

Article

Comprehensive Study on Freshwater Ecosystem Health of Lancang River Basin in Xishuangbanna of China

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Received: 27 April 2020; Accepted: 10 June 2020; Published: 16 June 2020



Abstract: The Lancang-Mekong River significantly affects the livelihood of residents in the basin as well as the lives of people in other regions of the world in terms of great development potential and its economic and ecological values. In the meanwhile, the river attracts the attention of countries in the basin and the international community because it raises potential for international conflicts. The Lancang-Mekong River leaves China from Xishuangbanna and the ecosystem status in Xishuangbanna constitutes one of the top concerns related to the basin. The study comprehensively evaluates the status of freshwater ecosystem health of the Lancang River in Xishuangbanna for the first time, with reference to aspects of ecosystem vitality, ecosystem services, as well as governance and stakeholders, firstly, linking the ecosystem and the benefits it provides as well as human activities as an organic whole. The methodology used, Freshwater Health Index, is newly developed and constitutes revision of the first attempt of its usage. Basically, the freshwater ecosystem in the studied area and period remains healthy according to the research, and the ecosystem is considered to be capable of providing sufficient services and benefits to meet the economic and societal development demands. Recommendations are proposed for more sustainable local freshwater management and utilization accordingly.

Keywords: Lancang River; Xishuangbanna; Freshwater ecosystem health

1. Introduction

The Lancang-Mekong River flows through China and five countries in the Indochina Peninsula. It is an important river in Southeast Asia and provides important freshwater resources for living, agriculture, industry, and hydropower generation for millions of people downstream. The fish species diversity in the Lancang-Mekong River is second only to the Amazon River [1]. Studies reveal that the basin is rich in mineral, oil and gas resources as well [2,3]. Furthermore, Tonle Sap Lake in Cambodia and the Mekong Delta in Vietnam are also important “fish silos” and “granaries” in Southeast Asia and even in the world. According to research of the Asian Development Bank, the fishery resources of Cambodia, originating mainly from the Tonle Sap Lake, rank first in the world for their productivity and fourth for their total catch despite the small size of the country [4]. Data show that Vietnam has become the main rice exporting country in the world since 1989 [5]. Therefore, the Lancang-Mekong River significantly affects the livelihood of residents in the basin and affects the lives of people in Southeast Asia, and even in other regions of the world in terms of great development potential and its economic and ecological values.

In recent years, rapid economic growth in the region has lifted millions out of poverty, and helped the six member countries make progress on their Sustainable Development Goals, such as Goal 1—No Poverty, Goal 2—Zero Hunger, Goal 8—Decent Work and Economic Growth, and others. However, the push for industrial development has resulted in significantly increased and diversified pollution and related risks. According to studies, the greenhouse gas emissions per capita in this region have more than doubled since 2001, and toxic discharges to air and water are increasing as well [6]. Besides, the economy is largely based on agricultural production in this region, and agriculture can be severely affected by climate change. Research shows that the Lancang-Mekong River basin is increasingly threatened by climate change [7], and extreme events show an increasing trend accordingly [8]. This has a significant impact on agricultural productivity, shipping, as well as the safety of people's lives and property.

Besides the economic and ecological importance, the transboundary Lancang-Mekong River has attracted the attention of countries in the basin as well as the international community because of the fact that it raises potential for international conflicts, as a result of uneven water resources distribution and environment pollution caused by industrial wastewater discharge or agricultural non-point pollution. Therefore, assessment and further governance of the aquatic ecological ecosystem in the Lancang-Mekong River basin is significant for regional water and food security, and is beneficial for conducting the comprehensive cooperation connected with the management and development of water and other related resources in the basin. Since the Lancang-Mekong River leaves China from Xishuangbanna Dai Autonomous Prefecture of Yunnan Province (Xishuangbanna), and becomes the boundary river between Laos and Myanmar, the ecosystem status in Xishuangbanna is one of the top concerns of countries in the basin and the international communities related to the basin.

Although there are already numerous studies on the ecology of Xishuangbanna, most of them focus on biodiversity conservation [9,10], implication analysis of rubber plantation [11–13], carbon-stock [14–16], impact of dam construction [17], as well as abiotic risk from environmental degradation in the region [18]. The health status of the aquatic ecosystem in Xishuangbanna was seldom reported.

Actually, concepts related to river ecosystem health were put forward many times previously. For example, Boulton [19], Karr [20], and Dos Santos et al. [21] used the term “river health”, which used ecological endpoints as proxies for an ability to meet human demands. Meyer [22] and Vugteveen et al. [23] presented the definitions for “stream health” and “river system health”, respectively, both of which included information on human attitudes and social institutions. As factors like increasing human demand for freshwater; pollution of rivers, lakes and catchments [24]; groundwater depletion [25]; and climate change have induced intensification of droughts [26] and floods [27], the intensification consequently imposes ever greater pressure on freshwater resources, and threaten biodiversity, food security, economic growth and human well-being. Pires et al. [28] evaluated water-related indicators against social, economic, environmental and institutional criteria and found that integrative, multi-metric indices are best-suited for measuring the complexity of water resource sustainability. Vollmer et al. [29] reviewed 95 distinct indices and found that although a subset of these multi-metric indices included biological, physical, and social indicators, they typically did not consider interactions among these dimensions, such as the link between ecological function and ecosystem services. Thus, Vollmer et al. [30] developed a conceptual framework and accompanying tool, the Freshwater Health Index, that draws attention to the relationships between healthy freshwater ecosystems and the ways in which they are governed by stakeholders as well as the benefits they provide, using an array of indicators that can be applied to a wide range of decision contexts at the scale of drainage basins. The new methodology was firstly applied in the evaluation of the Dongjiang River basin in southern China, which revealed the aspects to be improved for the methodology.

Given the importance of the Lancang River ecosystem health status in Xishuangbanna, such as to what extent the river ecosystem has been affected by human activities and the services it provides can meet local demand, together with the local governance and stakeholder engagement in river ecosystem governance and management, we jointly conducted the first freshwater ecosystem health

assessment with Conservation International, using the revised and localized Freshwater Health Index methodology. Furthermore, we proposed pragmatic and feasible advice on local freshwater management and sustainable utilization according to the assessment results.

2. Study Framework

2.1. Study Area

The studied area in this research is the Lancang River basin in Xishuangbanna, as marked in red in Figure 1. Xishuangbanna Dai Autonomous Prefecture (99°55′–101°50′ E, 21°10′–22°40′ N) is located in Yunnan Province of Southwestern China, which borders Lao PDR to the south and Myanmar to the southwest, and encompasses three county-level administrative units. Xishuangbanna is characterized by a mountainous landscape, with the elevation ranging from 389 to 2428 m derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM), with an area of 19,120 km² [12], and the northern-most tropical rainforest in the world is found here below 800 m asl [31]. It has a tropical monsoon climate, with a dry season between November and April, and a rainy season from May to October. The annual mean temperature varies from 21.7 to 15.1 °C [32], with the highest and lowest temperature of 25.3 and 8.8 °C, respectively. The annual precipitation ranges from 1193 to 2491 mm, of which more than 80% of falls are distributed during the rainy season from May to October [33].

