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Dynamic modelling of a shallow freshwater lake for ecological and economic sustainability

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Abstract

This research deals with the dynamic simulation modelling of a shallow freshwater lake ecosystem and analysis of potential sustainable management policies. The study region consists of a shallow freshwater lake and its surroundings, where fishing is a major commercial activity. The lake is under high nutrient loads, hence eutrophic with macrophyte dominance. The goal of this research is to find a balance between the ecosystem and economic activities in the region. To this end, a system dynamics model of the wetland is constructed. The results obtained from model simulations show that there is no threat of a shift to algal dominance in the near future. The major problem seems to be a potential decline in the welfare of the inhabitants, mainly due to unsustainable population increase. Different scenario runs reveal that the lake would have become eutrophic with algal dominance, if the crayfish population did not collapse due to a fungus disease in 1986. One particular scenario analysis (the recovery of crayfish sometime in the future within the model time frame) results in increase in crayfish harvest; hence in income from fishing, leading to betterment in social conditions. As for the alternative policies tested, 'improved agricultural techniques' is the only policy that leads to better social conditions, through increased yield per hectare. It is hoped that the dynamic simulation model will serve as a laboratory to study the different features of the eutrophication problem in shallow freshwater lakes and to analyse different policy alternatives with an integrated, systemic approach.

Keywords: Shallow freshwater lakes; Eutrophication; Dynamic simulation modelling; Sustainable management; System dynamics method

1. Introduction

Wetlands, in general, are extremely important and rich ecosystems. Similarly, shallow lakes form one of the most fragile ecosystem types on earth, and they are generally the first to perish under development activities (Barbier et al., 1997). Millions of people live near the shores of shallow lakes and their lives depend on conditions of those lakes. They have complex ecological structures and high rate of productivity, both of which support the bulk of diversity associated with freshwaters (Jeppesen et al., 1997a). Furthermore, shallow lakes are generally situated on farmable lowlands, which makes them more vulnerable to human disturbances.

Research on shallow lakes has intensified only recently. The report prepared by Moss (1998) has a reference section that constitutes a long list of valuable studies on shallow freshwater lakes. Amongst those, Jeppesen et al. (1990) deals with interactions between

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Nomenclature

BOD	: Biological Oxygen Demand (mg/l)
Chloro *a*	: chlorophyll *a*. An indirect measure of algal biomass (μg/l)
DHKD	: Doğal Hayatı Koruma Derneği (the Society for the Protection of Nature)
DO	: dissolved oxygen
DSİ	: Devlet Su İşleri (State Hydraulic Works)
GIS	: Geographical Information Systems
N	: nitrogen
NGO	: Non-Governmental Organisation
NH_4^+	: ammonia
NO_2^-	: nitrite
NO_3^-	: nitrate
P	: phosphorus
PO_4^{3-}	: phosphate
PVI	: Percent Volume Inhabited. A measure of a water body's volume that contains aquatic macrophytes
SE	: Secchi disk transparency (m)
TKV	: Türkiye Kalkınma Vakfı (the Development Foundation of Turkey)

different trophic levels, an important contribution to our understanding of shallow lakes. Also, Scheffer (1998) has a very useful book on ecology of shallow lakes.

Studies on shallow lakes suggest that there may be two alternative equilibria over a range of nutrient concentrations: a clear state dominated by macrophytes and a turbid state dominated by high algal biomass. Switches between these two states are possible. However, there are buffer mechanisms that may prevent such a switch even if the conditions are favourable it to happen. The resistance of buffer mechanisms depends on factors such as nutrient release from sediments, magnitude and duration of nutrient loading, hydraulic flushing rate and trophic structure, all of which have important implications for management of shallow lakes (Scheffer et al., 1993; Jeppesen et al., 1997b; Jeppesen, 1999).

Achieving both conservation and effective natural resource utilisation requires careful analysis of the region under study. The relations amongst wildlife, people, economics, government, etc. almost always constitute highly complex dynamic systems. So a holistic point of view is to be adopted and considerable amount of effort must be devoted to field studies to analyse the system and offer improvements.

Three sub-systems are essential elements in a sustainable management practice: *ecological*, *economic* and *social*. The ecological sector considers the ecological conditions on which life depends. The economic sector considers economic development and other non-market activities that contribute to socio-economic well-being. Finally, the social sector deals with demographics, equity and disparity within the human population. Also, the boundaries of the system must be carefully determined not to break any major links between elements. A crucial characteristic of a sustainable management practice is the contribution of various disciplines and involvement of all interested groups (Hardi and Zdan, 1998).

2. Study region

The region modelled is in Temperate Climate Belt, the wetland under study being in Turkey. The region consists of a shallow lake named Uluabat (or Apolyont), rivers flowing in and out of the lake, groundwater, and lands surrounding the lake. The precipitation in the region is characterised by wet–dry year cycles with a more or less regular pattern (as revealed by data). These cycles have important implications for the hydrological dynamics of Lake Uluabat. They affect the depth of the lake, most importantly during summer months. The changes in the depth of the lake, in turn, lead to changes in the ecological dynamics—most notably the trophic state—of the lake. The lake is an important nesting place for bird species, some of which are under the threat of extinction. Although the lake meets the Ramsar Criteria,[1] it was not under conservation status until recently. This situation

[1] The Ramsar Convention states, "Wetlands should be selected for the List on account of their international significance in terms of ecology, botany, zoology, limnology or hydrology. . . . the Ramsar Criteria include four clusters: (1) criteria for representative/unique wetlands, (2) general criteria based on plants/animals, (3) specific criteria based on waterfowl, and (4) specific criteria based on fish" (The Ramsar Convention Manual, 1997).

resulted in "development" activities, which damaged the ecosystem including the habitat of endangered bird species (ME, 1998). Crayfish (*Astacus leptodactylus*) population was an important element of the lake ecosystem until 1986, the year when the population was infected by fungus *Aphanomyces astaci* (Yarar and Magnin, 1997). The disease is commonly known as the 'crayfish plague'. The lake, under continuous load of organic wastes, is faced with the threat of further eutrophication (İnan et al., 1997). Presently, the orthophosphate concentration in the lake is around 0.09 mg. According to Jeppesen (1999), in most shallow lakes there is a threshold value of 0.1–0.15 mg P /l, above which macrophytes cannot maintain clear water state. Clearly, there is a risk of a switch to the phytoplankton dominated turbid state for the lake.

The inhabitants rely on fishing, agriculture and—until recently—crayfish harvest. Agriculture is the most pervasive way of subsistence among the inhabitants; on the other hand, fishing and its related industry are quickly replacing the crayfish harvest and industry (İnan et al., 1997). Tomato cultivation is most significant. The tomato paste factories in the region mostly process tomato from fields around the lake. The production equals 80% of Turkey's tomato paste production. The irrigation is done by water pumped from the lake and its major inflow, M. Kemalpaşa River. The intensive fertiliser and pesticide use may be potential sources for the pollution of the lake, which would in turn affect the agriculture. However, no empirical evidence is available yet (İnan et al., 1997; Demir et al., 1998).

Another problem about the wetland is intensive fishing. This is one of the main activities that have adverse effects on the fragile wetland ecosystem (MARA, 1994).

The industry in the wetland depends on agriculture. The—mostly organic—waste of these factories also threatens the wetland ecosystem. The installation of treatment facilities is the most important method to reduce the amount of wastes. Apart from these pollution sources, rivers carry toxic and organic wastes of factories and households in their catchments, further worsening the state of the lake (İnan et al., 1997).

There are also projects (some in construction phase) of Devlet Su İşleri (DSİ, State Hydraulic Works) put forward to regulate the hydrology of the lake. Though the inhabitants are somewhat aware of most of these problems, it is still important to educate them and thus raise the awareness to desired levels with the endeavours of local organisations, and NGO's such as Doğal Hayatı Koruma Derneği (DHKD, the Society for the Protection of Nature) and Türkiye Kalkınma Vakfı (TKV, the Development Foundation of Turkey).

The ultimate goal of this research is to find a balance between the ecosystem and human activities in the region, so as to secure a continuous improvement in well-being of the inhabitants while improving (or maintaining) the ecosystem. To this end, a systemic dynamic model of the wetland system is constructed by identifying the main elements and the interactions among them. After validation of the model, various policies are analysed by altering some parameters and/or relations in the model.

3. Model description

The model is constructed using system dynamics methodology, an effective tool in dealing with dynamic problems (such as tropical deforestation, chronic high levels of inflation, unsustainable population growth or in this study, excessive nutrient loading) (Forrester, 1968; Sterman, 2000). Understanding of how the existing physical processes, information flows and management strategies interact in creating the dynamics of the variables of interest is the focal point of this methodology. These elements and the relationships between them constitute the 'structure' of the system. Thus, it is said that the 'structure' of the system, operating over time, generates its 'dynamic behaviour patterns' (such as S-shaped growth, exponential growth or decline). The totality of model equations constitutes the 'structure' of the model. It is essential in system dynamics methodology that model structure should provide a valid description of the real system (Forrester and Senge, 1980; Barlas, 1996). The purpose in a typical system dynamics study is to reveal how and why the problematic behaviour is generated and to find leverage points in the system that would be effective in eliminating the problematic behaviour. These leverage points are then used to generate 'policies' (such as fish or agricultural manipulation) to improve the situation.

The main building blocks of a formal system dynamics model are *stocks*, *flows* and *auxiliary* (*converter*) variables. Stocks (symbolised by rectangles) are also known as levels or state variables. They represent major accumulations in the system. Flows (symbolised by valves), also known as rates, change the value of stocks. Stocks in a dynamic system in turn influence the values of flows. Flows represent activities that fill in or drain the stocks. Intermediate concepts or calculations are known as auxiliary variables or converters. Converters are computed from stocks, constants, data, and other converters—unless they are constants. (See Fig. 1e for illustrations of these three types of variables.) The focus and the time frame of the study are important in deciding which elements of the system are to be represented as stocks, flows or converters.

Most system dynamics studies are concerned with the long term rather than the short term, and hence, they are all related to sustainable management to a certain extent. There is considerable amount of study in the system dynamics literature on creating sustainable solutions to social, economic and organisational problems (Saeed and Radzicki, 1998). For instance, Wils (1998) evaluates the relative advantages of extraction and end-use efficiencies in natural resource management. More recently, Saysel et al. (2002) focus on a regional sustainable management application of system dynamics. On the other hand, this paper presents a more local application of the methodology concentrating on a lake's ecosystem.

The model has three sectors as mentioned earlier: *lake ecosystem*, *economic activities* and *social structure* on the periphery of the lake. Each consists of several sub-sectors (Güneralp, 2000) (Fig. 1a). The variables of the model are represented in italics throughout the paper.

The ecological elements of the lake and their interactions are modelled in the *lake ecosystem* sector. In construction of the ecosystem sector, limited studies done on shallow lakes have been used. The time unit is month and, for the purpose of this research, the lake ecosystem is modelled in just enough detail to reflect the fundamental system dynamics and to have a meaningful input–output exchange with the other two sectors. The *economic activities* sector includes all activities of the inhabitants with significant economic value, such as industrial facilities, farming around the lake and fishing. The *social structure* sector deals with the demographics of the inhabitants, tightly related with the functioning of the other two sectors. The acronyms used in the model are listed in Nomenclature.

