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Decision Support Tools for Water Resource Management: A Case Study of Bung Boraphet Wetland, Thailand

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Water and other natural resources of the Bung Boraphet Wetland in Thailand have been under increasing pressure from over-exploitation. Sustainable management and 'wise-use' of the Wetland's resources require achieving a balance between economic exploitation and conservation. Scientifically based decision support tools are vital to gain better insights into the complex interactions between the large wetland system, its contributing catchment and floodplain, and then pave the way for planning effective long-term management. This paper presents a summary of several decision support tools that we developed for Bung Boraphet. The tools are: (a) Water budget predictive model, (b) Land-use analysis using satellite imagery, and (c) Database linked Geographic Information System.

From a review of literature and field studies, we identified the factors that have the most serious impacts on long-term sustainability of Bung Boraphet. We also conducted field studies to collect primary data on hydrological parameters of the lake between December 2002 and May 2006. These and available secondary data were then used to develop a model for the daily water budget of the Wetland. Model calculations and observed water levels are highly correlated for this period, proving the veracity of the model. Evaporation loss of water is a critical factor during the dry seasons (~41% loss), as is extraction for irrigated rice grown in encroached areas around the lake (~55% loss). The modeling tool allows the analysis of different water use scenarios. For instance, the model forecasts that even if the weir height is raised by 0.5 m to a level of +24.5 m (MSL), as has been suggested by some stakeholders, irrigation water abstraction has to be reduced by 35% of the current consumption to maintain the recommended minimum water level (+23 m, MSL) for a sustainable fishery.

Insights into land use changes in the surrounding catchment and lake were gained by a series of Landsat 5 satellite images. A comparison of images shows that between 1993 and 2003, the irrigated area surrounding the lake doubled. At the same time, the submerged and emergent vegetation in the lake declined by 50%. The database linked GIS, which we developed, includes meteorological data and primary and secondary data on hydrology, water quality and biodiversity of the lake and its catchments, and covers the main rivers and their tributaries. Information from applying the decision support tools has stimulated discussions with key stakeholders, identifying the 'wetland values' that need protection, and the economic, environmental and social goals that need to be met by a future plan of management. As discussed in this paper, we have made a significant difference in the nature of the discourse on the management of Bung Boraphet by demonstrating the value of basing wetland management decisions on scientific information. The POM, which is being developed, is expected to receive multiple stakeholder support, so that Bung Boraphet's resources can be sustained for use by present and future generations.

Key words: Wetland, Bung Boraphet, Decision Support Tools, Water Budget, Satellite Imagery

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Introduction

Bung Boraphet, the largest freshwater wetland system in Thailand, is located in Nakhon Sawan Province (Fig. 1). The catchment area of the lake is approximately 4,288 km^2 and covers areas of Muang, Chumsang and Tatako districts. Klong Tatako and Klong Bon are the two main tributaries of the lake, and these have catchment areas of 3,141 and 1,124 km^2, respectively. Bung Boraphet was originally a natural wetland. In the 1970s, a weir was constructed to store water, which permanently flooded some of the wetland. In 1993, the height of the weir was raised to +24 metres (MSL), storing 177 million m^3 at full supply level (FSL) and flooding 148 km^2. The wetland-lake system and its resources are an invaluable part of the provincial economy, and they are also a highly significant national and international resource of biodiversity. Bung Boraphet is known to be habitat for 54 fish species (Thai Fisheries Department, 2005), 252 bird species and other rare and unusual flora and fauna (DNP, 2005).

Bung Boraphet and its catchment have been managed by multiple agencies using a regulatory approach. Increasing evidence of ecosystem deterioration, such as reduced biodiversity of fish and birds, diminished fishery yield and poor water quality (RID, 2004), suggests these management methods are not working. For example, the declaration of a 212 km^2 conservation zone around Bung Boraphet in the 1980s has failed to prevent human encroachment within this zone for intensive rice farming. Currently, 30,000 people occupy nearly 70% of the conservation zone (Rural Development Information Center, 2005). The Thai Fisheries Department manages Bung Boraphet to sustain an economically important fishery. Although the Fisheries Department recommends a minimum level of +23 m (MSL) to sustain the Wetland fauna and flora, the lake level has fallen below this minimum for long periods every year since 2001.