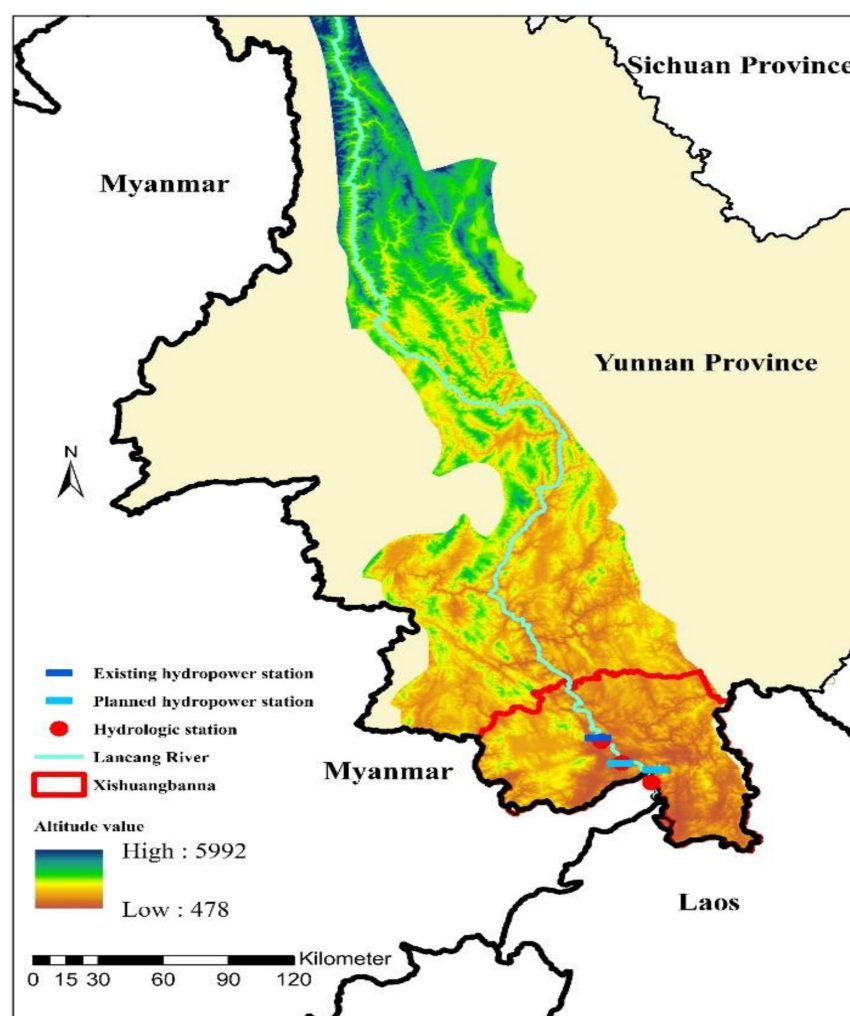


Figure 1. The Lancang river basin in Xishuangbanna.

According to local official statistics, both the permanent population and GDP in Xishuangbanna had increased annually from 2013 to 2017. By the end of 2018, the prefecture's permanent population reached to 1,188,000, and GDP for the whole year was 41.779 billion RMB, of which the primary industry accounted for 24.4%, the secondary industry accounted for 27.4% and the tertiary industry accounted for 48.2%. Basically, the growth value of the primary industry in Xishuangbanna mainly comes from agriculture and forestry; the growth value of the secondary industry mainly comes from sugar, tea, cement, rubber and other manufacturing industries as well as electric power enterprises; the growth value of the tertiary industry mainly comes from wholesale and retail industry, accommodation and catering industry, tourism service industry, and financial industry, etc., [34].

The main stream of the Lancang River in Xishuangbanna is 187.5km, and there are 2761 tributaries distributed in the region. The total length of the Lancang River network in Xishuangbanna is around 12,177 km, and the density of the river network is 0.633km per square kilometer [35].

2.2. Establishment of the Indices System

The Freshwater Health Index methodology aims to assess freshwater resource sustainability, using the conceptual framework comprising of three interacting components, i.e., governance and stakeholders, ecosystem vitality and ecosystem services. Stakeholders set and adapt rules within governance and market systems, and also, respond to them. Within the constraints and rules set by water governance, stakeholders modify ecosystems through land use change or conservation in order to exploit or manage freshwater ecosystems, and also, by developing infrastructure and technology to access water-based ecosystem services. Modifications to ecosystems and water withdrawals can alter the flow regime and water quality, and thereby, affect delivery of ecosystem services to beneficiaries, as shown in Figure 2.

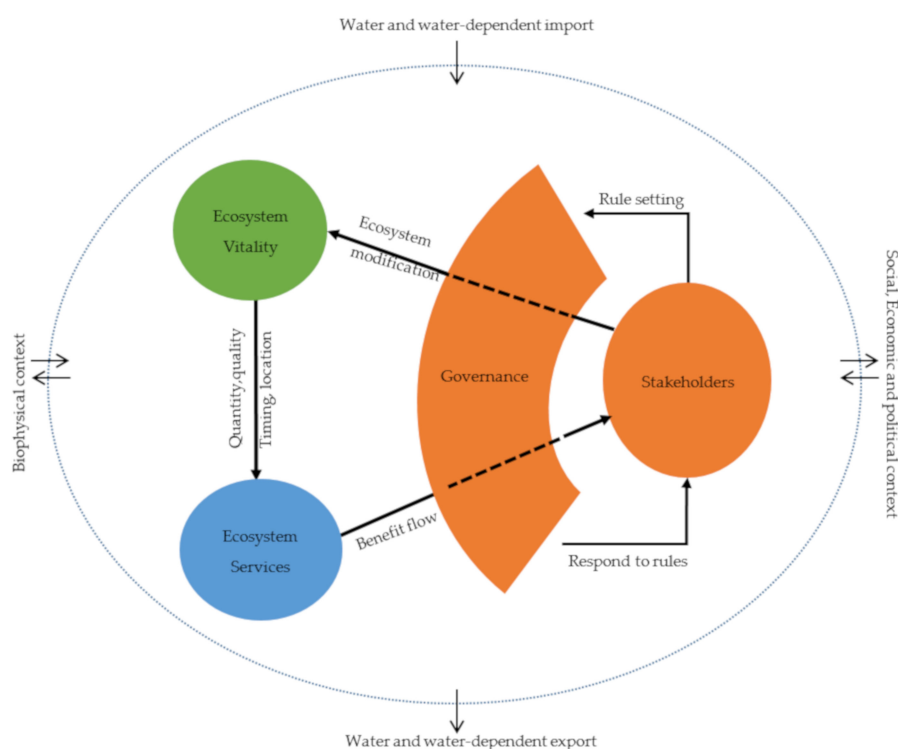


Figure 2. Interaction between governance and stakeholders, ecosystem vitality and ecosystem services [30]. Besides the interaction between the three components, the freshwater ecosystem is also impacted by external biophysical influences such as drought or climate change that affect ecosystem service delivery that can feed back to affect governance. Basins are also embedded within a broader social, political and economic context that can influence management of freshwater ecosystems.

Given this, the indicators for Freshwater Health Index methodology were selected in the context of the above three components (as shown in Tables 1–3). Each component has associated with it major indicators comprised of multiple sub-indicators. Selection of the major indicators and sub-indicators was informed by whether the indicators are representative, based on the specific conditions of the studied area, as well as whether empirical data are likely to exist, can be modeled, or can otherwise be collected efficiently.

Table 1. Ecosystem Vitality indicators.

