Freshwater health index assessment of the Tonle Sap basin

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មូលន័យសង្ខេប

បឹងទន្លេសាប និងអាងទន្លេគ្របដណ្តប់ស្ទើរតែពាក់កណ្តាលនៃផ្ទៃដីប្រទេសកម្ពុជា ដែលផ្ទុកនូវធនធានជលផលទឹកសាបដ៏ធំបំផុតមួយនៅលើពិភពលោក និងសម្បូរទៅដោយជីវចម្រុះ។ ខណៈដែលបឹងទន្លេសាប និងទំនាក់ទំនងរបស់វាជាមួយទន្លេមេគង្គត្រូវបានគេសិក្សាយ៉ាងទូលំទូលាយ រហូតមកដល់បច្ចុប្បន្ននេះសុខភាពទឹកសាបរបស់អាងទន្លេនេះត្រូវបានគេមើលរំលង។ យើងបានប្រើសន្ទស្សន៍សុខភាពទឹកសាបដើម្បីធ្វើការវិនិច្ឆ័យស្ថានភាពអាងទន្លេនៅខែធ្នូ ឆ្នាំ២០២១។ ភាពរឹងមាំនៃប្រព័ន្ធអេកូឡូស៊ីទទួលបានពិន្ទុ ៤១/១០០ ឯសេវាកម្មប្រព័ន្ធអេកូឡូស៊ីទទួលបានពិន្ទុ៧៥/១០០ ខណៈដែលអភិបាលកិច្ច និងភាគីពាក់ព័ន្ធទទួលបានពិន្ទុ៥៨។ ដូចគ្នានឹងការវាយតម្លៃសុខភាពទឹកសាបនៅផ្នែកផ្សេងៗនៃទន្លេមេគង្គ អាងទន្លេសាបផ្តល់នូវសេវាកម្មប្រព័ន្ធអេកូឡូស៊ីដ៏មានតម្លៃ។ ប៉ុន្តែសមាសភាពរបស់ប្រព័ន្ធជីវរូបបាតទឹករបស់វាត្រូវបានថយចុះ។ បណ្តាញទន្លេដែលបែកខ្ញែកគ្នាយ៉ាងខ្លាំងនៃអាង និងចំនួនខ្ពស់នៃប្រភេទរងគ្រោះ (ជាពិសេសត្រី) គំរាមកំហែងដល់អនាគតនៃជលផលដ៏សំខាន់របស់បឹង ដែលក្នុងនោះទទួលបានពិន្ទុមធ្យម៦០។ ភាគីពាក់ព័ន្ធបានវាយតម្លៃប្រព័ន្ធអភិបាលកិច្ចទឹក និងកម្រិតនៃការចូលរួមរបស់ភាគីពាក់ព័ន្ធថាមានកម្រិតមធ្យម។ ខណៈដែលជម្លោះនៅមានកម្រិតទាប ការអភិវឌ្ឍន៍ហេដ្ឋារចនាសម្ព័ន្ធប្រព័ន្ធធារាសាស្ត្រទំនងជានឹងប៉ះពាល់ដល់លំហូរទៅកាន់បឹង និងជះឥទ្ធិពលដល់ជលផល។ ភាគីពាក់ព័ន្ធត្រូវបានបែងចែកសារៈសំខាន់លើការផ្គត់ផ្គង់ទឹកដែលអាចជឿទុកចិត្តបាន និងធនធានជលផល ដែលបង្ហាញពីសក្តានុពលនៃចំនុចអាចកើតមានជម្លោះនាពេលអនាគត។ យើងបានកំណត់អត្តសញ្ញាណកង្វះទិន្នន័យ បង្ហាញពីថាមវន្តសង្គមសំខាន់ៗ ផ្តល់ឲ្យភាគីពាក់ព័ន្ធនូវទស្សនៈវិស័យទូលំទូលាយអំពីអាងទន្លេ និងបានគូសបញ្ជាក់ពីសារៈសំខាន់នៃបរិស្ថានដែលមានសុខភាពល្អសម្រាប់អនាគតនៃប្រព័ន្ធធនធានធម្មជាតិដ៏មានសារៈសំខាន់របស់ប្រទេសកម្ពុជា។

Abstract

The Tonle Sap Lake and River basin cover almost half of Cambodia's land surface, contain one of the world's largest inland fisheries and are rich in biodiversity. While the Tonle Sap Lake and its relationship to the Mekong River is well studied, until now the freshwater health of the basin has been overlooked. We used a freshwater health index to diagnose the basin's condition as of December 2021. Ecosystem vitality and ecosystem services scored 41 and 75, respectively, out of a possible 100, while governance and stakeholders scored 58. Consistent with freshwater health assessments in other parts of the Mekong, the Tonle Sap basin provides valuable ecosystem services. But components of its underpinning biophysical system are degraded. The basin's highly fragmented river network and high numbers of threatened species (particularly fish) threaten the future of the lake's vital fishery, which received a moderate score

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of 60. Stakeholders rated the water governance system and degree of stakeholder engagement as moderate. While the degree of conflict was low, the development of irrigation infrastructure will likely impact flows to the lake, thus affecting the fishery. That stakeholders were divided over the importance placed on the provision of a reliable water supply versus the fishery, indicates a potential future point of conflict. We identified data deficiencies, revealed important social dynamics, provided stakeholders with a basin wide perspective, and highlighted the importance of a healthy environment for the future of Cambodia's most important natural resource system.

Keywords Ecosystem services, ecosystem vitality, freshwater health index, governance, Tonle Sap basin.

Introduction

The Tonle Sap Lake is central to Cambodia's cultural identity and economy. The lake is a UNESCO Biosphere Reserve and central to what is arguably the world's largest and most productive inland fishery, the lower Mekong basin (Baran *et al*., 2013). The Tonle Sap basin provides 80% of the protein intake of Cambodian people (Hortle, 2007), supports extensive rice production (Mahood *et al*., 2020) and is home to 1.7 million people (Salmivaara *et al*., 2016). The Tonle Sap Lake and its flooded forests provide habitat for ca. 300 species of fish (Baran *et al*., 2013) and numerous threatened birds and mammals (Campbell *et al*., 2006). The Tonle Sap River connects the lake to the Mekong River and its unique pattern of seasonally reversing flow drives much of the lake's productivity. While the Tonle Sap Lake and its relationship with the Mekong River has been extensively studied (Uk *et al*., 2018), its basin has been largely overlooked. Ninety-five percent of this 87,940 km^2 basin lies within Cambodia (with 5% in Thailand) and comprises 46% of Cambodia's land surface. The basin contains extensive areas of forest and rice fields, the settlements of Battambang and Siem Reap, and the World Heritage listed Angkor Archaeological Park. The Tonle Sap Lake and river continue to be degraded due to overfishing (KC *et al*., 2017; Ngor *et al*., 2018b), climate change (Daly *et al*., 2020), hydropower dam development, irrigation, sand mining (Chua *et al*., 2022) and deforestation (Lohani *et al*., 2020; Chen *et al*., 2022).

We conducted a freshwater health index (FHI) assessment to gain a holistic understanding of the health of the Tonle Sap basin and inform management of this vital part of Cambodia and wider Mekong system. This is the second FHI assessment undertaken in the Lower Mekong basin, as a previous study assessed the transboundary Sesan, Srepok and Sekong River basin (Souter *et al*., 2020). The FHI 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 & cultural services; and stakeholders & 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 (Vollmer *et al*., 2018). The FHI aggregates data and knowledge from the social and natural sciences under a social-ecological framework to characterize the health of freshwater systems on a scale of 0–100. The process of undertaking an FHI assessment assists stakeholders in understanding freshwater ecosystem dynamics, how these are manipulated to affect water-related services and how the governance regime manages these dynamics. We use the results of the FHI assessment to make a series of recommendations to improve the freshwater health of the Tonle Sap basin.

Methods

Indicator calculation

We calculated scores for all major indicators within the three components of the FHI: ecosystem vitality, ecosystem services and governance & stakeholders. These scores were derived from assessments of 28 sub-indicators which were calculated using standard and modified methods. Several sub-indicators—groundwater storage depletion, sediment regulation and recreation—were not calculated due to a lack of data. Standard methods were calculated using the FHI toolbox (Shaad & Alt, 2020) and are described in the FHI user manual (FHI, 2021). Readers should consult the user manual for full details of the methodology, as modifications only are described hereafter. The assessment used the most current data available up to 31 December 2021.

Common data sets

We developed two new datasets which were used to calculate several FHI indicators. The Tonle Sap basin network is a combination of the '*Level 7 HydroBasins*' classification (Lehner & Grill, 2013) and the '*Major Flood Extent of the Tonle Sap Lake and Mekong Flooding*' map

(MLMUPC, 2011). This comprises 33 sub-basins which include the extent of permanent water of the Tonle Sap Lake and the inundated floodplain of the Tonle Sap Lake and Sen River as discrete sub-basins. The remaining 31 are river sub-basins, some of which were combined to remove very small basins. We derived the Tonle Sap River network from the HydroSHEDS 15 arc-second resolution drainage direction map (Lehner *et al*., 2006).

Ecosystem vitality

Water quantity was assessed as the deviation from natural flow regime (DvNF) metric as we did not assess groundwater storage depletion due to a lack of data. We calculated DvNF for pre- and post-regulation Tonle Sap Lake and river levels from three sites (Fig. 1, Table 1) using data obtained from the Mekong River Commission (MRC). The pre- and post- periods were summarized into a single average year by calculating the mean lake/river level for each month. We calculated the metric using the formula described in FHI (2021). The basin wide DvNF score was the geometric mean of DvNF scores from the three locations.