Since 1993, approximately 1 million m^3 of sediment is dredged from Bung Boraphet each year to maintain the water depth. This is a management response to prevent shallowing of the lake, due to sediment exported from the catchment (Thai Fisheries Department, 2005). One response to the need to reexamine the management of Bung Boraphet was a recent report by the Royal Irrigation Department (RID), which provided numerous management recommendations including a recommendation to increase the storage volume by 38% (Table 1), to provide more water for irrigation and to prevent further illegal settlement by increasing the permanently flooded area of the wetland (RID, 2004).

In this paper, we present some ‘Decision Support Tools’ that are specifically designed to analyze the complex water management issues of Bung Bo-

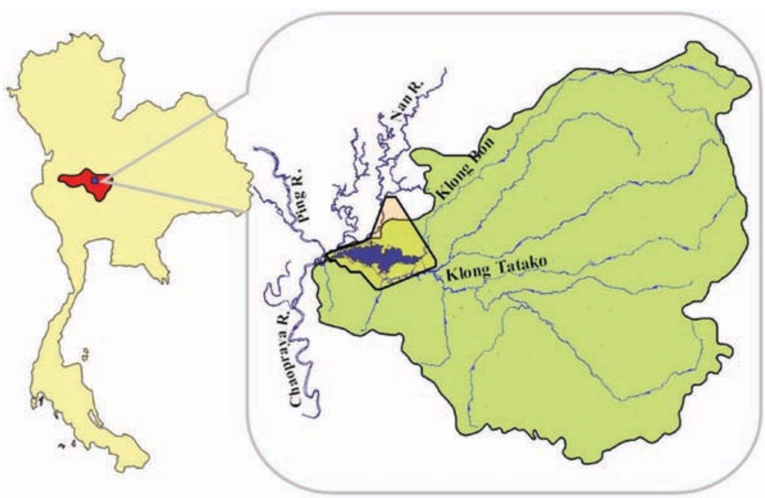

Fig. 1. Bung Boraphet Wetland in Nakhon Sawan Province, Thailand. On left - Thailand with Nakhon Sawan Province in red; On right - Bung Boraphet watershed in green, the conservation (restricted use) area in orange; Bung Boraphet Lake at full supply level in blue.

Table 1. Lake surface area and storage volume at specific lake water levels

Level (m, MSL)	Surface Area (Km^2)	Area (% FSL)	Storage Volume (m^3)	Volume (% FSL)	Comment
+21.77	27	18%	25	14%	Av. annual minimum (2002–2005)
+22.35	37	25%	44	25%	Av. annual minimum (1993–2001)
+23.00	66	45%	75	42%	Recommended minimum
+24.00	147	100%	178	100%	Current Weir height
+25.00	168	114%	245	138%	A proposed future weir height

Source: (Royal Irrigation Department, 2004)

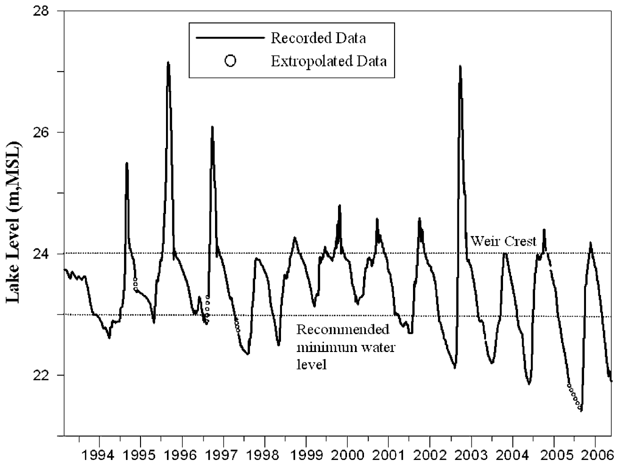

Fig. 2. Daily water level for Bung Boraphet

raphet. We also demonstrate the value of the tools in developing a Plan of Management (POM) for the wetland that follow the principles of 'wise-use' and 'best practice' international guidelines (Ramsar 2004).