Major Indicators	Sub-Indicators
Water quantity	Deviation from natural regime Groundwater storage depletion
Water quality	Deviation of concentration of total nitrogen (TN), total phosphorus (TP), permanganate index (PI), and anionic surfactant from environmental benchmark
Basin condition	Extent of Channel modification Land cover naturalness
Biodiversity	Changes in number and population size of species of concern, invasive and nuisance species

Table 2. Ecosystem Services indicators.

Major Indicators	Sub-Indicators
Provisioning	Water supply reliability relative to demand Biomass of fish, river prawn for consumption
Regulation and support	Sediment regulation Deviation of water quality metrics from benchmarks Flood regulation
Culture	Exposure to water-associated diseases Conservation sites and areas Water-related recreation

Table 3. Governance and Stakeholders indicators.

Major Indicators	Sub-Indicators
Enabling environment	Water resource management Rights to resources use Incentive and regulation Financial capacity Technical capacity
Stakeholder engagement	Information access and knowledge Engagement in decision making process
Vision and adaptive governance	Strategic planning and adaptive governance Monitoring and learning mechanisms Enforcement and compliance
Effectiveness	Distribution of benefits from ecosystem services Water-related conflict

2.3. Measurement and Aggregation of the Indicators

Sub-indicator scores for ecosystem vitality and ecosystem services are generally based on spatially distributed, monitored or modeled data across the studied region. Sub-indicator as well as major indicator scores for governance and stakeholders are obtained by designing and analyzing completed questionnaires; an example of the questionnaire can be found at <https://www.freshwaterhealthindex.org/user-manual>.

2.3.1. Deviation from Natural Regime

For the sub-indicator of “deviation from natural regime” (DvNF), we use monthly flow data under current and natural conditions for five years (in this study from 2013–2017) to calculate hydrologic deviation [36],

$$HD = \frac{\sum_{i=1}^{12} |m_i - n_i|}{\sum_{i=1}^{12} n_i} \quad (1)$$

where HD represents hydrologic deviation, m_i is monthly flow data accruing to current condition and n_i is modeled natural flow for the same period.

DvNF is calculated referring to the method used by Ladson et al. as follows:

$$DvNF = \begin{cases} 0 & \text{for } HD \geq 0.65 \\ 100 - \frac{100}{0.45}(HD - 0.2) & \text{for } 0.20 < HD < 0.65, \\ 100 & \text{for } HD \leq 0.20 \end{cases} \quad (2)$$

The score of DvNF 100 indicates near natural conditions, and 0 indicates high deviation.

2.3.2. Groundwater Depletion

For the sub-indicator of “groundwater depletion” (GwSD), we need to firstly identify areas of potential groundwater depletion problems.

$$GwSD = (1 - \frac{\sum a}{A}) \times 100 \quad (3)$$

where a is the area with depletion problems identified and A is the area being studied. The score of GwSD 100 indicates no groundwater storage depletion and 0 signs of widespread depletion.

2.3.3. Water Quality

For the major indicator of “water quality”, we use the Canadian Water Quality Index method [37] to calculate the deviation of concentration of total nitrogen (TN), total phosphorus (TP), permanganate index (PI), and anionic surfactant from the environmental benchmark, the concentration of the above four parameters are monitored by the hydrologic station in the studied region. Concentrations of Type III water pollutants, as set forth in the “Environmental Quality Standards for Surface Water of China (GB 3838-2002)”, perform as thresholds that the measured value should be below or within.

2.3.4. Extent of Channel Modification

The sub-indicator of “extent of channel modification” (ExCM) is composed of the combined dendritic connectivity index (cDCI) for potadromous and/or diadromous fish species and percent channel affected by modification (pCM). The cDCI measures the longitudinal connectivity of the river network while the pCM measures lateral connectivity. Because the Lancang River is a potadromous dominant system, we calculate only the combined dendritic connectivity index (cDCI) for potadromous, DCIp.

Cote et al. [38] assign barriers an associated passability value, p , which ranges from 0 to 1. This value depends on the physical, chemical and/or the hydrologic attributes of the barrier as well as the biology of the organism in question. In the absence of data, following Clarkin et al. [39], we assign each barrier a binary passability value. That is, either a barrier meets the designated fish passability criteria ($p = 1$) or not ($p = 0$). We start with $p = 0$ for all structures, and it is allowed to change to $p = 1$ according to the local conditions.

Thus, in this study,

$$cDCI = DCIp = \sum_{i=1}^n \frac{l_i^2}{L^2} \times 100\% \quad (4)$$

where n is number of fragments the studied river is divided into, L is the total length of the studied river and l_i is the length of i th fragment.

If local data on location of levees, dykes, channelization, etc., are available, then for each sub-basin, the percentage length affected, pCM_i , can be determined by expert judgement from 0 to 1 (0 for near-natural, 1 for fully channelized).

$$pCM = \left(1 - \frac{\sum_{i=1}^n l'_i pCM_i}{L'} \right) \times 100\% \quad (5)$$

where L' is the river network length and l'_i is length of river network in each sub-basin.

In this study, $cDCI$ and pCM has the same importance, thus,

$$ExCM = \sqrt{cDCI \times pCM} \quad (6)$$

2.3.5. Land Cover Naturalness

The indicator of land cover naturalness (LCN) describes the state and trend of land use/land cover (LULC) within the basin, according to the amount of human-induced transformation present. Naturalness exists on a gradient from completely natural to completely artificial [40]. In this study, the calculation method is developed based on index of naturalness methods described by Machado [41].

To calculate LCN, firstly, the determination of the naturalness weights of the studied area on a 0–100 gradient is needed, based on comprehensive analysis of factors like management of the water cycle, pollution emissions, and vegetation characteristics, combined with expert judgement. Management of the water cycle is used to indicate if the flow and/or use of water is manually altered to maintain a particular land use type. Pollution emissions are used to indicate if chemical and physical pollutants enter the local water cycle due to cultural practices. Vegetation characteristics indicate the degree of native vegetation and permanence of vegetative cover. If the studied area is natural, it means there is no flow or use of water being manually altered, no pollution emissions and the native vegetation is not destroyed. The naturalness weight of the studied area will be assigned as 100 accordingly. Otherwise, if the studied area is completely artificial, it means flow and/or water use in the area is highly manually altered, the pollution emissions are high, and there is no native vegetation remaining. The naturalness weight of the studied area will be assigned as 0 consequently.

The LCN score will be calculated by analyzing local land cover data and the Normalized Difference Vegetation Index (NDVI), comparing with the naturalness weights determined previously. The score of LCN ranges from 0–100, where 100 indicates the land cover is completely natural and 0 indicates completely artificial.

2.3.6. Biodiversity

The major indicator of biodiversity (BIO_i) composed of species of concern (ISC_i) and invasive and nuisance species (INS_i),

$$BIO_i = \sqrt{ISC_i \times INS_i} \quad (7)$$

where ISC_i is calculated in three parts: an index denoting the number of threatened and endangered species $I_{TE,i}$, a calculation of the change in the number of species of concern ΔSC_i , and the average population trend across all species of concern PT_i .

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

where $n_{TE,i}$ is the number of threatened and endangered species in the basin at time $t = i$.

$$\Delta SC_i = \frac{SC_{i-1}}{SC_i} \quad (9)$$

where ΔSC_i denotes the change in the number of species of concern from time $t = i - 1$ to time $t = i$, SC_{i-1} is the number of species of concern at time $t = i - 1$ and SC_i is the number of species of concern at time $t = i$.