3.1. Main assumptions for the model

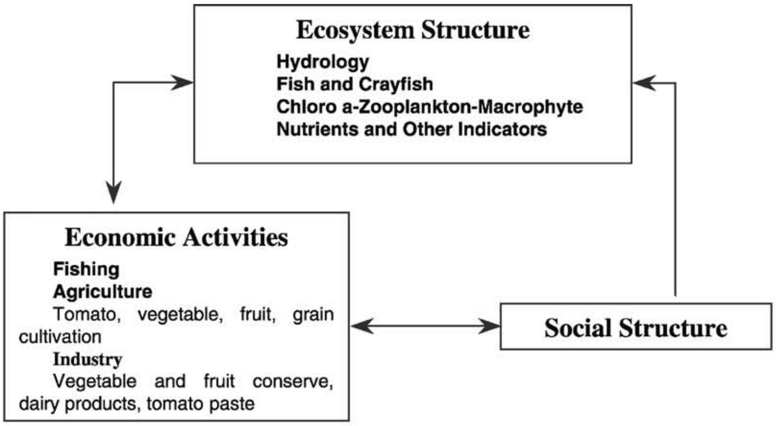
There are 11 major assumptions of the model:

- There are two major fish species in the lake: pike (*Esox lucius*) and carp (*Cyprinus carpio*).
- Regeneration of fish and crayfish takes place all year long.
- Flood plain mechanism (flooding of the lake's shoreline during peak seasons of the lake volume) is ignored in the model.
- *Immature pike/carp* and *immature crayfish* are not landed.
- *Macrophyte* cover area is based on lake surface area, since there is no available updated data on the lake bottom.
- Dynamics of nitrogen fixation by organisms and dissolved oxygen (DO) in the lake are ignored in the model.
- 1995 real prices are used.
- In initial conditions, 50% of crops processed in factories come from within the region and the rest from outside the region.
- The effect of rainfall on irrigation is assumed negligible.
- Only rural population in the region is considered.
- Random effects are ignored in the model because of the lack of available data and because randomness is unlikely to change the major behaviour patterns significantly. Therefore, average values are assigned to all parameters and inputs.

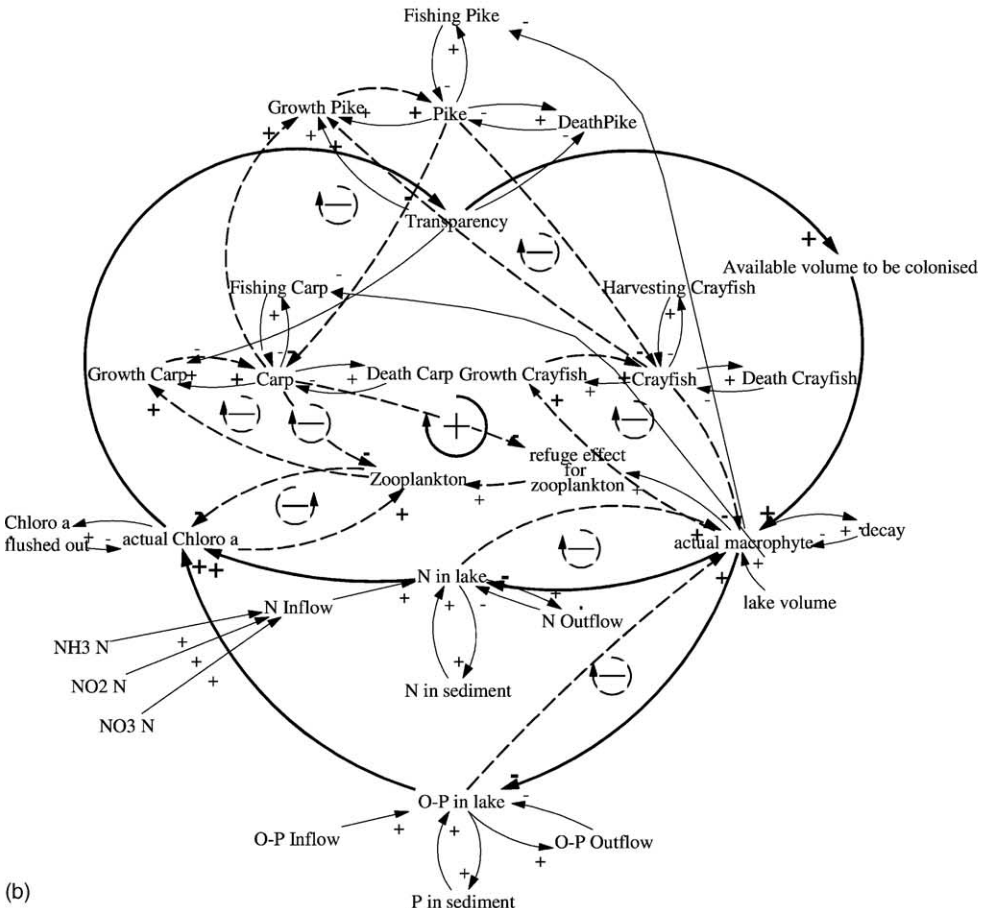
3.2. Lake ecosystem sector

The sector consists of four sub-sectors: *hydrology*, *nutrients and other indicators*, *chloro a–zooplankton–macrophyte* and *fish and crayfish*. A broad, summary causal-loop diagram of the ecosystem sector is given in Fig. 1b.

The *hydrology* sub-sector is the skeleton of the *lake ecosystem* sector. It is the sub-sector in which the physical state and the hydrological dynamics of the lake are modelled. This sub-sector consists of standard stock-flow equations that calculate natural inflows and



(a)



(b)

Fig. 1. (a) Model structure showing the sectors, sub-sectors and sections. (b) Broad causal-loop diagram of the *lake ecosystem* sector. (c) Fish-fishing effectiveness graph. (d) Broad causal-loop diagram of tomato cultivation from the *economic activities* sector. (e) Diagram of the *social structure* sector.

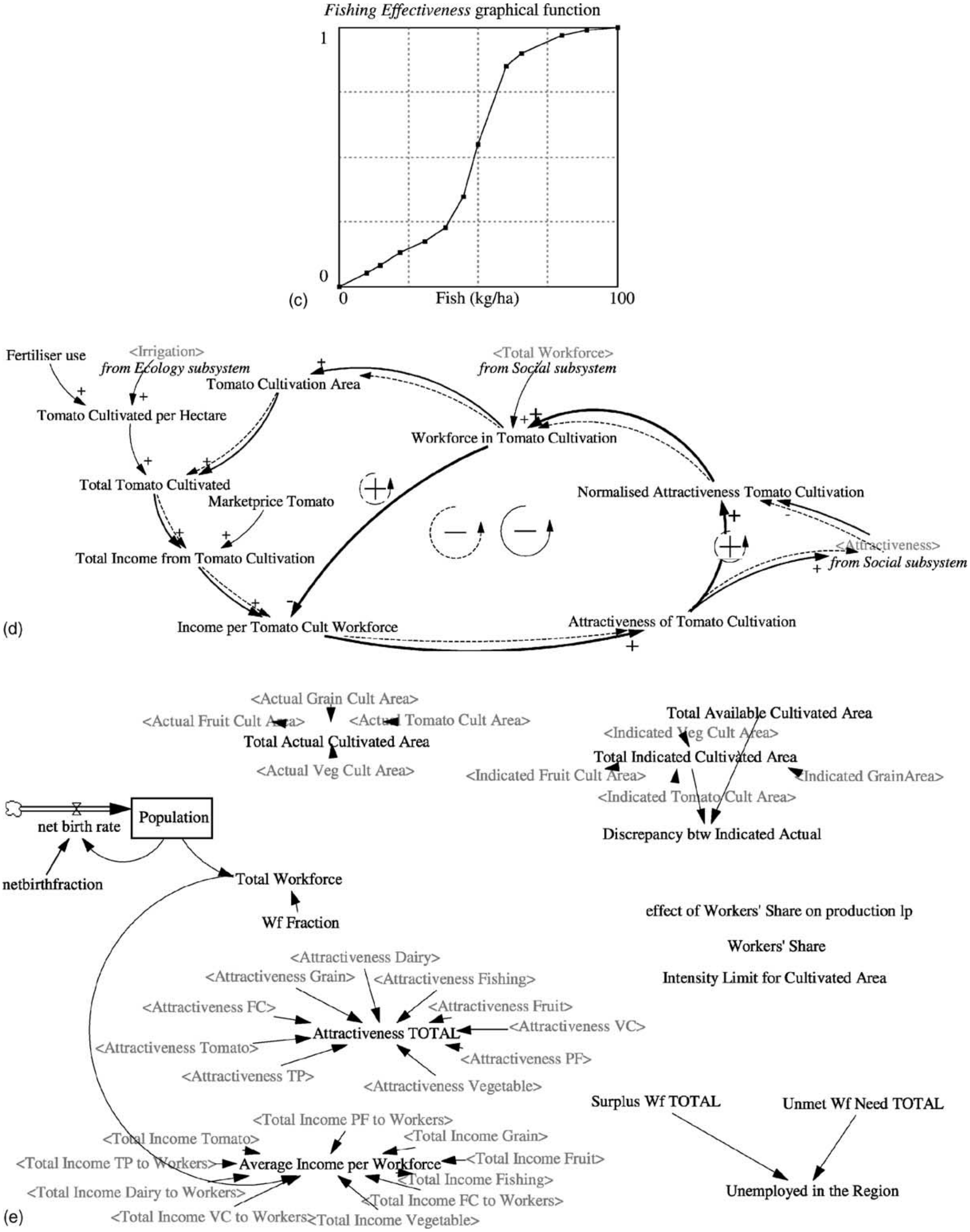


Fig. 1. (*Continued*).

outflows, mass balance (volume), surface area, depth of the lake, and the irrigation flow (which interacts with *the economy* sector). Groundwater is not included in the model due to the lack of available data.