Water Abstraction Issues

In recent years, abstraction of water from the lake for irrigation in the dry season has drawn the lake down below the recommended +23 m minimum level. Historical level records in Figure 2 show that between 1993 and 2001 the average annual low water level was below +23 m during 14% of the year (range of 0–33%). Since 2001, the irrigation demand has caused the dry season drawdown to increase markedly so that in those years the lake level was below +23 m for 40% of the time (range for 2002–2005 was 29%–56%) and the annual average minimum stored volume was 14% of the full supply. The recommended minimum water level of +23 m (MSL) to sustain the wetland's fauna and flora is not supported by any scientific arguments, but it does seem reasonable, as this level represents less than 20% of the inundated area and less than 15% of the volume of the full lake.

Decision Support Tools for Water Resource Management

We have developed a set of Decision Support Tools specifically for application in the management of Bung Boraphet. These include a Water Budget model, a Land Use pattern analysis based on remote sensing, a Geographic Information System (GIS) and a database.

Water Budget Concept and Methodology

Central Thailand has a monsoonal climate with a cyclic pattern of wet and dry seasons that are reflected in the water levels of Bung Boraphet (see Fig. 2). In the dry season between December and June, the water level of Bung Boraphet is drawn down by extraction from tributaries and canals upstream of the lake for rice irrigation. There are minor diversions of water for domestic users in Tatako District and for aquaculture. The inflows and outflows to the lake are illustrated in a conceptual model (Fig. 3). In the wet season between July and November, the lake level rises due to inflows from the catchment and from direct rainfall on the lake surface. There is potential for interbasin transfer from the Nan River, but this was not a significant water source during this study.

A daily water budget for Bung Boraphet was developed using the relationship between water quantity parameters and the lake volume described in the following equation:

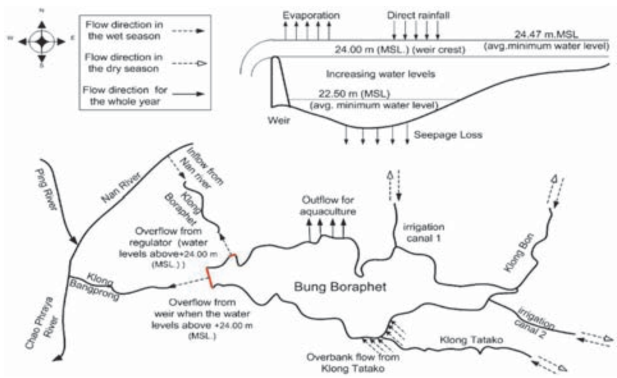

Fig. 3. Conceptual model of the Bung Boraphet water budget

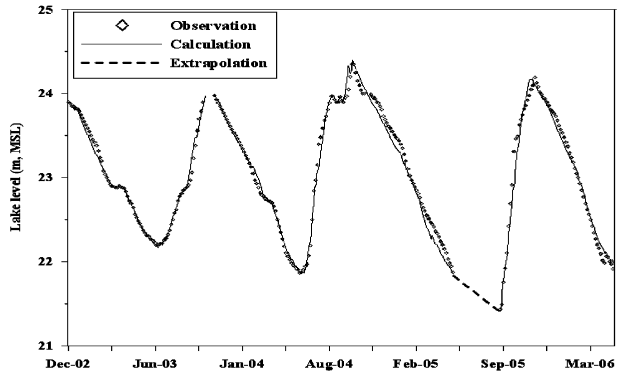

Fig. 5. Comparisons between observed and calculated daily lake water levels between December 2003 and May 2006.