Water quality is the geometric mean of six surface water quality sub-indicators: total suspended solids (TSS), total phosphorous (TP), total nitrogen (TN), total nitrate and nitrite (NO_2 & NO_3), Chemical Oxygen Demand (COD) and pH. We used the ecosystem service indicator method 2 (Shaad *et al*., 2022) to calculate a water quality index score for each parameter. A total of 1,249 monthly or bimonthly samples collected between August 1993 and December 2017 from six MRC monitoring stations (Backprea, Kampong Chnang, Kampong Luong, Phnom Krom, Phnom Penh Port and Prek Kdam: Fig. 1) were available and employed in analysis. We assessed water quality data for the last five years of sampling (2013–2017) against the lower Mekong basin protection of aquatic ecosystem thresholds for TP (< 0.13 mg/L) and NO_2 & NO_3 (0.5 mg/L) and protection of human health for COD (5 mg/L) (Ly & Larsen, 2016). The lowland river threshold was used for TN (<1.6 mg/L) (Hart *et al*., 1999). We established monthly TSS thresholds by calcu-

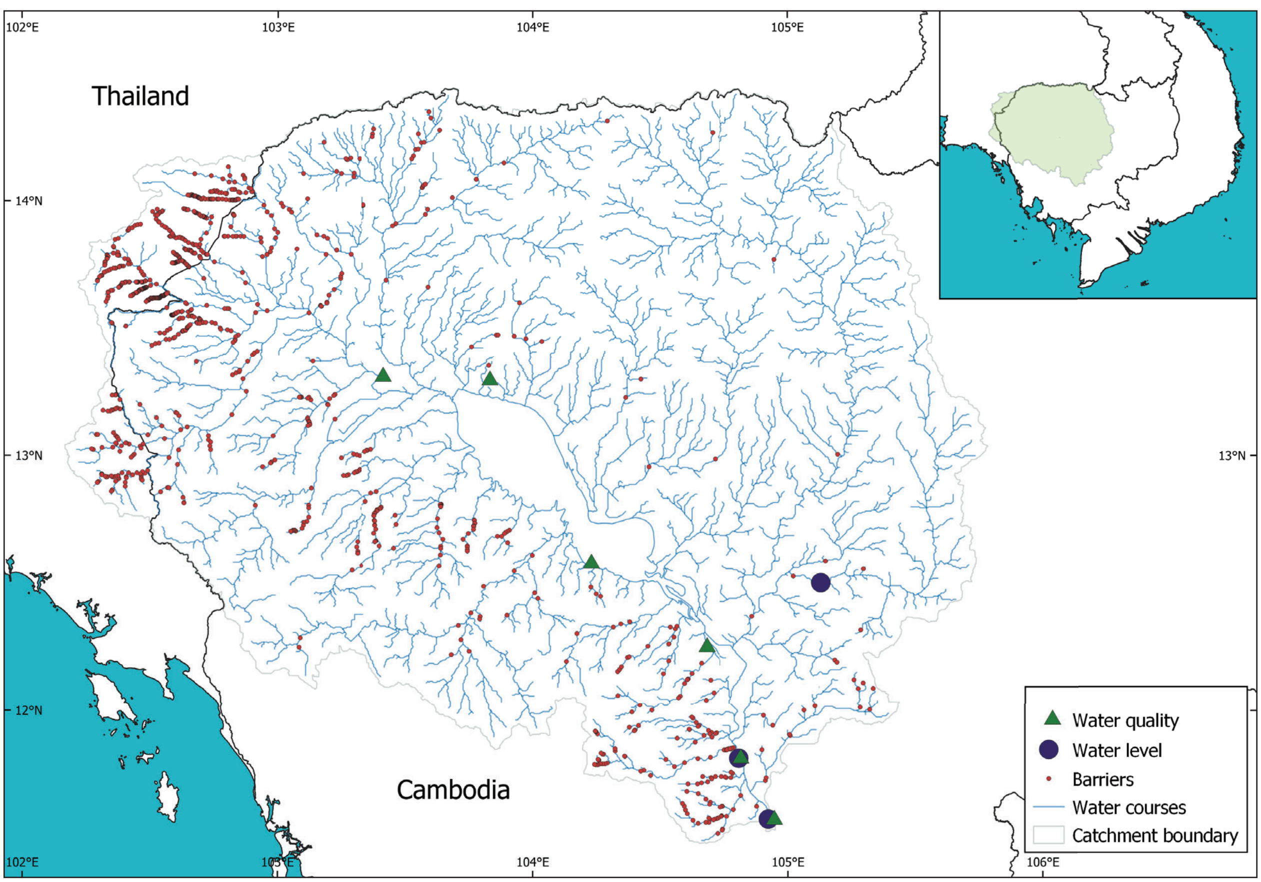

Fig. 1 Tonle Sap basin showing river height gauging stations, water quality monitoring stations and dams/barriers.

Table 1 Tonle Sap Lake and River level gauging stations used to calculate deviation from natural flow regime.

Gauge Location (No.)	Latitude (°N)	Longitude (°E)	Pre Regulation Period	Post Regulation Period
Prek Kdam (020102)	11.811	104.807	1 January 1960 – 31 December 1990	1 January 2014 – 31 December 2018
Kampong Thmar (620101)	12.501	105.1308	1 January 1962 – 30 April 1970; 19 May 1981 – 31 December 1990	1 January 2014 – 31 December 2018
Phnom Penh Port (020101)	11.573	104.923	1 January 1960 – 31 December 1990	1 January 2014 – 31 December 2018

lating the minimum and maximum TSS values for each calendar month from the earliest date of sampling to December 2012. We used these values as baseline thresholds, against which we assessed monthly data from January 2013 to December 2017.

Drainage basin condition is the geometric mean of three sub-indicators: bank modification, flow connectivity and land cover naturalness.

Bank modification measures the extent of unmodified river channel in the basin. Calculated in the FHI Toolbox, we used a 200 m buffer around the Tonle Sap River network and land cover data from the Cambodian Ministry of Environment's '*Cambodian Forest Cover 2016*' shapefile (MoE, unpubl. data). We used this dataset as it was of higher resolution than regional land cover datasets, though it did not include the 5% of the basin located in Thailand. Land cover types were assigned scores at an expert workshop held in Phnom Penh on 6 May 2022 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 2).

Flow connectivity assesses the disruption caused by dams and other barriers. Following Shaad *et al*. (2018), we used the unmodified HydroSHEDS 15 arc-second resolution drainage direction map and designated the junction of the Tonle Sap and Mekong Rivers as the basin outlet. We identified 1,076 dams and barriers using MRC (2015), ODC (2015), WLE Mekong (2016), local knowledge and examination of Google Earth satellite imagery. Most barriers were identified using Google Earth and ranged from numerous small earthen embankments—most abundant in Thailand—to large weirs and dams. We could only confirm the presence of fish passage for three barriers (Table 3). While the effectiveness of these three passages is unknown, we assigned a passability value of 0.75 to each for analysis. Many of the smaller barriers are likely to be inundated at high water levels allowing fish to pass but as we could not confirm this, all other barriers received a passability score of 0.

The dendritic connectivity index (DCI) evaluates both the loss of connectivity between the Tonle Sap basin and the Mekong River (DCId), which affects migratory fish, and between the various segments created within the basin due to the dams (DCIp), which also affects non-migratory fish. We calculated a combined index (cDCI) weighted by the proportion of migratory vs. non-migratory fish complied from eleven sources (Annex 1). Of the 356 species recorded, 191 were classified as white or migratory fish and 75 as resident grey or blackfish. Of the remainder, 24 were estuarine and 63 could not be classified on the information provided and were not included in our analysis. We set the percentage of migratory vs. non migratory fish at 72% and 28% respectively.

Land cover naturalness is a proxy indicator for the degree to which a river basin's natural systems regulate pollution, flooding, erosion and changes to infiltration and run-off. We calculated land cover naturalness using the FHI toolbox and by deriving land cover data from the Cambodian MoE's '*Cambodian Forest Cover 2016*' shapefile (MoE, unpubl. data) and the naturalness scores in Table 2.

Biodiversity signifies ecosystem health, with declining populations of native species, increasing numbers of threatened species and increasing populations of invasive and nuisance species indicating deteriorating conditions or ecosystem degradation. We used the FHI toolbox to calculate the biodiversity indicator and its two sub-indicators: species of concern, and invasive and nuisance species. Species of concern comprises three components. The first component comprises the proportion of threatened freshwater species, which was calculated using spatial data from IUCN (2019) for amphibians, terrestrial mammals, reptiles and the freshwater polygon groups for fish, molluscs, plants, odonates, shrimps, crayfish and crabs, and bird data from Birdlife International

Table 2 Land Use/Land Cover types, naturalness score and dengue exposure.