Phosphorus (P) and nitrogen (N) are the two major nutrients, bound by plants during photosynthesis. In Lake Uluabat, nitrogen is mainly present in the form of ${NO_2}^-$, ${NO_3}^-$ and ${NH_4}^+$, whereas phosphorus is mainly present in the form of ${PO_4}^{3-}$. Their concentrations in the lake water and the ratio of nitrogen to phosphorus are important parameters dictating the "trophic" state of the lake. Total nitrogen, the sum of nitrogen from all three sources, is used in the model. Orthophosphate is used in the model since data were not available on total phosphorus. The amounts of these two nutrients in the lake—both in the water and bound by the macrophyte—are represented as stocks *N*, and *O-P*, in milligrams. The concentrations of phosphorus and nitrogen in the lake water are calculated by dividing the corresponding stock value, *O-P* and *N* respectively, by the *Lake* stock and subtracting the portion bound by the macrophyte (Eqs. (1a) and (1b); Fig. 1b). *Nutrient use by macro* in Eqs. (1a) and (1b) represents the percentage of P and N bound by the macrophyte in the lake and reflects the role of macrophyte in regulating the nutrient levels—and thus algal biomass—of the lake. *Actual macrophyte* is defined as percent lake volume inhabited and is assumed to consume the same percentage of nutrients in the lake. Thus, *nutrient use by macro* is assumed equal to *actual macrophyte*, which competes with algal biomass for nutrients. In brief, *O-P in lake* and *N in lake* will give P and N concentrations, available to algae, respectively.

$$\textit{O-P in lake} = \text{If } (\textit{Lake} > 0) \text{ then } ((1 - \textit{nutrient use}) \times (\textit{O-P}/\textit{Lake})) \quad \text{else } 0 \tag{1a}$$

$$\textit{N in lake} = \text{If } (\textit{Lake} > 0) \text{ then } ((1 - \textit{nutrient use}) \times (\textit{N}/\textit{Lake})) \quad \text{else } 0 \tag{1b}$$

A portion of both phosphorus and nitrogen inputs is stored in sediments. Moreover, phosphorus and nitrogen in sediments are released back to water at a certain rate. This forms a feedback structure that may act as a buffer mechanism in certain cases. In general, sedimentation rate is higher, which results in nutrient excess in sediments and an internal nutrient supply to water body even if external input no longer exists. The result is prolonged and intensified eutrophication, which may be the case in Lake Uluabat.

Sewage from urban settlements, industrial areas, and nutrient flow from drainage basins are major sources for both nutrients. Nutrient flow from these sources are formulated as graphical functions and extrapolated into the future. However, another source for nitrogen is agricultural areas. Excess nitrogen, originating from fertilisers and not bound by plants or in the soil, leaks to the lake, whereas all the excess phosphorus from fertilisers is stabilised. Nutrient flow from agriculture depends on the cultivated area and the type of crop. It is worth noting that nitrogen fixation mechanism by organisms, which plays a role in nitrogen removal from water body, is not included in the model.

The concentration of bor, a toxic element (*bor in lake*, in mg/l) and Biological Oxygen Demand (BOD) concentration (*BOD in lake*, in mg/l) are computed in this sub-sector simply as water quality indicators. DO is ignored, since the decline in DO is significant only at organic waste discharge points and thus the complexities involved in its inclusion in the model are not justified. The suspended solid concentration in the lake, *SS in lake* in mg/l, is computed in this sub-sector; it affects transparency of the lake water.

Algal, macrophyte and zooplankton biomasses are calculated in the *water plants and zooplankton* sector (related parts in Fig. 1b). Algal biomass is represented by the *potential chloro a* content of the lake water, which is found by a logarithmic relationship between algal biomass (*potential chloro a*), P and N concentration of the lake (*O-P in lake* and *N in lake*) (Jørgensen, 1994). There are three such empirical relationships, each accepted valid for one of three cases depending on the value of the N:P ratio (Eqs. (2)–(4)) (Jørgensen, 1994):

for the case *N in lake*:*O-P in lake* ratio >12, the relationship is:

$$\log_{10}(\textit{potential chloro a}) = 1.45 \times \log_{10}[(\textit{O-P in lake}) \times 1000] - 1.14 \tag{2}$$

for the case the ratio <4:

$$\log_{10}(\textit{potential chloro a}) = 1.4 \times \log_{10}[(N \textit{ in lake}) \times 1000] - 1.9 \quad (3)$$

for the case the ratio >4 and the ratio <12:

$$\log_{10}(\textit{potential chloro a}) = \min(1.4 \times \log_{10}[(N \textit{ in lake}) \times 1000] - 1.9,\ 1.45 \times \log_{10}[(O\text{-}P \textit{ in lake}) \times 1000] - 1.14) \quad (4)$$

where *N in lake* and *O-P in lake* are expressed as mg/l; unit of *potential chloro a* is μg/l.

However, algae are controlled by its predator, *zooplankton* whose unit is mg/l. So, the *actual chloro a* is the algal biomass that can be observed in lake, although *potential chloro a* level "indicated" by P and N concentrations may be higher. A portion of the *actual chloro a* is continuously flushed out by the outflow of the lake (Fig. 1b). The algal growth sub-model may seem simplistic compared to more detailed formulations in the literature, but from our perspective the current detail level is sufficient for the purposes of this study. More complex and detailed eutrophication formulation will be considered in the future versions.

Macrophyte biomass unit is expressed as PVI (Percent Volume Inhabited). It is a function of P and N concentration of the lake and the N:P ratio. It is also affected by the *chloro a* level in the lake, since algae is more efficient in getting nutrients from water than macrophyte (Fig. 1b). As the *chloro a* level gets higher, macrophyte can absorb fewer nutrients. Algal biomass has also an indirect effect on macrophyte biomass via lake water transparency. *Transparency* is dictated by *actual chloro a* level and measured as Secchi disk transparency (SE) in metres (Jørgensen, 1994). Macrophyte is able to colonise the lake to a depth of three times the SE although the changes in lake transparency are not instantly reflected in the *actual macrophyte* biomass. It takes sometime for macrophyte to colonise newly available regions and to perish from regions with insufficient light conditions. This situation is represented in the model by the use of a third order exponential smoothing, with a delay constant of 12 months. The same is not the case for algae, since they are able to respond to changes in their environment almost instantly.

The struggle between macrophyte and algae is very significant for the overall ecosystem. The outcome of this struggle dictates the trophic state of the lake and largely depends on the positive feedback loop, formed mainly by nutrient concentrations (i.e. *N in lake* and *O-P in lake*), algae (i.e. *actual chloro a*), *actual macrophyte*, and *transparency*. The darker arrows in Fig. 1b depict this phenomenon.

The *fish and bird* sub-sector constitutes the top of the food chain. It is this sub-sector of the *lake ecosystem* sector that is directly linked to the *economy* sector via the fish industry. There are a number of fish species in the lake but two fish species are chosen as the indicators of the lake's trophic state: pike and carp (Fig. 1b). Fish that are between zero- and two-year-old are treated as separate immature fish stocks and are not reproductive. This allows both to differentiate the food needs/sources and to isolate the young fish from reproduction. Reproduction of fish is assumed to take place all year long since the climate is suitable. The unit of fish and crayfish stocks is kg/ha.

Pike is a predatory fish species. *Mature pike* preys on other fish including carp and crustaceans, such as crayfish and it prefers clear waters. Hence, reproduction and death of pike depend on the availability of sufficient food sources and transparency of the lake. Both of these factors are reflected in the model as graphical functions. On the other hand, the presence of *mature pike* means grazing pressure on *immature*/*mature carp*/*crayfish* forming a predator-controlled mechanism. The crucial point is that *mature pike* grazes on more abundant prey. In other words, when density of a prey species falls, grazing pressure on that species also decreases proportionate to the ratio of it to the total density of prey species. Though *actual macrophyte* contributes to clear water conditions favourable for *mature pike*, it also provides refuge for prey species, represented as a dimensionless variable *refuge against pike for carp* in the model.

Carp is a planktivorous fish; that is, it feeds mainly on zooplankton. The dynamics of carp is similar to pike. Food availability affects both reproduction and death rate of carp via graphical functions. However, since carp prefers turbid waters, its reproductive capacity increases as lake water becomes less transparent. Unlike pike, both *immature carp* and *mature* *carp* stocks experience grazing pressure. Since carp feeds on *zooplankton*, high carp density means low zooplankton density which means suitable growth conditions for algae. Algae (*actual chloro a*) cause turbidity, which favours reproduction of carp and puts more grazing pressure on *zooplankton*. The result is a turbid lake dominated by carp and algal blooms.

Fishing is an external, anthropogenic factor that has the potential of altering the functioning of the ecosystem. The amount of fish that is landed depends on the number of fishermen and fishing effectiveness. *Fishing effectiveness for pike/carp* is dimensionless and it is a function of *mature pike/carp* density (Fig. 1c). Fishing effectiveness is also affected by macrophyte to reflect the negative effect of macrophyte on fishing nets.

Although a fungi attack in 1986 has driven the crayfish population near extinction, crayfish is also included in the model. One reason is that there is always a possibility for the crayfish to recover in which case its economic and ecological consequences are worth analysing. Another is to test a highly debated policy option, the introduction of crayfish to the lake. Lake depth and macrophyte cover, the main food for *crayfish*, determine its reproductive capacity. Its death rate is a function of macrophyte cover too. There is a grazing outflow from both *immature crayfish* and *mature crayfish* stocks as in the carp, due to pike predation. *Crayfish harvest*, in kilograms per month per hectare, is a function of *mature crayfish* stock and is also adversely affected by *actual macrophyte*.

Specific data on population dynamics and feeding habits of birds is very limited. Further, they are assumed to have an insignificant effect on their prey species compared to other effects. Two bird species could be selected as indicators of bird presence on the shores of the lake. These are coot (*Fulica atra*), an herbivorous species and pygmy cormorant (*Halietor pygmeus*), a carnivorous one. Coot feeds on macrophyte; and pygmy cormorant feeds on fish. Therefore, since the conditions of macrophyte and fish in the model also give insight on the condition of birds, these latter are not included in the model.

Macrophyte provides certain degree of refuge for zooplankton against predation. Dimensionless *refuge effect for zooplankton* increases with increasing *actual macrophyte* biomass. However, when planktivorous fish biomass is high enough, the refuge effect diminishes dramatically no matter how high the macrophyte biomass is (Schriver et al., 1995).

Finally, note that there are a number of balancing (negative) feedback loops in the food chain in addition to the large reinforcing (positive) loop mentioned above. One can conjecture that the stability of the ecosystem would depend on the relative strength (dominance) of these two types of loops in the system (May, 1977; Scheffer, 1990). Most data specific to the lake are unfortunately unavailable, including carp and pike stocks in the lake. Hence, related parameter values were estimated either from literature or based on interpretations of incomplete data. For example, initial fish and crayfish stocks were estimated based on the amounts of fish and crayfish sold per year in the local market.

3.3. Economic activities sector

Three sub-sectors constitute the *economy* sector: *fishing*, *agriculture* and *industry*. The structures of these sub-sectors resemble each other.

There are *tomato*, *vegetable*, *fruit*, and *grain cultivation* sections in the *agriculture* sub-sector. The values for parameters such as *yield per hectare* (in kg/ha) and *market price* (in US$) are estimated from available literature (Madran, 1991; Ergüler, 1994; SIS, 1997). The structures of these sections are also similar to each other. Hence, only the *tomato cultivation* section is explained in detail as an example (Fig. 1d).