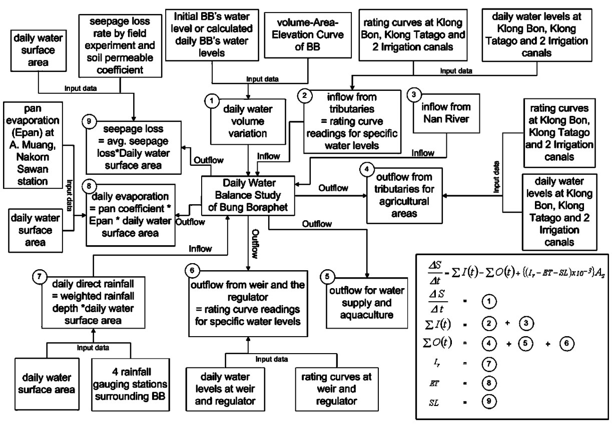

Fig. 4. A conceptual model of the Bung Boraphet water budget analysis

$$\frac{\Delta S}{\Delta t} = \Sigma I(t) - \Sigma O(t) + (I_r - ET - SL) A_S$$

where, ΔS is the difference in the lake volume for any time period (Δt); $\Sigma I(t)$ is the total net daily inflow; $\Sigma O(t)$ is the total net daily outflow; I_r is the daily increase in lake level due to rainfall; ET is daily fall in lake level due to evaporation from the surface; SL is the daily variation of the level due to seepage, and A_S is the lake surface area at a specific water level. The Bung Boraphet water budget schematized in Figure 4 illustrates the data inputs and the relationship between the budget components. The lake has a large catchment area so the full supply level (+24 m) is exceeded most years and the flood level exceeded +27 metres MSL in two of the past 12 years. At these times the lake inundates the flood plain and discharges to the Nan River (via the regulator) and to the Chao Phraya River over the weir.

Water Budget Model Calibration

A budget model was calibrated using daily data collected between 11 December 2002 and May 2006. The lake level was reset to the observed value at each transition from inflow to outflow (points 1–7 in Fig. 5) and when irrigation abstractions ceased at the end of the crop cycle (points 8–10). The observed and calculated lake water levels were closely correlated (for Inflow periods r=0.96; RMSE=2.4 MCM and EI=91%; whilst for Outflows r=0.99; RMSE=6.4 MCM and EI=98%).

Water Budget Model terms and Scenario Analysis

Over the period of the study, the rainfall on the lake water surface represented 28% of the total inflow. The runoff from the catchment was principally from the two main gauged catchment streams (Klong Tatako and Klong Bon). These rivers delivered 51% and 20% of the average annual inflow, respectively. Although lake levels were consistently low and irrigation water was in high demand during the study period, the Nan River was only a minor source representing less than 2% of the inflow (Table 2). Evaporation in the catchment area was seasonally adjusted using a pan-coefficient of 0.8–0.9 (Chow, 1964). Stream flows were estimated daily from staff gauges in the main inflows, calibrated for flow. Evaporation and abstraction for irrigation were the two largest contributors to

Table 2. Water Budget components for Bung Boraphet for years 2002–2006

	Losses ($m^3 \times 10^6$)					Inflows ($m^3 \times 10^6$)					
	Evap (%)	Seep (%)	Irrig[C] (%)	Disch[A] (%)	Total Out (%)	Direct Rain (%)	Klong Bon (%)	Klong Tatako (%)	Irrig. Canals (%)	Nan River (%)	Total In (%)
Av. Vol. Wet Season	35.2 (92)	0.1 (0.2)	0 (0)	3.3 (7.4)	39 (100)	59.8 (27)	42.1[B] (20)	106[B] (51)	4.5[B] (2.1)	2.9 (1.3)	215 (100)
Av. Vol. Dry Season	63.3 (42)	0.1 (0.1)	83.1 (55)	4.2 (2.8)	150.7 (100)	9.7 (100)	—	—	—	—	9.7 (100)
Cum. Ann average	98.5 (52)	0.2	83.1 (44)	7.5	189.2	69.4	42	106.2	4.5	2.9	225

Notes: A-Discharges downstream over weir through the regulator; **B**-This is the net inflow as wet season extractions cannot be measured; **C**-This irrigation term only represents water extracted from the lake via Klong Bon, Klong Tatako and irrigation canals. In the wet season, farmers also extract water from canals before it reaches the lake. This term is not calculated, but can be estimated from our farmer surveys.