For as many of these species as data are available, population trends are calculated for the relevant time period for each species as:

$$\Delta N_{i,j} = \ln\left(\frac{N_{i,j}}{N_{i-1,j}}\right) \quad (10)$$

where $\Delta N_{i,j}$ is the change in population size or abundance measure from time $t = i - 1$ to time $t = i$, j is the species, $N_{i-1,j}$ is the population size of species j at time $t = i - 1$ and $N_{i,j}$ is the population size of species j at time $t = i$.

Following the methods of the Living Planet Index [42], the average of the population trends across all species for which data are available is then calculated as follows:

$$\overline{\Delta N_i} = \frac{1}{n_i} \sum_{j=1}^{n_i} \Delta N_{i,j} \quad (11)$$

where $\overline{\Delta N_i}$ is the average of population size or abundance changes from time $t = i - 1$ to time $t = i$, n_i is the number of species for which there is population/abundance trend data across the time period. Final population trend value across all is,

$$PT_i = \exp(\overline{\Delta N_i}) \quad (12)$$

Thus,

$$ISC_i = \min\{ISC_{i-1} \sqrt{I_{TE,i} \times \Delta SC_i \times PT_i}, 100\} \quad (13)$$

For the very first assessment of the basin at time $t = 1$, $ISC_0 = 100$. For cases where no information is available on population/abundance trends, $PT_i = 1$.

Similarly, the index for invasive and nuisance species, INS_i , is also calculated in three parts: an index denoting the number of invasive and nuisance species $I_{IN,i}$, a calculation of the change in the number of invasive and nuisance species ΔIN_i , and the average population trend across all invasive and nuisance species PT_i . The calculation method for each value is in the same way of the sub-indicator of “species of concern”.

2.3.7. Sub-Indicators for Ecosystem Services

For the evaluation of sub-indicators for ecosystem services, a systematic process was created that attempts to describe and quantify the ability of an ecosystem to deliver the services under particular demand. The assessment is carried out by dividing the studied area into spatial units, in which the delivery of ecosystem services can be evaluated. Three dimensions are considered for the evaluation, i.e., scope (F1), frequency (F2) and amplitude (F3). These dimensions are similar to those used in the CCME water quality index and mirror the aspects of “risk source”, “exposure” and “consequences” used in many risk calculations [43].

The three dimensions are defined as:

Scope (F1): The number of spatial units in the studied area that are unable to meet the specific objective or threshold.

Frequency (F2): The frequency with which the specific objectives or thresholds are not met, indicating the frequency with which a particular demand is not met by services delivered by the ecosystem in the studied area.

Amplitude (F3): The magnitude with which the specific objectives or thresholds are not met, indicating the gap between a particular demand and the services delivered by the ecosystem in the studied area.

The value for each dimension is scaled between 0 and 100 before combining into a final score. Data quality and availability to determine the three dimensions will vary based on the local condition, and in some cases, only one or two of the three dimensions can be calculated. Therefore, the number of dimensions and associated evidence levels [44] should be reported when calculating the final score as follows:

If only F1 can be determined (low evidence),

$$ESI = 100 - F_1 \quad (14)$$

If F1 and F2 can be determined (medium evidence),

$$ESI = \sqrt{(F_1^2 + F_2^2)/2} \quad (15)$$

If all three dimensions can be determined (high evidence),

$$ESI = 100 - \sqrt{(F_1^2 + F_2^2 + F_3^2)/3} \quad (16)$$

where ESI represents respective sub-indicator for ecosystem services, the score for ESI ranges from 0 to 100, 100 indicates the respective ecosystem service meets the demand totally, and 0 indicates that the respective ecosystem service cannot meet the demand at all.

2.3.8. Sub-Indicators for Governance and Stakeholders

For the investigation of sub-indicators for governance and stakeholders, a survey with a Likert-type 5-point scale is designed, which comprised of approximately 50 questions, organized into 12 modules corresponding to the sub-indicators. The survey includes metadata on location within the studied basin as well as sectoral affiliation, and is proposed to be completed by a variety of local freshwater ecosystem stakeholders, such as representatives from government, scientific institutions, industries, Non-Governmental Organizations (NGOs), local communities, etc. The survey responses will be averaged and normalized to give indicator scores on a 0–100 scale. Although responses are averaged for the group, the disaggregated data allow for within sample comparative analysis, to identify potential factions based on geographic location and/or affiliation.

2.3.9. Aggregation of the Indicators

Once sub-indicator scores of the studied area were measured, they were normalized to a common non-dimensional scale of 0–100. These non-dimensional sub-indicator scores were then aggregated to provide an overall score for each major indicator. The major indicators were further aggregated to provide an index value for each component. Although the three main components separately can highlight the source of the greatest problems or the most prominent factors contributing to sustainability [30], we further aggregated the indices across the three components for the comprehensive assessment of the local freshwater ecosystem health status for future comparison. Prior to aggregation, weights need to be assigned to denote greater or lesser importance of the role of each indicator for assessing freshwater health in the studied area. As demonstrated by Vollmer et al. [30] using the Analytic Hierarchy Process (AHP) [45] method, this weighting exercise provides not only a quantitative input to the aggregation of sub-indicators, but also reveals stakeholders' preferences. The AHP method is well-suited to our hierarchical indicators and allows a large number of stakeholders to provide input, recognizing that the relative importance of ecosystem services as well as governance and stakeholders indicators is a subjective matter in the current study.

For the Lancang River in Xishuangbanna, quantitative information to evaluate the indicators primarily came from in situ monitored water quality and discharge datasets, provincial statistical yearbooks, land cover maps, the China Biodiversity Red List, IUCN Red List, and the SWAT model.

These were used to calculate indicator scores for most ecosystem vitality and ecosystem services components. The modeled data were justified by field investigation and reference review.

Exceptionally, because of the unavailability of required data, the sub-indicator of “water-related recreation” for “culture” indicator of the ecosystem services component was calculated by designing a six question survey, which was completed by 20 volunteers with different backgrounds.

The governance and stakeholders indicators were determined qualitatively and were elicited by a 64 question survey using a Likert-type 5-point scale, which was organized into 12 modules corresponding to the sub-indicators. The survey was completed by 33 stakeholders coming from the government, scientific institutions, NGOs, enterprises and local communities.

We elicited the weights of all indicators and sub-indicators as well as the three components from stakeholders with a three-level analytic hierarchy process; the weights are calculated using a balanced scale in the BPMSG AHP online system [46], a web-based tool for using the AHP in group decision making.

3. Results

3.1. Weights and Indicator Scores for Lancang River in Xishuangbanna

In this study, weights of components and indicators convey the importance stakeholders place on the corresponding aspects in the basin. Among the three components, ecosystem vitality was assigned the highest weight of 0.55, followed by ecosystem services, which obtained a similar weight to governance and stakeholders. Within the ecosystem vitality component, “water quality” was weighted the highest at 0.37, followed by “water quantity” at 0.28. “Basin condition” was weighted the lowest at 0.15. Within the ecosystem services component, “provisioning” was weighted the highest at 0.46, followed by “regulation and support”, which was slightly lower at 0.42, “culture” achieved the lowest weight at 0.12. Under the governance and stakeholders component, “enabling environment” was weighted the highest at 0.48, followed by “vision and adaptive governance”, “stakeholder engagement”, both of which were weighted less than half of the highest one, and “effectiveness” was weighted at 0.1, which was half as important as “stakeholder engagement” again.