Tomato Cultivated per Hectare is a function of irrigation and tomato harvest (*Total Tomato Cultivated*) depends on the land allocated to tomato cultivation (*Tomato Cultivation Area*). Total income increases as total tomato harvested increases (*Market price* is constant). This income increases the welfare—in US$ per person per month—of the inhabitants relying on tomato cultivation, which also defines the attractiveness of tomato cultivation for other people. This attractiveness is normalised by dividing it by the sum of attractiveness values from all economic activities. This facilitates comparison amongst the attractiveness values of all economic activities. Thus, these normalised values represent how people prefer different economic activities, depending on their relative attractiveness. The multiplication of normalised attractiveness of tomato cultivation (a dimensionless number between 0 and 1) with total workforce determines the workforce in tomato cultivation (Fig. 1d). The land on which tomato is cultivated is an increasing function of the workforce. The maximum value it can reach is the total arable land around the lake (*Total Available Cultivated Area*).

The main interactions between the *agriculture* sub-sector and the lake are the irrigation of fields and excess fertiliser returning back to the lake from fertilised lands. It is assumed that *fertiliser use* per month is currently three times more than the actual need to represent the excessive use by the farmers. Total actual irrigation, in litre per month, is affected negatively when the water level in the lake drops down.

Fishing sub-sector has a similar structure. It is clear from Fig. 1c that increased income draws more workforce to fishing, subsequently increasing the pressure on fish. This in turn inevitably reduces total fish landed as a result of diminished fish stocks since the lake does not have the capacity to sustain extreme levels of fishing. Hence, fishing from the lake is affected by the fish stock in the lake. This is exactly what is observed in the lake today. This will either exterminate fish from the lake or reduce the *fishing workforce* to a sustainable level depending on the prevailing conditions.

In the *fishing* sub-sector, total fish landed is affected by *fishing effectiveness*. *Fishing effectiveness* is dimensionless and reflects the effect of fish density and macrophyte. *Actual fishing* is the sum of *crayfish harvest*, *pike* and *carp* landings, computed by multiplying *fishing pike*/*carp* (in kg/ha per month) with the *lake surface area* (in ha).

Factories near the lake either process crop from agricultural lands or fish. For different reasons, fish processing factories get fish from outside the region since almost all fish landed in the lake is sold in the domestic market. An increase in agricultural yields in the region directly implies an increase in the production rate of factories. Therefore, the expansion of the agricultural industry depends on the amount of harvests and available workforce. If there occurs a decline in harvests, this affects the factories negatively.

The fundamental balancing (negative) feedback structure applies also here, with slight modifications. For example, the market price (e.g. *market price TP* in the tomato paste industry) is constant and the production (*tomato paste production*) is a linear function of it. In addition, the workforce (*Actual Wf Need TP*) depends on the production amount. If workforce is greater than workforce supply (*Wf Supply TP*), then this indicates a labour shortage in the area and it is assumed that this shortage is compensated by hiring from the unemployed workforce (*Surplus Wf Total*) and if necessary, workforce from outside the region which is assumed always available (Eq. (5)). If workforce supply is greater than actual workforce then there is a surplus labour (*Surplus Wf TP*), which has the same meaning as it has in the *agriculture* sub-sector. (However, there is no concept of “unmet workforce need” in the agriculture sub-sector, since a certain level of cultivation implies that there must have been enough people to cultivate it. The same is true for the fishing sub-sector.)

$$\begin{aligned} &\textit{Unmet Wf Need TP}\\ &\quad = \text{If } ((\textit{Wf Supply TP} - \textit{Actual Wf Need TP}) < 0)\\ &\qquad \text{then } (\textit{Actual Wf Need TP} - \textit{Wf Supply TP})\\ &\qquad \text{else } 0 \end{aligned} \tag{5}$$

The main interaction between factories and the lake is the discharge of the factories. Since discharges are mainly organic, it is assumed that they are only composed of organic wastes (e.g. *Organic Waste Discharge TP*, in metre cubed per month, in the tomato paste industry). These discharges may play a significant role in the probable further eutrophication of the lake. Also, the discharges of some other industrial facilities outside the periphery but inside the catchment of the lake also reach the lake via the main inflow river (*M. Kemalpaş a River*). These discharges are represented as external inputs in the *nutrients and other indicators* sub-sector.

3.4. Social structure sector

Demographic indicators are modelled in the *social* sector (Fig. 1e). *Population* dynamics, *total workforce*, *average income per workforce* of the regional population are all computed in this sector.

Only the rural population is considered in the study. *Net birth fraction* for the region is 1.75% per year (TKV, 1998). Assuming an average of five persons per family of which one male is in the working age, the *total workforce* in the region is one fifth of the *population*. The difference between total surplus workforce (*Surplus Wf Total*) and total unmet workforce need (*Unmet Wf Need Total*) gives the *unemployed in the region*. Surplus workforce from sub-sectors with full employment is employed in sub-sectors with non-zero unmet workforce need. However, unmet workforce need may be higher than surplus, in which case it is assumed that hiring workforce from outside the region meets the remaining workforce need. This is a common practice in the Uluabat region. On the other hand, if unmet workforce is less than surplus than there is non-zero *unemployed in the region* (Eq. (6)). This sector also provides parameters required to calculate the allocation of workforce amongst competing economic activities, such as fishing, agriculture or industrial processing. The allocation is done for each sub-sector using the ratio of the attractiveness value of that sub-sector (e.g. *Attractiveness TP*) to *Attractiveness Total* (the sum of the attractiveness values of all economic activities).

$$\begin{aligned} &\textit{Unemployed in the Region} \\ &\quad = \text{If } ((\textit{Surplus Wf Total} - \textit{Unmet Wf Need Total}) > 0) \\ &\qquad \text{then } (\textit{Surplus Wf Total} - \textit{Unmet Wf Need Total}) \\ &\qquad \text{else } 0 \end{aligned} \tag{6}$$

4. Validation and the base run

Verification and *validation* testing, done by carrying out some standard procedures, follow the model construction stage (Barlas, 1996). In *verification*, the equations were checked against careless errors and dimensional consistency was ensured on both sides of all equations. Control/trace variables were also used in the model to prevent formulation errors.

Validation tests were carried out both on individual sub-sectors in isolation and on the whole model. The model passed these *structural* and *behavioural* validation tests (Güneralp, 2000). Structural tests assess the logical validity of model equations, by evaluating them one by one and by testing their behaviour under extreme/stress conditions. In behaviour validation, the model-generated behaviour patterns of major variables were evaluated based on available data on Lake Uluabat and the literature on shallow freshwater lakes. The validity tests showed that the model-generated behaviour is consistent with the literature and limited available data. Clearly, it would be possible to establish a stronger case if more numerical time-series data were available (Güneralp, 2000). Therefore, extensive validation tests should be carried out with more data in the future. The present level of validation of the model is not enough to draw exact conclusions. However, lack of recorded data severely restricts our current options and collecting new dynamic data necessitates long time periods. It should also be kept in mind that the main purpose of the model is to capture the broad dynamic behaviour patterns of the real system, not provide "point" predictions.

4.1. The base run

The base run of the model was simulated under the pre-mentioned set of assumptions, graphical functions and parameter values which reflect the current conditions in the region (Güneralp, 2000). The time frame of the study is 34 years, from the year 1982 to 2016. Time axis is in months in model-generated output graphs; a second scale in years is added below the axis for explanatory purposes. The discussion in the text is done using years as the time unit.

4.1.1. Lake ecosystem sector

A striking output obtained from the base run is that a shift to algal dominance in the lake will not occur, although eutrophication continues. This statement is crucial since there is a widespread acceptance that such a shift will occur in the near future if current conditions persist. However, *mature pike* population controls *immature and mature carp* population, and *actual macrophyte* takes out the nutrients from the lake water, controlling algal growth. So, clear water conditions persist in the lake at least for the next 15 years.

Two types of oscillations are observed in lake hydrological dynamics. The smaller ones are seasonal oscillations caused by fluctuations in the major inflow source, i.e. *M. Kemalpaş a River*. The larger oscillations are the result of wet–dry year cycles. 1988–1996, 2003–2008, 2014–2015 periods are dry years (i.e. months 72–168, 252–312 and 384–396). The only notable point in *irrigation* is the slight decrease in water drained because of the decline in the *lake depth*. Mean nitrogen concentration, *N in lake* and mean phosphorus concentration, *O-P in lake* are not critically high: 0.5393 and 0.0744 mg/l, respectively. The mean phosphorus concentration is well below the approximate threshold values, 0.1–0.15 mg P/l, stated in Jeppesen (1999). However, the increase in phosphorus concentration is worth noting until the crayfish population ails and collapses, i.e. month 60. Furthermore, its mean during the period 1982–1986 (between months 0 and 60) is 0.1024 mg/l (Fig. 2a). Although nitrogen is the limiting nutrient until 1994, the increase in phosphorus concentration is critical and deserves a scenario analysis on "what if the crayfish never go infected"? (refer Section 5.1.1). After 1994, phosphorus is the limiting one during spring, and nitrogen during fall (Fig. 2b). Also, *suspended solid concentration* in the lake is around 100 mg/l; again a reasonable value due to reduced suspended solid loading from the major inflow in recent years. The fluctuations in these variables are caused by fluctuations in their loading, except suspended solid fluctuations, which are the result of seasonal fluctuations in inflow and outflow sources of the lake. Also, BOD and borax concentrations are well below the dangerous levels.

Actual macrophyte cover is approximately 55 PVI during dry years and 40 PVI during wet years. Overall, the average *actual macrophyte* cover in the lake bottom is around 50 PVI. *Actual chloro a* level in the lake is always below 50 μg/l, except for a period just before the collapse of the crayfish population in which *actual chloro a* concentration reaches 84.7 μg/l. *Actual chloro a* level is controlled by both *actual macrophyte*, via nutrient concentrations, and *zooplankton*, which does not experience a high grazing pressure from planktivorous fish (Fig. 2c).

Transparency is below 1.5 m most of the time in a year and is the same as the lake depth for certain periods. Its average value is slightly more than 1 m. Although average *transparency* is greater in wet years than dry years, the portion of the lake transparent in dry years is larger than that in wet years (Fig. 2d).

The *mature crayfish* stock is near zero due to the fungal disease, but not totally extinct. This provides an opportunity for the crayfish population to overcome the disease. Since pike grazes on carp and crayfish, the collapse of crayfish stock causes the grazing pressure on carp to increase. This results in increased control on carp. *Mature pike* population is about 3.5 times more than that of *mature carp*. Considering that it is enough for pike to control carp in a lake when its population is twice that of carp, the lake is secure from becoming eutrophic with algal dominance. In addition, the lake is not turbid favouring reproduction of pike over that of carp. Fig. 2e shows the population dynamics of the fish species. It is also worth mentioning that macrophyte prevalence causes approximately a 30% decrease in *fishing effectiveness*.

The fast decrease in *actual macrophyte* together with the algal bloom and the up and down in *mature carp* population, coinciding with the peak in phosphorus concentration just before the crayfish collapse deserves closer inspection. Smaller oscillations in *actual macrophyte* are caused by oscillations in nutrient concentrations (Fig. 2f). Oscillations in *immature*/*mature pike*/*carp*, *actual chloro a*, and *transparency* are largely due to seasonal fluctuations in hydrological cycle and to a smaller extent as a result of oscillations in nutrient concentrations. Neither small nor large oscillations are the result of predator–prey dynamics.