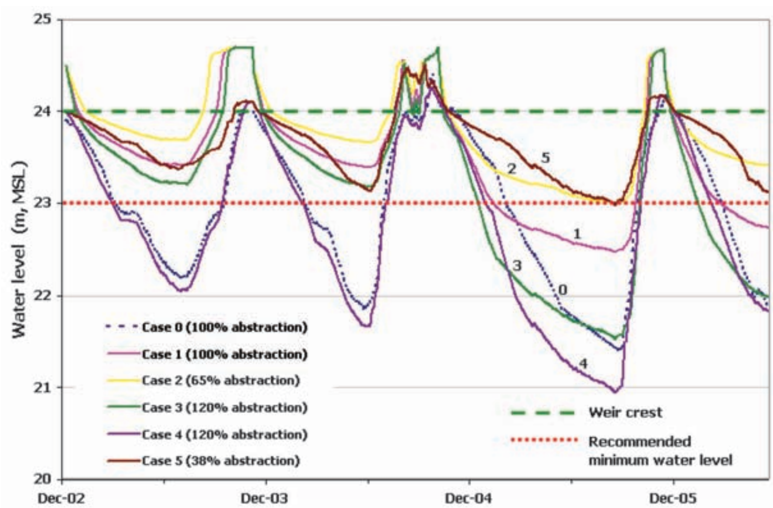

Fig. 6. Modeled water level scenarios in Bung Boraphet for different management responses

water loss, representing 52% and 44% of the average annual loss from the storage (Table 2). Seepage estimated by the closed tube method (AIT, 1983) represented less than 1% of the total discharge, whilst the discharges downstream through the weir and regulator were also minor terms during these low flood years (2002–2005). The differences in the inflow and loss parameters between wet and dry seasons are also described in Table 2. The irrigation term underestimates the total consumption as we measured net inflow to the lake during the wet season, so abstractions during that period are undetected.

To demonstrate the capability of the Water Budget Model as a management tool, we used it to predict the lake water level for the past 4 years with five different combinations of weir height and abstraction volumes (Scenario Analysis). These scenario results are compared with the current situation (Case 0; weir crest +24 m (MSL); daily abstraction set as 100%) in Figure 6. In Cases 1–3, the weir crest was raised by 0.5 m. In Cases 0, 4 and 5, the weir level was unchanged but the abstraction rate varied as a fixed percentage of the daily abstraction volume. If the weir crest had been 0.5 m higher between 2002–2006, and the abstraction rate 65% of the current rate (Case 2), the lake would have been above the recommended level. Abstraction at the current rate (Case 1) would have drawn the lake below the recommended level in 2 of the 4 years. A 20% increase in abstraction (Case 3) was similar to Case 1 but the drawdown in 2005 and 2006 was more extreme, matching the current situation (Case 0). When the weir height was not changed (i.e. +24 m), an abstraction volume of only 38% of the current amount was needed to keep the lake above the recommended minimum level each year (Case 5). The worst case (Case 4) shows the impact of a 20% increase in abstraction with no increase in weir height. This produced a drawdown pattern similar to Case 0 in 3 of the 4 years, but in 2004 the drawdown was significantly lower and longer than Case 0.

Modeling is a powerful tool for analysing different water use scenarios objectively and with scientific rigour. Management attention should focus on the farming practices of irrigators using water in the dry season, when the lake level is affected by abstraction. The costs and benefits of proposals to raise the weir height or divert water from the Nan River could also be rigorously evaluated using this type of modeling tool.

Remote Sensing to Monitor Changes in Land Use and Wetland Habitat

Land use changes can cause significant impacts on tropical wetland environments. Farming on sloping lands in Thailand has resulted in severe soil erosion and exponential increases in sediment transport to drainage channels and reservoirs (ICEM, 2003). We conducted a temporal and spatial analysis of land use changes in the lake and surrounding areas using Landsat 5 images collected between 1993 and 2003. The images were all collected when the lake level was +23 m (MSL), so they are directly comparable. We used PCI Geomatica™ V.9.1 software to analyze the different vegetation types and water clarity characteristics of the Bung Boraphet catchment in the Landsat 5 images with band R : G : B=4 : 5 : 3 for the land-use classification. The enhanced images (Fig. 7A) were analysed to measure the extent of submerged and emergent wetland plant cover. This declined by 50% between 1993 and 2003. At the same time, continuous dredging operations have produced a pool of turbid water, centered on the location of the dredge, which has expanded from an insignificant area in 1993 to cover a third of the lake in 2003. The images were also analysed to determine the extent of the irrigated area around the lake in the dry season (Fig. 7B and 8B). This doubled between 1993 and 2003.

