An Earth Observation and Integrated Assessment (EOIA) approach for the sustainable governance of a socio-ecological system: the case of the Lake Naivasha basin, Kenya

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An Earth Observation and Integrated Assessment (EOIA) approach for the sustainable governance of a socio-ecological system: the case of the Lake Naivasha basin, Kenya

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Abstract

For the sustainable governance of river basins a wide range of variables from natural and human subsystems may need to be studied as the effectiveness of governance can be judged from a wide range of perspectives. Governance of natural resources is affected by processes that are taking place across various scales and by interventions from multiple levels of organization. Especially when there is competition over scarce resources among stakeholders and interests there is a need for Integrated Assessment (IA). An IA may result in indicators for sustainable governance through the integration over scientific disciplines in ways and at temporal and spatial scales meaningful to stakeholders. This implies that knowledge from different scientific disciplines, focusing on different subsystems, should be used for incorporating interdependencies that are of critical importance for overall system dynamics. The design of appropriate model structures (e.g. extent, resolution) depends on the spatial and temporal resolutions of the available data, levels at which process interactions take place and the desired level of output presentation for stakeholders. The quality of an Integrated Assessment approach relies on extensive datasets. In this regard, this study explores the added value of using detailed spatial information derived from Earth Observation (EO) time-series.

As an example the Lake Naivasha basin (Kenya) is studied. In this study knowledge gaps are identified and discussed. The scientific disciplines covered in this study are hydrology, limnology, ecology, socioeconomics and governance. Finally a framework for IA is assembled around a proposed set of sustainability indicators for the Lake Naivasha basin.

Key words Integrated Assessment, Earth Observation, Lake Naivasha basin, hydrology, socio-economics, limnology, ecology, governance.

1 Introduction

Reliable availability of good quality freshwater resources is of critical importance to socioeconomic development and environmental sustainability. Water scarcity results from a mismatch between demand for water and it's availability in space and time and is observed in many places all over the world. In order to analyze this mismatch complex interdependencies and interactions between human and natural systems should be analyzed at different temporal and spatial scales. On the one hand human interference in natural systems affects indicators of environmental sustainability, while on the other hand changes in natural systems affect indicators of socioeconomic development. Many integrated water resources management (IWRM) tools enable an improved understanding of the consequences of human interventions at different levels and a better evaluation of water demand management alternatives (e.g. Loucks and van Beek, 2005). However, only few model applications take into account the effect of interactions between socio-economic processes (e.g. those leading to water use) and ecological systems, let alone doing this in a spatially-explicit way. The interdependencies (e.g. due to feedback mechanisms) may be very important, especially in case of strong variations in water availability and quality in time and space (e.g. van Oel et al., 2011a). Consequently, for the sustainable governance of river basins natural and human subsystems need to be studied jointly and knowledge from different scientific disciplines should be assembled using an Integrated Assessment (IA) approach.

In this study stakeholders and scientists from different disciplines have jointly assembled an indicator-set that forms a basis for an IA approach. Next to traditional data sources special attention is devoted to the use of spatial data derived from Earth Observation (EO). IA is applied to overcome knowledge gaps that would result from (parallel) mono-disciplinary approaches. In order to assist stakeholders in achieving sustainable governance results are presented in such a way that spatial and temporal complications become clear are meaningful to stakeholders at the different levels at which decisions are made.

Lake Naivasha basin case study

For many East African water systems increasing human populations and economic activities induce pollution, unsustainable exploitation of living resources such as fisheries and loss of biodiversity (e.g. Odada et al., 2003; 2006). One of these water systems is the Lake Naivasha basin in Kenya (Figure 1). The ecological wealth and recent economic developments in the area are strongly connected to the freshwater lake which is a reliable source for irrigation and supports a rich variety of flora and fauna species. The case of the Lake Naivasha basin is exceptional in both supporting a wetland of international importance for biodiversity conservation and a national economic hotspot at the same time (Harper and Mavuti, 2004). By many, the development related to the horticultural industry in the area is seen as an example of a successful economic growth path to be copied by other African countries. Export of flowers sustains an economy that previously suffered from low employment and production. However, the rapidly growing population, excessive water abstractions for irrigation[1], changing land use, and inflow of pollutants put the ecosystem under pressure (e.g. Becht et al., 2005; Harper and Mavuti, 2004; Otiang'a-Owiti and Oswe, 2007). Over the years many interest groups have analyzed the Naivasha case and explored and proposed all kinds of interventions (e.g. AWS, 2011; LNROA, 1993; WWF, 2011). Also, international scientists from various disciplines have studied different aspects of Lake Naivasha and its environment. A large part of the literature is relevant to the sustainable governance of the socio-ecological system. However, only little of the considerable amount of knowledge produced has been translated into actual management or policy. This may be partly due to a mismatch between literature and the actual requirements of decision-makers. Another major concern involves the availability and accuracy of available data on meteorological parameters, water abstractions, water quality, etc. An example is the development of the Water Allocation Plan which, according to its authors, suffered from 'major information constraints' (WRMA, 2010).

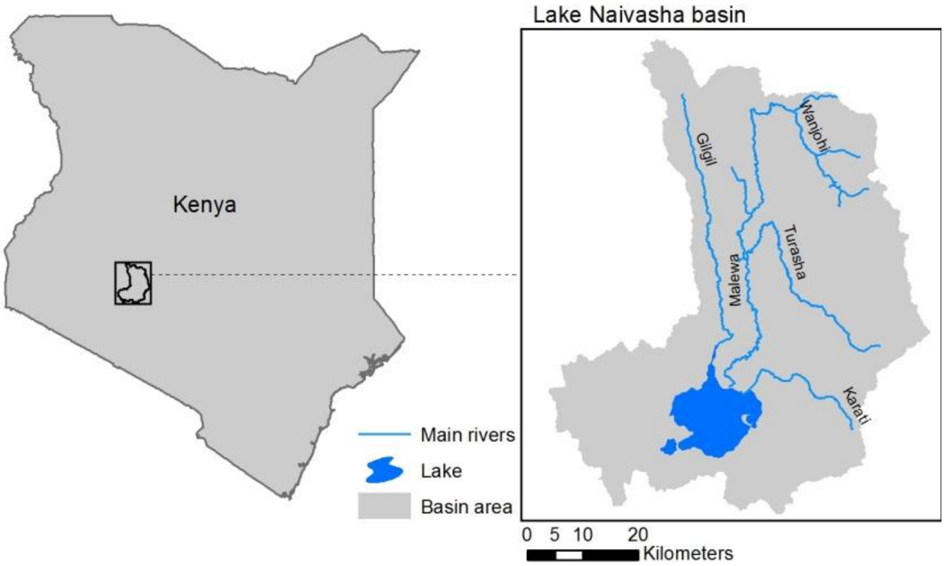

Figure 1 Lake Naivasha basin and its main rivers and tributaries.