Raster Category	Raster ID	Naturalness Score	Dengue Exposure	Description	Degree of Naturalness; Water Cycle Modification; Vegetation
Evergreen forest	1	100	0	Trees maintaining their leaves all year	Natural and semi-natural; None; Native
Semi-evergreen forest	2	100	0	Mixed evergreen and deciduous trees	
Deciduous forest	3	100	0	Mixed dry deciduous and dry dipterocarp forest	
Flooded forest	9	100	0.5	Tonle Sap Lake forests and shrublands	
Water	22	100	0	Open fresh water	
Grassland	17	100	0.25	Grasslands	
Wood shrub	5	60	0	Evergreen and deciduous woodland < 5 metres high	Cultural assisted sys-tem; Low; Mixed, high diversity
Forest regrowth	10	60	0	Naturally regenerated forest previously impacted by logging, agricultural land use, and human induced fire, etc.	
Rubber plantation	8	50	0.5	Existing rubber plantations	Transformed system; Low to Moderate; Permanent cover with atypical species
Tree plantation	14	50	0.5	Introduced trees (e.g., eucalyptus, cashew etc.)	
Paddy field	15	50	0.5	Rice paddy field	Transformed system; Low to Moderate; Seasonal cover with atypical species
Crop land	16	30	0.5	Arable and tillage land, agroforestry systems under the tree plantation and forest thresholds.	Transformed system; Moderate to High; Seasonal cover with atypical species
Village	19	10	1	Houses and gardens	Completely artificial; Moderate to high; Sparse to no cover
Rock	20	10	0.25	Naturally exposed rocks or mines, quarries and gravel pits.	
Sand	21	10	0.25	Thin soil or sand, dry salt flats, beaches, sand dunes.	
Built-up area	18	1	1	Buildings and construction	Completely artificial; High; Sparse to no cover

(2019). We included all listed aquatic species except those classified as possibly extant, due to a lack of confirmed records. The second component, change in the number of species of concern, was not calculated as this is the first basin assessment, whereas the third component, average population trend, was calculated using unpublished nest count data comparing 2017 and 2021 numbers for seven species of colonial nesting birds at Prek Toal (MoE, unpubl. data).

The number of invasive and nuisance species in the Tonle Sap basin was determined through a literature review (primarily van Zalinge (2006)) and information from regional experts who assessed the degree of invasiveness of introduced species present within the basin.

Ecosystem services

The ecosystem services metric comprises three major indicators: provisioning, regulation & support and cultural &

Table 3 Barriers in the Tonle Sap Lake basin with known fish passage.

Barrier Name	Latitude (°N)	Longitude (°E)
Sala Taaun	13.141	103.221
Stung Pursat Weir	12.487	103.809
Stung Pursat Weir	12.333	103.702

aesthetic. Unless otherwise stated, we employed method 2 of Shaad *et al*. (2022) to calculate each sub-indicator for provisioning and regulation & support using data that measured either one or more of, a spatial (F_1) measure of the system's ability to provide the ecosystem service, a temporal (F_2) measure of how frequently the system fails to provide the ecosystem service, and the magnitude (F_3) of deviation from the threshold value.

Provisioning is the geometric mean of two sub-indicators: water supply reliability relative to demand and biomass for consumption. We calculated water supply reliability relative to demand as the geometric mean of monthly average sustainable irrigation areas (%) across Cambodia from the 2020 scenario in MRC (2018: section 6.1.1, Table 6–8, p. 43). Biomass for consumption was calculated from 2,951 daily fish catch monitoring records collected from four community fisheries areas (Anlong Reang and Ou Ta Prok in Pursat Province; and Doun Sdaeung and Pov Veuy Senchey in Kampong Thom Province) on the Tonle Sap Lake from 1 January 2015 to 31 August 2019. One fisherman in each community recorded the total weight of fish they caught each day. As fishers considered a daily catch of 1.5 kg of fish to be the minimum required to meet their daily subsistence needs, we set this value as the threshold. In the event of fishers catching no fish we calculated the metric using a nominal weight of 0.01 kg, otherwise the equations were intractable.

Regulation & Support is the geometric mean of three sub-indicators: deviation of water quality metrics from benchmarks, flood regulation and exposure to water-associated diseases. We calculated deviation of water quality metrics from benchmarks using 20 surface water quality parameters: TSS, TP, TN, pH, electrical conductivity (EC), dissolved oxygen (DO), COD, total NO_2 & NO_3, 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. Samples were obtained at the same time and from the same sites as those assessed for the ecosystem vitality water quality indicator. Lower Mekong basin benchmark values for 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). We adopted an agricultural value for EC of 700 mS/m (Ly & Larsen, 2016) and the lowland rivers threshold for TN (<1.6 mg/L) (Hart *et al*., 1999). Water quality data for 2013–2017 were compared against these benchmarks. For the other parameters, we established monthly minimum and maximum TSS thresholds for the ecosystem vitality water quality indicator (Souter *et al*., 2020). Five of these parameters (TOTP, Mg, Cl, $NO_2 + NO_3$ and NH_4) recorded zero values, which were converted to 0.01 to enable the indicator to be calculated.

We calculated flood regulation from the Prek Kdam (No. 020102) gauging station on the Tonle Sap River which had both flood and flood warning levels (10 m & 9.5 m respectively) using the water level time series data from 1 January 2014 to 31 December 2018.

We calculated exposure to water-associated diseases as dengue fever exposure using the water associated disease index (WADI: Dickin *et al*. 2013) exposure indicator. We developed the index following Souter *et al.* (2020) using four datasets (Table 4) analysed using the Google Earth Engine to derive exposure values for each month of 2021 and land cover exposure values (Table 2). We set an exposure value of 0.25 and the final indicator score was the geometric mean of the 12 monthly values.

Table 4 Dengue WADI exposure indicator components and data analysed in Google Earth Engine.

Component	Dengue WADI Factor	Data Source
Climate	Maximum temperature; Precipitation	Wan *et al*. (2021); Funk *et al*. (2015)
Land environment	Land cover	'*Cambodia Forest Cover 2016*' shapefile (MoE, unpubl. data)
Human environment	Population density	CIESIN (2018)

Cultural & aesthetic ecosystem services were calculated using the conservation/cultural heritage sites sub-indicator. We calculated this using a protected areas map derived from two sources (ODC, 2016; IUCN & UNEP-WCMC, 2017) per Souter *et al.* (2020). We did not calculate the recreation sub-indicator because although there are tourism operations on the Tonle Sap Lake, evaluation required a dedicated survey for which we did not have the resources.

Governance & stakeholders

The governance & stakeholders metric comprises four major indicators: enabling environment, stakeholder engagement, vision & adaptive governance and effectiveness, which include 12 sub-indicators. We assessed the governance & stakeholders metric via an online questionnaire in English (Annex 2) which asked stakeholders to rate their level of agreement with 54 statements using a standard five-point Likert scale (e.g., Vollmer *et al*. 2021). Survey responses were anonymous and 15 people with specific knowledge of the Tonle Sap and its governance system completed the survey. While their perceptions were their own, they were employed by government agencies, non-government organizations and academic institutions.

Indicator weighting

To ensure that our aggregated values for ecosystem services and governance & stakeholders reflected stakeholder preferences, we asked the stakeholders that completed the governance & stakeholders survey to also complete the FHI indicator weighting exercise. Respondents used a swing weighting approach (Edwards & Barron, 1994), which was conducted online in English following Souter *et al*. (2020). Their individual weights were aggregated by arithmetic mean, while their level of consensus or agreement on the weights was calculated based on Shannon α and β entropy (Goepel, 2013).

Results

Our Tonle Sap FHI assessment gave three scores: Ecosystem vitality=41, ecosystem services=72 and governance & stakeholders=58 (Fig. 2).

Ecosystem vitality

Water quantity scored 66 with the two lake sites, Prek Kdam (68) and Kampong Thmar (67), scoring slightly higher than Phnom Penh Port (64) which is located at the junction of the Tonle Sap and Mekong Rivers.

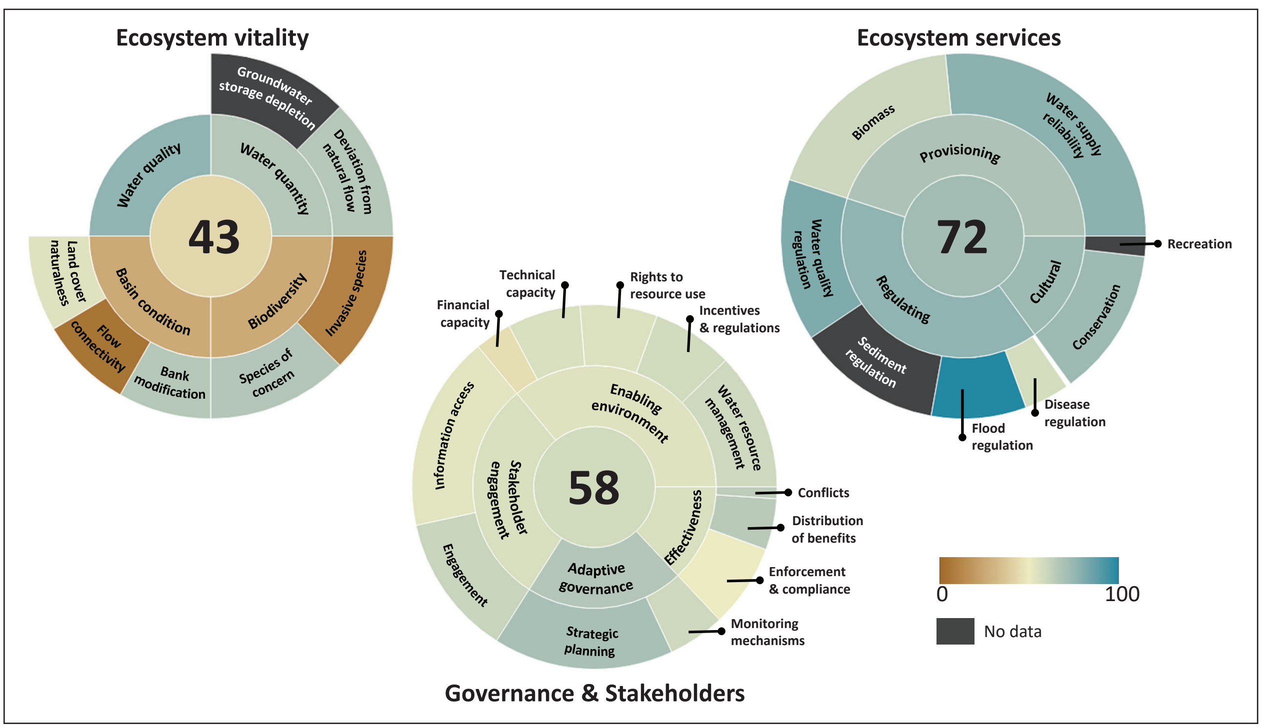

Fig. 2 Summary FHI scores for the Tonle Sap basin, as of December 2021. The size of each wedge reflects its relative weight in determining aggregated indicator (or component) scores.

