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Framework tool for a rapid cumulative effects assessment: case of a prominent wetland in Myanmar

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Abstract The wetland of focus, Inle Lake, located in central Myanmar, is well known for its unique biodiversity and culture, as well as for ingenious floating garden agriculture. During the last decades, the lake area has seen extensive degradation in terms of water quality, erosion, deforestation, and biodiversity concomitant with a major shift to unsustainable land use. The study was conducted, with an emphasis on water quality, to analyze environmental impacts (effects) changing the ecosystem and to comprehensively evaluate the environmental state of the ecosystem through an innovative Rapid Cumulative Effects Assessment framework tool. The assessment started with a framework-forming Participatory Rural Appraisal (PRA), which quantified and prioritized impacts over space and time. Critically important impacts were assessed for "intra-inter interactions" using the loop analysis simulation. Water samples were analyzed while geographic information system (GIS) and remote sensing were used to identify water pollution hotspots. It was concluded that out of a plethora of impacts, pollution from municipal sources, sedimentation, and effects exerted by floating gardens had the most detrimental impacts, which cumulatively affected the entire ecosystem. The framework tool was designed in a broad sense with a reference to highly needed assessments of poorly studied wetlands where degradation is evident, but scarcely quantified, and where long-term field studies are fraught with security issues and resource unavailability (post-conflict, poor and remote regions, e.g., Afghanistan, Laos, Sudan, etc.)

Keywords Remote sensing · Intra-inter interactions · Participatory Rural Appraisal · Water quality · Floating gardens

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Introduction

Cumulative effect assessment (CEA) was defined as an assessment of an overall effect on the environment resulting from incremental, cumulative, and interactive impacts of an action when added to other past, present, and reasonably foreseeable future actions (Hegmann et al. 1999). The cumulative effects on an ecosystem may possibly result from the interaction between anthropogenic and natural drivers of change. Qualitative, stressor-based CEA approaches were practiced under the environmental assessment process (Dube 2003), and these approaches consisted of significant compilations of individual studies into a weight-of-evidence ranking of important changes. The focus of CEA is to understand the drivers associated with the system due to the introduction of change to the environment. CEA is strategically used to generate scientific knowledge on local to global range impacts with a view to supporting the decision-making process for sustainable development (Piper 2001).

CEA of active human development encroaching on the ecological integrity of wetlands will facilitate the wetlands' conservation and sustainable use through Integrated Water Resources Management. It is a key effort in alleviating the constant threat to global wetlands' very existence (MA 2005). Anthropogenic impacts and climate change are a key subset of perturbations for wetland ecosystems and their components. Major drivers that account for wetland degradation are land conversion, population explosion, pollution, unsustainable extraction practices, infrastructure development, and introduction of exotic invasive species (MA 2005).

Drivers (or stressors) are of two kinds: (i) direct drivers which act directly on the "ecosystem and its components" and (ii) indirect drivers linked to direct drivers through a distant bond and influence which control the direct drivers (MA 2005). The impacts on the lake ecosystems are felt due to changes (either positively or negatively) created by the drivers in the ecosystem. For example, change to land use pattern, nutrient flow from municipality and agriculture fields, changes to microclimatic condition, i.e., temperature and rainfall pattern, and exotic invaders are considered as direct drivers of change. The population explosion and booming economies exert additional pressure on the ecosystem in order to make up the gap between demand and supply. All these indirect drivers act together and develop causal relationship between ecosystem components and thus slowly begin to erode the system stability (MA 2005).

The diverse functions of wetlands include floodwater control, recharge of aquifers, retention of sediment (Furuichi et al. 2009), water purification, regulation of water flow and water quality, maintaining and safeguarding biodiversity, providing hotspots for tourism, and recreational activities (Ingelmo 2013). The products from wetland ecosystems are highly important for sustaining local economies and serve as a major source of income to local people.

Southeast Asia contains a major portion of wetlands of international significance with only 14 % of the wetland area under protection (MA 2005). One of such poorly protected, albeit highly significant wetlands situated in central Myanmar, Inle Lake, has been observed to degrade due to anthropogenic activities over the last decades. Some researchers have shown that Inle Lake faced combined threats from natural and anthropogenic activities causing reduction in lake storage capacity, deterioration of water quality, and the effect on navigability. Water quality has constantly deteriorated as a result of the application of chemical fertilizers and pesticides in the floating garden agriculture along with organic pollution from point and nonpoint sources, man-made changes in the lake water level, and increasing sedimentation due to major deforestation (Akaishi et al. 2006; Su and Jassby 2000; Furuichi et al. 2009; Furuichi and Wasson 2010). Sediments carried by creeks and waterways add an additional burden to the lake bed, thus reducing the mean depth of the lake (Furuichi and Wasson 2010; Cho and Corazon 2010).

The present study focused on the identification of impacts on valued ecosystem components with a view to prioritizing the most critical impacts affecting the components. The intra-inter interactions of the impacts were studied using a computer simulation tool. Participatory Rural Appraisal (PRA) technique was employed to collect information on impacts in three states (past, present, and foreseeable future), and impact strengths were analyzed through Rapid Impact Assessment Matrix (RIAM) tool as demonstrated by Pastakia and Jensen (1998). The objectives of the study were (i) to identify the most critical impacts affecting the particular wetland, Inle Lake, and (ii) to develop an innovative rapid assessment framework tool for CEA of a poorly studied wetland through selective integration of a number of assessment tools. Notably, the framework tool is expected to simplify and significantly facilitate assessment work on wetlands characterized by a chronic paucity of available data due to scarce assessment resources. Ironically, such wetland ecosystems represent the global majority of heavily impacted water bodies.

Materials and methods

Study area

This study area was selected after a careful review of various environmental issues/threats to the lake ecosystem. The area is one of the biodiversity hotspots of the country and also supports livelihoods of a considerable number of households residing in and around the lake. The Inle Lake ecosystem is located in the state of Shan in Central Myanmar and is the second largest wetland in the country. The lake is strategically located between the geographic coordinates of 20° 27′–20° 40′ N and 96° 52′–96° 57′ E and has an approx. length of 23 km and width of 6.5 km with a catchment area of 3700 km^2 (Fig. 1). The average annual rainfall ranges between 900 and 1200 mm of which >90 % is received during the wet season (May–September). Four major streams, namely, Nam Let Chaung, Yebei Chaung, Kalaw Chaung, and Chaung drain into the lake. Floating tomato gardens (hydroponic cultivation techniques) used by the local residents are concentrated mostly in the western part of the lake. More than 60 % of the lake catchment area is utilized for permanent or seasonal agricultural activities. This unique ecosystem comprises both freshwater and terrestrial components with diverse flora and fauna of high endemicity (Sidle et al. 2007).

The famous *Intha* communities along with other ethnic groups traditionally live in stilt houses in and around the lake. Their primary livelihood depends on aquaculture, fishing, and floating garden agriculture. Ethnic and cultural diversity, scenic beauty, and famous pagodas attract large and ever-increasing numbers of tourists, both domestic and international. At present, an average of 20,000 foreign and 200,000 domestic tourists visits the lake ecosystem annually (Ingelmo 2013; Sett and Liu 2014).

