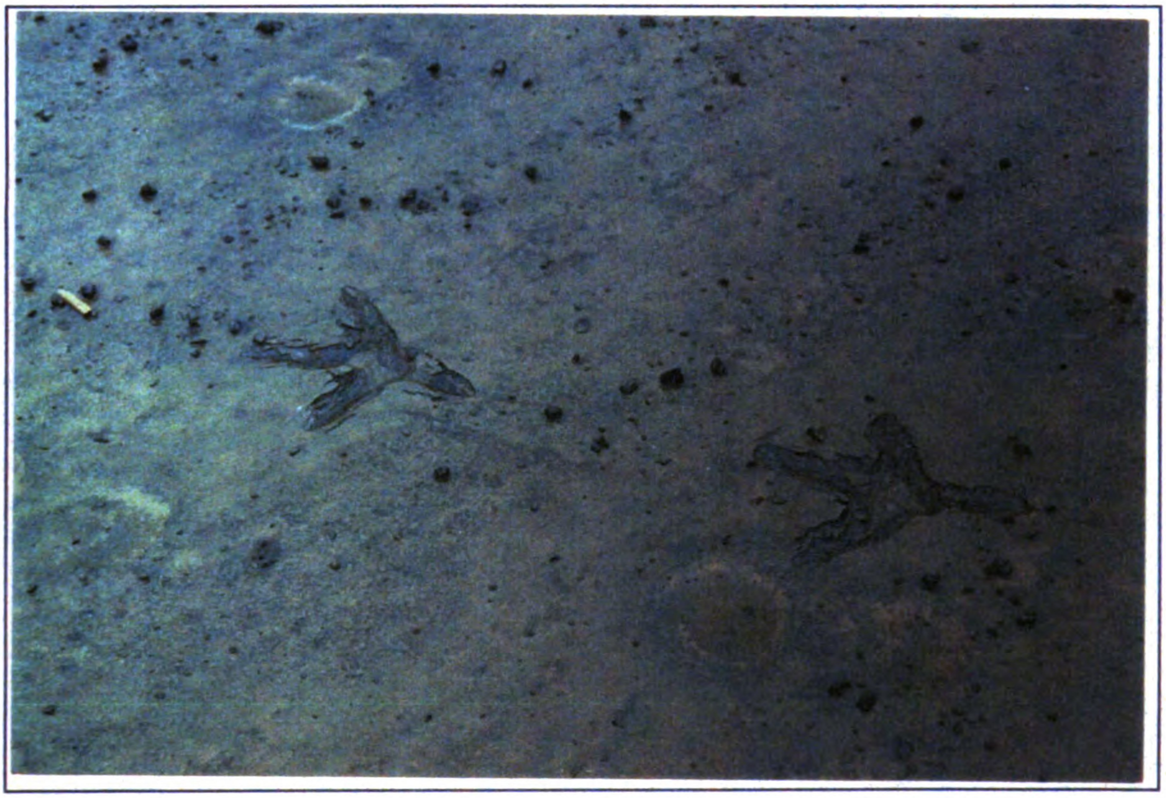
A Review of North American Water Quality Assessment and Management Technologies for Application to Lake Nakuru, Kenya, Africa.



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RETURNING MATER

Acknowledgments

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Introduction

In North America, researchers have been developing and refining prediction models and methods that assess water quality within watersheds. These methods are based on land use, land cover type, and related physical features including soil type, rainfall and evapotranspiration data, and water body characteristics within a watershed. These technological approaches may be applied to other regions of the world, such as Lake Nakuru in Kenya, Africa.

The problems of Lake Nakuru's ecosystem are not unique, but the circumstances surrounding them are relatively uncommon. This paper will explore water quality prediction technologies that have helped other regions of the world cope with and solve problems concerning wetland protection and conservation, water quality, and the balance between the urban and natural environments. By using Geographic Information Systems (GIS), remote sensing, and watershed modeling technologies and techniques, the source or sources contributing to Lake Nakuru's existing water quality condition may be examined. To illustrate the potential of these technologies and techniques to an African case study, I will describe Lake Nakuru's watershed characteristics and explain the relevance of these North American technologies and techniques to the issues and problems facing Lake Nakuru.