Water quality scored 77 and comprised high scores for all parameters except for COD and TP which had moderate and low scores respectively (Table 5).

Drainage basin condition scored 22, which comprised scores for bank modification (66), flow connectivity (3) and land cover naturalness (54). For bank modification, the highest proportion of water course banks ran through rice fields (rubber and tree plantations were minor components), followed by natural vegetation (Table 6). For land cover, rice fields were the predominant land type followed by natural vegetation (Table 6).

Biodiversity scored 26. Species of concern scored 67 as we recorded 72 threatened species out of a total of 1,057. Most threatened and Critically Endangered species were fish (Actinopterygii), which were also the most species-rich group (Table 7). Nest counts for three of the seven bird species monitored at Prek Toal declined between 2017 and 2021: milky stork *Mycteria cinerea* (-60%), painted stork *M. leucocephala* (-6%) and Asian openbill *Anastomus oscitans* (-9%). Nest counts for the remaining four species increased: greater adjutant *Leptoptilos dubius* (+21%), lesser adjutant *L. javanicus* (+24%), spot-billed pelican *Pelecanus philippensis* (+25%) and oriental darter *Anhinga melanogaster* (+6%).

The invasive and nuisance species indicator scored 10 as we identified nine highly invasive species (Table 8). Van Zalinge (2006) recorded 21 exotic species from the Tonle Sap Biosphere Reserve and surrounds. Of these, we identified 16 species as having either high or moderate impact or abundance in the Tonle Sap Basin. Twelve of these were plants, three were fish and one was an invertebrate.

Table 5 Individual F_1, F_3 and ecosystem service indicator (ESI) scores for water quality parameters in 2013–2017.

Parameter	F_1	F_3	ESI
Total nitrogen	100	1.0	90.2
Total phosphorus	100	28.2	46.9
pH	83.3	0.4	94.6
Chemical oxygen demand	100	9.2	69.7
Total nitrate & nitrite	75	4.95	80.7
Total suspended solids	66.7	3.75	84.2

Table 6 Bank modification (BM) and land cover naturalness (LCN) proportions for the Tonle Sap basin.

Degree of Naturalness / Vegetation	% Modification	
	BM	LCN
Natural and semi-natural: Native	33.8	18.9
Cultural assisted system: Mixed high diversity	6.8	4.9
Transformed system: Permanent cover with atypical species / rice paddy	40.5	55.1
Transformed system: Seasonal cover with atypical species	16.6	13.6
Completely artificial: sparse cover with grass	2.1	5.5
Completely artificial: none	0.2	1.9

Ecosystem services

Ecosystem services scored 75 and comprised scores of 70 for provisioning (weighting of 0.45), 82 for regulation & support (weighting 0.40) and 73 for cultural & aesthetic (weighting 0.15). The weightings achieved a high degree of consensus at 68%.

Provisioning (70) comprised indicators for water supply relative to demand which had a score of 78 (weighting 0.59) and biomass for consumption, which had a score of 60 (weighting 0.41). Fishers at all four sites failed to catch sufficient fish for their daily subsistence on at least one occasion (F_1=100). They also fell below the threshold on 51 occasions (F_3=16). The fisher in Pov Veuy Senchey caught no fish on three occasions between 14–16 April 2017. There was a low degree of consensus (27%) in the weightings between the two sub-indicators, highlighting that stakeholder opinions were polarized i.e., strongly favouring either water supply or biomass.

Regulation & support scored 82 and comprised three indicators for which the weightings received a high degree of consensus (80%). While we could not assess sediment regulation, the weighting this received from stakeholders (0.32) suggests they viewed it as an important service worthy of further investigation.

Deviation of water quality metrics from benchmarks scored 81 (weighting 0.36). Individual indicators ranged from 42 for dissolved oxygen to 100 for electrical conductivity and ammonia (Table 9). 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.

Table 7 Number of IUCN Red List species present in the Tonle Sap basin categorized by higher taxonomic groups. Status: CR=Critically Endangered, EN=Endangered, VU=Vulnerable, NT=Near Threatened, LC=Least Concern, DD=Data Deficient.

Status	Actinopterygii	Aves	Reptilia	Amphibia	Mollusca	Mammalia	Odonata	Plantae	Decapoda	Total
CR	6	2	3					1		12
EN	5	6	2	1	2	1		1	1	19
VU	15	3	6	6	13	3	2	2	1	51
NT	11	15		3	20			1	1	51
LC	315	76	90	38	77		142	122	30	923
DD		1								1
Total	352	102	101	48	112	4	144	127	33	1,056

Table 8 Invasive species present in the Tonle Sap basin, based on the risk of species being invasive in the Tonle Sap Biosphere Reserve according to van Zalinge (2006). Invasive score was assigned by regional experts: 1=High impact/abundance, 2=Moderate impact/abundance.

Common name	Binomial	Family	Invasive Risk	Invasive Score
Giant mimosa	*Mimosa pigra*	Fabaceae	Major threat	1
Giant sensitive mimosa	*Mimosa invisa*	Fabaceae	Uncertain	1
Sensitive mimosa	*Mimosa pudica*	Fabaceae	Uncertain	2
Water lettuce	*Pistia stratiotes*	Araceae	Low/abundant	2
Candlebush	*Senna alata*	Fabaceae	Low	1
Seedbox	*Ludwigia hyssopifolia*	Onagraceae	Low	1
Para grass	*Urochloa mutica*	Poaceae	Uncertain / common	2
Hippo grass / creeping paddy weed	*Echinochloa stagnina*	Poaceae	Uncertain / locally dominant	2
Cutgrass	*Leersia hexandra*	Poaceae	Uncertain / locally dominant	2
Water hyacinth	*Eichhornia crassipes*	Pontederiaceae	Invasive	1
Guinea grass	*Megathyrsus maximis*	Poaceae	-	1
Apple snail	*Pomacea* spp.	Pilidae	High	1
Red-bellied pacu	*Piaractus brachypomus*	Characidae	Substantial	1
Nile tilapia	*Oreochromis niloticus*	Cichlidae	Uncertain	2
African catfish	*Clarias gariepinus*	Clariidae	Uncertain	1

Flood regulation scored 100 (weighting 0.21) as the highest river level recorded during the assessment period (9.03 m) was less than either the flood or flood warning levels. Water associated diseases scored 57 (weighting 0.10). Exposure to dengue fever was highest in August (ecosystem service indicator [ESI] score of 40) and lowest in May (ESI score 83).

Cultural & aesthetic scored 73 (weighting 0.15). One hundred and eighty-nine kilometres of river bordered protected areas and 4,220 km of river were contained within protected areas. This gave a percentage of river length protected score of 28. Stakeholders gave conservation of cultural heritage a weighting of 0.88 compared to 0.12 for recreation (not assessed) with a high degree of consensus at 95%.

Table 9 Deviation of water quality metrics from benchmarks (DyWO) F_1, F_3 and indicator scores for 21 water quality parameters for 2013–2017.

Water Quality Parameter	F_1	F_3	DyWO Score
Total suspended solids	50	4.3	85
Total phosphorous	66.7	2.9	86
Total nitrogen	100	1.0	90
pH	83.3	0.4	95
Electrical conductivity	0	0	100
Dissolved oxygen	100	34.0	42
Chemical oxygen demand	100	9.2	70
Total nitrate and nitrite	83.3	2.8	85
Ammonia	0	0	100
Ammonium	50	0.3	96
Calcium	100	0.8	91
Magnesium	100	4.8	78
Sodium	100	4.8	78
Potassium	100	0.5	93
Alkalinity	100	0.9	91
Chloride	100	18.2	57
Sulphate	83.3	0.7	92
Calcium/Magnesium	83.3	3.1	84
Sodium/Chloride	100	15.3	61
Sodium/Potassium	83.3	2.2	87
Calcium/Sulphate	100	0.5	93

Table 10 Summary of weighted scores for governance & stakeholder indicators.

Governance & Stakeholders Major- (bold) & Sub- Indicators with Stakeholder Weightings [ ] and Consensus (%)	Weighted Score
Aggregate score	58
Enabling environment [0.36] – 79%	**55**
Water resources management [0.34]	59
Rights to resource use [0.19]	55
Incentives & Regulations [0.20]	58
Technical capacity [0.18]	56
Financial capacity [0.09]	45
Stakeholder engagement [0.30] – 14%	**56**
Information & knowledge [0.58]	53
Engagement in decision-making [0.42]	61
Vision & Adaptive governance [0.21] – 47%	**67**
Monitoring mechanisms [0.24]	59
Comprehensive planning & Adaptive management [0.76]	70
Effectiveness [0.13] – 94%	**56**
Enforcement & compliance [0.57]	50
Distribution of benefits from ecosystem services [0.35]	65
Water-related conflict [0.08]	64

Governance & stakeholders

Governance & stakeholders scored 58 (Table 10). Vision and adaptive governance received the highest major indicator score (67), within which comprehensive planning & adaptive management had the highest sub-indicator score (70) and received the highest weight. Among the other major indicators, enabling environment scored 55, whereas stakeholder engagement and effectiveness both scored 56 (Table 10). Among the sub indicators, financial capacity scored the lowest at 45.