Data collection

Data on water quality, quantity, sediment flow, demographic details, and land use maps were collected from the respective Government agencies, NGOs, and research/academic institutes. The water quality parameters such as temperature, pH, salinity, and dissolved oxygen (DO) were measured in situ. A total of 34 points were earmarked across the lake, and the locations were noted down using e-Trex10 Garmin-GPS device. The DO profile and water temperature were measured at three

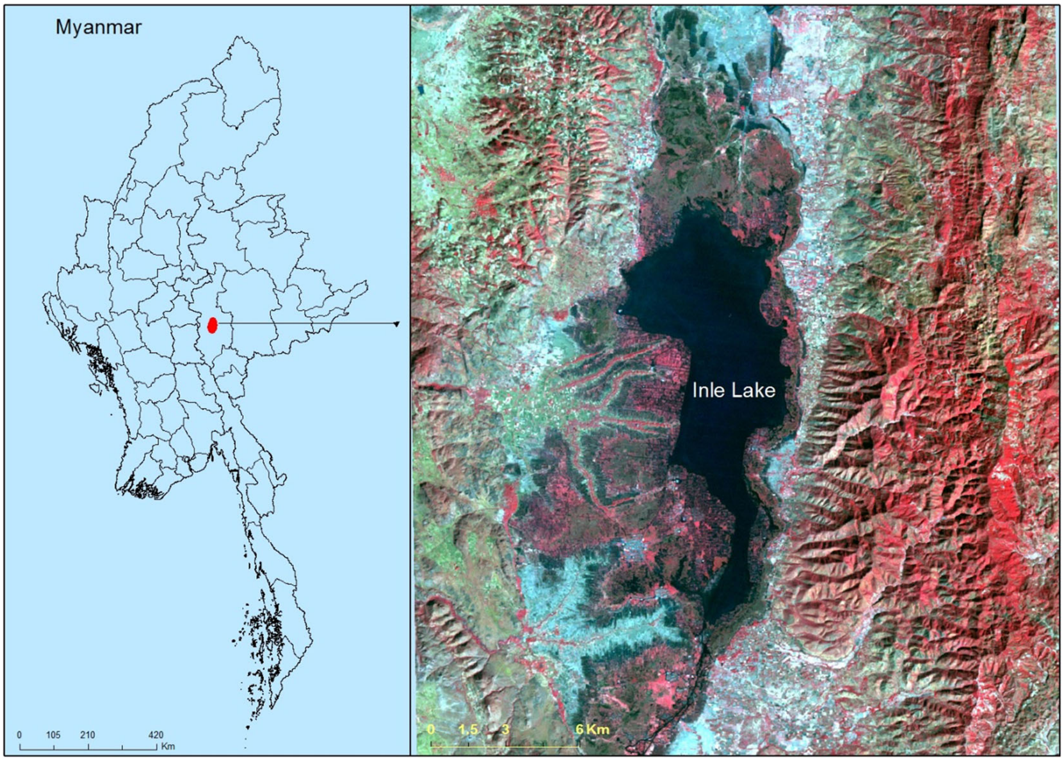

Fig. 1 Map of the Inle Lake catchment area (single-column; reproduced in color on the Web only)

different depths (surface, 1.0 and 2.0 m) with YSI-550A meter. Similarly, salinity/conductivity and water pH were measured by using Hach Pocket Pal™ meter. Other water quality parameters (total suspended solid (TSS) and chlorophyll *a*) were measured by using satellite imagery. Landsat-5TM 7 band image (15 February 2011) was acquired and used to analyze chlorophyll *a* and suspended solids (TSS) in water. Sampling locations along with water quality data were imported into ArcGIS 10 to map the surface water quality. Various water quality layers were overlaid to generate pollution hotspots of the lake.

Chlorophyll a estimation

Distribution of the chlorophyll *a* (Chl *a*) concentration was estimated and mapped over the lake using Landsat Thematic Mapper. Landsat Thematic Mapper (TM) has been widely used for monitoring of inland water quality parameters because of the sufficient spatial resolution and because of the suitable spectral range of data acquisition (Hadijimitsis et al. 2006). For Chl *a* analysis, we acquired the satellite image during the month of February 2011. Before conducting the quantitative analysis of the data, a post-calibration was performed of the constant gain and offset to convert the image digital number (DN) to spectral radiance. The spectral radiance was also corrected for atmospheric effects to obtain the surface reflectance values. A geometric correction was not performed because the level of the processing of the Landsat images included this correction.

Since atmospheric conditions play a key role in determining the amount of reflected radiation reaching satellite sensors, in order to estimate lake water quality parameters, such as Chl *a*, the atmospheric contribution was removed prior to the measurement. To atmospherically correct the images, we used the correction provided for TM data calibration with the image processing software ERDAS Imagine 9.2 by applying the correction suggested by the Landsat-7 Science Data User's Handbook (Landsat Handbook 7). The presence of Chl *a* and aquatic humus determines attenuation in the reflectance in band 1 (blue) and 3 (red) and an increase in reflectance in band 2 (green) (Cheng et al. 2013; Mayo et al. 1995). The attenuation of reflectance in band 3 is lower than in band 1 due to the counteracting backscattering of suspended sediments. To develop an algorithm or chlorophyll estimation using TM data, the effect of the total suspended sediment on reflectance should therefore be taken into consideration. By subtracting band 3 from the reflectance in band 1, a correction for the additional radiance caused by scattering of nonorganic sediment is introduced. For our analysis, we adopted a model suggested by Brivio et al. (2001), where the atmospherically corrected reflectances in band 1 and 3 were normalized by the reflectance in band 2: *a* (μg/L)=0.098×(band 1−band 3) / band 2 (Mayo et al. 1995). This model was applied to all the Landsat images to estimate the spatial distribution of Chl *a* in the Inle Lake.

Cumulative effects hotspot analysis

Geographic information system (GIS) tools were used to create a spatial database with all the water quality data indicating DO, pH, salinity, and Chl *a* level. In the case of Inle Lake, spatial analysis tool, inverse distance weighting (IDW) interpolation algorithm, was applied for the simulation of the geographic distribution of the qualitative water parameters. According to this algorithm, linear interpolation was used to interpolate data from water sampling points in a restricted neighborhood search area (Fortin et al. 2005; Riad et al. 2011). The attribute of this method is that nearby locations are more likely to have similar values and linear interpolator weights. Interpolated data Z^ (X_0), at unsampling location X_0, are as follows:

$$\widehat{Z}(X_0) = \sum_{j=1}^{m} w_j * Z(X_j) \tag{1}$$

$$\widehat{Z}(X_0) = j = 1 \tag{2}$$

where

$Z(X_j)$ the value of the water quality parameter z at the sampling location j

m the number of neighboring sampling locations

w_j are weights according to the distance between the unsampling location X_0 and the sampling locations xj such that $\sum_{j=1}^{m} wj=1$.

IDW method was finally used as follows (Fortin et al. 2005):

$$\widehat{Z}(X_0) = \frac{\sum_{j=1}^{m} Z(X_j) * d_{ij}^{-k}}{\sum_{j=1}^{m} d_{ij}^{-k}} \tag{3}$$

where

k the distance influence coefficient, which is usually 1 or 2.

d_{ij} distances between the unsampling location i (X_0) and the sampling locations j (X_j).

The water quality thematic maps were obtained by the application of the interpolation method for pH, DO, salinity, and Chl *a*. Weighted indexing table was created (data not shown) for each output spatial raster to assign a percentage of influence according to its importance, so the hotspots are established. Each cell value was multiplied by its percentage influence then added to create the output spatial raster of water quality. A weighted indexing table has been adopted to suggest the ideal location for the lake water quality parameters. The weights in the present study were given upon the experience of other specialists from previous studies (Elbeih 2007). The hotspot analysis was done as based on the OECD and WHO standards for fresh water lakes (OECD 1982).

Impact identification

The data collected from various available secondary sources were found to be inefficient and incomplete to carry out cumulative effect assessment (CEA) on the Inle Lake ecosystem (Fig. 2). Participatory Rural Appraisal (PRA) was conducted to collect baseline information on the lake (details of the catchment area, local stakeholders, valued ecosystem components (VECs), and potential environmental impacts) through discussions and semistructured questionnaire surveys. There were about 35 groups of villages in and around Inle Lake catchment area, and these were classified as upland village cluster, lake village cluster, and wetland village cluster. At least one PRA and two focus group discussions were conducted in the each cluster of villages with the representation from each village and also representation from various stakeholders, such as civil society, government agencies, schools, etc. This tool indeed helped to generate both qualitative and quantitative information about the lake and its surrounding areas on a temporal scale; i.e., the status of each impact in the past, present, and forecast for future was accounted for. The villagers were asked to note down VECs of the lake and various environmental impacts affecting the lake ecosystem. The communities were asked to rank the impacts by assigning a score between 0 and 10 on three different timescales, i.e., past (10–15 years before), present, and future (10–15 years from now). A total of 39 environmental impacts on Inle Lake were shortlisted by the communities for further analysis.