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[1] In 1984 the Government of Kenya (Anon, 1984) estimated that a 'safe level' of the lake would be maintained if no more than $16.5\times10^6 m^3 yr^{-1}$ was abstracted from the lake system. At that time the inflow from streams was assumed to be unaffected by upstream abstractions as they (i.e. the existing licensed abstraction volume) were very limited at the time. Whether such estimation is of any use to decision-making at all is highly debatable since the natural climatic variation has been considerable (e.g. Verschuren et al., 2000). The current level of abstractions from the lake, the lake aquifer and the reduced inflow due to upstream abstractions has been 4 times higher at least around the year 2000 (Becht and Harper, 2002).

2 Material and methods

For the Lake Naivasha basin case study, sustainability indicators, knowledge gaps and ways to overcome these knowledge gaps are discussed according to the following steps:

1) A description of literature by discipline with regard to the Lake Naivasha basin case is given for the following disciplines: governance, hydrological system, aquatic ecological system, terrestrial ecological system, socio-economic system. The knowledge gaps of these disciplines are described in this section.
2) In Section 3 an approach is presented to integrate the results of studies from different disciplines (Figure 1).

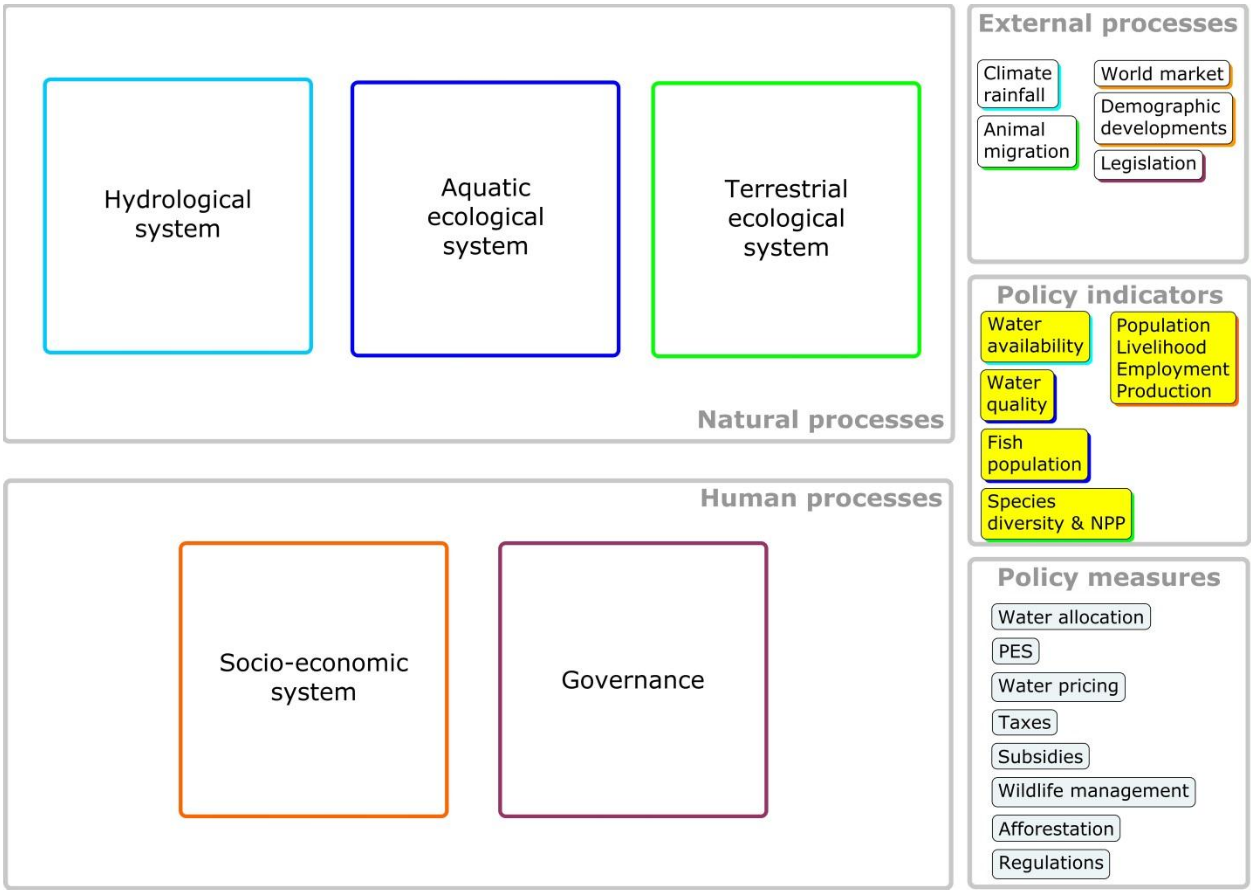

Figure 2 Isolated (sub) systems, external processes, identified indicators for sustainable governance and possible measures for intervention

2.1 *Governance*

2.1.1 *Current knowledge on the governance of the Lake Naivasha basin*

The socio-institutional context of water policy and legislation in Kenya influences water resources management and development of the Naivasha basin. With regard to the legislative framework for water governance the Water act (2002) and the subsequent subsidiary legislation described in the Water Resources Management Rules (2007) applies. Among many other things the Water Act regulates decentralization, privatization and commercialization of water utilities.

The process of devolution of power is ongoing and includes the installation of Water Resources, Users Associations (WRUAs) at the sub basin level. Three relevant spatial levels for decision-making are the basin level, sub-basin level and local level (Figure 3). For water management the basin level (WRMA, 2010) and sub-basin level (e.g. WRUA Upper Turasha Kinja, 2008) are relevant, whereas water use occurs at the local level.