All major indicators and sub-indicators were evaluated and indicator scores ranged from 50.3 to 100 (out of 100) across all components. The weights and scores for the indices are shown in Figure 3, where color gradient depicts scores for each indicator as well as components and the Freshwater Health Index in the Lancang River in Xishuangbanna, and the size of the wedge depicts the weight each one was assigned.

3.2. Ecosystem Vitality and Ecosystem Services

From the study, we discovered that there is coherent contact among the three components, especially between ecosystem vitality and ecosystem services components, the major indicators and sub-indicators interact closely, and it is better to jointly analyze the indicators under these two components.

The complex topography and climate in Xishuangbanna have resulted in it being one of the global biodiversity hotspots [33,47]. According to local official statistics, there are 10 natural preserves with an approximate total area of 4145 km² in the prefecture, among which 2 are national-level, and the preserves account for 22.2% of the area of Xishuangbanna. Furthermore, the area within the ecological red line accounts for 42.01% of the total area in the prefecture, which is unique in China, aims to promote the balance within population, resources and environment, as well as the synergy of economic, social and ecological benefits. Due to the importance of ecosystem protection in Xishuangbanna, ecosystem vitality received a much higher weight than the other two components. This also can be used to explain why the sub-indicator of “conservation sites and areas” got a high score as 95.

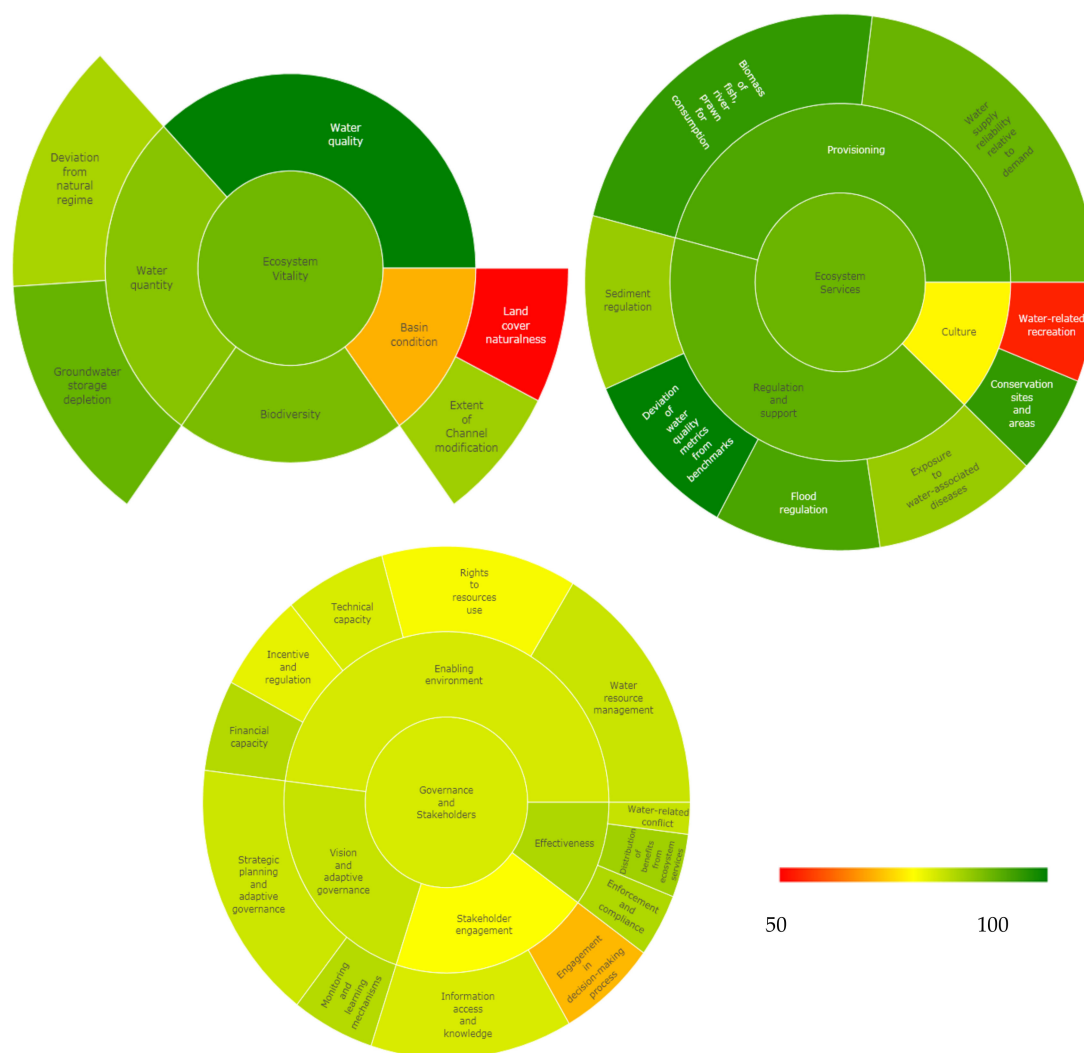


Figure 3. Summary results for Freshwater Health Index indices of Lancang River in Xishuangbanna. The results are grouped into three components. Color gradient depicts scores for each indicator, green indicates score of 100, and red indicates score of 50. The size of each wedge depicts the weight the corresponding indicator was assigned.

Accordingly, from analysis of land cover and the local NDVI data (as shown in Figure 4a), the land cover naturalness in the studied area is very high. Nevertheless, according to the field investigation and reference review, there is significant transformation from natural forest vegetation to monoculture cash crops like rubber, banana, and tea in Xishuangbanna. According to Chiwei Xiao et al. [12], the total area of rubber plantations increased about 5.9 times from 1987 to 2018, showing clear expansion trends from centralization to scattering in Xishuangbanna. Unlike natural vegetation, the rapid expansion of rubber farming has exerted negative effects on local ecosystems such as biodiversity, soil and water conservation [48,49]. The community structure of rubber forest is relatively simple; it cannot effectively buffer and intercept precipitation like natural forest, and the splash of precipitation as well as the erosion of surface runoff on soil will increase consequently in rubber forest [50]. Furthermore, rubber trees need to absorb large quantities of water from the underground to ensure the output of its products, which brings huge survival pressure to the ecosystem around rubber trees. In addition, research shows that the concentration of organic substances and soil nutrients like nitrogen in rubber forest is significantly reduced compared with those in natural forest [51], which has a negative impact on the growth of all kinds of plants. Accordingly, the local biodiversity is threatened as well.