Consequently, pike is able to suppress carp throughout the simulation time frame, in spite of a decrease in its population during the first few years, preventing the so-feared algal blooms, and hence yielding high level of *transparency* and broad *actual macrophyte* cover on the lake bottom. This result points to the potential vital role fish manipulation may play in fighting eutrophication.

4.1.2. Economic activities sector

In the *agriculture* sub-sector, inefficiencies in irrigation (e.g. *Irrigation Tomato*) during dry years cause a slight fall in yield per hectare (e.g. *Tomato Cultivated per Hectare*), which is reflected in income per workforce (e.g. *Income per Wf Tomato*). Cultivated areas (*Total Actual Cultivated Area*) increase as workforce in agriculture increases as a result of *population* growth. On the other hand, a decreasing trend begins in *normalised attractiveness* of each crop as *Total Actual Cultivated Area* reaches the available arable lands (*Total Available Cultivated Area*) in the year 1996 (month 168). The reason is that while workforce supply in agriculture keeps increasing, *Total Available Cultivated Area* stays constant. As a result, income per workforce diminishes and, consequently, *attractiveness* drops. However, since the increase in *total workforce* is greater than the decrease in *attractiveness*,

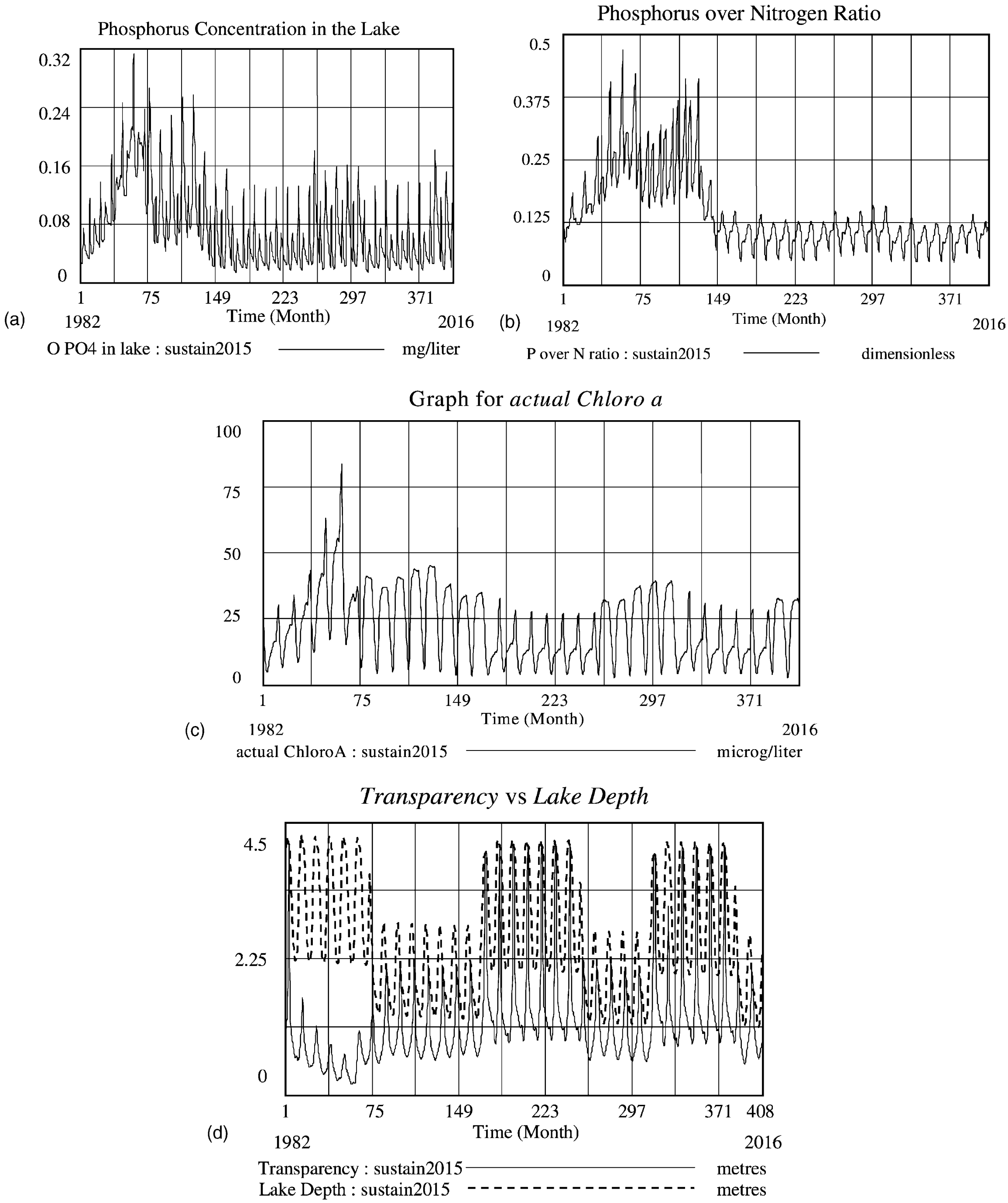


Fig. 2. (a) Base run behaviour of phosphorus concentration in the lake. (b) Base run behaviour of phosphorus over nitrogen concentration ratio. (c) Base run behaviour of *chloro a* level in the lake water. (d) Base run behaviour of *transparency* as compared to *lake depth*. (e) Base run population dynamics of *mature pike*, *carp* and *crayfish*. (f) Base run behaviour of *actual macrophyte* cover in the lake. (g) Base run behaviour of *fishing workforce*. (h) Base run behaviour of *average income per workforce* in the region.

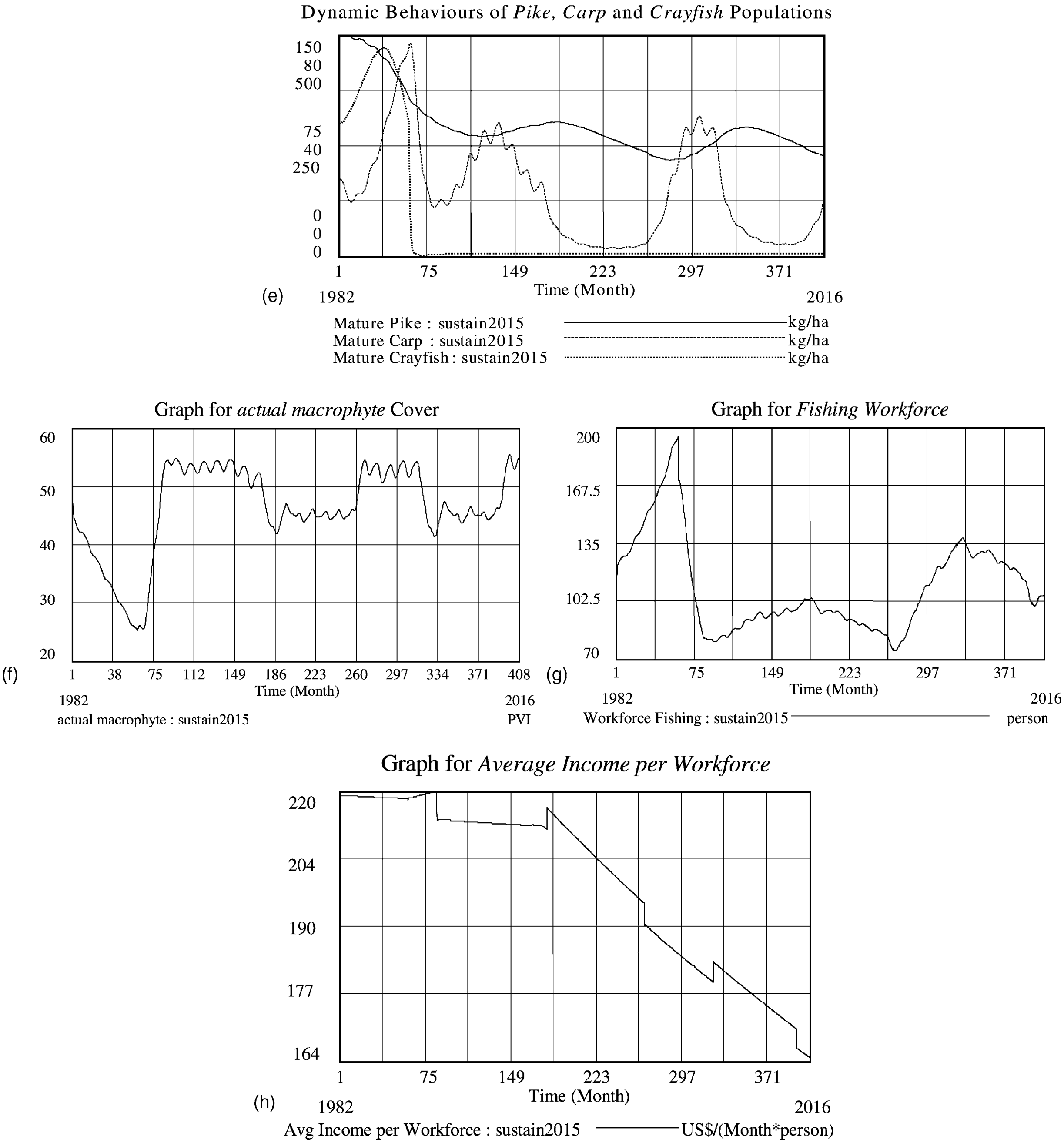


Fig. 2. (*Continued*).

workforce supply keeps increasing. Furthermore the *workforce* also increases; in fact it is equal to *workforce supply* in this run. Namely, every person who is willing to work in the *agriculture* sub-sector finds opportunity to do so. This means the critical *Intensity Limit for Cultivated Area*, which defines the maximum workforce that can be supported, is not reached in any of the areas in the *agriculture* sub-sector.

The situation in the *industry* sub-sector is quite different. Although the production in factories (except fish processing) experiences a drop during dry years (as a result of drops in yields), this does not affect *income per workforce*. The reason is that workforce to be employed each year, i.e. *Actual Wf Need* is dictated by the level of production in the factories. So, *attractiveness* in this sub-sector stays the same. However, *normalised attractiveness* increases since *normalised attractiveness* of the agriculture sub-sector decreases.

Fishing workforce, while increasing during first few years as a result of high *attractiveness of fishing* amongst inhabitants and *population* growth, experiences a sharp decline at the end of year 1986 (month 60) when the fungi hit the crayfish stock in the lake (Fig. 2g). Although it does not follow a smooth pattern, *normalised attractiveness of fishing* declines throughout the simulation time-frame. However, *fishing workforce* increases slightly after the year 2000 (month 216) mainly due to an overall increase in fish stocks in the lake (Fig. 2e).

The most notable dynamics of this sector is the decline in *fishing workforce* as a result of the collapse of crayfish population in the year 1986. Also, the decline in total normalised attractiveness of the *agriculture* sub-sector as a result of the crowding of cultivated areas (compared to an increase in total normalised attractiveness of the *industry* sub-sector) are worth mentioning. On the other hand, *normalised attractiveness of fishing* stays more or less constant after the year 1986, while it was increasing prior to that year.