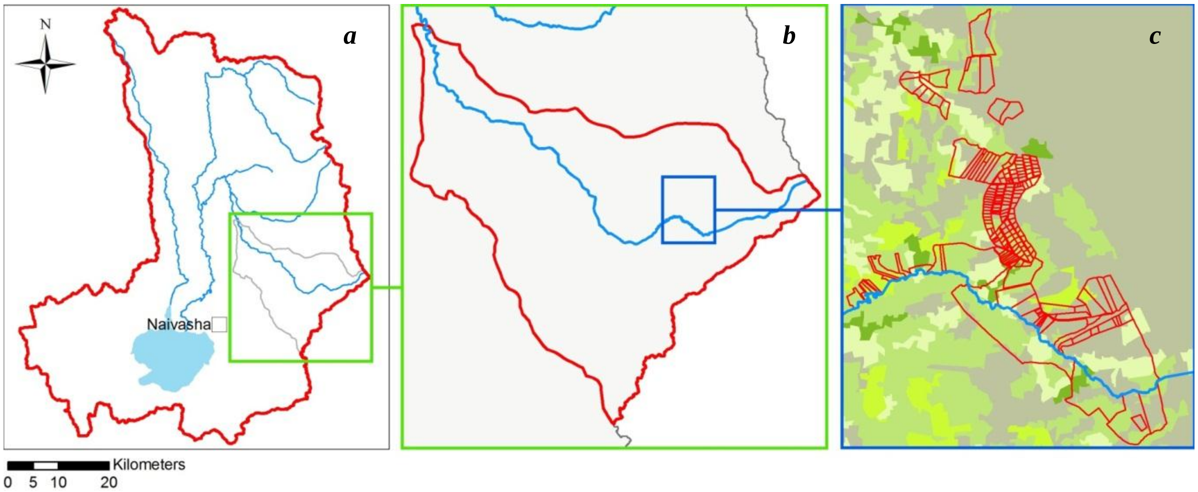

Figure 3 Different levels of decision-making in the Lake Naivasha basin: basin level (**a**), subbasin level (**b**: WRUA Upper Turasha Kinja) and the local level (**c**: a Payment for Ecosystem services scheme coordinated by World Wildlife Fund Naivasha).

In the Water Allocation Plan (WAP) for the Lake Naivasha basin (WRMA, 2010) it is stated that 'current indications are that all is not well'(WRMA, 2010). Problems mentioned as far as Lake Naivasha is concerned include low lake levels and turbidity. Drivers mentioned include high (and as yet unlimited) water abstraction, high nutrient inflows, introduced alien species and loss of terrestrial lakeshore vegetation. The WAP aims to bring abstraction into compliance with amounts allocated on permits reducing total allocation by 10% by 2012. Furthermore, the WAP proposes to tie water allocation to water availability. The WAP therefore sets out the level of abstraction permitted for each state of the resource for different water bodies (i.e. river flow, lake water, ground water). Possible governance interventions include water allocation, payment for ecosystem services (PES) schemes, water pricing, permitting, subsidizing, wildlife management and afforestation.

2.1.2 Knowledge gaps for the governance of the Lake Naivasha basin

To date limited progress towards sustainable management has been made (Harper et al., 2011). The Water Allocation Plan (WAP) for the Lake Naivasha basin (WRMA, 2010) addresses the tension between the need to protect the environment and basic human rights of access to the water resources and consumptive use for economic development. Economic activities include intensive horticultural and floricultural production, livestock production, geothermal power generation, tourism and service industries. The WAP aims at the 'management of the lake' in such a way that the lake and its associated resources are used in a 'sustainable way' (WRMA, 2010) with a focus on water quantity.

The availability and accuracy of the data have been a constraint in the formulation of the plan. This applies to hydrological records, water abstractions and data on permits in particular (WRMA, 2010). Moreover, the WAP recognizes its ‘grave weakness which is lack of compliance to and enforcement of the plan’ (WRMA, 2010) and concludes that ‘the benefits of the WAP can only be realized if stakeholders work collectively towards implementing the plan.

Water governance may include efforts to motivate resource users to reduce the negative externalities of their activities. In a river basin context these negative externalities are typically (but not exclusively) caused by resource users in upstream areas and harm the interests of resource users downstream. With regard to water quantity, alternative land uses may lead to changes in runoff, for instance due to changes in land cover or water abstractions for irrigation. With regard to water quality alternative land management practices may influence sediment loads and nutrient loads that end up downstream. The exact magnitude of the effects of these interventions is unclear.

2.2 Hydrological system

2.2.1 Current knowledge on the hydrology of the Lake Naivasha basin

Among the documented attempts to understand present-day[2] hydrology of the Lake Naivasha basin studies by McCann (1974) Gaudet and Melack (1981), Åse et al. (1986) and Becht and Harper (2002) are most comprehensive. These studies have largely focussed on the water-budget of the lake rather than on understanding hydrological processes in the entire Lake Naivasha basin. The results of these studies with regard to the ‘natural’ water balance of Lake Naivasha are summarized in Table 1. A significant amount of water is lost to groundwater outflow and direct or indirect abstractions. Estimates for the water balance of the Lake Naivasha basin as a whole are summarized in Table 2.

Groundwater hydrology is highly relevant for the water budget of Lake Naivasha as has been stressed since many years (e.g. Nilsson, 1932; Sikes, 1936). This applies to both subsurface water flows directed towards the lake (McCann, 1974; Ojiambo et al., 2001) and outflow, which is responsible for the lake to be fresh (Gaudet and Melack, 1981; McCann, 1974; Richardson and Richardson, 1972). Estimates of net annual groundwater outflow from the lake ranges between $18\times10^6 m^3$ and $\sim50\times10^6 m^3$ (Åse et al., 1986; Becht and Harper, 2002; Clarke et al., 1990; McCann, 1974; Ojiambo and Lyons, 1996).

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[2] With regard to hydrological processes for time frames of two hundred years and beyond there are several interesting studies to be consulted (e.g. Bergner and Trauth, 2004; Bergner et al., 2003; Olaka et al., 2010; Stoof-Leichsenring et al., 2011; Verschuren, 2001; Verschuren et al., 2000).

Table 1 Estimates of the 'natural' annual water budget for Lake Naivasha. This table shows estimates for the period before 1980, thus, before large-scale water abstractions commenced to impact.

	McCann (1974)	Gaudet and Melack (1981)	Ase, Sernbo & Syren (1986)		Becht and Harper (2002)
Hydrologic budget item ($10^6 m^3 yr^{-1}$)	various sources and years	1973-1975 avg (including Oloiden)	1972-1974 avg*	1978-1980 avg	long term average (1932-1981)
Total inflow	**380**	**337**	**279**	**375**	**311**
Precipitation	132	103	106	135	94
River Discharge	248	185	148	215	217
Surface Runoff		0.6			
Groundwater Inflow		49			
Total outflow	**380**	**368**	**351**	**341**	**312**
Evapotranspiration swamp	109	14			
Evaporation from lake	237	298	284	288	256
Groundwater outflow	34	44			
Abstractions for irrigation and industry		12			
Groundwater outflow			67**	53**	56
Assumptions					
Precipitation (mm)	650	683	575	709	648
Evaporation (mm)	1700	1989	1542	1504	1788

*For this study the the numbers from the water level changes (in mm) to actual volumes have been recalculated, using the height-area relation presented by Åse et al. (1986, Figure 2.7) . Two errors made in summations by Åse et al. (1986), Table 4.3 have been corrected. These are the values for July 1973 and April 1974.