Stakeholder preferences ranged widely for the four major indicators, with enabling environment rated as most important and effectiveness as the least important (Table 10). There was a high degree of consensus in weightings for the major indicators (72%). Weightings within the sub-indicators also varied widely as did the levels of consensus. Although consensus for enabling environment was high (79%), the highest degree of variance within individual questions were those regarding the quality and clarity of rules for handling wastewater and fisheries.

Discussion

Our December 2021 FHI assessment revealed that while the Tonle Sap basin's environment was stressed (with an ecosystem vitality score of 41), it provided ecosystem services (score of 72), although not to the full extent required. This was within a functioning but somewhat variable governance and management system (governance & stakeholders score of 58). Thus, without improvement, the stressed environment may not be able to support the current level of ecosystem service provision in the future. Whether the current system of governance and stakeholder engagement can respond to the need to improve environmental conditions is uncertain.

The low score for ecosystem vitality was due to low scores for drainage basin condition and biodiversity. The land cover naturalness score was influenced by over half the basin having being transformed, largely to grow rice. The assessment's lowest score of three, for flow connectivity, was due to the large number of barriers within the basin. Our assessment identified many more barriers than were previously known from the Tonle Sap basin (see Baran *et al*., 2007). Most barriers were found in Thailand, where long sections of stream appear to have been modified to form small continuous irrigation ponds. Furthermore, recent large-scale irrigation development was recorded in Cambodia. The construction of three fish passes—while acknowledging and attempting to solve the connectivity problem—had no effect on the overall score.

Our application of the flow connectivity index did not account for the full complexity of the Tonle Sap's fish biodiversity. Seventy-two percent of the lakes fish are migratory and many move between the lake and its tributaries. Ideally, we would assess connectivity separately for each tributary, but without tributary specific species lists or population sizes this was not possible. Large numbers of fish migrate long distances from the Tonle Sap Lake up the Mekong River where barriers are also a significant issue (Souter *et al*., 2020). These were also not assessed and neither was the influence of the Dai fishery in the lower reaches of the Tonle Sap River, which blocks fish passage through harvest, although its impact is debated (Grenouillet *et al*., 2021). While a more in-depth assessment of connectivity within the Tonle Sap system is warranted, the large number of barriers we identified will impact on its fish fauna, most of which is migratory. Further threats to the basin's fish fauna were revealed by the biodiversity assessment, as most threatened and critically endangered species were fish. There were also numerous invasive and nuisance species.

Our higher deviation in natural flow regime scores from the lake compared to the Tonle Sap/Mekong River junction suggests that local basin inflow has a moderating effect on larger changes in flow from the Mekong. However, the growth of irrigation and hydropower development within the Tonle Sap Basin—particularly over the last decade—could alter this moderating effect, causing a further departure in the lakes' flow regime from natural conditions.

Our ecosystem vitality score revealed a stressed environment, signs of which are appearing in the provision of ecosystem services. The stress on the basin's biodiverse fish fauna is concurrent with the reduced ability of the lake to provide local fishers with a subsistence level catch. In calculating water supply relative to demand, we relied upon a whole of Cambodia estimate, calculated using a simplified method, rather than Tonle Sap basin specific data. The increase in irrigation development within the Tonle Sap basin suggests that this current high level of service provision is likely to decline in future as water is captured and used for irrigation at the expense of other uses, such as providing flow to sustain the Tonle Sap fishery. While stakeholders weighted water supply relative to demand as being of higher importance than biomass for consumption, there was a low degree of consensus, indicating the potential for future conflict. This highlights the need to accurately assess water consumption and demand within the basin.

Regulation & support received the highest ecosystem service score and all of its components measured scored highly. Deviation of water quality metrics from benchmarks received the highest score for sub-indicators, although point and non-point sources of pollution have been documented around floating villages and the Tonle Sap River (Ung *et al*., 2019; Shivakoti & Pham, 2020; Sor *et al*., 2021). Our flood regulation indicator must be viewed with low confidence as it was calculated from only a single site. Sediment regulation was viewed as the second most important regulation & support service but could not be calculated due to a lack of data. The productivity of the Tonle Sap Lake is driven by high levels of sediment inflow from the Mekong River. This highlights the difficulty of assessing the freshwater health of the Tonle Sap basin in isolation from the rest of the Mekong basin.

One of the most common comments regarding the management system for the Tonle Sap was that while numerous plans and policies had been developed, implementation had been limited due to a lack of resources. This was supported by our survey results with comprehensive planning & adaptive management receiving the highest sub-indicator score, whereas financial capacity and enforcement & compliance received the lowest (Table 10). Jurisdictional overlap between government departments and moves to decentralize power to the provinces—which lack technical capacity—were also seen to hinder effective management. The assertions that information to support decision making is often lacking and that stakeholder consultation could be improved were also supported by our survey results.

Our FHI results can guide management of the Tonle Sap basin. First, adequate capacity and resources are required for the implementation of existing management policies and plans. While examining existing plans and policies was beyond the scope of our study, we recommend priority be given to those that address ecosystem vitality, primarily: restoring natural vegetation cover, threatened species conservation, managing the impact of invasive species and improving fish passage. To preserve and increase the supply of ecosystem services, we recommend improved fisheries management and ensuring that irrigation development does not negatively impact the fishery, primarily through reductions in flow to the Tonle Sap Lake. The localized impact of point source water quality pollution and extensive development of the catchment in Thailand also deserves further investigation.

In conclusion, the poor environmental condition of the Tonle Sap basin and areas of stress in delivering ecosystem services is concerning given their importance for Cambodia. Increased irrigation development and consequent future water diversion has the potential for conflict. While the governance system for basin was partially functioning, it needs to be improved to meet the challenges posed by increased development and poor environmental health. Several important areas where data are lacking include water use and sediment supply. The complex relationship between the Tonle Sap Lake, its local basin and the wider Mekong basin presented challenges in undertaking this assessment.

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Annex 1 Fish species of the Tonle Sap basin

The presence of fish species in the Tonle Sap basin were compiled from ten sources (Lim *et al*., 1999; Lamberts, 2001; Chan *et al*., 2008, 2017; Hartmann *et al*., 2013; Kong *et al*., 2017; Ainsley *et al*., 2018; Marsden *et al*., 2018; Ngor *et al*., 2018a; Pool *et al*., 2019). Information in these references regarding migratory life history and that in Baran *et al*. (2014) were used to develop a consensus position on whether fish are Migratory (M), Non-migratory (NM), Estuarine (E), or could not be classified. Mr=Marine, W=White, G=Grey, B=Black, O=Opportunist, P=Present but no migratory information provided. Figures in Baran *et al*. (2014) indicate the level of evidence for the species being migratory, 1 being the lowest 3 the highest.

Species	**Baran *et al*. (2014)**	**Lim *et al*. (1999)**	**Lamberts (2001)**	**Chan *et al*. (2008)**	**Hartmann *et al*. (2013)**	**Kong *et al*. (2017)**	**Chan *et al*. (2017)**	**Marsden *et al*. (2018)**	**Ngor *et al*. (2018a)**	**Ainsley *et al*. (2018)**	**Pool *et al*. (2019)**	**Consensus**
Aaptosyax grypus	2								W			M
Acanthocobitis sp.									B			NM
Acanthopsis spp.									B			NM
Acanthopsis sp. 1				W				P				M
Acanthopsis sp. 5				W				P				M
Acanthopsoides delphax	2			W					W			M
Acanthopsoides gracilentus	P			W					W			M

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Acanthopsoides hapalias					P							-
Achiroides leucorhynchos	P			W			W		W			M
Albulichthys albuloides	P	P		W			W		W			M
Ambastaia sidthimunki									W			M
Amblypharyngodon chulabhornae										P		-
Amblyrhynchichthys truncatus	2	P		W			W		W			M
Amblyrhynchichthys sp.								P				-
Anabas testudineus	P	P	B	B		NM	B	P	B	P	NM	NM
Anguilla marmorata	3			W					W			M
Arius caelatus				W								M
Arius maculatus				Mr					E			E
Arius sona				Mr								E
Aris stromi		P										-
Arius venosus									E			E
Arius sp.							W					M
Aulopareia janetae									E			E
Bagarius bagarius	P			W					W			M
Balitora meridionalis									W			M
Bagarius suchus				W					W			M
Bagarius yarrelli	2			W								M
Bagrichthys macracanthus								P				-
Bagrichthys obscurus				W					W			M
Bagrius sp.							W					M
Balitoropsis zollingeri									W			M
Bangana behri	2			W								M
Bangana sp.				W					W			M
Barbodes altus		P	W									M
Barbodes aurotaeniatus										P		-
Barbodes rhombeus									G			NM
Barbonymus altus	P			W				P	G			NM
Barbonymus gonionotus	P	P		W				P	W		M	M
Barbonymus schwanenfeldi	P			W					G			M
Belodontichthys dinema		P										-
Belodontichthys truncatus	P			W			W		W			M
Betta prima					P							-
Boesemania microlepis	P	P		W			G		G			NM