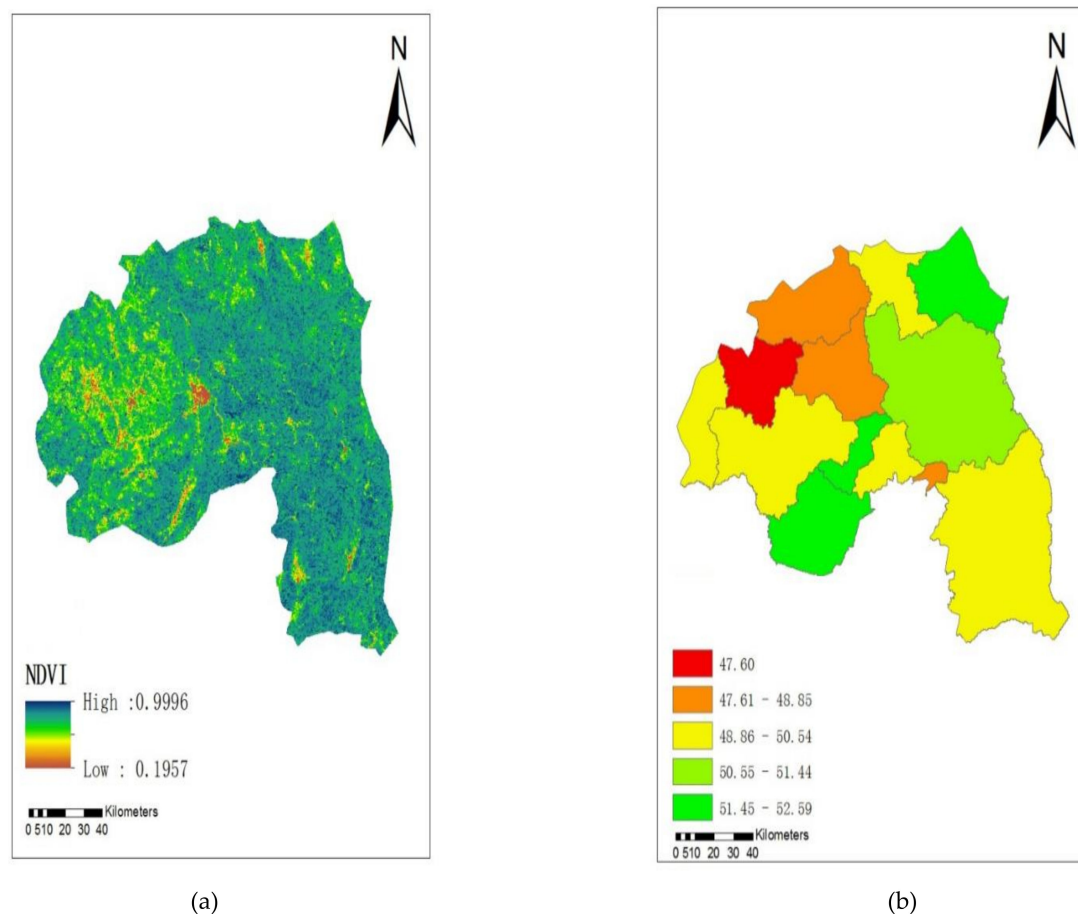


Figure 4. The naturalness of Xishuangbanna under different conditions: (a) The NDVI data in Xishuangbanna in 2017; (b) The score of land cover naturalness indicator in Xishuangbanna in 2017.

Therefore, calculations concerning this indicator incorporate the naturalness weight, which describes the variation of land use/cover status and trend from a completely natural gradient to a completely artificial one based on changes caused by human activities, as elaborated by Machado [41]. We determined the naturalness weights of the studied area via a literature review and interviews with key local stakeholders, and got the score of land cover naturalness indicator as 50.3 consequently (as shown in Figure 4b), through analysis of land cover/land use data and NDVI of the Lancang River in Xishuangbanna.

As studied, Xishuangbanna is one of the world's 34 biodiversity hotspots [47], and many valuable and rare species are clustered in its natural vegetative ecosystems [52]. However, the topography and climate condition also provide a favorable ecological environment for the survival and spread of invasive and nuisance species, especially *Chromolaena odorata*, *Ageratina adenophora*, and *Pomacea canaliculata*. Xishuangbanna has launched an investigation into these invasive and nuisance species and taken measures such as manual/mechanical eradication, chemical control, ecological control; since 2011, the invasive and nuisance species have been effectively controlled [53]. According to the China Biodiversity Red List and IUCN Red List analysis, the biodiversity remains at high level in the studied area. However, we revised the score of biodiversity as 88, considering the negative impact from monoculture plantation, mainly rubber plantation, with local stakeholders' judgment.

Xishuangbanna features abundant water resources with annual precipitation ranges from 1193 to 2491 mm [33], and there is nearly no water supply stress. Comparing the modeled data and monitored hydrologic information, the existing runoff of the Lancang River in the studied area is generally close to the natural one, despite a small gap, which can be explained by the melting of the Himalayan glaciers having a specific impact on the runoff variations of the Lancang-Mekong River. It is consistent with

the study conducted by Jing et al. [54] and Hu et al. [55]. Furthermore, we obtained a high score for the sub-indicator of “groundwater depletion” from the SWAT model and the score indicates that the groundwater storage depletion in Xishuangbanna remains at a low level. This is also in accordance with the field investigation that local stakeholders primarily rely on surface water allocation to meet their needs, while the groundwater abstraction is only used for industrial production of bottled water, indicating that there is a very small percentage of groundwater storage in Xishuangbanna being used. Therefore, the major indicator of “water quantity” under ecosystem vitality obtained a score of 86.7.

The economic structure in Xishuangbanna is dominated by the primary and tertiary industries, and the secondary industry holds a relatively small share, focusing on the manufacture of sugar, tea and rubber, followed by a lower proportion of cement and hydropower production. Furthermore, as a result of marketing demand combined with the government dissemination, farmers are preferable to produce green food using biological control or ecological farming technologies rather than chemical fertilizers or pesticides. We analyzed the environmental monitoring data from three national-controlled hydrologic stations, i.e., the prefecture’s hydrologic station, Menghan station and Guanlei station, which distribute at the upper, middle, lower Lancang River in the studied area, respectively, marked as red solid circles in Figure 1. The monitoring environmental data indicate that, water quality in the studied area remains at Type II as described in the “Environmental Quality Standards for Surface Water of China (GB 3838-2002)”, except that the water quality was at Type III monitored at Menghan station in 2015. There are five types of water qualities defined in the “Environmental Quality Standards for Surface Water of China (GB 3838-2002)”, and Type I is the strictest. Water with Type II quality is mainly suitable for a primary protected area of a surface water source of centralized drinking water, habitat of rare aquatic organisms, spawning ground of fish and shrimps, feeding ground of juveniles, etc. Water with Type III quality is mainly suitable for a secondary protected area of a surface water source of centralized drinking water, fish and shrimp wintering ground, migration channel, fishery waters such as aquaculture areas, and swimming areas. We calculated the score of “water quality” via the Canadian Water Quality Index method [40], taking concentrations of Type III water pollutants in the “Environmental Quality Standards for Surface Water of China (GB 3838-2002)” as the thresholds. The score of “water quality” under the ecosystem vitality component is 100, and the score of “deviation of water quality metrics from benchmarks” under ecosystem services is also given 100 consequently.

As shown in Figure 1, the solid square in dark blue indicates an existing hydropower station, and the solid square in light blue indicates a planned hydropower station. Figure 1 shows that there is only one existing hydropower station, namely Jinghong hydropower station, on the Lancang River in Xishuangbanna, with two others planned to be constructed, namely Ganlanba hydropower station and Mengsong hydropower station [17]. However, there are more than 200 small Type II reservoirs (reservoirs with a capacity greater than or equal to 100,000 m³ but smaller than 1 million m³) on its tributaries according to the field investigation. Research indicates that building dams or reservoirs unavoidably induces changes in river flow regimes, sediment regimes and wetland morphology and geomorphology [56,57], leaving rivers fragmented [58]. Thus, the construction of dams for hydropower stations as well as reservoirs results in channel fragmentation to some extent in the studied area. Furthermore, it is put forward that river damming has caused increasing threats on fish resources as a result of the inundation of habitats, isolation of fish populations, and interruption of migratory paths triggered by dam blockage and reservoir impoundment [59,60]. We obtained lengths of studied fragments of the river through geographic information system (GIS) analysis, and got the score for “extent of channel modification” as 84.4.