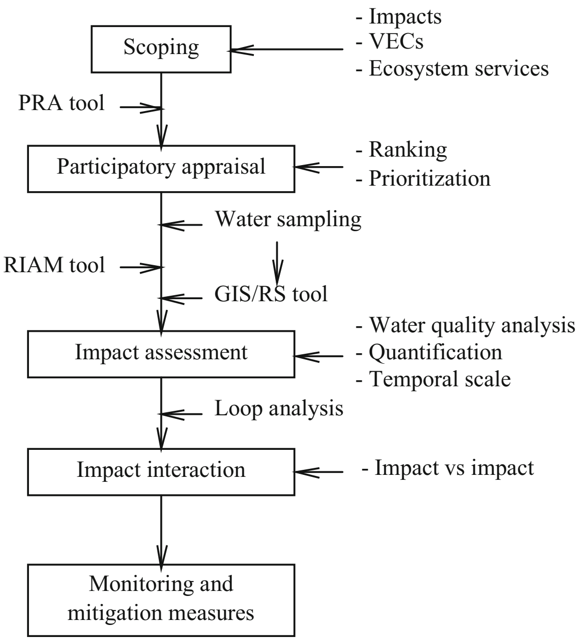

Fig. 2 Conceptual framework tools for rapid cumulative effect assessment

Impact assessment

RIAM tool, a DHI group software application (http://www.dhigroup.com/SolutionSoftware/RIAM.aspx), was selected to prioritize the impacts previously shortlisted by the communities and stakeholders of the lake (Pastakia and Jensen 1998; Kumar et al. 2013). The selected impacts were classified into four different categories as per RIAM tool: (1) physical/chemical (PC) impacts, involving water pollution, developmental activities, land use change, deforestation, etc.; (2) biological/ecological (BE) impacts involving those related to renewable natural resources, biodiversity conservation , interaction between species, etc.; (3) social/cultural (SC) impacts involving those related to human aspects of the environment, including social subjects, human development agenda, etc.; and (4) economical/operational (EO) impacts involving all impacts triggered by economic activities in the ecosystem. The impacts were further classified into two categories as shown in Tables 1 and 2, i.e., A (criteria that are important and have the capacity to influence the overall score individually) and B (criteria which are important but cannot influence the overall score individually). The following matrix operations were carried out to obtain environmental score (ES) for each impact.

This matrix operation was as follows:

$$(\mathrm{A1}) \times (\mathrm{A2}) = \mathrm{AT}\ (\mathrm{A\ Total}) \tag{4}$$

$$(\mathrm{B1}) + (\mathrm{B2}) + (\mathrm{B3}) = \mathrm{BT}\ (\mathrm{B\ Total}) \tag{5}$$

$$(\mathrm{AT}) \times (\mathrm{BT}) = \mathrm{Environmental\ Score\ (ES)} \tag{6}$$

Impact interaction

Based on the RIAM tool ES, only five critical impacts with highest negative ESs were selected for the impact interaction study. An impact interaction tool, i.e., loop analysis (http://ipmnet.org/loop/loopanalysis.aspx), was selected for the impact interaction analysis, as this tool provided qualitative information on the state of an impact through pictorial notation (signed digraph) which was used to elucidate interactions among critical impacts (Levins 1975; Dambacher and Ramos-Jiliberto 2007). The loop analysis was simulated through five major steps: development of square (or community) matrix, stability check through characteristic polynomial equation and Routh-Hurwitz determinants, calculation for an adjoint matrix, impact prediction, and simulation. An impact interaction matrix was developed by assigning three values (i.e., −1: negative impact, 0: null impact, 1: positive impact) and was based on the following matrix operations. These representations were used to qualitatively describe direct causal effects between component variables, such as increase, decrease, or no effect. Finally, the characteristic polynomial equation was used to check the stability of the model.

$n \times n$ Jacobean (community)Matrix, $A=[a_{ij}]$ $[a_{ij}]=[x_1,x_2,x_3]$…….. where $x_1, x_2, x_3 \ldots x_n$ are variables (i.e., environmental impacts in this case)

$[a_{ij}]$ influence of x_j on x_i

$$A^{-1} = \mathrm{adj}\ A/\det\ A \tag{7}$$

$$-A^{-1} = \mathrm{adj}{-A}/\det{-A} \tag{8}$$

Feedback matrix $(T)=\mathrm{per}\ (\min A_{ij})^{\mathrm{trans}}$
Weighted prediction matrix $(W)=|\mathrm{adj}A|/T$

Table 1 Impact category and criteria for RIAM

Criteria	Scale	Description
A1. Significance of the impact	4	Critical
	3	High
	2	Moderate
	1	Minimum
	0	None
A2. Magnitude of change	3	Major positive benefit
	2	Significant improvement in status quo
	1	Improvement in status quo
	0	No change in status quo
	−1	Negative change to status quo
	−2	Significant negative disadvantage or change
	−3	Major disadvantage or change
B1. Permanence of the impact	3	Permanent (11–20 years)
	2	Temporary (1–10 years)
	1	No change/not applicable
B2. Reversibility of impact	3	Irreversible impact
	2	Reversible impact
	1	No change/not applicable
B3. Cumulative impact	3	Cumulative/synergistic
	2	Noncumulative/single
	1	No change/not applicable

From Pastakia and Jensen (1998)

Table 2 Class/range bands used for RIAM

Environmental score (ES)	Range band/class	Description of the class
72 to 108	E	Extremely positive impact
36 to 71	D	Significantly positive impact
19 to 35	C	Moderately positive impact
10 to 18	B	Less positive impact
1 to 9	A	Reduced positive impact
0	N	No alteration
−1 to −9	−A	Reduced negative impact
−10 to −18	−B	Less negative impact
−19 to −35	−C	Moderately negative impact
−36 to −71	−D	Significantly negative impact
−72 to −108	−E	Extremely negative impact

From Pastakia and Jensen (1998)

The local stability of the Jacobean (community) matrix was checked by characteristic polynomial equation:

$$\det(A-\lambda I) = \lambda^3 + c_1\lambda^2 + c_2\lambda + c_3 \quad (9)$$

Results and discussion

VEC and services

Approx. 30 VECs were identified in the PRA exercise in four sample villages located in different parts of the lake area. The VECs were classified into three major categories: physical, biological, socioeconomic, and cultural. Prioritization of the VECs was done by the local communities as based on the importance of VECs for the ecosystem and their relative importance to sustain its integrity. Overall ranking of important VECs was done by its cumulative score obtained from all surveyed villages. Water quality and water quantity were ranked among the top VECs, because of the utmost importance to the ecosystem's sustainability.

Similarly, ecosystem services listed in MA (2005) were also ranked for the Inle Lake ecosystem through PRA exercises. The food and freshwater production and water purification were the top 3 services offered by Inle Lake ecosystem. Communities are highly dependent on the lake for their livelihoods: they use lake water for recreational activities, for drinking after partial purification and for hydroponics to purify wastewater discharged by the Nyaungshwe Township's local inhabitants.

Impact quantification and prioritization

A list of primary and secondary impacts affecting the Inle Lake ecosystem was listed after thorough discussions with local communities, government agencies, civil society experts, academics, and review of available literature. As a result, more than 40 impacts affecting the lake ecosystem, either positively or negatively, were listed.