4.1.3. Social structure sector

The *population* and *total workforce* are increasing. There is an increase in unemployed in the rural population, which is expected because the arable lands are limited and businesses have limited capacity (*Total Available Cultivated Area* is constant). Fishing cannot absorb this unemployed workforce. Attractiveness of all three main income sources (i.e. agriculture, industry and fishing) in the region is contracting. Likewise, *average income per workforce* in the region is also declining (Fig. 2h). Thus, the result of the base run simulation is that the welfare of people in the region worsens over time. In addition to the first decline in 1986, there is a steeper decline after about 1997. One reason is that the demand for arable lands (*Total Indicated Cultivated Area*) increases so much that it exceeds *Total Available Cultivated Area*, resulting in less land for each crop type. Another reason is the increase in the unemployed workforce. These are reflected in the general welfare of people in the region as a decline in *average income per workforce*. It is also worth noting that dry–wet year cycles affect *average income per workforce*, hence the welfare to some extent. In dry years, the fishing yield and the income from fishing are relatively low. The *average income per workforce* in the beginning of the year 2000 is approximately US$200 in 1995 base prices (Güneralp, 2000).

Consequently, it is observed that there is an increase in the number of unemployed and a decline in welfare of inhabitants especially after the year 1997 (month 180), as a result of limited arable lands and limited capacity of businesses. This is the most notable dynamics in this sector. The saw-toothed pattern is the result of dry–wet year cycles. It is lower in dry years because both fish landing and agricultural yield drop due to less water available in the lake.

5. Scenario and policy analyses

Through scenario and policy analysis, a number of modifications on the base model are discussed in order to gain a better understanding of the system and improve it with policy recommendations.

5.1. Scenario analysis

5.1.1. No crayfish population collapse in 1986

The fast increases in phosphorus concentration, carp population and the high algal bloom just around the crayfish population collapse in the beginning of year 1987 (month 60) together with the fast decline in pike population deserves closer inspection (refer Section 4.1.1). Therefore, a scenario analysis regarding “no crayfish population collapse in 1986” was done to find out what would happen in the lake ecosystem in that case.

The result is surprising. The carp becomes the dominant fish species with the decline of pike and the lake loses its clear water state, the insufficient grazing pressure on carp and also the high fishing pressure on pike playing the main roles. It becomes turbid and switches to a eutrophic state characterised by high algal blooms and sparse or no macrophyte cover (Fig. 3a). Run names sustain2015 and sustain2015noD denote the cases of the crayfish being infected and not being infected, respectively. The transition takes place in 1990 (month 96). Thus, surprisingly, it can be concluded that the collapse of crayfish is not a purely negative event as it has typically been considered.

5.1.2. Crayfish recovers in the future

Although the fungi still affect the crayfish population, it is reported that there is considerable *immature crayfish* population in the lake. The fungi affect the species by preventing them from changing their outer skeleton. As a result, the crayfish is not totally extinct from the lake and this gives the hope that it may be able to re-colonise the lake sometime in the future. The recovery, if realised, will most probably have major implications on fishing and the lake ecosystem. The time the crayfish will recover, if it ever recovers, is uncertain. Hence, possible recovery scenarios are analysed with three different recovery times. It is assumed that recovery takes place in a very short time rather than being a gradual process.

First, "recovery in the beginning of the year 2000 (month 216)" scenario is analysed. With the disappearance of the fungi, *mature crayfish* stock shows a

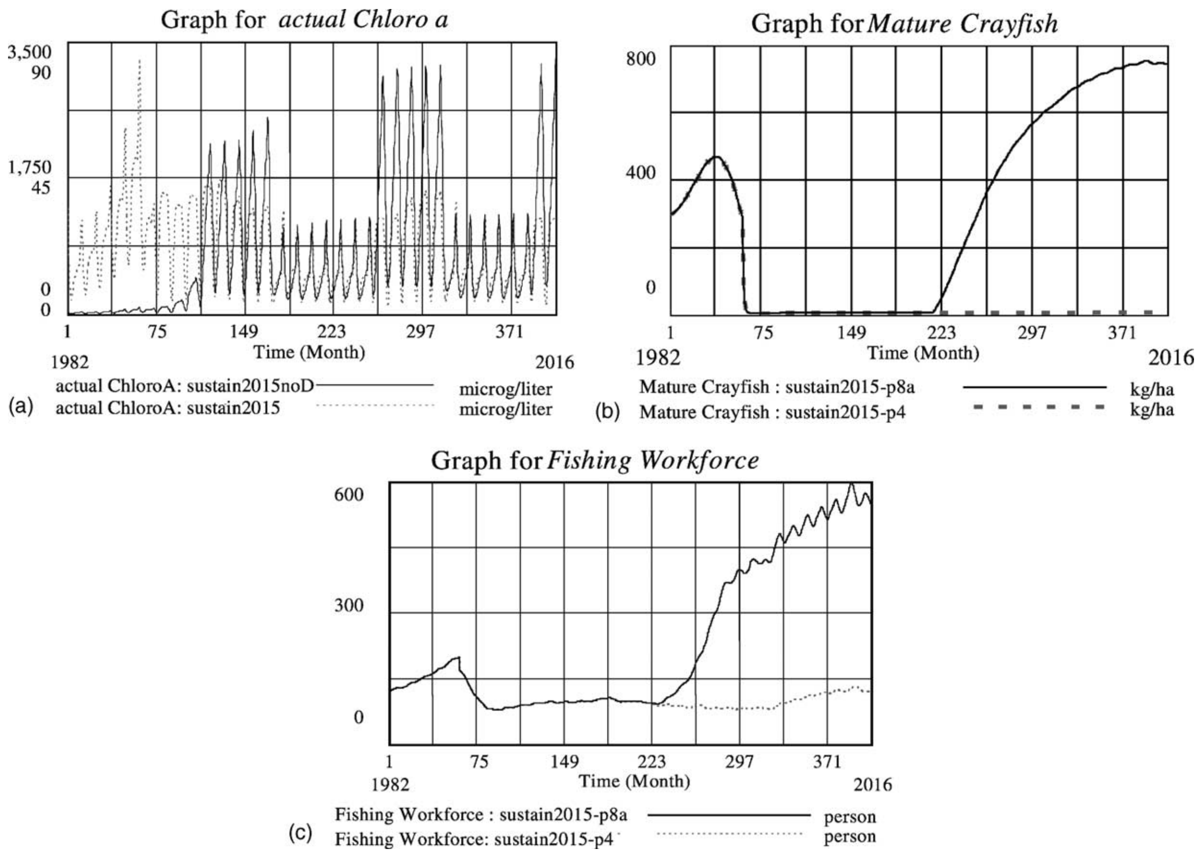


Fig. 3. (a) *Chloro a* level dynamics in case of no *crayfish disease* and *disease*. (b) Dynamics of *mature crayfish* in case of recovery in 2000 and no recovery in the time-frame of the study. (c) *Fishing workforce* in case of recovery in 2000 and no recovery in the time-frame of the study. (d) Hydrology sub-sector when all three policies are implemented (policy-related variables are underlined). (e) *Actual macrophyte* cover in the lake with and without dam. (f) Behaviour of *mature carp* in case of water level regulation and no regulation. (g) *Transparency* in case all three policies implemented and no implementation. (h) *Average income per workforce* in case of *improved productivity* and no improvement. (i) Behaviour of *mature crayfish* in case of *crayfish* introduction and no introduction. (j) *Chloro a* level in case of harvesting all every week and no harvest at all. (k) *Transparency* in case of harvesting all every week and no harvest at all.

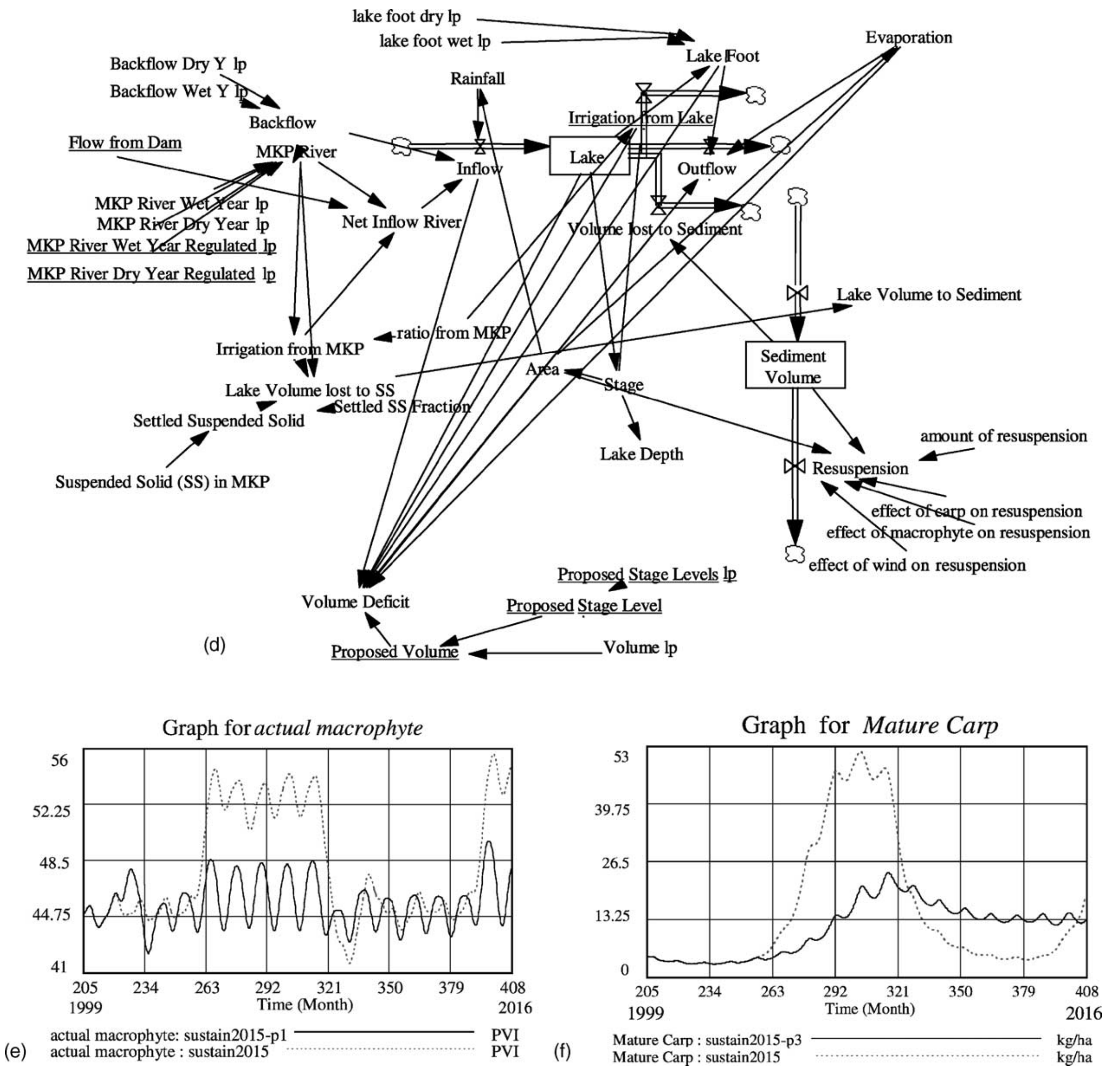


Fig. 3. (*Continued*)

fast increase and seems to reach steady state at approximately 750 kg/ha around the year 2013 (month 372) (Fig. 3b). Accordingly, *immature crayfish* stock also shows an increase. Pike also flourishes, as does crayfish since more crayfish is available in addition to the present carp stock as a food source. Final equilibrium values of both species are higher than their initial stock values before the *disease*. There is a slight decrease in *actual macrophyte* cover due to *crayfish feeding* but *transparency* is virtually not affected.

