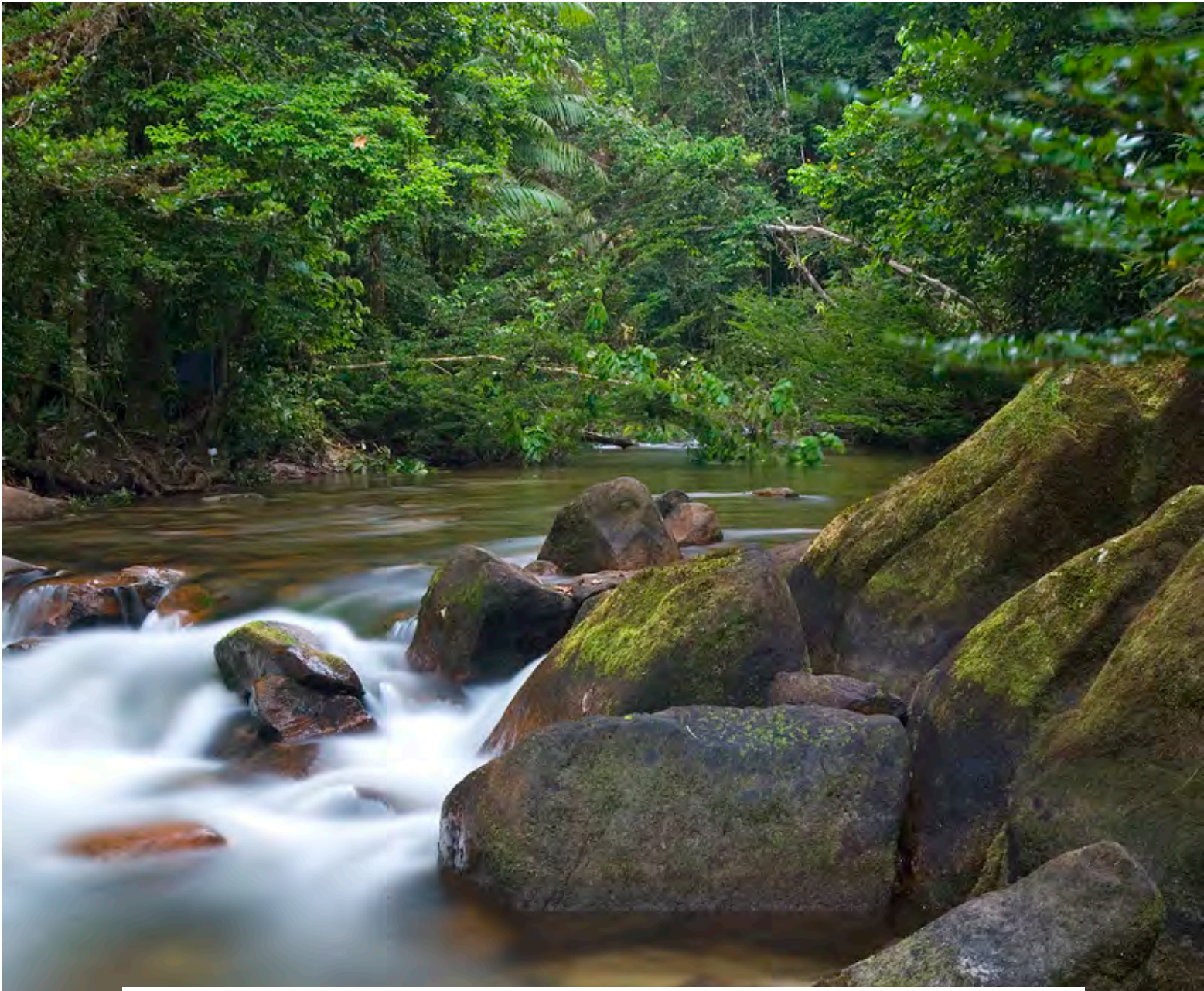
Gippel, C.J., Y. Zhang, X. Qu, W. Kong, N.R. Bond, X. Jiang, and W. Liu (2011) River health assessment in China: comparison and development of indicators of hydrological health. ACEDP Australia-China Environment Development Partnership, River Health and Environmental Flow in China. The Chinese Research Academy of Environmental Sciences, the Pearl River Water Resources Commission and the International WaterCentre, Brisbane, September.

Hart, B.T., B. Maher and I. Lawrence (1999) New generation water quality guidelines for ecosystem protection. *Freshwater Biology*, 41(2), 347–359, doi:10.1046/j.1365-2427.1999.00435.x.

IUCN (2012) IUCN Red List Categories and Criteria: Version 3.1., Second edn., IUCN, Gland, Switzerland and Cambridge, UK.

IUCN and UNEP-WCMC (2017) The World Database on Protected Areas (WDPA) (On-line), Cambridge, UK UNEP-WCMC. Available from: www.protectedplanet.net (Accessed 2 March 2017)

- Lehner, B. and G. Grill (2013) Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, 27(15), 2171–2186, doi:10.1002/hyp.9740.
- Ly, K., and H. Larsen (2016) 2014 Lower Mekong regional water quality monitoring report, Vientiane, Lao PDR.
- Mekong River Commission (MRC) (2015a) Land Cover Map 2010 (Dry) of the Lower Mekong Basin. Available from: <http://portal.mrcmekong.org/search/search> (Accessed 25 July 2017)
- Mekong River Commission (MRC) (2015b) Land Cover Map 2010 (Wet) of the Lower Mekong Basin. Available from: <http://portal.mrcmekong.org/search/search> (Accessed 25 July 2017)
- Open Development Cambodia (2016) Natural Protected Areas. Available from: <https://opendevelopmentcambodia.net/profiles/natural-protected-areas/> (Accessed 17 September 2016)
- Osborn, T., J. Barichivich, I. Harris, G. van der Schrier and P. Jones (2016) Monitoring global drought using the self-calibrating Palmer Drought Severity Index (in “State of the Climate in 2015”). *Bulletin of the American Meteorological Society*, 97, S32–S36.
- Piman, T., T.A. Cochrane, M.E. Arias, A. Green and N.D. Dat (2013) Assessment of flow changes from hydropower development and operations in Sekong, Sesan, and Srepok Rivers of the Mekong Basin. *Journal of Water Resources Planning and Management*, 139(6), 723–732, doi:10.1061/(ASCE)WR.1943-5452.0000286.
- van der Schrier, G., J. Barichivich, K.R. Briffa, and P.D. Jones (2013) A scPDSI-based global data set of dry and wet spells for 1901-2009. *Journal of Geophysical Research: Atmospheres*, 118(10), 4025–4048, doi:10.1002/jgrd.50355.
- Wild, T.B. and D.P. Loucks (2014) Managing flow, sediment, and hydropower regimes in the Sre Pok, Se San, and Se Kong Rivers of the Mekong basin. *Water Resources Research*, 50(6), 5141–5157, doi:10.1002/2014WR015457.



馮氏

經綸慈善基金有限公司
VICTOR AND WILLIAM FUNG FOUNDATION LTD



BRIDGE



CONSERVATION
INTERNATIONAL