The impacts were classified into four subcategories by the RIAM tool. These were PC, biological, sociocultural, and economic impacts studied over space and time. Likewise, the strength of impacts was measured by taking into consideration the significance of impacts (4: critical, 3: high, 2: moderate, 1: minimum, 0: none), impact magnitude (+3 to −3), impact permanence (3: permanent, 2: temporary, 1: no change), impact reversibility (3: irreversible, 2: reversible, 1: no change), and cumulative impacts (3: cumulative/synergistic, 2: noncumulative/single, 1: no change). A simple matrix operation was carried out to arrive at a certain quantitative value known as an ES, which ranged from −108 to +108 ($-E$ to E) as in Pastakia and Jensen (1998). A negative ES indicated negative nature of an impact and vice versa. A total of 39 impacts were taken for further mathematical treatment, namely, 16 physical/chemical (PC), 9 biological/ecological (BE), 9 sociocultural (SC), and 5 economic/operational (EO) impacts as shown in Table 3.

Out of 39 impacts identified, 28 fell into the negative impact category and 11 fell into the positive impact category. Eleven impacts were found to be in the significantly negative impact category (Fig. 3a, Tables 4 and 5). Based on their ESs, all physical/chemical and biological-ecological impacts were found to be on the negative side of the chart. Impacts such as sedimentation, pollution, infrastructure development, and water surface encroachment by the floating gardens were the major impacts in the past.

Compared to the past trend of impacts, 29 out of 39 impacts identified fell into the negative impact category as shown in the present trend (Fig. 3b, Tables 4 and 5). However, it could be observed from the graph that the negative strength of the impacts has reduced. Various projects, such as soil and water conservation, de-silting, removal of aquatic weeds, community capacity building, and awareness programs, were under way in the area and helped to mitigate some negative impacts. Despite of all the efforts by various stakeholders and agencies, impacts such as sedimentation, pollution, and infrastructure development inside the lake, unsustainable agricultural practices continued to dominate in the negative impact category.

The predicted strength of future impacts was purely hypothetical; however, it was found to have a strong correlation with the past and present states of impacts (Fig. 3c, Tables 4 and 5). Assuming that the present strength of impacts continues to accumulate in a similar fashion, the lake sustainability will be seriously compromised by year 2020/2025. The chart indicates that 50 % of total impacts fall into the moderate to extremely negative impact category. Impacts such as changes to lake water volume, sedimentation, changes to fishery production, extinction of native fish species, and

Table 3 List of environmental impacts on Inle Lake ecosystem

Physical/chemical (PC) impacts	Biological/ecological (BE) impacts
PC1: changes in Inle Lake water volume	BE1: changes in the lake fisheries production
PC2: changes in lake sedimentation rate	BE2: changes in native/local fish diversity
PC3: changes in water level and depth of lake	BE3: changes to the avifauna diversity
PC4: changes in open water surface area of the lake	BE4: changes to aquatic plants (floating, submerged plants, and plants in natural floating gardens)
PC5: changes to land use pattern in the catchment area	BE5: changes in the primary production function of the lake
PC6: changes to vegetation cover in the catchment area	BE6: invasion of exotic aquatic species (fish and aquatic weeds)
PC7: changes to population density and growth rate	BE7: changes in the pollution load from settlements
PC8: changes to agriculture land holding	BE8: changes in nonpoint source pollution load on the lake
PC9: land conversion (barren land to cultivable land and forest area to agriculture land, etc.)	BE9: changes in the bird foot island area (peninsula in the western bank of the lake)
PC10: industrial development and resource exploitation	Socioecological/cultural (SC) impacts
PC11: changes to waste disposal strategy	SC1: changes to housing pattern in the catchment area
PC12: changes to village infrastructure and commercial establishments	SC2: changes to road infrastructure and navigation routes inside lake
PC13: hydropower development and diking	SC3: changes to community water supply and sanitation infrastructure
PC14: changes in the area of floating garden	SC4: changes in the quality of life (upstream and downstream)
PC15: application of inorganic fertilizer and pesticides in the floating gardens	SC5: changes to aesthetic landscape
PC16: changes to flow pattern in the creeks and flow diversion	SC6: changes in health and education infrastructure
Economical/operational (EO) impacts	SC7: changes in cultural heritage and religious infrastructure, i.e., monasteries
EO1: changes in the income from floating garden agriculture	SC8: changes in government policy and planning particularly for the lake
EO2: changes in the income from inland farming	SC9: changes to social groups and other self-help groups
EO3: changes in the income from fishery activity	
EO4: changes in the income from tourism industry	
EO5: changes in the employment opportunity	

PC physical/chemical, *BE* biological/ecological, *EO* economical/operational, *SC* socioecological /cultural

nutrient load from settlements and floating gardens will permanently destabilize the ecosystem.

Impact interaction (loop analysis)

In order to understand the cumulative nature of the impacts affecting the lake ecosystem, both qualitative and quantitative tools were tested. The use of quantitative tools allowed for prioritization of critically important impacts, whereas the qualitative tools (loop analysis computer-based simulation) indicated the nature of impacts, the way these were acting and interacting with each other.

Five critical impacts chosen were as follows: lake sedimentation (SD), floating gardens (FG), population growth rate (PG), lake water pollution (wastewater from municipal sources, agricultural land runoff, and nutrient leaching from extensive floating tomato gardens) (WP), and infrastructure development (ID). Figure 4 indicates the input matrix as "signed directed acyclic graph of impacts." Table 6 shown here is part of the matrix operation. The loop analysis provided an alternative check and measure for the stability of the lake ecosystem. In this case, the selected five parameters studied were affecting one another, both positively and negatively.

Water quality

Dissolved oxygen

The DO concentrations were measured at 34 locations (Fig. 5), and sampling points were equally distributed to cover the entire lake surface area (on 30–31 October 2011, time 9.30 a.m. to 11.30 a.m.). Three different depths were probed: surface, 1 and 2 m. USEPA (1986) and various other freshwater quality studies suggested that the minimum DO concentration should be in the range of 4–5 mg/L to ensure sustainability of lake aquatic life. The mean DO concentration was found to be 2.8, 1.7, and 0.5 mg/L at surface, 1-m, and 2-m depths, respectively. A possible reason for such low DO could be an overfertilization and agricultural runoff (nutrients leaching out of the floating gardens, wastewater discharge from in-lake stilt houses, and from the large Nyaungshwe Township). Moreover, the mean DO has been constantly decreasing since 2001 when it was 7.5 mg/L (further discussed in the "Physical water quality characteristics" section).

Fig. 3 Number and state of impacts evaluated by RIAM tool. **a** Reference year: 1990/1995. **b** Reference year: 2011/2012. **c** Reference year: 2020/2025. *PC* physical/chemical, *BE* biological/ecological, *SC* social/cultural, *EO* economical/operational