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Botia caudipunctata								P				-
Botia eos								P				-
Botia helodes		P		W								M
Botia modesta				W				P				M
Botia morleti		P		W								M
Botia sidthimunki				W								M
Botia sp. cf. *beauforti*				W								M
Botia sp. cf. *lecontei*		P		W								M
Botia sp.							W					M
Brachirus harmandi	2			W				P				M
Brachirus orientalis	P			W				P				M
Brachirus panoides									E			E
Butis amboinensis									E			E
Catlocarpio siamensis	2	P		W			W		W			M
Channa gachua	P			B	P				B	P		NM
Channa grandinosa				B								NM
Channa lucius	P	P		B			B	P	B			NM
Channa marulioides	P			B					B			NM
Channa melasoma				B								NM
Channa micropeltes	P	P	B	B					B			NM
Channa striata	P	P	B	B	P	NM		P	B	P		NM
Chelonodon fluviatilis		P										-
Chelonodon nigroviridis		P										-
Chitala blanci	2	P		W					W			M
Chitala lopis	P			W					W			M
Chitala ornata	P	P		W			G		W			M
Cirrhinus cirrhosus	P			W					W			M
Cirrhinus jullieni	1			W				P	W			M
Cirrhinus microlepis	2	P	W	W			W		W			M
Cirrhinus molitorella	3	P							W			M
Cirrhinus prosemion				W								M
Clarias batrachus	P	P	B	B	P				B	P		NM
Clarias gariepinus	P			B				P				NM
Clarias macrocephalus	P	P		B				P	B	P		NM
Clarias meladerma	P								B			NM
Clarias nieuhofii									B			NM

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Clarias sp.									B			NM
Clupeichthys aesarnensis	P	P		W								M
Clupeichthys goniognathus		P		W								M
Clupeichthys sp.											NM	NM
Clupeoides borneensis		P		W							M	M
Clupisoma longianalis									W			M
Clupisoma sinensis	2			W								M
Coilia lindmani	P	P							E		NM	NM
Coilia macrognathos	P	P							E			NM
Coilia sp.							E					E
Corica laciniata	P			W								M
Cosmochilus harmandi	3	P		W			W		W			M
Crossocheilus atrilimes	2			W					W			M
Crossocheilus reticulatus	2							P	W			M
Cyclocheilichthys apogon	1							P		P	M	M
Cyclocheilichthys armatus	2	P				NM			G	P		M
Cyclocheilichthys enoplos	1	P		W		M			W		M	M
Cyclocheilichthys furcatus	3			W								M
Cyclocheilichthys lagleri		P								P		-
Cyclocheilichthys repasson	P			W				P	G			M
Cyclocheilichthys tapiensis				W								M
Cyclocheilos furcatus									W			M
Cynoglossus cynoglossus		P										-
Cynoglossus feldmanni	P	P		W								M
Cynoglossus microlepis	2			W					E			M
Cyprinus carpio	P	P		W					W			M
Dangila cf. *cuvieri*		P										-
Dangila kuhli		P										-
Dangila lineata		P										-
Dangila spilopleura		P	O									E
Danio albolineatus					P							-
Dasyatis laosensis	2			W								M
Datnioides polota	P								W			M
Datnioides undecimradiatus	P			W					W			M
Dermogenys siamensis					P					P		-
Discherodontus ashmeadi	P								W			M

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Discherodontus parvus									W			M
Devario leptos	P								W			M
Ellochelon vaigiensis				E								M
Esomus longimanus								P		P		-
Esomus metallicus	P								B	P		NM
Esomus sp.											NM	NM
Euryglossa harmandi		P										-
Euryglossa orientalis		P										-
Euryglossa panoides		P										-
Gambusia affinis				B					B			NM
Garra cambodgiensis	P							P				-
Garra fasciacauda	1			W				P	W			M
Glossogobius aureus	P	P							E			NM
Glossogobius giuris									E			E
Glyptothorax fuscus	P								W			M
Glyptothorax laosensis	P								W			M
Gobiidae ksan									B			NM
Gymnothorax tile									E			E
Gyrinocheilus aymonieri	P	P						P				-
Gyrinocheilus pennocki	2			W				P	W		NM	M
Hampala dispar	P	P		W				P	W			M
Hampala macrolepidota	P	P	W	W				P	W		NM	M
Helicophagus waandersi	2			W					W			M
Hemiarius stormii				Mr					W			M
Hemibagrus filamentus	2						W		W			M
Hemibagrus spilopterus	P			W				P	W			M
Hemibagrus wycki	2			W				P	W			M
Hemibagrus wyckioides	1			W					W			M
Hemipimelodus borneensis				Mr								E
Hemipimelodus intermedius				Mr								E
Hemisilurus mekongensis	2			W								M
Hemimyzon pengi									W			M
Henicorhynchus caudimaculatus		P										-
Henicorhynchus cryptopogon		P										-
Henicorhynchus lobatus	3		O	W		M			W	P	M	M
Henicorhynchus siamensis	3	P		W		M		P	W	P	M	M

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Heterobagrus bocourti				W				P				M
Hypophthalmichthys molitrix	P			W					W			M
Hypophthalmichthys nobilis	P			W								M
Hyporhamphus limbatus	P	P		E				P			M	M
Hypsibarbus lagleri	3			W		M			W			M
Hypsibarbus malcolmi	3			W					W			M
Hypsibarbus pierrei	1							P				M
Hypsibarbus suvattii	P								W			M
Hypsibarbus vernayi				W					W			M
Hypsibarbus wetmorei	2			W				P	W			M
Kryptopterus cryptopterus	P	P		W					W		NM	M
Kryptopterus geminus											NM	NM
Labeo chrysophekadion	P			W		M	G	P	W		M	M
Labeo dyocheilus	P			W					W			M
Labeo rohita	P			W					W			M
Labiobarbus leptocheilus	1								W		M	M
Labiobarbus lineatus	2			W		M			W			M
Labiobarbus siamensis	1			W		M	W	P	W	P	M	M
Laides longibarbis	P			W								M
Laubuka lankensis										P		-
Laubuka laubuca									G			NM
Lepidocephalichthys hasselti					P					P		-
Leptobarbus hoeveni	2	P	W	W					G		M	M
Leptobarbus rubripinna							W					M
Lobocheilos melanotaenia	2	P		W				P	W			M
Luciosoma bleekeri	2			W				P	W		NM	M
Luciosoma setigerum	P	P										-
Lycothrissa crocodilus	P	P		E					E		NM	NM
Macrochirichthys macrochirus	P	P		W			W		G			M
Macrognathus circumcinctus	P			W					B			-
Macrognathus maculatus	P	P										-
Macrognathus siamensis	P	P		W					B	P		-
Macrognathus taeniagaster	P	P										-
Mastacembelus armatus	P	P		W				P	E			-
Mastacembelus erythrotaenia	P	P							W			M
Mastacembelus favus	P	P										-

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Mastacembelus sp.							B					NM
Megalops cyprinoides				B					E			NM
Mekongina erythrospila	3			W								M
Micronema apogon		P	W	W								M
Micronema bleekeri		P		W				P				M
Micronema cheveyi				W				P	W			M
Micronema hexapterus									W			M
Micronema micronema		P										-
Micronema sp.							W					M
Misgurnus anguillicaudatus	P								W			M
Monopterus albus				B				P	B	P		NM
Monotrete barbatus				E								E
Monotrete cambodgiensis								P				-
Morulius chryosphekadion		P	W									M
Mugil cephalus				E								E
Mystacoleucus obtusirostris									W			M
Mystus albolineatus	P	P		W		NM		P	G			NM
Mystus atrifasciatus	P	P		W					G	P		NM
Mystus bocourti	P					NM			G			NM
Mystus filamentus		P										-
Mystus multiradiatus	P	P		W					G	P	M	M
Mystus mysticetus	P	P		W				P	G	P	M	M
Mystus nemurus	P	P										-
Mystus singaringan	P	P		W		NM			G			NM
Mysus wicki		P										-
Mysus wickioides		P										-
Mystus wolffii	P	P		W								M
Mystus sp.			B									NM
Neolissochilus blanci				W					W			M
Nemacheilus pallidus					P					P		-
Nemapteryx nenga									W			M
Netuma thalassinus				Mr								E
Notopterus notopterus	P	P	W	W		NM		P	G	P	NM	-
Ompok bimaculatus	P	P		W				P	G		NM	NM
Ompok eugeneiatus		P								P		-
Ompok hypophthalmus		P		W					G			-

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Ompok siluroides										P		-
Ompok urbaini											NM	NM
Onychostoma fusiforme									W			M
Onychostoma gerlachi									W			M
Ophisternon bengalense				B				P				NM
Opsarius koratensis	P	P										-
Opsarius pulchellus	P	P										-
Oreochromis niloticus	P			B								NM
Osphronemus exodon	P			B					B			NM
Osphronemus goramy	P			B					B			NM
Osteochilus hasselti		P		W				P			M	M
Osteochilus lineata											NM	NM
Osteochilus lini	P			W				P	W	P		M
Osteochilus melanopleura	P		W	W				P	W			M
Osteochilus microcephalus	1			W				P	W			M
Osteochilus schlegeli	1	P		W					G			M
Osteochilus vittatus	P					NM			W	P	M	M
Osteochilus waandersii	3			W				P	W			M
Osteogeneiosus militaris				Mr					E			E
Oxyeleotris marmorata	P	P		W				P	W	P		M
Oxygaster anomalura										P		-
Oxygaster pointoni										P		-
Pangasianodon gigas	2			W								M
Pangasianodon hypophthalmus	2	P		W			W		W			M
Pangasius bocourti	3			W					W			M
Pangasius conchophilus	2			W					W			M
Pangasius djambal	1			W					W			M
Pangasius krempfi	3			W					W			M
Pangasius larnaudiei	2	P		W			W		W		M	M
Pangasius macronema	2			W					W		M	M
Pangasius mekongensis	1			W								M
Pangasius micronemus				W								M
Pangasius pleurotaenia				W				P				M
Pangasius polyuranodon	3			W					W			M
Pangasius san-itwongsei				W								M
Pangasius siamensis		P		W								M