Dam or reservoir construction has two-fold impacts on flow controlling and sediment trapping, the possible positive and negative impacts of the hydropower projects are summarized as shown in Table 4.

Table 4. Possible positive and negative impacts of the hydropower projects on flow and sediment regulation.

Action	Positive Impacts	Negative Impacts
Flow controlling	Increase capacity for flood control, according to state of the basin report [61], although MRC basin-wide assessments of climate impact on flood behavior suggest that flooded areas might increase by 4.6% to 27.3% by 2060; for the last ten years, no clear trend can be seen in the extent of flooding, possibly as a result of increased dam/reservoir regulation; More assured dry season flows and creation of extra irrigation opportunities, according to Postel et al. [62], dam construction has increased secure water supply by 28% globally, a figure expected to grow to 34% by 2025. Ease navigational activities in dry seasons in many places, as with the development of commodity economy and increase in trade, shipping becomes more and more large-scale and needs a deepwater navigation channel.	Changes in the river's natural flow pattern, and possible increase of flow fluctuation, according to Vörösmarty et al. [63], large dams intercept more than 40% of the water discharge of rivers globally; Shift of the flood regime, flood arrival delays, shorter flooding period, e.g., Keskinen et al. [64] show that the floodplain area in Tonle Sap is expected to be reduced by 25% by the year of 2042 due to cumulative impacts from flood dynamics and hydrology caused by hydropower reservoirs combined with climate change.
Sediment trapping	Ease navigation in river, less problems with sedimentation, as dams help to reduce sediment in the navigable routes, making it easier to keep the channels clear [65].	Decrease flux of sediments and nutrients, according to Vörösmarty et al. [63], half of the reservoirs showing a local sediment trapping efficiency of 80% or more.

According to Yunnan Water Conservancy Yearbook, as a result of the special topographical and climate conditions in Yunnan province, the precipitation in the rainy season accounts for more than 80% of the total throughout a year. Furthermore, Yunnan has been regarded as a “disaster” province since ancient times, with floods and droughts often occurring alternately, because of the fact that mountains and plateaus stand on 94% of its territory. Therefore, the provincial government puts emphasis on water conservancy and continues to increase investments in this aspect. Xishuangbanna has witnessed great improvements in the capacity of water supply guarantee and disaster prevention and mitigation through water conservancy projects, with nearly no floods taking place. Hence, the score of “flood regulation” obtained is very high as 92.7.

As shown in Table 4, research indicates that reservoir construction represents the most important influence on land–ocean sediment fluxes [62,66]. However, sediment transport rates in the Lancang-Mekong River are poorly documented and there is no reliable definitive study. In order to calculate the score for “sediment regulation”, we simulated the sediment contents in the studied basin during 2013–2017 using the SWAT Model, and the results show that there is no obvious change during the studied period. Combined with the field investigation and interviews from local stakeholders, the score of “sediment regulation” is assigned as 85.

Indicator of “exposure to water-associated diseases” measures the prevalence of water-associated diseases. Disease risks can be increased by modifications to freshwater habitats, stagnation due to altered flow, as well as contamination of water by human wastes [67,68]. Among the water-associated diseases, cholera, typhoid fever as well as malaria have attracted high attention in the studied area [69,70]. Due to the influence of geographical location, natural environment and social factors, the occurrence and prevalence of epidemics in Xishuangbanna are characterized by universality, multiple diseases and threat of foreign import. Therefore, Xishuangbanna faces severe challenges in terms of epidemic prevention and control. Nevertheless, since successfully controlling SARS in 2003, Xishuangbanna has gradually established sound disease prevention and control systems, i.e., epidemic prevention and control becoming regular, hardware construction and emergency response capacity enhanced significantly. Through the interviews with experts from Xishuangbanna Center for Disease Control and Prevention, there were no cholera cases diagnosed during the studied period. When it comes to typhoid fever, there were more than 300 diagnosed for typhoid and paratyphoid fever in 2014, and 0 in other years of the studied period. For malaria, there were 4 diagnosed in 2014, 13 in 2013

and 0 in other studied years. Basically, occurrence of water-associated diseases is well controlled, and the score for this indicator is obtained as 85.

Indicator of “water-related recreation” measures the degree to which fresh waters have societal value in the form of recreational and tourism opportunities such as hiking, camping, boating, angling, etc. The indicator of “water-related recreation” in the study is calculated by measuring the time people spend on recreational activities in connection with freshwater ecosystems. The comprehensive questionnaire analysis indicates that local stakeholders spend little time on water-related recreation and this indicator got a low score as 53.3. This can be explained in two ways. On the one hand, the valid questionnaires which were used for analysis were mainly completed by staff of government or public institutions and students, indicating relatively low representativeness. On the other hand, it reflects great room for development and improvement of water-related recreation in Xishuangbanna.

3.3. Governance and Stakeholders

Stakeholders of the studied area are diversified and it is of vital importance to sustainable development of the river basin whether executing agencies concerned can conduct river basin planning and policy making from the perspective of macro management, and in the meanwhile, implement effective projects on basin investment, infrastructure construction as well as basin protection from the perspective of micro management and effectively coordinate stakeholders. However, the relevant work is extremely complicated. The weight assigned to this component lies between ecosystem vitality and ecosystem services, and much lower than the one for ecosystem vitality, indicating that in local stakeholders’ perception, ecosystem vitality is much more important than local governance and stakeholders’ engagement.

The scores for indicators under the governance and stakeholders component are generally lower than those under the other two components, showing that this should be a priority area of concern for the Lancang River basin in Xishuangbanna. Among all the indicators, more than one-third got scores under 80, the lowest score is even under 70 (the sub-indicator of “engagement in decision making process”), and the rest are a bit higher than 80. Although indicators in this part cannot be accurately quantified and are highly subjective, the low governance and stakeholders scores offer insight into areas that may require attention as the basin undergoes changes, whether from population growth, economic restructuring, or climate change.

The weighting revealed that stakeholders consider the indicator of “enabling environment” twice as important as “vision and adaptive governance” and “stakeholder engagement”, four times as important as “effectiveness”, which comprised of sub-indicators of “enforcement and compliance”, “distribution of benefits from ecosystem services”, and “water-related conflict”. On the one hand, this indicates that the studied area is abundant with water, and there is hardly any water use stress existing. On the other hand, it shows that there is great room for improvement in stakeholders’ perception that stakeholder engagement as well as effectiveness of water-related conflict resolution and benefits distribution are also vital to local freshwater ecosystem management. This underlines governance problems which need to be addressed for more sustainable development in the studied area.

4. Discussion

The study firstly comprehensively assessed the freshwater ecosystem health status of the Lancang River in Xishuangbanna, Yunnan province of China, from aspects of ecosystem vitality, ecosystem services, as well as governance and stakeholders, linking the ecosystem and the benefits it provides as well as human activities as an organic whole. The methodology used, Freshwater Health Index, is newly developed and it constitutes revision of the first attempt of its usage.