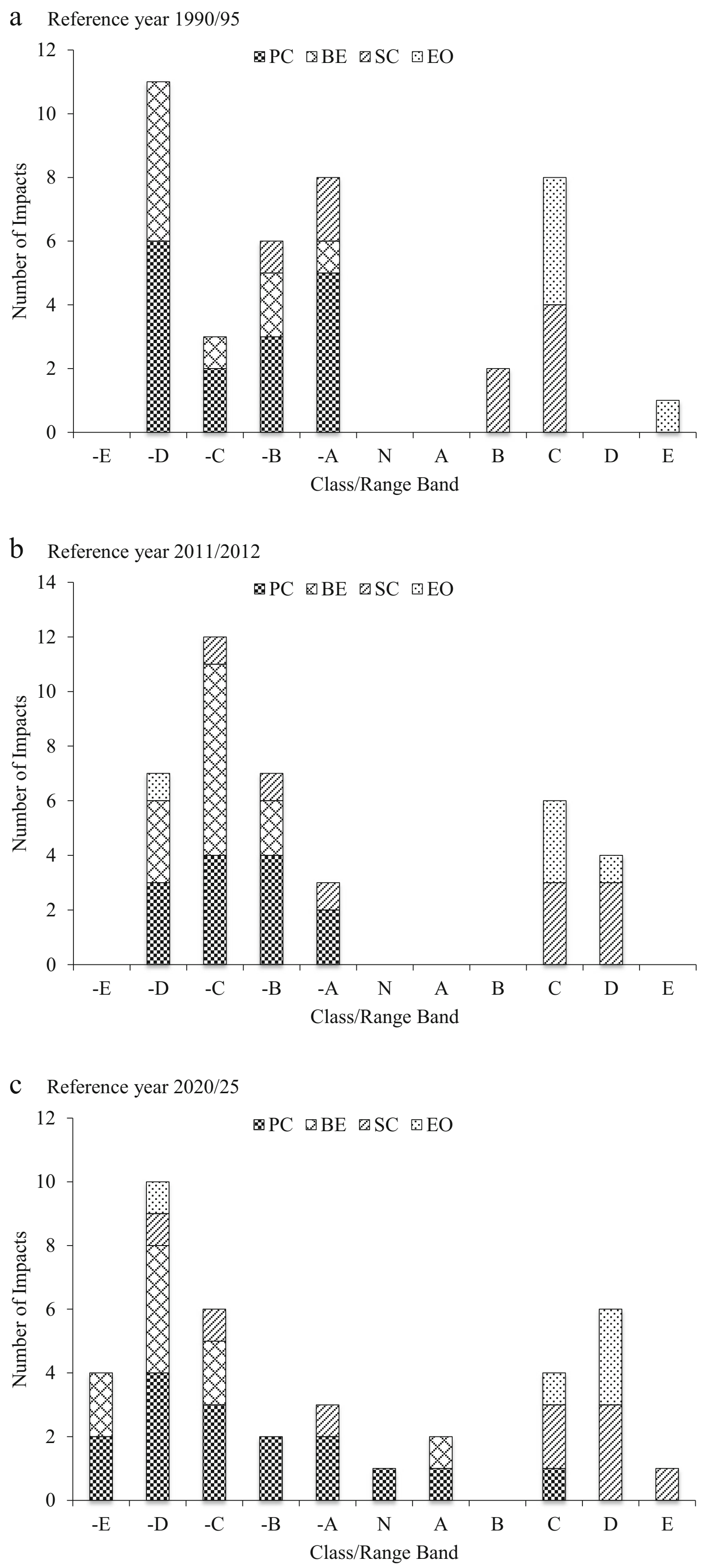

Table 4 Input values and RIAM scores for PC, BE, EO, and SC (past: year 1990/1995, present: year 2011/2012, and future: year 2020/2025)

Components	A1	A2	B1	B2	B3	ES	Class	A1	A2	B1	B2	B3	ES	Class	A1	A2	B1	B2	B3	ES	Class
Physical/chemical (PC) impacts	Past (year 1990/1995)							Present (year 2011/2012)							Future (year 2020/2025)						
PC1: Inle Lake water volume	1	−1	2	2	1	−5	−A	2	−2	2	2	2	−24	−C	4	−3	3	3	3	−108	−E
PC2: lake sedimentation rate	3	−2	3	3	2	−48	−D	3	−2	3	3	3	−54	−D	3	−3	3	3	2	−72	−E
PC3: water level and depth of lake	1	−2	−2	2	1	−2	−B	2	−2	2	2	1	−20	−C	2	−2	2	2	2	−24	−C
PC4: open water surface area of the lake	1	−1	2	2	1	−5	−A	2	−2	2	2	2	−24	−C	2	−2	2	2	2	−24	−C
PC5: land use pattern in the catchment area	2	−2	2	2	2	−24	−C	3	−2	3	2	2	−42	−D	3	−2	3	2	2	−42	−D
PC6: vegetation cover in the catchment area	3	−2	2	2	2	−36	−D	2	−2	2	2	2	−24	−C	2	2	2	2	2	24	C
PC7: population density and growth rate	3	−2	3	3	2	−48	−D	4	−2	3	3	2	−64	−D	3	−2	3	3	2	−48	−D
PC8: agriculture land holding	1	−1	1	1	1	−3	−A	1	−1	1	1	1	−3	−A	1	−1	1	1	1	−3	−A
PC9: land conversion	1	−1	2	2	2	−6	−A	2	−2	2	2	2	−24	−C	1	−2	2	2	2	−12	−B
PC10: industrial Development and resource exploitation	2	−1	2	2	2	−12	−B	3	−1	2	2	2	−18	−B	3	−2	2	2	2	−36	−D
PC11: waste disposal strategy	3	−2	2	2	2	−36	−D	2	−2	1	1	1	−12	−B	2	1	1	1	1	6	A
PC12: village infrastructure and commercial establishments	3	−2	3	2	2	−42	−D	1	−1	2	2	2	−6	−A	1	−1	2	2	2	−6	−A
PC13: hydropower development and diking	2	−2	3	2	3	−32	−C	2	−2	3	2	3	−32	−C	3	−2	3	2	3	−48	−D
PC14: area of floating gardens	3	−2	3	2	3	−48	−D	2	−2	2	2	3	−28	−C	2	−1	2	2	2	−12	−B
PC15: application of inorganic fertilizer and pesticides	2	−1	2	2	2	−12	−B	2	−1	2	2	3	−14	−B	2	0	2	2	2	0	N
PC16: flow pattern in the creeks and flow diversion	1	−1	1	1	1	−3	−A	2	−1	2	2	2	−12	−B	2	−2	2	2	2	−24	−C
Biological/ecological (BE) impacts																					
BE1: lake fisheries production	2	−2	2	2	2	−24	−C	3	−2	2	2	2	−36	−D	3	−3	3	2	2	−63	−D
BE2: native/local fish diversity	1	−2	2	2	2	−12	−B	1	−3	3	3	2	−24	−C	3	−3	3	3	2	−72	−E
BE3: avifauna diversity	1	−1	1	1	1	−3	−A	2	−2	2	2	2	−24	−C	2	−2	2	2	2	−24	−C
BE4: aquatic plants	3	−2	2	2	2	−36	−D	1	−2	2	2	2	−12	−B	1	−1	2	2	2	−6	−A
BE5: primary production function of the lake	3	−2	3	2	2	−42	−D	2	−2	3	2	2	−28	−C	3	−3	3	2	2	−63	−D

Table 4 (continued)