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Pangasius sp.							W		W			M
Parachela maculicauda	P	P				NM			G	P		NM
Parachela oxygastroides										P	NM	NM
Parachela siamensis	P								G	P		NM
Paralaubuca barroni	P							P				-
Paralaubuca harmandi	1			W								M
Paralaubuca riveroi	1							P	G			M
Paralaubuca typus	2	P		W		M		P	W		NM	M
Parambassis apogonoides	P	P					G		G	P	NM	NM
Parambassis siamensis	P								G		NM	NM
Parambassis wolffi	P	P		W		NM	G		G		NM	NM
Pao cambodgiensis									G			NM
Pao cochinchinensis									G			NM
Pao leiurus									E			E
Periophthalmodon septemradiatus									B			NM
Phalacronotus apogon	1								W			M
Phalacronotus bleekeri	2								W			M
Phalacronotus kryptopterus											NM	NM
Phalacronotus micronemus	P								W			M
Piaractus brachypomus									B			NM
Plotosus canius				E								E
Polynemus borneensis		P										-
Polynemus dubius	P								E			E
Polynemus longipectoralis		P		E								E
Polynemus melanochir									E			E
Polynemus multifilis							E		E			E
Poropuntius deauratus	P			W					W			M
Poropuntius normani	P							P				-
Pristolepis fasciata	P	P		W		NM		P	B	P	NM	NM
Probarbus jullieni	2	P		W			W		W			M
Probarbus labeamajor	3			W					W			M
Pseudolais pleurotaenia	2								W			M
Pseudomystus siamensis	P			W				P	W			M
Puntioplites bulu	2	P							W			M
Puntioplites falcifer	3			W		NM			W			M
Puntioplites proctozysron	P	P		W				P	W			M

Annex 1 Cont'd

Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Puntius brevis	P	P							B	P	NM	NM
Puntius masyai		P										-
Puntius orphoides	P			W				P				M
Puntius rhombeus	P			W	P							M
Puntigrus partipentazona										P		-
Raiamas guttatus	1			W					W			M
Rasbora atridorsalis	P							P				-
Rasbora aurotaenia	1	P								P	NM	NM
Rasbora borapetensis	P								G	P		NM
Rasbora daniconius		P							G			NM
Rasbora dorsinotata				W								M
Rasbora hobelmani	P	P						P				-
Rasbora myersi								P				-
Rasbora pausisquamis		P										-
Rasbora paviana	P	P		W	P			P		P		M
Rasbora tornieri	P	P				NM		P	G			NM
Rasbora trilineata	P								G	P		NM
Rasbora sp.				W								M
Rasbosoma spilocerca									G	P		NM
Scaphognathops bandanensis	1			W					W			M
Scaphognathops stejnegeri				W								M
Scatophagus argus				W								M
Schistura aramis									W			M
Schistura athos									W			M
Schistura crabro									W			M
Schistura daubentoni	P								W			M
Schistura latifasciata									W			M
Scleropages formosus									B			NM
Setipinna melanchir		P					E					E
Syncrossus beauforti	3								W			M
Syncrossus helodes	2								W			M
Systomus orphoides		P								P		-
Systomus rubripinnis							G		W			M
Tenualosa thibau-deaui	3	P		W			E		W			M
Tenualosa toli	3	P		W					E			E
Tetraodon sp.											NM	NM

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Species	Baran *et al.* (2014)	Lim *et al.* (1999)	Lamberts (2001)	Chan *et al.* (2008)	Hartmann *et al.* (2013)	Kong *et al.* (2017)	Chan *et al.* (2017)	Marsden *et al.* (2018)	Ngor *et al.* (2018a)	Ainsley *et al.* (2018)	Pool *et al.* (2019)	Consensus
Thynnichthys thynnoides	2	P	O	W		M		P	G	P	M	M
Tor laterivittatus	P			W					W			M
Tor sinensis	2			W					W			M
Tor tambroides	2			W					W			M
Toxotes chatareus	P	P					E					-
Toxotes microlepis	P	P		W					E			M
Trichogaster microlepis	P	P		B								NM
Trichogaster pectoralis	P	P		B								NM
Trichogaster trichopterus	P			B								NM
Trichogaster sp.							B					NM
Trichopodus microlepis						NM	B		B	P	NM	NM
Trichopodus pectoralis							B		B			NM
Trichopodus trichopterus									B	P	NM	NM
Trichopsis pumila										P		-
Trichopsis vittata	P				P					P		-
Trichopterus microlepis											NM	NM
Wallago attu	P	P	W	W			W	P	W			M
Wallago leerii	3	P		W								M
Xenentodon cancila	P	P		W		M			W			M
Xenentodon canciloides	P	P										-
Xenentodon sp.										P	NM	NM
Yasuhikotakia caudipunctata	P								W			M
Yasuhikotakia lecontei	P								W			M
Yasuhikotakia modesta	2								W			M

Annex 2 Governance & stakeholders survey, Tonle Sap freshwater health index

The freshwater health index is an analytical tool developed by Conservation International and partners to promote freshwater security and the sustainable management of freshwater ecosystems. It provides a comprehensive assessment of freshwater ecosystems along three dimensions—ecosystem vitality, ecosystem services, and governance—with a goal of linking science, policy, and practice.

This survey is designed to gather information for the governance assessment and aims to understand the views of different stakeholders from the Tonle Sap River basin on the coordinating mechanisms, participatory processes, governance effectiveness, and long-term planning within the region. Your response to the survey and all questions is voluntary. Your valuable advice will provide a basis for a comprehensive assessment of the

Annex 2 Cont'd

state of the current governance system within the Tonle Sap basin. Your answers will remain anonymous, but we ask for your opinions (not the views of your institution) as well as basic identifiers of your country and affiliation. The information collected will only be used for research purposes, and personal data will be kept confidential. Thank you for your cooperation and help.

Current affiliation

Government; NGO; Research/academia; Industry; Other

Unless otherwise stated all questions are assessed according to the following criteria:

Based on your own knowledge of the current situation, please evaluate the degree to which the following functions are being fulfilled throughout the basin. Provide a rating between 1 and 5 following the criteria below. Please skip any items which you do not feel qualified to answer.

Rating	Criteria
1	Strongly disagree with statement
2	Disagree with statement
3	Neutral
4	Agree with statement
5	Strongly agree with statement

Water resource management (1 of 12)

Integrated water resources management is a guiding framework for coordinating both development and management of all resources within a basin, to maximize welfare without compromising ecological sustainability. In some cases a single agency, such as a river basin authority, is responsible for coordinating and overseeing these functions; the questions below focus on the specific functions as managed within your jurisdiction (e.g. transnational, national or provincial) regardless of whether they are all carried out by the same agency.

A) Implementation of existing water resource development and management policies are well coordinated. For example: if there is catchment organization or commission, how effective is it in coordinating the different agencies, levels of government (e.g., national, provincial, local), and private interests when establishing integrated development plans for the catchment?

B) Infrastructure such as dams, reservoirs, and treatment plants are centrally managed or coordinated. For example: dam operators communicating the timing and volume of reservoir releases, or assessing cumulative impacts of dams.

C) There is (adequate) financial contribution towards water resources management. For example: cost-sharing for common projects, or collecting user fees/taxes.

D) Ecosystems conservation priorities are developed and actions implemented. For example: protecting forested watersheds, maintaining wetland/river connectivity, or developing an aquatic species biodiversity action plan.

E) Dispute resolution mechanisms are used to settle potential conflicts between districts or stakeholders within the catchment. For example: negotiations mediated by the provincial government to reach consensus.

Rights to resource use (2 of 12)

Clear and enforceable rules are recognized as a requirement for the efficient use of scarce resources, and as a means of resolving conflicts. These rules encompass various uses and users of water, and can be both formal (i.e., legislated by a government body) or informal rules administered by communities.

A) Rules for allocating water among different sectors (e.g., municipal, industrial, agricultural) are clear and transparent. For example: prioritizing water according to use, or limits on the timing and amount of water that can be withdrawn.

B) Rules for allocating water among administrative boundaries (e.g., cities, provinces, countries) are clear and transparent. For example: prioritizing water according to use, or limits on the timing and amount of water that can be withdrawn.

C) Rules for groundwater abstraction are clear and transparent. For example: guidelines regarding the depth of wells, or amount of water that can be withdrawn within a certain time period.

D) Rules for wastewater handling and water pollution are clear and transparent. For example: guidelines regarding the discharge of wastewater (e.g. pollutant concentrations, volume, temperature, time of release) into water bodies.

E) Rules for managing land use (including aquaculture) to safeguard water resources are clear and transparent. For example: guidelines regarding soil management practices, the amount of forested land in watersheds, or the volume of runoff allowed for a given plot of land.

F) Rules for freshwater fisheries are clear and transparent. For example: guidelines on catch limits, protected species, or fishing methods.