The result explained above is entirely different than the result presented in Section 5.1.1, although there is abundant crayfish population in the lake in both cases. The reason for this distinction is the “pike to carp ratio”. If it is less than or equal to three, as was the case before and during the year 1986 (months 48–60)

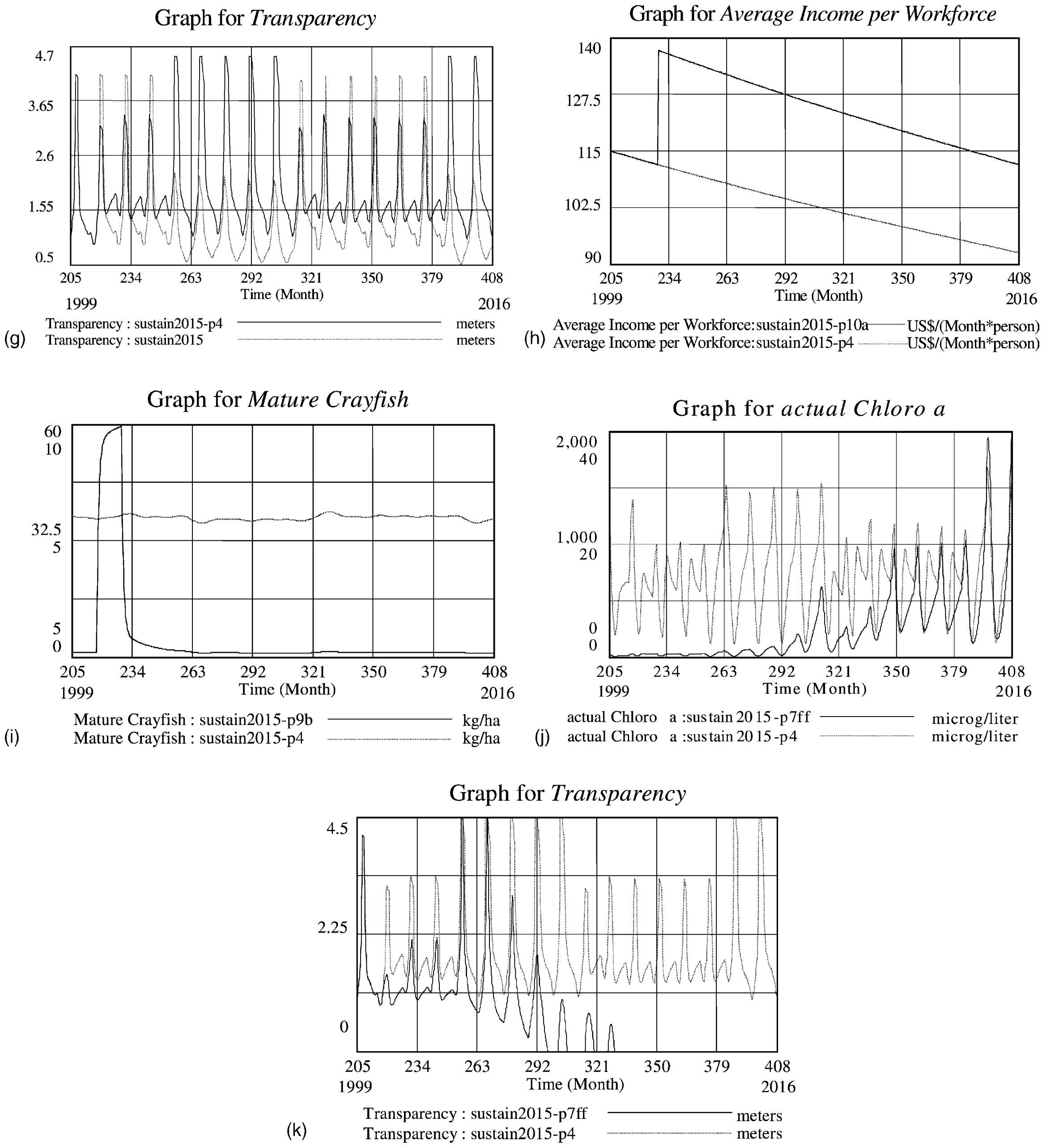


Fig. 3. (*Continued*).

(refer Section 5.1.1), the presence (or recovery) of crayfish favours carp population. If the ratio is larger than or equal to four, as has been the case after the year 1986, the presence (or recovery) of crayfish favours pike population.

With the increase in crayfish and pike, the *fishing workforce* reaches almost 600 people toward the year 2015 (month 396) (Fig. 3c). The increase in *fishing workforce* has a positive impact on the social structure. The number of *Unemployed in the Region* decreases substantially. Scenarios in which recovery takes place in the beginning of the years 2005 and 2010 generate similar results. In Fig. 3b and c, run names sustain2015-p8a and sustain2015-p4 are for the cases where the recovery takes place in the year 2000 and no recovery ever takes place, respectively.

Finally, it is concluded that the overall effect of the crayfish recovery on the lake ecosystem, trophic and social structure is positive as long as the pike to carp ratio is at least four. The runs are done not on the base model but on a modified version in which the planned DSİ projects are assumed to be operational in the beginning of the year 2000 (month 216) (refer Section 5.2.1).

5.2. Policy analysis

Policy runs are done based on those policies proposed both in reports on the lake and in literature regarding hydrological regulations on the lake, agriculture and fishing. The results are used to design recommendations for the management of the lake region. All policies are introduced in the model in the beginning of the year 2000 (month 216) and the time horizon is taken to be 16 years (i.e. until the beginning of year 2016).

5.2.1. Policy options related to hydrological dynamics of the lake

The dramatic decrease in the *lake water level* during dry years causes several problems regarding *irrigation*, *actual macrophyte* cover, and *fishing*. Since the water level is diminished, it becomes hard to pump water out for *irrigation*. The *actual macrophyte* cover tends to increase in dry years due to increased light penetration to the lake bottom. The combined effect of increased *actual macrophyte* cover and low water level is decreased navigation ability for fishing boats.

The differences in average water levels between wet and dry years are caused by the fluctuations in the main inflow source, *M. Kemalpaş a River*. To control these fluctuations, DSİ has begun the construction of a dam on the main inflow source. When completed, the dam will reduce the fluctuations between dry and wet years to a great extent. In addition, the regulated flow will contain virtually no suspended solids.

In conjunction with the dam, it is planned to construct a new regulator to the outflow of the lake. While the dam regulates the fluctuations of the inflow between dry and wet years, the regulator will serve a similar purpose to regulate the seasonal fluctuations in the lake. In addition to these, an extension to the existing Uluabat irrigation is in construction phase. When the extension is completed, 10,828 ha of cultivated lands will be irrigated in addition to the currently irrigated lands.

The policies are brought into the model one by one. The resulting hydrology sub-sector when all three policies are introduced is provided in Fig. 3d. The time lag required for the dam to stock water is ignored. Also the fact that regulated flow enters the lake from a different point is not represented in the model.

The effect of the dam on the lake is as expected. The *average lake water level* in dry years is increased and has a value close to that of wet years. The *sedimentation rate* slows down considerably. The *actual macrophyte* cover is about 45 PVI throughout dry years due to increased water level, while it used to be more than 55 PVI in dry years (Fig. 3e). However, this is not compensated by an increase in *actual chloro a* level as might be expected at first, since the suspended solid flow into the lake is diminished by the dam affecting carp negatively and furnishing conditions for *zooplankton* growth. The overall increase in *transparency* as a result of the decrease in *suspended solid concentration* is the reason for the carp's decline. In Fig. 3e, run names sustain2015-p1 and sustain2015 refer to the cases where the new dam is operational and no dam exists (i.e. base run), respectively. The effect of the dam on *irrigation from the lake* is also positive. The mean value of *irrigation from the lake* increased from 1193 million to 1231 million litres per month.

Secondly, the activation of the new regulator in the outflow of the lake is analysed. The seasonal-regulated *lake water levels* are proposed by Altınayar (1998) so as to resemble the seasonal *lake water levels* in wet years (Table 1). These proposed levels are to be attained by controlling the major outflow via the new regulator. The effect on *actual macrophyte* cover is similar to that of the dam construction. Since *suspended solid concentration* is not affected as much, light conditions are only slightly improved as a result of the effect of outflow regulation on *chloro a flush out*. This policy has the greatest effect on carp amongst the three policies analysed in this section (Fig. 3f). There is not much change in *sedimentation rate* from

Table 1
Proposed monthly regulated *lake water levels* (Altınayar, 1998)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Elevation (m)	5	5.5	5.5	5.5	5	4.5	3.8	3.3	3.1	2.7	2.9	3.3

the base run and the *lake water level* is close to the one in the presence of the dam case. In Fig. 3f, run names sustain2015-p3 and sustain2015 refer to the cases where the regulator is implemented and no regulator is implemented (i.e. base run), respectively.

The analysis of the last component, the irrigation extension proves that the lake has a huge irrigation potential. New irrigated lands subject to an irrigation extension project are outside the region. Therefore, the activation of the extension project affects only the *lake depth*, though not substantially.

When all three policies are implemented in the model simultaneously, it is observed that the dam has the biggest effect amongst all (Fig. 3g). The major effect of the policies is on the lake water conditions and the lake ecosystem. Their effect on the *social* sector is minor. However, it should be noted that flood plain mechanism, which plays an essential role in fish spawning, is not included in the model. The dam would affect both the lake ecosystem and social structure negatively leading to a reduction in the natural flood plain area of the lake with an expected decrease in the fish recruitment. In Fig. 3g, run names sustain2015-p4 and sustain2015 refer to the cases where all considered policies are implemented and none implemented (i.e. base run), respectively.

5.2.2. Policy options related with agriculture sub-sector

The yield per hectare (e.g. *Tomato Cultivated per Hectare*) values in the base model reflect the average values. *Population* is increasing while the *Total Available Cultivated Area* is limited. Therefore, trying to increase yield per hectare through improved agriculture technologies stands as a viable policy option.