Remote sensing images are a powerful demonstration of the extent of the spatial and temporal changes that have occurred in the Wetland-lake complex and the surrounding catchment landscape in the past 15 years. The evidence of landscape change from remote sensing is supported by measurements of low water clarity in a broad area around the dredge (data not presented), and by the trend of increasing water extraction for irrigation.

Database and Geographic Information System

We developed a database to easily store, modify and extract natural resource information on the Bung Boraphet region, and to support planning for future lake management. There is an extensive primary data set collected between 2002 and 2006 that consists of daily rainfall data at four locations, daily water levels and rating curves at four inflow points and outflow points, and lake water quality data at more than 20 locations for more than 10 events. A secondary data set of meteorology, hydrology, water quality and biodiversity of the Wetland and its catchments has been assembled from a number of official sources. A Geographic Information System for Bung Boraphet has also been developed for creating, storing, analyzing and managing spatial data and associated attributes. The GIS encompasses areas within the boundary of the Wetland's large catchment and its sub-catchments, and also administrative boundaries, rainfall and runoff stations within and in surrounding catchments, main roads, irrigation canals, as well as rivers and their tributaries. The database and the GIS are both accessible at: http://maxlearn.eng.ku.ac.th/bb/login/ilogins.php

Plan of Management

We provided the land-use change information, fieldwork data and the outcomes of the modeled scenarios to stakeholders to stimulate discussion on the likely impacts of manipulating the Wetland