Generally, the freshwater ecosystem in the studied area and period remains healthy according to the research, and the ecosystem is considered to be capable of providing sufficient services and benefits to meet the economic and societal development demands. However, there are still aspects for local stakeholders to improve for more sustainable freshwater management and utilization.

Comparing to the assessment conducted in the Dongjiang River basin, which used the same methodology, there are obvious differences in weight assigned to indicators as well as scores obtained for the indicators between the two basins [30]. This well reveals the areas on which stakeholders place importance in different basins. In the meanwhile, it helps to discover the similar weakness of the methodology during its usage, as well as the aspects which the local government and stakeholders commonly need to improve in the management and sustainable utilization of the freshwater ecosystem.

Regarding the assessment in the Dongjiang River basin, the indices were not further aggregated across the three components, since demonstrating the values for the three main components separately can highlight the source of the greatest problems or the most prominent factors contributing to sustainability. In the current study, we aggregated the indices across the three components for future comparison. Among the three components, ecosystem vitality was assigned the highest weight, indicating ecosystem vitality is the most concerned about in the studied basin. However, as Dongjiang is the primary water source for more than 40 million residents, including the world's largest urban agglomeration comprising of Shenzhen, Hong Kong, Dongguan and others, water allocation and quality have emerged as top priorities because of population growth and urbanization in the basin. Even though human needs like water supply are currently being met fairly well (ecosystem services got the score of 82), this is at the expense of the region's ecology (ecosystem vitality got the score of 60).

All major indicators were evaluated, except for "culture" in the Dongjiang River basin, because no suitable data existed to calculate the indicator of "water-related recreation". Although we calculated "water-related recreation" by designing a simple survey in Xishuangbanna, which was completed by volunteers with different backgrounds, the result is rather subjective. Similarly, there are no monitoring data for groundwater or sediment loss that exist, and the scores for "groundwater storage depletion" and "sediment regulation" are calculated from modeling data combined with literature or field investigation in both the Dongjiang and Lancang River in Xishuangbanna. These are highlighted as a data gap in both local governance and scientific research.

The governance and stakeholders indicators were determined qualitatively and were elicited by an approximate 60 question survey using a Likert-type 5-point scale in the studies of the Dongjiang and Lancang River in Xishuangbanna. The survey was completed by stakeholders coming from government, scientific institutions, NGOs, enterprises and local communities. During the completion of survey analysis, we found that the design of the questionnaire is complex and covers too many fields, so it is difficult for the stakeholders to answer all the questions effectively. The stakeholders and experts also put forward suggestions for further improvement of the questionnaire from various perspectives. In the follow-up study, we will focus on improvement of the questionnaire design, including expanding sample coverage and integrating more localized indicators. Although there are few comprehensive studies on freshwater ecosystem health in the studied area previously, research is conducted on aspects such as sustainable management of land use, encouraging stakeholders' engagement, etc., which are important for the local freshwater ecosystem health.

As natural rubber is widely consumed in China, it has been listed as a key strategic natural resource, and domestic production of rubber in China is limited to tropical areas rich in biodiversity. Rapid conversion over the last few decades has left little remaining natural forest outside of protected areas in Xishuangbanna consequently [71]. To improve land use management, Xu et al. [11] surveyed the availability of ecological and socioeconomic indicators, which can help with the analytical integration of decision making in Xishuangbanna and the Mekong Region. The indicators can also play a role in tracking ecological and socioeconomic changes. The ecological indicators include two types. One is the structural biodiversity indicator, mainly considering biodiversity at the genetic, species, and ecosystem levels. The other type is the functional diversity indicator, which can be measured through habitat fragmentation, management of protected areas, and the creation of connectivity across the landscape. As for socioeconomic indicators, increases in rural peoples' income, the participation of local people in land use decision making, and local infrastructure development are suggested to be measured. We can find the common concerns in promoting sustainable management and utilization of

local ecosystem from the concept, i.e., the importance of biodiversity to ecology, the habitat to maintain biodiversity, as well as stakeholders' participation.

Based on a landscape productivity model for two management systems, i.e., state-farm and smallholder plantations, Zhuang et al. [72] developed indicators of economic value and biodiversity loss for rubber plantations in Xishuangbanna, aiming to promote forest restoration without forcing smallholders to forego profits. The economic value was reflected by constructing a spatially explicit map of net present value (NPV) of rubber plantations, and biodiversity loss was calculated through the predictive equation, as previous studies have demonstrated a strong negative correlation between elevation and species diversity of seed plants in Xishuangbanna [73]. The study shows that forest restoration programs can be created on sites where rubber NPV is negative or vulnerable to market volatility; conversion of forests to rubber plantations above 900 m elevation and on slopes steeper than 24 degrees should be banned; and mixed "Jungle rubber" should be developed, particularly in those locations with high ecological values for watershed protection, soil erosion reduction, and biodiversity conservation. This is of huge importance for stakeholders to better manage land use in Xishuangbanna.

As one of the weaknesses, stakeholders' engagement in decision making process need to be enhanced in Xishuangbanna according to the current study. Yang et al. [74] proposed that the government can start by improving school education on environmental and natural resource management to improve public participation. Moreover, a comprehensive plan to promote public participation in data collection, decision making, and performance appraisal is necessary, and the public's rights to participation must be clearly stated in relevant laws and regulations. This is meaningful for the local government's reference.

Based on the study, as well as the comparison with the Dongjiang river basin, the following suggestions are provided for local freshwater ecosystem management and sustainable utilization.

Firstly, an appropriate number of eco-friendly water-related recreational projects, which organically combine natural capital utilization and economic development, can be developed to enhance the well-being of the local residents as well as tourists, and promote water-related eco tourists.

Secondly, in light of ecology conservation as well as local farmers' income, introduction of eco-friendly agroforestry or construction of eco-friendly rubber and banana plantations is suggested, for example, finding the balancing point between forest coverage and rubber plantation on a local scale, or planting native economic species under rubber trees, so as to facilitate green transformation of local rural economy.

Thirdly, actions should be taken and awareness should be enhanced to strengthen freshwater ecosystem management by developing effective planning for usage and conservation of water resources, as well as increasing stakeholder engagement in decision making and effectiveness of aquatic ecosystem service distribution conflicts, thereby promoting local freshwater ecosystem management in a holistic manner.

In the future, we will regularly conduct the assessment in the studied area using the same methodology, in order to monitor if the suggestions work in proper way, and to formulate further advice for local sustainable development. Furthermore, we will also carry out the assessment using the same methodology in the upper Lancang and lower Mekong River for comparison, to promote coordinated development in the whole basin.

Author Contributions: Conceptualization, methodology, formal analysis, Z.W. and X.L.; investigation, draft preparation, visualization, and editing, Z.W.; review, Z.W., X.L., T.L.; supervision, T.L.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Conservation International Foundation.

Acknowledgments: The authors would like to thank Derek Vollmer's team of Conservation International Foundation for their guidance on local application and optimization of the research methodology; Ouyang Wei's team of Beijing Normal University for providing technical support for data analysis; Ecology and Environment Bureau of Xishuangbanna Dai Autonomous Prefecture for coordinating in the research investigation; other people who have provided assistance in the process of research.

Conflicts of Interest: The authors declare no conflict of interest.

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