The yield per hectare variables are multiplied with *improved productivity*, a dimensionless variable added to the base model to reflect the effect of improved agricultural techniques. A 30% increase in yields per hectare is analysed. The increase in agricultural yield also causes an increase in production in related industrial sub-sectors. The workforce demand in these sub-sectors increases, resulting in a decrease in the value of *unemployed in the region* and an increase in *average income per workforce* (Fig. 3h). Since the increase in yield per hectare is assumed to occur without additional use of fertilisers, the nutrient concentrations in the lake are unaffected. Also the amount of water used is the same as before. Therefore, the policy has no effect on the lake ecosystem and hydrology. In Fig. 3h, run names sustain2015-10a and sustain2015-p4 refer to the cases where improved productivity is achieved beginning from year 2000 and no improvement in productivity takes place, respectively.

Bringing the amount of fertiliser use to normally required levels by the crop is also analysed independent of the former policy. The local farmers use more fertiliser than normally required believing more fertiliser means more yields, which is not necessarily true. So it is assumed in the base model that fertiliser use is three times the required amounts. When the base model is modified accordingly it is seen that the nutrient concentrations decrease as expected. The average *actual macrophyte* cover decreases down to around 41.5 PVI while there occurs no significant change in *actual chloro a* level. This is because the macrophyte makes use of the excess nutrients in the lake at present. Hence, a decrease in nutrient loading first strikes the macrophyte domination in the lake. The decrease in *refuge effect of macrophyte for carp* cause higher grazing pressure on *immature*/*mature carp* stocks. The slight increase in *fishing effectiveness* as a result of decreased *actual macrophyte* cover does not cause a remarkable change in the fishing sub-sector. Consequently, the effect of the policy is not significant on any of the sectors.

5.2.3. Policy options related with fishing sub-sector

The effect of the fungal disease, which hit the crayfish stock, on the *fishing* sub-sector has been detrimental. The *disease* is still prevalent within crayfish population and there is no known cure to get rid of it.

The introduction of healthy crayfish from other lakes is offered as a policy option by some decision makers. However, taking such an action, while the disease is still prevalent in the lake, would fail (Dr. Meryem Beklioğlu, personal communication). The experiments conducted on the model are in agreement with this view.

First, the introduction of 750 tonnes (50 kg/ha) of *mature crayfish* per week for one year is analysed. They do not generate the desired result, that is the re-establishment of *mature crayfish* stock in the lake (Fig. 3i). The introduction of the same amount of *immature crayfish* instead of *mature crayfish* is also a failure. The *disease* keeps the *immature crayfish* from growing and causes them to die. In Fig. 3i, run names sustain2015-p9b and sustain2015-p4 refer to the cases where new crayfish is introduced to the lake and no crayfish is introduced, respectively.

In the light of these analyses, it is concluded that it is best to help the lake ecosystem to recover from the *disease* by its internal dynamics, instead of anthropogenic interventions, especially when the cost of such interventions is taken into account.

5.2.4. Macrophyte clearance from the lake bottom

Macrophyte clearance is a long debated policy option in order to control eutrophication in the management of shallow lakes. There have been some experiences related to the harvest of macrophyte from the lake bottom. Such practices in shallow freshwater lakes have resulted in undesirable outcomes (Dr. Meryem Beklioğlu, personal communication). First of all, clearance of macrophyte is a burdensome process. It requires special equipment developed for this purpose. Even with the equipment, the efficiency is low. The reason is that macrophyte is able to spread fast, especially if the conditions favour macrophyte presence. Second and more importantly, even if the clearance succeeded, the result is typically a switch to a eutrophic state with turbid waters and high algal blooms. This also proves that macrophyte presence acts, in fact, as a buffer before eutrophication (Schriver et al., 1995).

In spite of the facts delineated earlier, this policy is still being proposed by some decision makers to control eutrophication in the shallow lakes of Turkey. Therefore, to demonstrate the extent of its infeasibility, the policy is tested in the model. In the first case, half of *actual macrophyte* cover is harvested per month from the beginning of the year 2000 (month 216). This resulted in a decrease in macrophyte cover but the decrease is far from being satisfactory. *Actual macrophyte* cover drops to just below 40 PVI, whereas *actual chloro a* concentration is unaffected. The policy does not cause major changes in other parts of the model. Then, a much more ambitious course of action is adopted: To harvest all macrophyte in the lake bottom every week from the beginning of the year 2000 to the beginning of the year 2008. This resulted in a dramatic decrease in *actual macrophyte* (down to 15 PVI) and after a short period of time, all macrophyte is lost from the lake bottom. The macrophyte is cleared, however, just to open way for the dominance of algae (i.e. algal blooms), high turbidity, the loss of pike and the establishment of a stable carp population (Fig. 3j and k): The characteristics of an eutrophic lake dominated by phytoplankton! The *fishing workforce* increases since the productivity of the lake is increased resulting in an increase in the total biomass. However, one should keep in mind that carp does not have a high economical value: a fact not represented in the model. In reality the effort required to clear all macrophyte cover may be lower. However, it is evident that the eventual outcome will be the same.

In Fig. 3j and k, run names sustain2015-p7ff and sustain2015-p4 refer to the cases where a harvest of all macrophyte cover per week takes place and no such harvest takes place, respectively.

5.3. Comparison with related studies

Asaeda and Van Bon (1997) developed a dynamic model for eutrophication to understand the effects of macrophytes on algal blooming in shallow lakes. The model is applied to a lake in the Netherlands and displays satisfactory agreement with the real data. In a related study, Xu et al. (1999) developed two dynamic models that describe phosphorus-food web dynamics with and without macrophytes in Lake Chao ecosystems. Results from both models are in satisfactory agreement with the observed data. The main result of our study—that macrophyte restoration can decrease phytoplankton biomass and increase fish biomass leading to improved lake ecosystem health—is in agreement with both of these studies (Asaeda and Van Bon, 1997; Xu et al., 1999). Hongping and Jianyi (2002) proposed a similar eutrophication model with four main algae species instead of one for a shallow eutrophic lake in China. Their model shows that removing phosphorus in sediment is best strategy to fight the eutrophication. This result is in agreement with our observation that sediment may be a crucial source of phosphorus for the lake ecosystem.

Janssen (2001) focused on managing lake eutrophication using an approach similar to our study; namely, through the integration of ecological and social dynamics. His model too includes the dynamics of the lake, the behaviour of agents using phosphorus for agricultural purposes, and the interactions between ecosystem and farmers. However, he adopted a more detailed economic representation including measures, such as tax manipulation and higher target level for returns on the use of phosphorus. Again with a similar approach, Tyutyunov et al. (2002) assessed economic and ecological dynamics of the Azov Sea simultaneously using a stochastic simulation model. They found that current fishing rates induce a high risk of population decline in the fisheries, somewhat similar to the case in Lake Uluabat. Their model further reveals that the extinction risk remains high even in the absence of fishing, suggesting that additional conservation measures are necessary to improve the environmental conditions.

There are also models that simulate both spatial and temporal variability in a lake to represent the unsteady and three-dimensional form of eutrophication (Soyupak et al., 1997; Tufford and McKellar, 1999; Cioffi and Gallerano, 2000). Such a detailed vertical spatial representation is not needed for shallow lakes like Lake Uluabat. Time frames of the above models are generally short compared to our model, ranging from a few days to one year. McDermot and Rose (2000) concentrated on fish population dynamics in a lake. Unlike ours their individual-based model tracks the daily activity of individuals of several fish species. It is used to evaluate the effects of biomanipulation (piscivore enhancement) for its ability to sustain improved water quality. Predicted total zooplankton consumption is used to predict effects on algae and water quality.

The well-established aquatic ecosystem model 'Rostherne' was recently improved as to incorporate fish and zooplankton dynamics (Krivtsov et al., 2001). The model includes features such as seasonal changes of solar radiation and water temperature, chemical budgeting, stratification of the water column, dynamics of detritus and its chemical constituents, which are absent in our model (being relatively irrelevant for our specific research questions). Concentrating more on aquatic biogeochemical cycling, the study of Krivtsov et al. naturally lacks social and economic dynamics, which are imperative in our case. Our model presented in this paper is unique in its systemic and comprehensive approach. It represents ecological, economic and social dynamics in detail levels just enough to allow a time horizon and research scope much larger than most of the eutrophication models found in the literature.

6. Conclusions and further research

The major aim of this study was to construct a framework to analyse the interactions between the ecological, economic and social factors in a wetland. To this end, a system dynamics model of a shallow freshwater lake and its surroundings is built. Partial validation tests done with available data and qualitative tests indicate that the model constitutes a plausible and coherent hypothesis. Some of the needed data from the region are either unavailable or unreliable. So, although the available validation results are an important initial step in the right direction, there is a need for more data for better validation, to obtain more exact, implementable results. The conclusions listed below should be regarded with this fact in mind.

The interesting result obtained in the base run is that the so-feared switch to a eutrophic state with seasonal algal blooms is not likely to occur in the near future, and there is no sign that it will in the more distant future. The main undesirable outlook, mainly the result of the unsustainable population increase, is a decrease in welfare of the rural inhabitants over time (Güneralp, 2000).

Two scenario analysis runs are conducted. The first asks what if crayfish population did not collapse due to the fungus disease in 1986. The answer is that the lake becomes turbid and eutrophic with dominance of carp and seasonal algal blooms. The second scenario investigates what results will emerge, if crayfish recovers from the *disease* sometime in the future. Fishing becomes a major income source again, improving social conditions. Pike increases, suppressing carp further. *Transparency* is almost not affected.

Next the projects, planned or being currently constructed by DSİ are introduced into the model. It is observed that they have no significant effect on the ecosystem, except the decrease in macrophyte cover. There is no major betterment in socio-economic conditions.

The introduction of healthy crayfish in the model to overcome the existing *fungal disease* proves to be ineffective in re-establishing of healthy *crayfish* stock in the lake. Simulation runs also show that the application of macrophyte clearance for a short period of time is not enough. In addition, application for a long period of time leads to the eutrophication of the lake with dominance of phytoplankton, and turbid waters. These findings are in agreement with evidence found in the literature.

None of the above-mentioned policy options results in the betterment of social conditions. On the other hand, the use of *improved agricultural techniques* does provide better social conditions, with no adverse effects on the lake ecosystem and hydrology.

The model is expected to provide a laboratory, where different management strategies regarding shallow freshwater lakes in particular and wetlands in general can be tested. The research results are also hoped to make some contribution to the general theory/literature of sustainable management. These results are being shared with Ramsar Convention Bureau, DHKD, and TKV. The model itself will also be made available to the interested institutions. Further research may concentrate on improved representations of the *economic activities* and *social structure* sectors. Collecting field data to improve the estimates of certain model parameters and integrated analysis with GIS would also be beneficial. The *lake ecosystem* sector may also be enhanced, as more information in shallow lake ecology becomes available. The inclusion of processes, such as nitrogen fixation mechanism by organisms, inbreeding in case of low population densities and further elaboration of the model performance under random effects also stands as a challenge for future study (Güneralp, 2000).

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