Lake Nakuru's Watershed

Africa's Great Rift Valley, which stretches from Ethiopia to Mozambique for a total of 6400 km in length, is lined with a number of inland lakes, including Lake Nakuru (Baskaran 1995). Lake Nakuru's latitude is 0° 22' S and it's longitude is 36° 05" E, placing it marginally north of the equator (Burgis and Symoens 1987) and 157 km from Kenya's largest city and capital, Nairobi (Kilimanjaro Adventure Travel, Kenya Wildlife Service 1996). Lake Nakuru's altitude is roughly 1760 m above sea level. The lake itself covers an area of 36-49 km^2, while ranging in depth from 0.56 - 4.5 m (Vareschi and Jacobs 1984) making it an extremely shallow lake (Kilimanjaro Adventure Travel, Kenya Wildlife Service 1996). Lake Nakuru lies in a warm and semi-arid climate (Njuguna 1988), where evaporation is usually greater than precipitation. Because of this and other factors, such as uneven flow from contributing rivers and streams and human water use, the lake level may fluctuate greatly from year to year. The largest and most rapid lake level declines usually occur in January and February when temperatures are highest, humidity and rainfall are low, and winds are high (Melack 1988). The high water mark for the lake occurred in 1905 (Olindo 1996), but over the past twenty years the lake has receded 2 km and experienced "dry-outs" in 1967, 1988, 1993, and 1994 (SciFinder News Net 1996). There does appear to be a pattern regarding dry periods for that region: years with less than 700 mm of rainfall occur every 5-6 years, while rain below gauge (down slope or downstream from the actual gage) occurs every 6-8 years (Melack 1988). Essentially, a drought of varying severity occurs almost every five years.

Because of the volcanic activity associated with the formation of the Great Rift Valley, Lake Nakuru is subsequently alkaline in nature. Volcanic soda has dissolved in rainwater making many of the lakes in this region alkaline and somewhat brackish (Baskaran 1995). "Nakuru" actually means little bitter-water lake. These soda lakes are, however, highly productive with high primary production rates and large crops of algae (Njuguna 1988). Lake Nakuru's salinity and alkalinity allows extreme densities of blue algae to survive (Vareschi and Jacobs 1984), which in turn support between one and two million lesser flamingoes (*Phoeniconaias minor*) (Nyeki 1993) as well as the fish species, *Tilapia grahami* Boulenger (Boulenger 1912), which were imported in the early sixties to help combat the fight against malaria-carrying mosquitoes (Vareschi and Jacobs 1984). The climate not only affects lake levels, but salinity levels as well. Salinity levels are usually highest from September to March (Melack 1988).

In 1960, a portion of the area that is now known as Lake Nakuru National Park was set aside as a bird sanctuary. In 1964, Lake Nakuru was integrated into this area (Burgis and Symoens 1987). Three years later, Lake Nakuru National Park was established and in 1968 opened to the public. Lake Nakuru National Park now covers an area of 188 km^2 including the lake (Kilimanjaro Adventure Travel, Kenya Wildlife Service 1996). Figures 1, 2 (page 6), and 3 (page 7) supply location maps with increasing proximity to Lake Nakuru, respectively. Figure 4 (page 8) is a map of the national park.