**Derived from the difference between the observed lake volume changes and the calculated volume changes as reported by Åse et al. (1986).

Table 2 Water balance of the Lake Naivasha basin.

Hydrologic budget item ($10^6 m^3 yr^{-1}$)	Natural budget estimate (McCann, 1974)	Recent budget estimate based on Salah (1999), Becht and Harper (2002), Becht (2007) and Mekonnen and Hoekstra (2010)
Precipitation in the entire catchment	2761	2750
Evapotranspiration in the catchment	2161	2120
Evapotranspiration from lake swamps	109	50
Evaporation from Lake Naivasha	237	250
Subsurface outflow to the Lake Nakuru-Elmenteita and Ol Bolossat basins	40	50
Subsurface outflow to Basal aquifer (including geothermal reservoirs)	214	220
Water use / blue water footprint	-	60

2.2.2 Knowledge gaps in understanding the hydrology of the lake Naivasha basin

There are large uncertainties and gaps associated with the available data-sets for rainfall, discharges, evapotranspiration, groundwater levels and land use and water abstractions from rivers, aquifers and the lake. Moreover, studies on the effect of land use change and climatic variability on the water balance (and water quality) are largely unknown. Literature on the effect of water abstractions for irrigation on lake volumes and levels does exist (Becht and Harper, 2002) but the exact magnitude is highly uncertain, especially for abstractions from ground water and alluvial aquifers.

Another factor of interest to water balance calculations is the lake level–area–volume relationship. This may be based on bathymetric surveys. Bathymetric surveys for Lake Naivasha include the ones conducted in 1927 as reported by Thomson and Dodson (1963), in 1983 (Åse et al., 1986)[3], in 1998 (REMCONSULT, 1998)[4], in 2001 (Rupasingha, 2002)[5]. Especially at high

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[3] A Lowrence X-15^{M} echo sounding instrument was used.

[4] A NASA Echo Sounder and a Deep-staff for shallow water were used.

[5] A Fish Finder 100 sonar bathymetry instrument was used.

lake levels the relation is somewhat uncertain. Next to the importance for water balance calculations, information on the level–area–volume relationship is of interest for the aquatic and terrestrial ecologic systems.

For the whole of the Lake Naivasha basin an estimated $254\times10^6 m^3 yr^{-1}$ infiltrates away from the basin toward deep basal aquifers, including geothermal reservoirs from where it then migrates north and southward again (McCann, 1974). According to McCann (1974) it may only become possible to demonstrate a relationship between shallow aquifers and deeper geothermal zones 'until geothermal waters have been produced for many years' (McCann, 1974). Lake water has been detected in steam releases south of Lake Naivasha (Darling et al., 1990; Ojiambo et al., 2001; 2003), suggesting a connection between geothermal power generation and the Lake Naivasha water budget does exist.

2.3 Aquatic ecological system (limnology)

2.3.1 Current knowledge on the aquatic ecologicy of Lake Naivasha

For Lake Naivasha human-induced changes in land- and water use have resulted in environmental perturbations in the ecosystem which have contributed to a transformation from a clear lake to a turbid lake already years ago (e.g. Harper et al., 1990). Internal and external drivers, as a result of both natural and human processes, influence the spatiotemporal turbidity dynamics in Lake Naivasha. Among the external drivers affecting the integrity of the lake ecosystem the introduction of alien species and physical-chemical degradation are most important (e.g. Gherardi et al., 2011). The physical-chemical degradation is fueled by the inflow of large amounts of nutrients (i.e. Phosphorus and Nitrogen) and sediments enhancing the lake's turbidity (e.g. Harper and Mavuti, 2004; Kitaka et al., 2002; LNROA, 1993). Natural protection against this inflow has been offered by swampy vegetation fringes surround the lake (e.g. Hickley et al., 2004). Obviously, the effectiveness of these fringes in preventing the inflow into the lake also depends on the lake water level. Next to the fixed fringes and swamps also floating mats of papyrus and other flora can extract nutrients from the open water (e.g. Adams et al., 2002). Stoof-Leichsenring et al. (2011) nicely summarize a range of indicators for a 200 year period until 2006 at one central location in the main lake, including sedimentation and nutrient loads.

Fish populations also play a role in the lake's turbidity and are in turn affected by the lake's turbidity itself (e.g. Britton and Harper, 2006; Gherardi et al., 2011; Hickley et al., 2004; Mavuti, 1990). The fish community in Naivasha is exclusively exotic (Gherardi et al., 2011). Over the last decade one single species has become dominant: the Common carp. This carp is believed to have arrived accidentally in 1999 and became totally dominant after 2003 (Britton et al., 2007). Also the introduction of the Louisiana Crayfish in 1970 has influenced turbidity dynamics because of its destructive impact on floating-leaved and submerged plants within a decade (Harper et al., 2011). Many other studies discuss important issues related to recent turbidity dynamics, blooms and collapse of various species (e.g. Harper et al., 2002; Hickley and Harper, 2002).

2.3.2 Knowledge gaps aquatic ecological system

Although many interesting elements of Lake Naivasha's aquatic ecological system are known due to high quality analyses the internal turbidity dynamics and accurate estimates of its response to perturbations and interventions remain largely unknown. Obviously the socio-economic, terrestrial ecological and hydrologic systems play a role but the exact relations and their significance have remained unclear to date.

2.4 Terrestrial ecological system

2.4.1 Current knowledge on the terrestrial ecology around Lake Naivasha

Since the first half of the 20th century several studies have focused on the biodiversity in/around Lake Naivasha (e.g. Jenkin, 1929) followed by many others like Gaudet (1977; 1979), Gaudet and Muthuri (1981), Harper and Mavuti (2004) and Morrison and Harper (2009). These studies have demonstrated the critical importance of the biodiversity in the functioning of the whole lake ecosystem. Amongst the ecosystem services emanating from the rich biodiversity, regulation and buffering the flow of materials into the lake has been studied well. In particular the dominant swamp species *Cyperus papyrus* (papyrus) plays an important role in the uptake and entrapment of soluble and particulate nutrients and sediments along the main inflow rivers (Harper and Mavuti, 2004; Harper et al., 1995). Recently the amount of papyrus has declined dramatically (Hickley et al., 2004). Lake level fluctuations play a role in the process of germination of papyrus which enabled Gaudet (1977b) to explain the wetland plant species richness on the basis of this unpredictable water rise and fall leaving a mosaic of different connected habitats. However, as stated by Harper and Mavuti (2004), there is no evidence that (moderate) lake level fluctuations alone induce biodiversity loss, and that present lake level fluctuations influenced by human activities are greater than the past (natural) fluctuations.