Components	A1	A2	B1	B2	B3	ES	Class	A1	A2	B1	B2	B3	ES	Class	A1	A2	B1	B2	B3	ES	Class
BE6: invasion of exotic aquatic species	3	−2	2	2	3	−42	−D	3	−2	2	2	3	−42	−D	3	−2	2	2	3	−42	−D
BE7: pollution load from settlements	2	−3	2	2	3	−42	−D	3	−3	2	2	3	−63	−D	4	−3	2	2	3	−84	−E
BE8: nonpoint source pollution load	2	−1	2	2	2	−12	−B	2	−1	2	2	2	−12	−B	2	−2	2	2	2	−24	−C
BE9: bird foot island area (peninsula)	3	−2	3	3	2	−48	−D	2	−2	3	3	2	−32	−C	2	−3	3	3	2	−48	−D
Socioecological/cultural (SC) impacts																					
SC1: housing pattern in the catchment area	1	−1	2	2	1	−5	−A	1	−1	3	2	2	−7	−A	1	−1	3	2	2	−7	−A
SC2: road infrastructure and navigation routes inside lake	2	−1	2	2	2	−12	−B	2	−1	2	3	2	−14	−B	2	−2	2	3	2	−28	−C
SC3: community water supply and sanitation infrastructure	2	2	2	2	1	20	C	2	3	2	2	2	36	D	3	3	2	2	2	54	D
SC4: quality of life (upstream and downstream)	2	2	2	2	2	24	C	3	3	2	2	2	54	D	4	3	2	2	2	72	E
SC5: aesthetic landscape	1	−1	2	2	1	−5	−A	2	−2	2	2	2	−24	−C	2	−3	2	2	2	−36	−D
SC6: health and education infrastructure	2	2	2	2	2	24	C	2	2	3	2	2	28	C	2	3	3	2	2	42	D
SC7: cultural heritage and religious infrastructure	2	2	2	2	2	24	C	2	2	2	2	2	24	C	2	2	2	2	2	24	C
SC8: government policy and planning	2	1	2	2	2	12	B	2	3	2	2	2	36	D	3	3	2	2	2	54	D
SC9: social groups and other self-help groups	2	1	2	2	2	12	B	2	2	2	2	2	24	C	2	2	2	2	2	24	C
Economical/operational (EO) impacts																					
EO1: income from floating garden agriculture	2	2	3	2	2	28	C	2	3	2	2	2	36	D	2	3	2	2	2	36	D
EO2: income from inland farming	2	2	2	2	2	24	C	2	2	3	2	2	28	C	2	2	3	2	2	28	C
EO3: income from fishery activity	2	2	2	2	2	24	C	2	−3	2	2	2	−36	−D	3	−3	2	2	2	−54	−D
EO4: income from tourism industry	2	2	2	2	1	20	C	2	2	3	2	2	28	C	2	2	3	3	2	32	D
EO5: employment opportunity	2	2	2	2	1	20	C	2	2	2	2	2	24	C	2	3	2	2	2	36	D

Water pH

The pH of a natural freshwater body should be in the range of 6.5–9.0 (USEPA 1986). A pH value in the range of 7.5–8.5 is the best range for growth of algae in a freshwater ecosystem. The pH value of Inle Lake water was measured to be in the range of 7.7–8.6 (mean 8.0). Most lakes arrive at an acidic stage over a period of

Table 5 Summary of scores for PC, BE, EO, and SC (past: year 1990/1995, present: year 2011/2012, and future: year 2020/2025)

Range Class	−108 to −72 −E	−71 to −36 −D	−35 to −19 −C	−18 to −10 −B	−9 to −1 −A	0 N	9 to 1 A	18 to 10 B	35 to 19 C	71 to 36 D	108 to 72 E
Summary of scores for past (year 1990/1995)											
PC	0	6	2	3	5	0	0	0	0	0	0
BE	0	5	1	2	1	0	0	0	0	0	0
SC	0	0	0	1	2	0	0	2	4	0	0
EO	0	0	0	0	0	0	0	0	4	0	1
Total	0	11	3	6	8	0	0	2	8	0	1
Summary of scores for present (year 2011/2012)											
PC	0	3	4	4	2	0	0	0	0	0	0
BE	0	3	7	2	0	0	0	0	0	0	0
SC	0	0	1	1	1	0	0	0	3	3	0
EO	0	1	0	0	0	0	0	0	3	1	0
Total	0	7	12	7	3	0	0	0	6	4	0
Summary of scores for future (year 2020/2025)											
PC	2	4	3	2	2	1	1	0	1	0	0
BE	2	4	2	0	0	0	1	0	0	0	0
SC	0	1	1	0	1	0	0	0	2	3	1
EO	0	1	0	0	0	0	0	0	1	3	0
Total	4	10	6	2	3	1	2	0	4	6	1

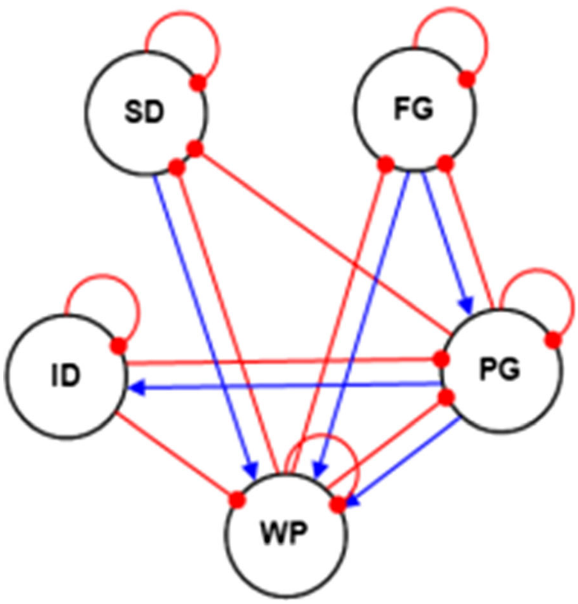

Fig. 4 Signed directed acyclic graph of impacts (positive interaction (*line ended with a pointed arrow*), negative interaction (*line ended with a solid circle*) (double-column; reproduced in color on the Web only)

time; however, Inle Lake water is naturally slightly alkaline. The most likely cause of the alkaline condition of Inle Lake water is Kalaw creek, which flows over limestone quarries and sedimentary rock formations leaching calcium carbonate.

Physical water quality characteristics

The physical water parameters were analyzed over three different years by using available data. A progressive decline in DO values was noted over the period. The mean DO was 7.5 mg/L in October 2001 and 4.0 mg/L in December 2004 (Akaishi et al. 2006), while during November 2011 (present study), the mean surface DO (2.8 mg/L) was surprisingly low even though the lake was in its full water capacity and visually at a best possible state. The apparent reasons were high waste organic loading and anaerobic silt at the bottom. In addition, it has been observed that the lake became shallower year by year because of sedimentation and deposition of dead biomass. The historical records indicate that the lake water level used to be 7.0 m during the wet season and 4.0 m during dry season (Akaishi et al. 2006). However, the present mean water level was found to be only 3.12 m, while the lake was overflowing (October 2011). The western part of the lake was found to be shallower compared to the eastern part due to two main reasons, namely, sediments carried over to the lake by major creeks from the western slopes and abandoned floating gardens settling in the area at the bottom (Furuichi et al. 2009; Furuichi and Wasson 2010).

Application of remote sensing for determination of Chl a concentration

Landsat-5TM 7 band image (15 February 2011) was used to analyze chlorophyll *a* (Chl *a*) concentration in the lake. An empirical equation was used to calculate the Chl *a* concentration by using various bands of the image. According to Brivio et al. (2001), the bands 1–4 (from 450 to 900 nm) are in the spectral range where light enters the water to an adequate depth. The presence or absence of Chl *a* was determined by using three bands (band 1—blue, the band 2—green, and band 3—red).

The Chl *a* concentration was found to vary throughout the lake (Fig. 6), with up to 40 μg/L in open water surface area, 40–45 μg/L in the floating garden area, and exceeding 70 μg/L in a number of densely populated areas (Phaung Daw Oo pagoda and in-lake villages).