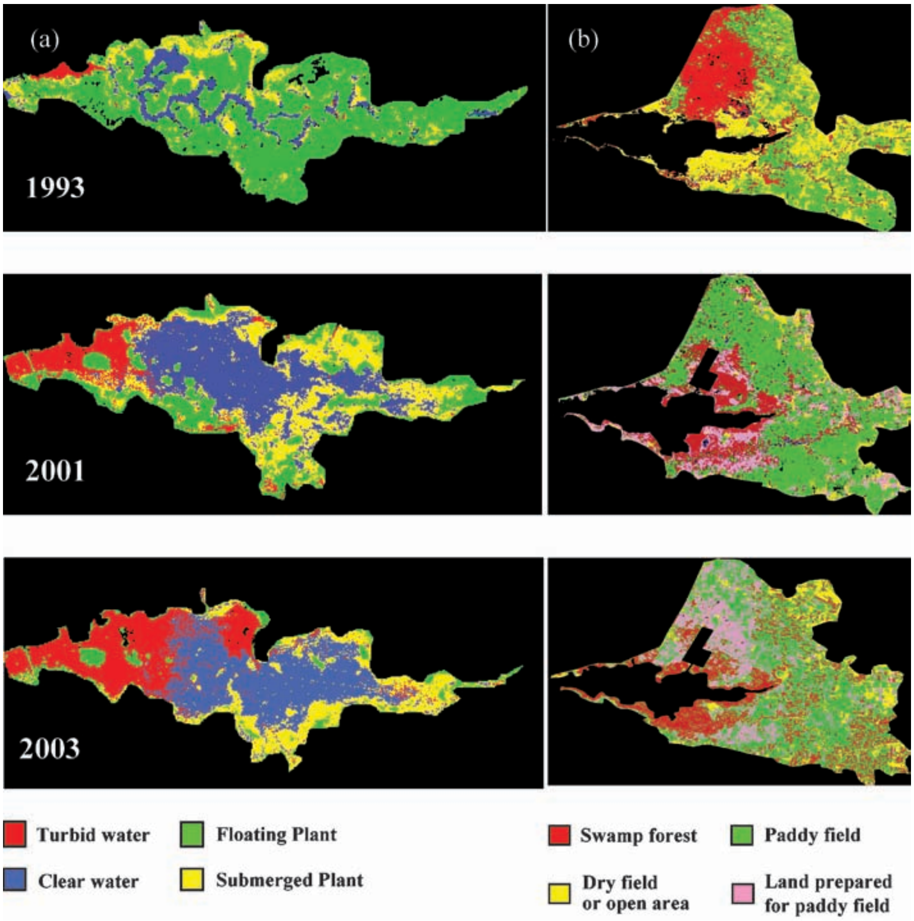

Fig. 7. Landsat imagery showing changes in the (a) Wetland, and (b) surrounding catchment

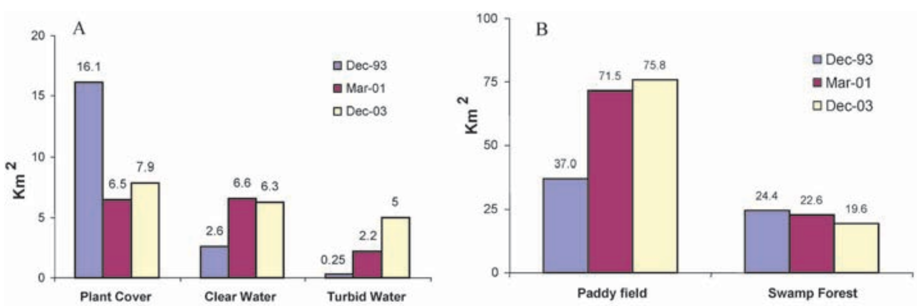

Fig. 8. Changes in land use and composition of a) Bung Boraphet Wetland and b) Catchment area between 1993 and 2003, from analysis of Landsat images

water level. There is general agreement amongst stakeholders that the Bung Boraphet ecosystem is degrading and that the 'stressors' summarized in Table 3 are causing these changes. The stakeholders also agreed on economic, environmental, and social 'Wetland Values' that need to be protected (Table 3). Our view is that the Decision Support Tools we have developed can provide a factual basis for discussion of management issues such as the benefit and cost of sediment dredging, the need to modify water extraction practices or the extent and the impact of land encroachment. The scientific information we have gathered has been used to prepare a 'draft' Plan of Management for Bung

Table 3. Significant environmental issues to be managed at Bung Boraphet

Issue	Comment
Water quantity	High loss by evaporation and increasing extraction for farming reduce the lake volume to an unacceptably low level in the dry season.
Water quality	Poor water quality due to human activities in the watershed and in the lake.
Sediment load from catchment	Increased sediment loads to the lake from human activities in the floodplain (farming etc).
Turbid lake water	Resuspension of sediment in mid lake by dredging that produces a permanent turbid water plume.
Loss of hydraulic connectivity	Hydraulic connection between river, lake and floodplain are fundamental for high fishery productivity of wetland systems. The weir and regulator structures limit fish movement between the Chao Phraya system and Bung Boraphet. Land reclaimatioon and flood mitigation work on the floodplain reduces its connectivity with the lake.
Losses of biodiversity	There is mounting evidence of habitat loss, habitat fragmentation and reduced biodiversity (i.e. fish, birds).

Table 4. Bung Boraphet Wetland's Values

Economic Values	Social Values	Environmental Values
○ Livelihoods	○ Scientific	○ Biodiversity/Genetic resources
○ Eco-tourism	○ Recreational	○ Productivity/Range of habitats
○ Flood mitigation	○ Educational	○ Water quality improvement
		○ Water quantity

Boraphet. This plan sets goals that attempt to balance the economic, social and environmental needs identified by the stakeholders (Table 3). The POM also addresses key management issues, including the interaction between multiple user groups and stakeholders, and inter-agency cooperation. We see the draft POM as a mechanism to generate further discussions on a 'best management practice' framework for the Wetland.