According to Harper et al. (2011) exotic species drive the dynamics of the food web within the lake without seriously influencing terrestrial ecology. As true as this may be, the terrestrial ecologic system around the lake depends on the lake with its freshwater and the nutrients it distributes on its shores and into the surrounding aquifer. According to a survey in 1972 by McCann (1974), the size of the papyrus swamp was 63.9 km^2. A more recent assessment showed that papyrus covered only around 10% of what it covered in the 1970s (Morrison and Harper, 2009). According to Morrison and Harper (2009) this is due to a combination of lake level declines and destruction by ungulates and human clearance.

2.4.2 Knowledge gaps terrestrial ecological system

Current knowledge on the terrestrial ecological system is mostly focused on a very narrow fringe around the lake or a limited amount of sampling sites (e.g. Morrison and Harper, 2009), possibly due to an interest in the water quality and fluctuations of the lake levels. Despite the emphasis on the narrow strip, Harper and Mavuti (2004) assert there is no evidence that lake level fluctuations alone induce biodiversity loss. Thus there is a need to focus on the wider context to understand the role of biotic and abiotic processes that regulate the ecosystem's productivity and species diversity. These processes include, but are not limited to, the recharge of groundwater, herbivorous grazing and direct human clearance. Thus far no spatially-explicit analysis has been done to quantify the role of multiple and inter-linked mechanisms that regulate the productivity and species diversity on the wider area surrounding of Lake Naivasha.

2.5 Socio-economic system

2.5.1 Current knowledge on the socio-economical system of the Lake Naivasha basin

In recent decades both the population in the Naivaha basin has increased from around 250 000 in 1980 to over 600 000 in 2009 (Kenya population census 2010). Urban population (i.e. in the towns of Naivasha and Gilgil) amounts to an estimated 150 000. Moreover several informal ‘urban’ settlements have emerged close to Lake Naivasha with an estimated population of over 50.000 around 2003 already. Such settlements are lacking appropriate waste management and sewage treatment (Harper and Mavuti, 2004). This has contributed to the degradation of the lakeshore immediately below these informal settlements where people go for washing, laundry cleaning and watering of livestock and (Harper and Mavuti, 2004). Tourist activities in the region, rural-urban migration as a result of falling farm income from traditional cash crops, expansion of commercial enterprises and good prospects for job opportunities are major factors for population pressure in the region (IUCN/LNRA, 2005).

All over the Lake Naivash basin agricultural activities associated with land use and land management have intensified along with the increasing population. As an effect more water is abstracted for irrigation and more nutrients are added to the environment by the application of fertilizers. Since 1992 an inter-basin water transfer has been operational involving a pipeline that allows for the transfer of water from the Lake Naivasha basin to the Lake Nakuru basin. Starting from the early 1980s the horticultural developments have caused a shift in the landownership and drastically influenced land use pattern around Lake Naivasha, mostly due to a growing population that was attracted by employment opportunities in the agro-industrial sector (Becht, 2007). In 2002 horticultural sector close to Lake Naivasha was responsible for an estimated amount of 25.000 employees (Enniskillen, 2002). Commercial fishery started in 1959 (Harper et al., 2011). Fish included introduced types of bass and tilapias and fish catch has varied due to over-fishing and water level fluctuations (Muchiri et al., 1994).

As the Lake Naivasha basin and its population have experienced increasing pressures various disputes and disagreements have arisen about the processes responsible for the problems experienced (Becht et al., 2005). Beside conflicts of interest and disagreements on responsibilities there are serious factual disagreements. Due to a lack of knowledge on how the socio-ecological system works the mental models of those involved diverge strongly. Important factual unknowns involve processes that influence the water cycle and the nutrient cycle in the basin. With regard to the water cycle a critical unknown is the amount of water abstracted for irrigation and the relative contributions of users in the different parts of the basin. With regard to the nutrient cycle there are no accurate estimates on the amount of fertilizers and agrochemicals used in agriculture and the number of cattle grazing along the lake shores.

2.5.2 Knowledge gaps socio-economical system

Most literature that deals with socio-economic activities that relate to environmental degradation that is caused by human activity (e.g. Becht et al., 2005; Harper et al., 2011). Some of the literature also addresses how livelihoods relate to and ecosystem services (e.g. Ellis-Jones, 2007). There is a serious concern about data availability with regard to socio-economic indictors at relevant spatial levels.

3 Overcoming the knowledge gaps through Integrated Assessment

3.1 Integrated Assessment Framework

For the project 'an earth observation- and integrated assessment (EOIA) approach to the governance of the Lake Naivasha basin, Kenya' it is explored how Earth Observation (EO) and derivative geo-information may be used to overcome the problem of the availability of accurate data at relevant scales. The scientific tool we apply is a system description based on an Integrated Assessment (IA). IA aims to integrate knowledge over a range of relevant disciplines, and to provide new information how complex real-world systems might behave, thus enabling decision-making. Cross-sectoral implications that might be missed in more traditional assessments (e.g. Maxim et al., 2009) can be explicitly explored in ways that are meaningful to stakeholders. This is achieved by making available knowledge (information on processes and variables) at scales relevant to decision-makers, in particular for local, sub basin and basin level stakeholders. Through a series of stakeholder workshops[6] and consultations during the period 2008-2011, a set Integrated Assessment indicators for sustainable governance has been composed. These indicators include spatially-explicit descriptions of:

- livelihoods, employment, population density and economic production
- water availability (covering alluvial zones, aquifers and the lake)
- water quality (with a focus on turbidity)
- Species diversity & net primary productivity (covering flora and fauna abundance and richness)

These indicators and their relationships with the sussystems covered in this study are shown in Figure 4. Governance should aim at interventions in the system in such a way that sustainability indicators are affected.