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Incentives and regulations (3 of 12)

Various management tools, from conventional regulations to market-based instruments can be applied within a governance system. Having a variety of tools offers opportunities to increase the efficiency of interventions (e.g., cost per unit outcome) or lead to a more equitable distribution of benefits.

A) Environmental and social impact assessments for all major water projects, regardless of funding source, are carried out prior to decisions being taken. For example: environmental impact assessment (EIA) that is submitted to a government body for evaluation.

B) There are financial incentives for environmental stewardship. For example: mechanisms for providing payments for watershed services provided by upstream stakeholders (e.g., farmers, forest managers, local governments).

C) There are market-based exchange schemes. For example: tradeable water rights, wetland mitigation banking, pollutant trading, inter-basin transfer schemes or REDD+ initiatives.

D) There are honorary recognition programs in water resources management. For example: publishing lists of industries with good environmental performance, or awards for local governments practicing good water stewardship.

E) There is a land use zoning policy that is designed to support water management. For example: requirements for riparian buffers, floodplain development, or forested catchment zones.

Technical capacity (4 of 12)

Lack of local capacity is often cited as an impediment to a variety of issues in resource management. Here we are referring to people employed in areas of water resource management, service delivery, monitoring and enforcement, and related research, but excluding international consultants.

A) There is an adequate number of staff (including local consultants) to fulfil necessary functions. For example: backlogs (work waiting to be done) in a particular agency, or open positions remaining vacant due to lack of candidates.

B) Staff have sufficient expertise to fulfil necessary functions. For example: hydrologists to evaluate a proposed dam, or fisheries ecologists to assess fish stocks.

C) There are opportunities for professional training and certification on water resources management. For example: financial support or time allocated for continuing education courses related to improving technical skills.

Financial capacity (5 of 12)

Water resource development and management is often under-financed, particularly for services that do not generate revenue, such as ecosystem protection. Although financial capacity can be measured directly as a function of existing allocations relative to estimated budget needs, qualitative information is also useful in providing insights and identifying priorities.

A) There is sufficient investment in water supply development. For example: financial resources for building and maintaining reservoirs or irrigation systems.

B) There is sufficient investment in service delivery systems. For example: financial resources for building and maintaining water distribution networks (i.e. piped supply) or household wells.

C) There is sufficient investment in wastewater handling and treatment. For example: financial resources for building and maintaining community toilets, or treatment systems to process waste water.

D) There is sufficient investment in ecosystem conservation and rehabilitation. For example: financial resources for protecting wetlands to mitigate flood risk, remediating impaired streams, or rehabilitating fish stocks.

E) There is sufficient investment in monitoring and enforcement. For example: financial resources for evaluating EIAs, collecting environmental data, inspecting facilities, and enforcing regulations.

Information access and knowledge (6 of 12)

Sound water governance requires information on a range of topics and from many sources. Even in cases where data and information are abundant, if they are not made accessible (across agencies, with citizens, etc.) then they are less likely to aid in wise decision making.

A) Information is accessible to interested stakeholders. For example: reports made freely available through a website, or data available upon request to the agency with the information.

B) Information meets expected quality standards, in terms of frequency, level of detail, and subjects of interest to stakeholders. For example: time series data on streamflow, water levels, or water quality for specific locations within the basin.

Annex 2 Cont'd

C) Information is transparently sourced. For example: methods used to collect data are documented, or authors (source) of these data are clearly identified.

D) All available, sound and relevant information is routinely applied in decision-making. For example: modifying an infrastructure project based on EIA results, or adjusting fisheries management guidelines based on fish catch data.

Engagement in decision-making processes (7 of 12)

Stakeholder engagement encompasses the process by which any person or group with an interest in a water-related topic can be involved in decision-making and implementation. It is associated with improved information transfer, better targeted and more equitable plans and policies, improved transparency and accountability, and reduced conflict.

A) All relevant stakeholders have been identified and notified when considering major decisions. For example: mapping and notifying stakeholders affected by a proposed water supply infrastructure project (e.g. construction of a water supply dam).

B) Stakeholders (men and women) are able to provide comments prior to major decisions being taken. For example: consultation meetings or an information gathering period where stakeholders may provide input regarding a policy or project.

C) Representatives from catchment district and other actors meet regularly to exchange information and, when appropriate, take decisions. For example: steering committee or other political meetings convened by the Cambodian government, workshops convened by a provincial agency or NGO.

D) Decisions are made based on stakeholders' participation. For example: processes for reaching joint agreements among a group of stakeholders prior to approval of a major policy or project, or projects being revised subsequent to stakeholder feedback.

Enforcement and compliance (8 of 12)

In many societies, there is a gap between laws and their actual enforcement, reflecting either insufficient capacity or a lack of accountability. Enforcement and compliance can be ensured through fines, incentives, or social pressure, but weak enforcement leads to poor management and a lack of confidence in the system.

A) Surface water abstraction guidelines are enforced. For example: industries restricted from withdrawing more than a specified amount of surface water, or farmers sanctioned for withdrawals during the dry season.

B) Groundwater abstraction guidelines are enforced. For example: farmers or industries restricted from pumping more than a specified amount of groundwater.

C) Flow requirement guidelines are enforced. For example: dam operators meeting the expectations of downstream water users, to meet environmental flows, human water needs, and/or flood protection.

D) Water quality guidelines are enforced. For example: industries and communities complying with requirements related to pollutant discharges, or non-negotiable fines are levied on violators.

E) Land use guidelines are enforced. For example: environmentally sensitive zones (e.g., catchment forests and wetlands) being protected from development or degradation.

Distribution of benefits from ecosystem services (9 of 12)

Equity is an important issue in water resource management, most closely associated with access to safe water and sanitation. Here we extend the concept to include all benefits from ecosystem services in the basin (water and sanitation, fisheries, flood mitigation, water quality maintenance, disease regulation, and cultural services).

A) Low income (rural) communities benefit from ecosystem services. For example: poor households' access to improved water supply sources at a reasonable cost, protection from inland flood risks, or rural compared to urban populations' benefits.

B) Local communities benefit from ecosystem services. For example: exercising customary rights related to water, including for consumptive as well as cultural uses, or maintaining traditional fisheries.

C) Women and girls benefit from ecosystem services. For example: amount of time collecting water for households, or provision of toilets for females.

D) Resource-dependent communities benefit from ecosystem services. For example: fishermen and smallholder farmers' incomes compared to other economic sectors.

E) All districts and stakeholders share in the benefits from ecosystem services. For example: water for irrigation, water for industry, and tourism.

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Water-related conflict (10 of 12)

Tensions among stakeholders are expected when there is competition for scarce resources such as water. An effective governance system should prevent tensions from escalating into conflicts, here defined as a difference that prevents agreement, and therefore delays or undermines a decision taken with the basin.

A) There are frequent conflicts due to overlapping decision making powers (e.g., between national governments in transboundary systems, provincial and national government, or between agencies). For example: disputes between the local environmental bureau and a national ministry about authority within a floodplain, or between agencies in managing agricultural pollution.

B) There are frequent conflicts about water rights allocation. For example: disputes about how water is allocated between two municipalities, or between agricultural and industrial users.

C) There are frequent conflicts about access to water resources. For example: disputes about having access to safe water and sanitation, or the costs of such access.

D) There are frequent conflicts regarding the placing of infrastructure. For example: disputes about reservoir development and resettlement plans for residents and land owners, or downstream impacts to fisheries or water users.

E) There are frequent conflicts over water quality and other negative downstream impacts. For example: disputes between upstream and downstream stakeholders about dry season flows or pollution concentrations.

Monitoring and learning mechanisms (11 of 12)

Policy and planning decisions about water resources management are ideally based on sound data and information, which must be collected on a regular basis. Monitoring entails costs and so data collection should be based on needs and assessed relative to resource constraints, where a comparatively wealthy basin might invest in higher spatial and temporal coverage of information.

Provide a rating between 1 and 5 following the criteria below.

Rating	Criteria
1	Data are very poorly monitored, or not monitored at all
2	Data are poorly monitored
3	Data are acceptably monitored
4	Data are well monitored
5	Data are very well monitored

A) Overall standard of water quantity monitoring. For example: streamflow being regularly measured, estimated, or modeled in the basin.

B) Overall standard of water quality monitoring. For example: water quality samples taken from water bodies and measured, or water quality being modeled based on data related to discharge of pollutants.

C) Overall standard of biological and ecological monitoring. For example: surveillance undertaken to assess aquatic species (e.g., harvested, threatened, invasive) populations or communities (e.g. macroinvertebrates).

D) Overall standard of monitoring access to, and use of, water. For example: household surveys administered to estimate the coverage of access to improved water and sanitation sources, or estimates of farmers' groundwater extraction.

Strategic planning and adaptive governance (12 of 12)

Comprehensive planning is the process of developing goals and objectives concerning water quantity and quality, surface and groundwater use, land use change, river basin ecology, and multiple stakeholders' needs. Adaptive management refers to the ability to handle changes, unintended consequences, or surprises to the water resource system through updating planning and processes using new information

A) A shared vision is established and used to set objectives and guide future development. For example: goals for improvement are jointly established by multiple stakeholders, or a process is in place for developing local water plans that inform higher-level (provincial or national) plans.

B) There are strategic planning mechanisms. For example: basin-specific spatial plans or management plans that guide investments and policy, or climate change adaptation plans.

C) There is an adaptive management framework that is effectively applied. For example: updating plans to reflect new knowledge or changing economic development priorities, or to address issues such as climate change.