Table 6 Input community matrix, adjoint matrix of input community matrix, and weighted predictions and loop analysis

	Input matrix					Adjoint matrix					Weighted matrix				
	SD	FG	PG	WP	ID	SD	FG	PG	WP	ID	SD	FG	PG	WP	ID
SD	−1	0	−1	−1	0	4	−2	−1	−1	2	0.4	0.33	0.2	0.2	0.25
FG	0	−1	−1	−1	0	−1	3	−1	−1	2	0.33	0.43	0.2	0.33	0.33
PG	0	1	−1	−1	−1	−2	1	3	−2	−1	1	0.33	1	1	0.2
WP	1	1	1	−1	−1	3	1	−2	3	−1	1	0.2	0.5	1	0.2
ID	0	0	1	0	−1	−2	1	3	−2	4	1	0.33	1	1	0.4

SD lake sedimentation, *FG* floating gardens, *PG* population growth rate, *WP* lake water pollution, *ID* infrastructure development

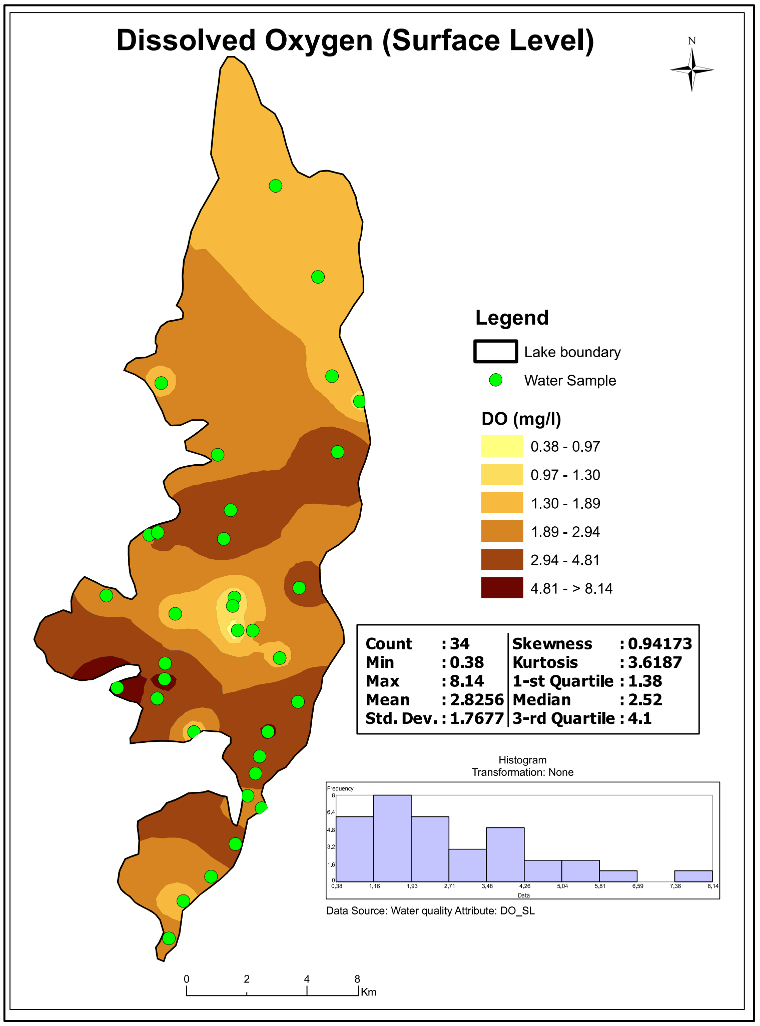

Fig. 5 Lake surface DO profile (double-column; reproduced in color on the Web only)

According to the OECD Lake Classification Scheme for the lake trophic status (OECD 1982), Inle Lake can thereby be considered eutrophic, with a high possibility of algal growth during the dry season indicating significant pollution levels.

Cumulative effects hotspot analysis

As a result of the rapid field survey and prior impact analysis described above, the generated water quality layers (indicating DO, pH, salinity, Chl *a* levels) were overlaid with maps (not shown) of the floating garden density and sedimentation (indicated by water depth and suspended solids) in order to identify cumulative impact hotspots in the lake in September 2011 (Fig. 7). The layers were as follows: DO (<3.0 mg/L), pH (>8.0), salinity (>200 mg/L), temperature (>25.6 °C), water depth (<2.5 m), Chl *a* (>50 μg/L), and SS (>20 mg/L). Four hotspots were identified, all in the southwestern and southeastern parts of the lake. Rapid analysis of all the main and secondary impacts identified allowed explaining the origin of hotspots as follows. Hotspots 1, 2, 3, and 4 appeared to be caused by excessive application of chemical fertilizers on the tomato floating gardens, untreated waste discharge from village stilt houses and domestic animals, as well as from similar sources (resorts, hotels, pagodas, monasteries, markets, etc., inside and around the lake), and sedimentation. The level of contamination was quite low in the northern part of the lake where the pollutants/nutrients were being filtered through and absorbed by extensive natural floating and emergent vegetation, such as cattail, common reed, and other aquatic weeds, and, to a lower extent, by water hyacinth.

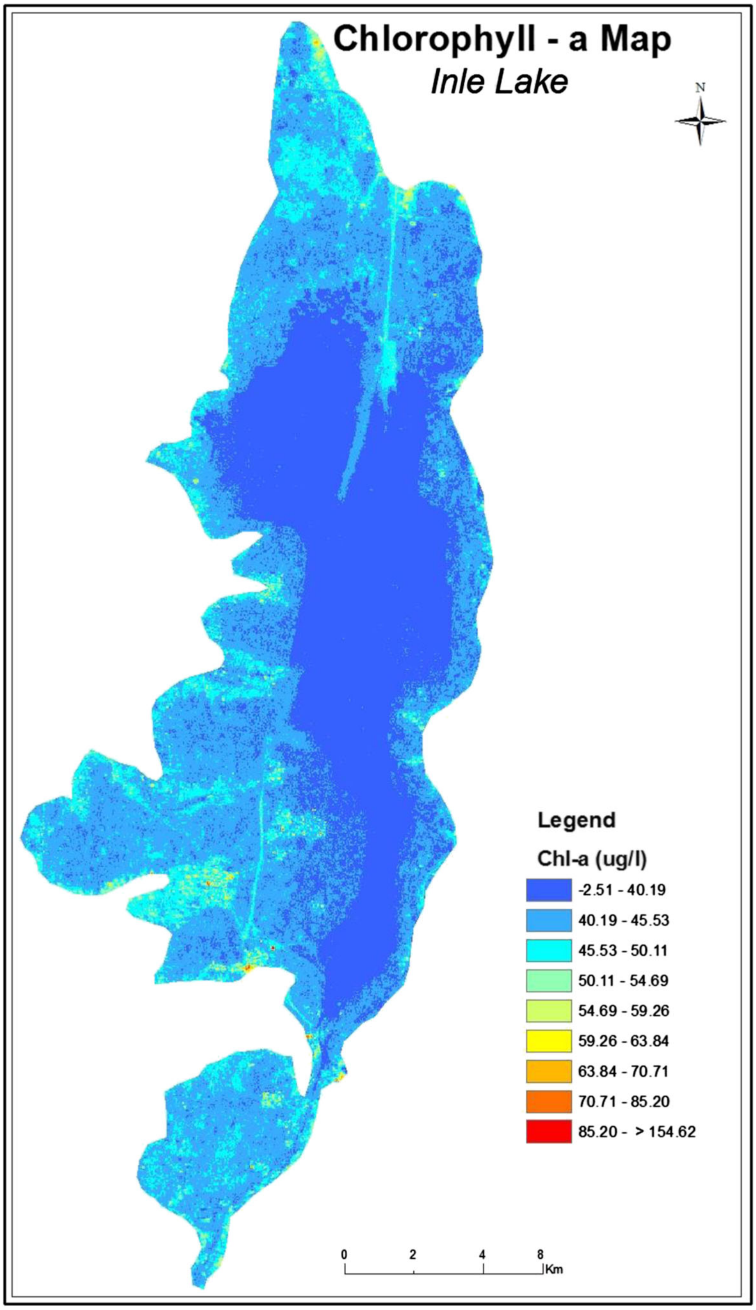

Fig. 6 Lake chlorophyll *a* profile (double-column; reproduced in color on the Web only)

Impacts of floating garden agriculture

The tomato floating gardens were introduced in the lake in the early 1960s as an innovative biotechnology and, since then, have fast become one of the highlights of the lake's cultural heritage. Lucrative financial benefits and the low investment required stimulated their rapid and ever-increasing extension with a growth rate of 9.4 % per annum (Fig. 8). Hence, the gardens at present cover approx. 30 % of the lake area. Higher productivity leads to an increased application of chemical fertilizers and pesticides, which easily leach out into the lake water. These cause detrimental impacts on the natural lake ecosystem such as a marked decrease of light availability to the biota due to a shading effect and reduction of water depth through enhanced release of suspended