Two important processes exemplifying the interdependency of the different systems are the flows of water and nutrients between (sub) systems (Figure 5). Obviously many human activities depend on clean freshwater from the lake whereas recently the freshwater availability is seriously influenced by human abstraction (e.g. Becht and Harper, 2002). Natural fluctuations due to climate variability have caused lake depth to fluctuate between 5m and 40m at its the

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[6] Stakeholder workshops are organized for i) defining indicators of sustainability, scenarios and intervention alternatives, ii) verifying system representations and model set-up and iii) visualization of results and conflicts for validation and evaluation.

deepest part over the past ages (e.g. Verschuren et al., 2000). Only from the 1950s onwards anthropogenic influence on the lake has become significant. It has been estimated that water abstractions from the lake and its aquifer have lowered lake levels in the order of 4-6m over the period 1980-2000 (Becht and Harper, 2002). Also for water quality the interdependency is well established as increased turbidity levels in the lake cause health threats and nuisance whereas human activities enhance eutrophication (Hubble and Harper, 2002; Stoof-Leichsenring et al., 2011).

For studying subsystems and their linkages use is made of time-series of spatially-explicit data (mostly using Earth Observation techniques) and spatially-explicit modeling for depicting the dynamics of the phenomena of interest.

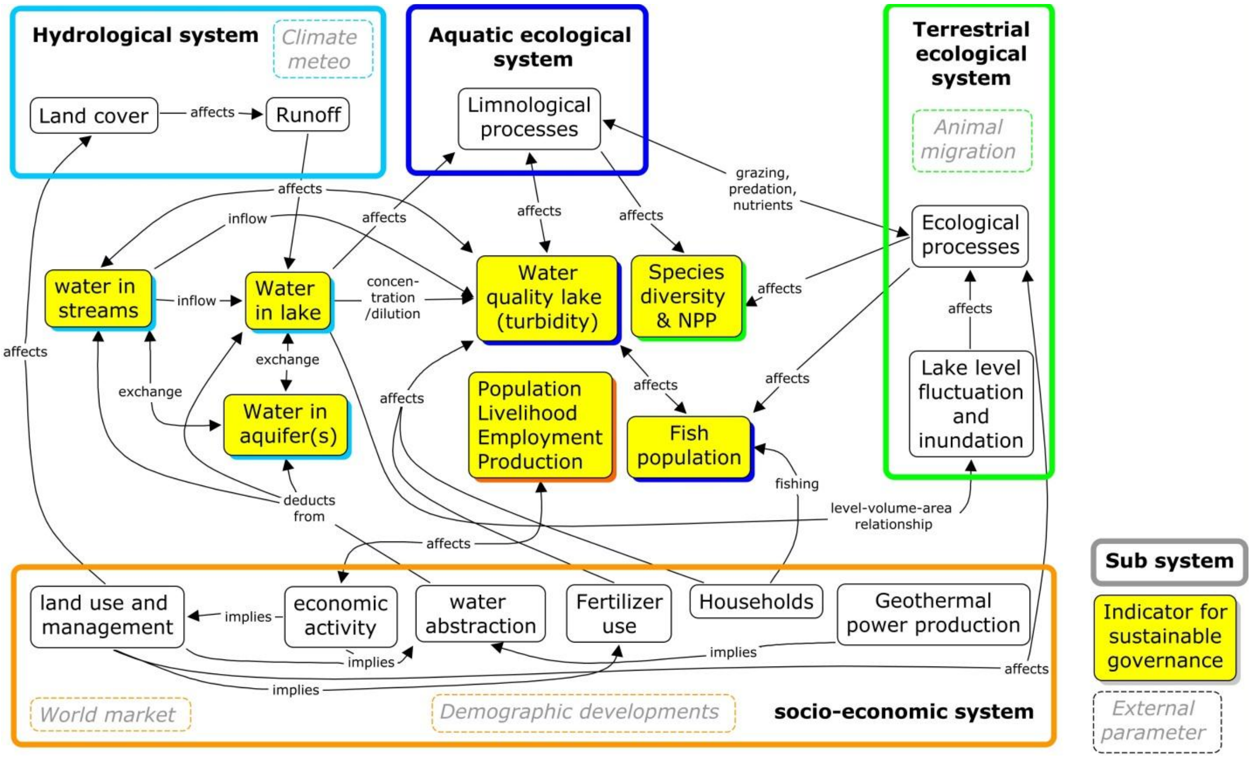

Figure 4 Simplified schematization of links between sub-systems and Integrated Assessment indicators for the sustainable governance of the Lake Naivasha basin.

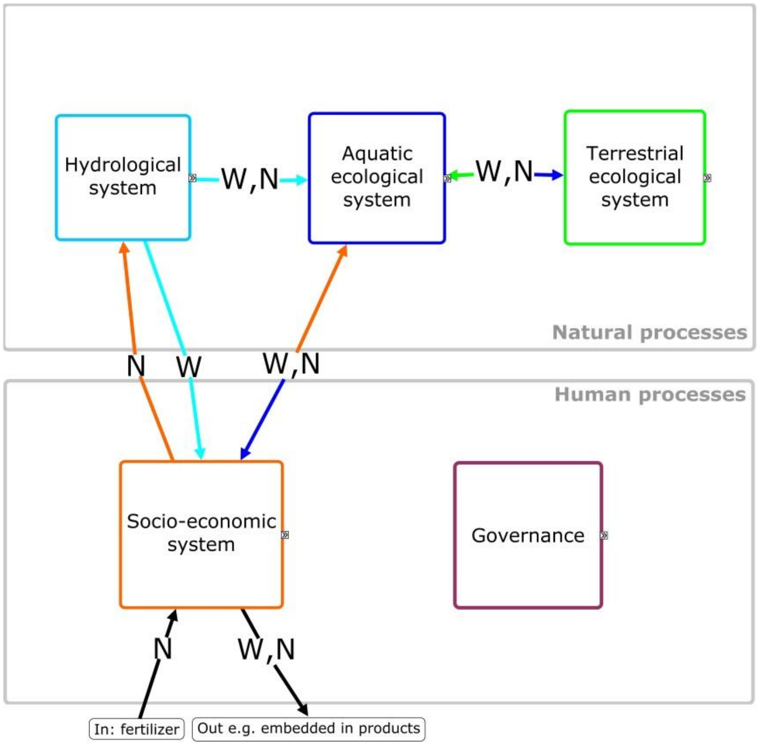

Figure 5 Example for interdependencies between sub systems: fluxes of water (W) and Nutrients (N) between the subsystems.

With regard to the hydrological system the current study addresses the human influence (water abstractions, land use, land management) on the hydrologic system in more detail. Following a hydrological processed based approach, impacts of land use conversions are investigated as well as the role of hydro-climatological variability on the hydrological system. The use of Earth Observation techniques, household surveys and hydrological modeling are employed to enhance understanding of the system. Next to the use of EO for land use classification, estimating water abstractions for irrigation and meteorological parameters it is also applied for exploring its suitability for monitoring lake level variations following an initial study by Bijker et al. (2011).