Discussion

There is much evidence of deterioration in the Bung Boraphet wetland ecosystem from the increasing human exploitation of this water resource. The loss of plant cover shown in satellite images is one indicator of ecosystem degradation that can be linked to a number of human activities like abstraction of water in the dry season causing prolonged drawdown that kills submerged plants, sediment dredging that muddies the water and deprives submerged plants of the light they need to grow, and possibly increased harvesting of plant material for new commercial markets.

A key feature of productive wetland ecosystems is the hydraulic connectivity between the permanent water (river and lake) and the surrounding floodplain, which allows transfer of energy from the terrestrial systems into the aquatic system in floods especially by passage of fish (Junk and Wantzen, 2003). Hydraulic connectivity is reduced by human construction of weirs and dykes, so maintenance and restoration of connectivity must be a primary consideration in any future management plans for Bung Boraphet.

The water usage scenario analyses illustrate the usefulness of the water budget model for predicting the quantity of water in Bung Boraphet under different conditions. The weir at Bung Boraphet has created a shallow tropical lake, in which evaporation dominates the water balance. Proposals to

Table 5. Goals[A] for Wise-use of Bung Boraphet's Water Resources

Goals[A]	Task
Goal 1	To manage Bung Boraphet and its catchment wisely: ○ Co-ordinate management actions by appointing a 'Steering Committee' representing all major stakeholders. ○ Recognise the connection of the wetland to its catchment and follow an integrated catchment management approach.
Goal 2	To manage the economic values of Bung Boraphet for long term sustainable use: ○ Maintain non-hunting zone and non-fishing zone by appointing a "Wetland Keeper" (i.e a local committee). ○ Change land use pattern in the floodplain, ownership of land and future settlement. ○ Educate farmers (irrigation practices, demonstration school) and encourage efficient water-use (i.e. change to less water consuming crops, conservation farming, and crop diversification).
Goal 3	To manage the water level of Bung Boraphet to conserve and enhance the environmental values: ○ Maintain an appropriate water level to preserve fish habitat, stock, and breeding; and reduce over extraction for farming ○ Improve water quality to promote growth of water plants; discontinue sediment dredging and creation of islands ○ Maintain hydraulic connectivity between the river, the lake and the floodplain through correct operation of the regulator and fish ladder and to the floodplain (floods) ○ Maintain flood mitigation capacity; reduce land reclamation on floodplain ○ Enhance bird habitat (Manage invasive species (weeds); Enhance diversity of wetland vegetation (reintroduce species that have been lost)
Goal 4	To manage the social values of Bung Boraphet: ○ Maintain education values- Enhance information and Education Centre. ○ Promote recreational values- Promote Bung Boraphet as a tourism destination. ○ Promote use as a scientific resource- Study site for natural processes

Notes: A-Targeted goals developed at the initial stakeholder workshop

store more water in this system either by diversion from other sources or by raising the weir height must recognize that 50% of all new stored water will be lost to evaporation. The water management of Bung Boraphet Lake must be integrated with resource management plans for the Bung Boraphet sub basin and with the entire Chao Phraya basin, whilst also providing a hydrological regime that can sustain the wetland ecosystem. This requires agreed protocols for filling and discharge/extraction of water, and scientifically based targets for amplitude and duration of drawdown cycles over annual and decadal periods. For example, indices based on area of flood plain inundation each year have been used elsewhere to predict annual fisheries productivity.

Conclusion

Seven percent of Thailand is wetlands (Omakup, 2001), and historically the welfare of Thai people has been highly dependent on the productivity of these ecosystems. Intensifying economic development is placing ever more pressure on these water resources. Whilst natural threats to wetlands, such as climate change, drought and floods may be unavoidable, excessive impacts caused by human development are preventable. In our opinion, the major factors causing significant environmental impacts in Bung Boraphet are over-extraction of water from Bung Boraphet for farming, dredging of the lake and loss of connectivity between the lake and floodplain. The natural resources of the Bung Boraphet system urgently need a new co-ordinated basin management approach. The decision support tools we have developed are based on rigorous science. They add to the understanding of the system and offer opportunities to manage the system sustainably for the benefit of both the current and future generations.

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