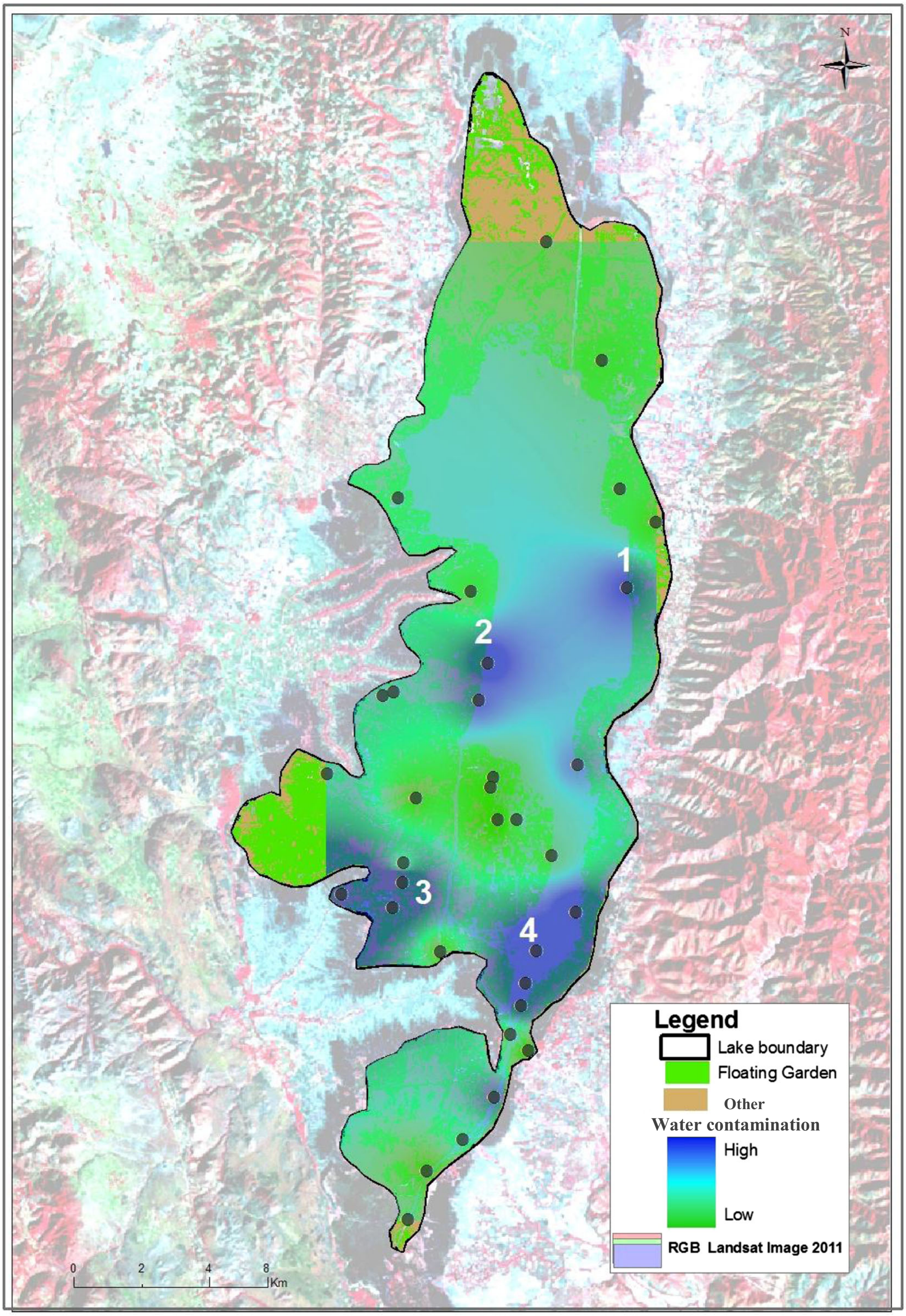

Fig. 7 Hotspots of cumulative impacts (effects) on the lake ecosystem using neighborhood analysis and overlay of raster outputs of water quality parameters and land use classifications (double-column; reproduced in color on the Web only)

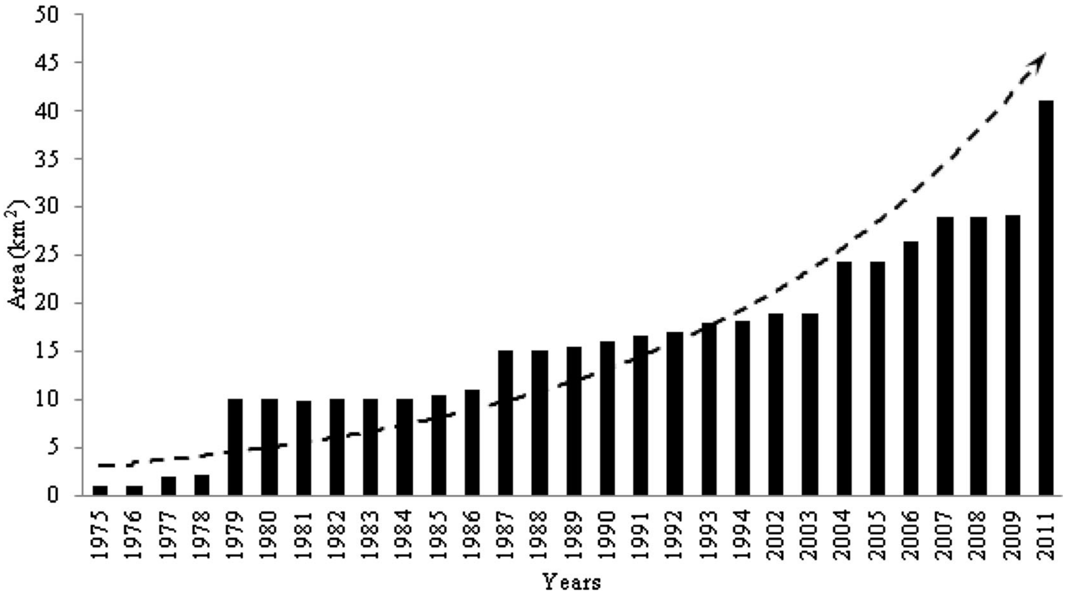

Fig. 8 Temporal variation of lake floating gardens (1975–2011) (modified and updated from Akaishi et al. 2006) (double-column; reproduced in color on the Web only)

solids. The floating beds, whose lifespan varies from 15 to 40 years, are prepared by using aquatic weeds and bottom silt. When the thickness of the bed increases, the farmers split it horizontally to generate other two to three beds, thereby further increasing total garden area.

The floating garden agriculture is a highly important economic activity for the local community, but there is a limit to which the lake ecosystem can sustain this taxing activity without compromising the very existence of natural ecological balance. The assessment of impacts on the lake ecosystem undertaken with the use of the developed framework tool suggested that if the agricultural growth continues unabated at present rates, which incidentally, has an obvious tendency to dramatically increase, the lake may irreversibly lose its ecological integrity.

Conclusions

An innovative CEA framework tool was developed for the evaluation process of the environmental state of a highly significant wetland in Myanmar. The framework tool proved to be a rapid, straightforward, and comprehensive way for the assessment of detrimental, mostly anthropogenic, impacts (effects) in order to affect timely mitigation measures. PRA combined with the loop analysis served as an initial framework which guided additional data generation through RS-GIS, water survey, and field observations. The assessment led to a conclusion that pollutions from municipal sources, floating garden agriculture, and sedimentation were the most critical impacts affecting the lake ecosystem. These and other impacts led to rapidly deteriorating water quality, proliferation of aquatic weeds, and sharp decline in the average depth of the lake. The assessment strongly suggested that, if the business-as-usual scenario is pursued in the area, the ecosystem would face major and potentially irreversible challenges in the near future. Therefore, a comprehensive mitigation plan is urgently needed.

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