With regard to the aquatic ecological system, the use of Earth Observation data for monitoring Chlorophyll-*a* and total suspended solids (TSS) is explored. Images are used to retrieve water quality parameters such as chlorophyll-*a* and total suspended solids. This is coupled with weekly to bi-weekly ground measurements of chlorophyll-*a* and total suspended solids taken in year 2011. A process model will be developed to study turbidity dynamics in more detail. By studying the lake system in a spatially-explicit way the linkages to the hydrological, terrestrial ecological and socio-economic subsystems may become more apparent.

For studying the terrestrial ecology around lake Naivasha extensive use is made of Earth Observation techniques. The MODIS NDVI series is used to make spatiotemporally-explicit estimates for the Net Primary Productivity (NPP) in the ecosystem. Combined with plot measurement of productivity and enclosure experiments the system dynamics are studied in great detail. In addition ASTER and LANDSAT data are used for estimating the spatial distribution of NPP of the different land cover types. The derived NPP from remote sensing products will be later linked to a herbivore model to evaluate the coexistence of both plant and herbivore species. ASTER DEM is used to derive the Topographical Position Index (TPI) allowing for estimating soil moisture. Lake level data, bathymetric data and the ASTER DEM are used to determine inundation frequencies around the lake. By studying the terrestrial ecological system dynamics around the lake in a spatially-explicit way the linkages to the hydrological, limnological and socio-economic subsystems may become more apparent.

With regard to the socio-economic system Earth Observation techniques are applied together with socioeconomic data (household survey) and environmental data. In this way the major socioeconomic driving forces of land use and land cover changes in the Lake Navaisha basin are explored. In addition, this study employs a choice experiment method of environmental valuation to value environmental services and analyze livelihood impacts of payment for ecosystem services (PES) schemes on ecosystem services providers (e.g. upstream communities) and receivers (e.g. downstream communities). First results include an exploration of the relationship between land use/land cover and population density (Mulatu et al., 2011).

In Table 3 the relevant aspects of the sub systems (scientific disciplines) covered in project are summarized.

The choice for scales and levels of analysis is important for most scientific disciplines. Especially when knowledge from different scientific disciplines is combined scale issues are important (Gibson et al., 2000). Different spatial extents and relevant spatial elements are given in Figure 6 and an impression of the different types of fieldwork sampling locations is given in Figure 7.

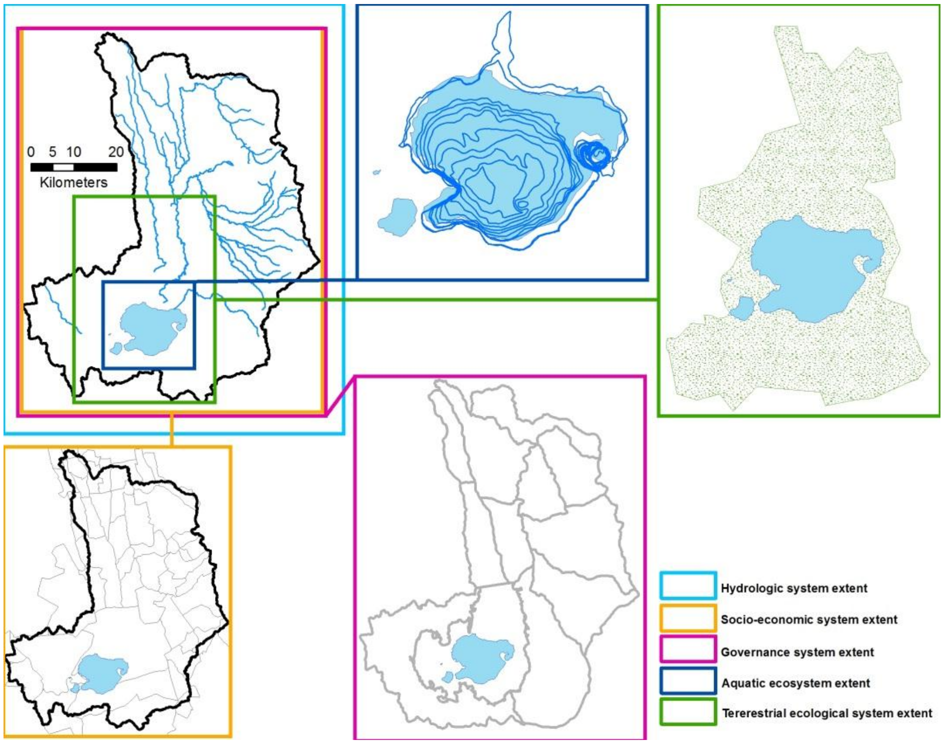

Figure 6 The extents and relevant spatial elements for the different focus disciplines of the EOIA project.

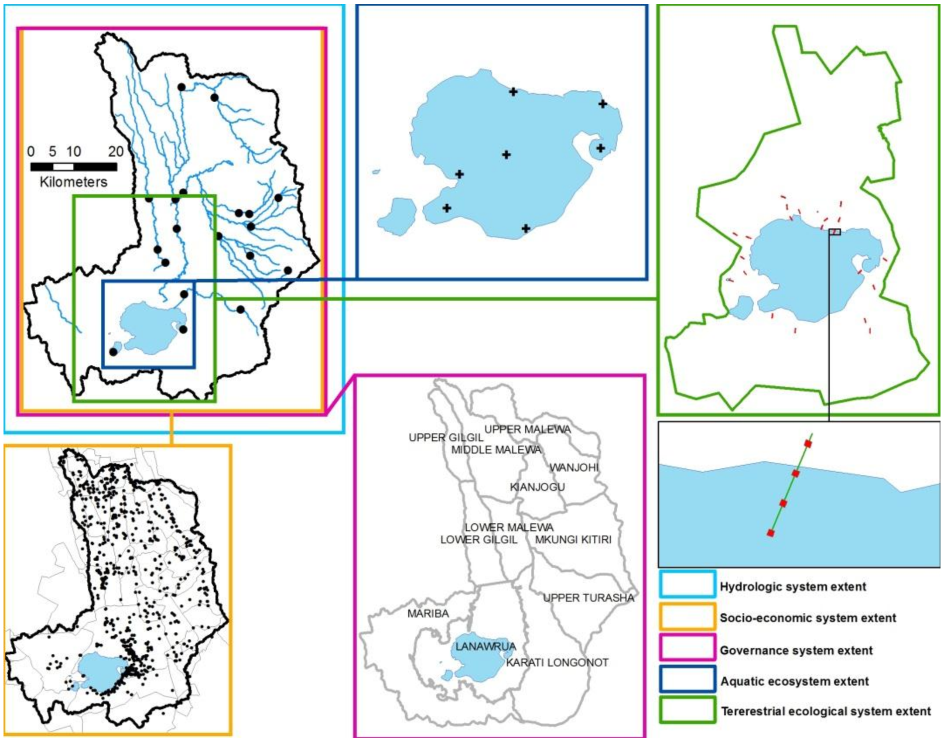

Figure 7 Fieldwork locations for the different focus disciplines of the EOIA project. The following things are shown: for the hydrologic system discharge measurement stations; for the aquatic ecological system water quality sampling sites; for the terrestrial ecological system transects along the lake shore; for the socio-economical system water abstraction locations; for the governance system water resource users associations sub catchments are shown.

3.2 Tools for Integrated Assessment modeling

For organizing spatially explicit data series use is made of the PostGIS (PostGIS, 2011). Vizualization of results is done by using Web Mapping Services (WMS) through Mapserver (OSGeo, 2011) and will be published on open access websites (e.g. VirtualKenya, 2012)

One of the modeling techniques applied is spatially-explicit agent-based modeling allowing for representing human-environment interactions (van Oel and van der Veen, 2011). According to Maxim et al. (2009) the DPSIR framework is unsatisfying for analytical purposes because the simple causal relations assumed cannot capture the complexity of interdependencies in the real world. To capture the complexities related to human-environment interactions agent-based modeling may be applied. Examples of how to use agent-based modeling (ABM) for water resources use and management include Berger et al. (2007) and Van Oel et al. (2010). ABM may be actively linked to data base technology and can benefit from knowledge from GIS science.

Furthermore, ways are explored that build on experience with spatial conflict mapping and spatial multi-criteria analysis (e.g. Makropoulos and Butler, 2006; Zucca et al., 2008).

Table 3 Characteristics of the sub systems (scientific disciplines) covered in the Earth Observation and Integrated Assessment project.

Water quantity	**Water quantity**	**Spatial scale**	**Temporal scale**	**Main social agents**	**EO instrument (s)**	**IA Indicator(s)**	**Software environments for system dynamics**
Hydrologic system							
rainfall-runoff water balances	erosion (sediment, nutrients)	*Extent:* whole basin (including lake) *Resolution:* rainfall (mm), land cover at field level (~ha)	*Resolution:* minutes-years	Water users Water user-collectives land owners	LANDSAT (30m) ASTER (15m) ASTER DEM (30m) MSG (2km) WORLDVIEW (0.55m)	water availability	SWAT (Arnold et al., 1998) MODFLOW (USGS, 2012)
Aquatic ecological system							
inflow into lake	turbidity dynamics, sedimentation	*Extent:* lake & riparian zone *Resolution:* lake zones (cm-ha)	*Resolution:* minutes-years	fishermen	MODIS (250m) MERIS (300m) ASTER (15m)	water quality fish population	DELFT3D (Deltares, 2010) PC Lake (Janse, 1997)
Terrestrial ecological system							
water availability for vegetation (lake level variations)	biomass, net primary production, grazing intensities	*Extent:* riparian zone & wider terrestrial savannah *Resolution:* rainfall (mm), lake level fluctuations (cm-ha), biomass (gram/m^2)	*Resolution:* minutes-years	water users wildlife managers herdsmen land owners	LANDSAT (30m) ASTER (15m) ASTER DEM (30m) MODIS (250m)	species diversity net primary productivity (vegetation)	NetLogo (Wilensky, 1999)
Socio-economic system							
abstractions ecological services (runoff)	fertilizer use ecological services (land management)	*Extent:* nation, basin *Resolution:* land use (ha), local communities (ha), stakeholders (ha-km^2)	*Resolution:* days-years	water users, water user-collectives, fishermen, herdsmen, tourists	LANDSAT (30m) ASTER (15m) WORLDVIEW (0.55m)	population livelihoods employment production	NetLogo (Wilensky, 1999)
Water governance							
intervention (water allocation, scarcity alarm-levels, PES, etc.)	intervention alternatives at different levels (e.g. water treatment, turbidity alarm-levels, PES schemes)	*Extent:* nation, basin *Resolution:* sub basin, administrative units	*Resolution:* months-years	user collectives governmental org. non-governmental org.	-	-	-
Integrated Assessment							
water availability and use	turbidity dynamics, sedimentation	*Extent:* nation, basin *Resolution:* local, sub basin, basin and administrative units	*Resolution:* days-years *Period*: 1980-2030	all stakeholders at various levels	all the above	all the above	NetLogo (Wilensky, 1999) OpenMI (Gregersen et al., 2007)

4 Discussion and conclusion

For a high quality integrated assessment subsystems need to be studied in depth while considering the different interests that are addressed in a joint effort of scientists and stakeholders. For the case of the Lanke Naivasha basin, hydrology cannot be understood when studied in isolation. Human activities influencing land cover and water abstractions are of critical importance. With regard to limnology, turbidity dynamics are influenced by has internal and external factors. Fisheries depend on socio-economics and inflow of nutrients and sediments depends on hydrological and ecological processes. Also terrestrial ecology depends on hydrology. The extent to which environmental flow requirements are met depends on the runoff generated in the Lake Naivasha basin. Moreover, the socio-economic system is linked to the physical environment by means of ecosystem services/resources. Governance and the emergence of collective action depend on the state of the natural environment. Local circumstances and differences in resource availability in upstream and downstream parts of the basin may lead to collective action and influences willingness to pay of participate in PES schemes or other types of co-management.

When performing an integrated assessment of a socio-ecological system one needs to incorporate the spatial complexity of the relevant processes. Because many systems are linked by their geographic overlap geographical information is particularly helpful for integration and interdisciplinary research.

River basins are generally seen as natural units for integrated water resources management (IWRM), although they could just as easily be regarded as political units (Warner et al., 2008). When water resources are managed by local authorities or user communities there is not always a ‘natural’ need to co-operate with a downstream party (van Oel et al., 2011b). In this regard there is also growing consensus in the social sciences that there is no optimal level or scale for water management (e.g. Van der Zaag and Gupta, 2008) The suitability and acceptability of water management on a certain scale partly depends on the perspective that is chosen and partly on the political culture of a particular country or region (Molle, 2006). Moreover, manageability of water resources can differ considerably between upstream and downstream parts of a basin (van Oel et al., 2009). IWRM in semi-arid environments can benefit from the application of methods that explicitly address the role of resource users in changes and variations in resource availability and its distribution over space and time.

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