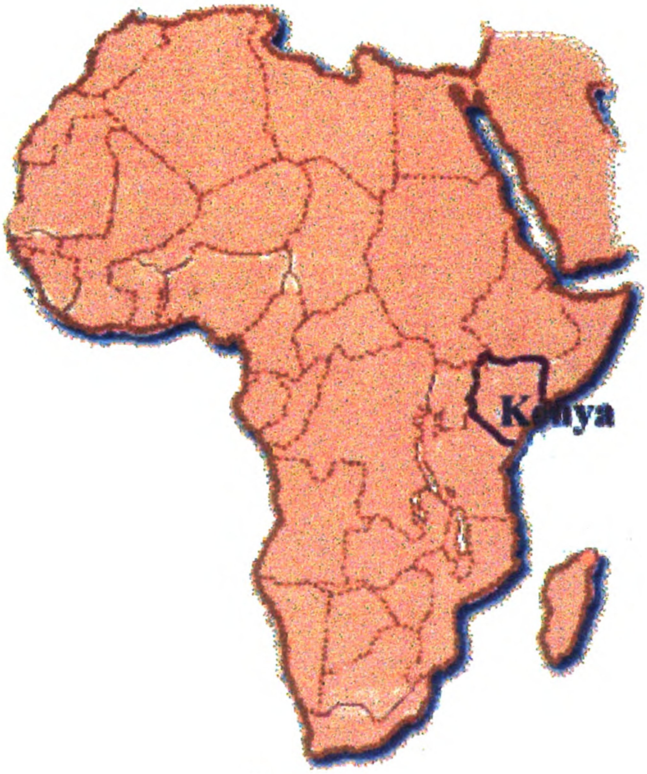


Figure 1. Africa

Source: http://www.intelred.es/dimensiones/select/Africa/bottom-Africa.html

Figure 2. Kenya

Source: http://www.footventure.co.uk/keninfo.html

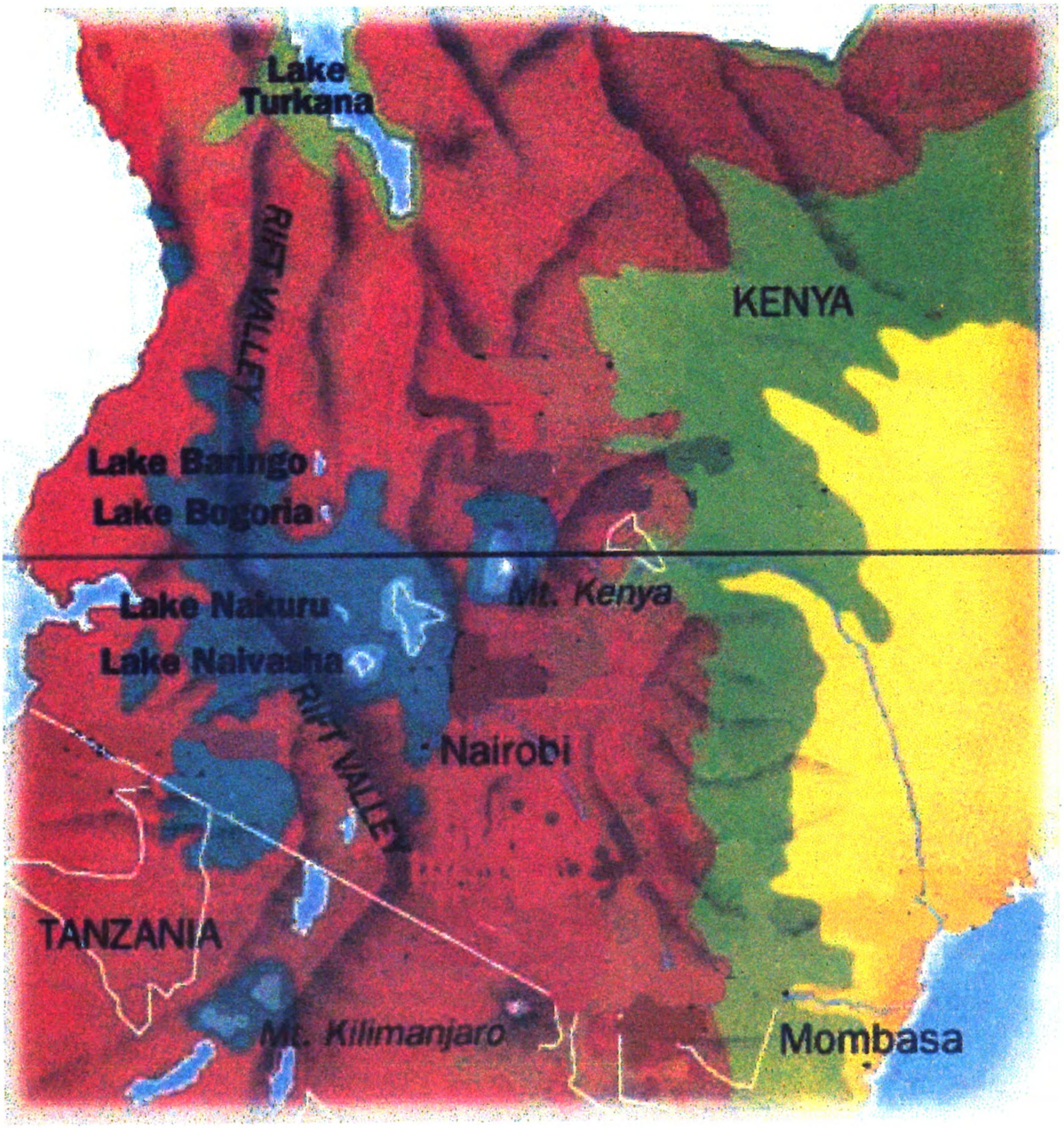
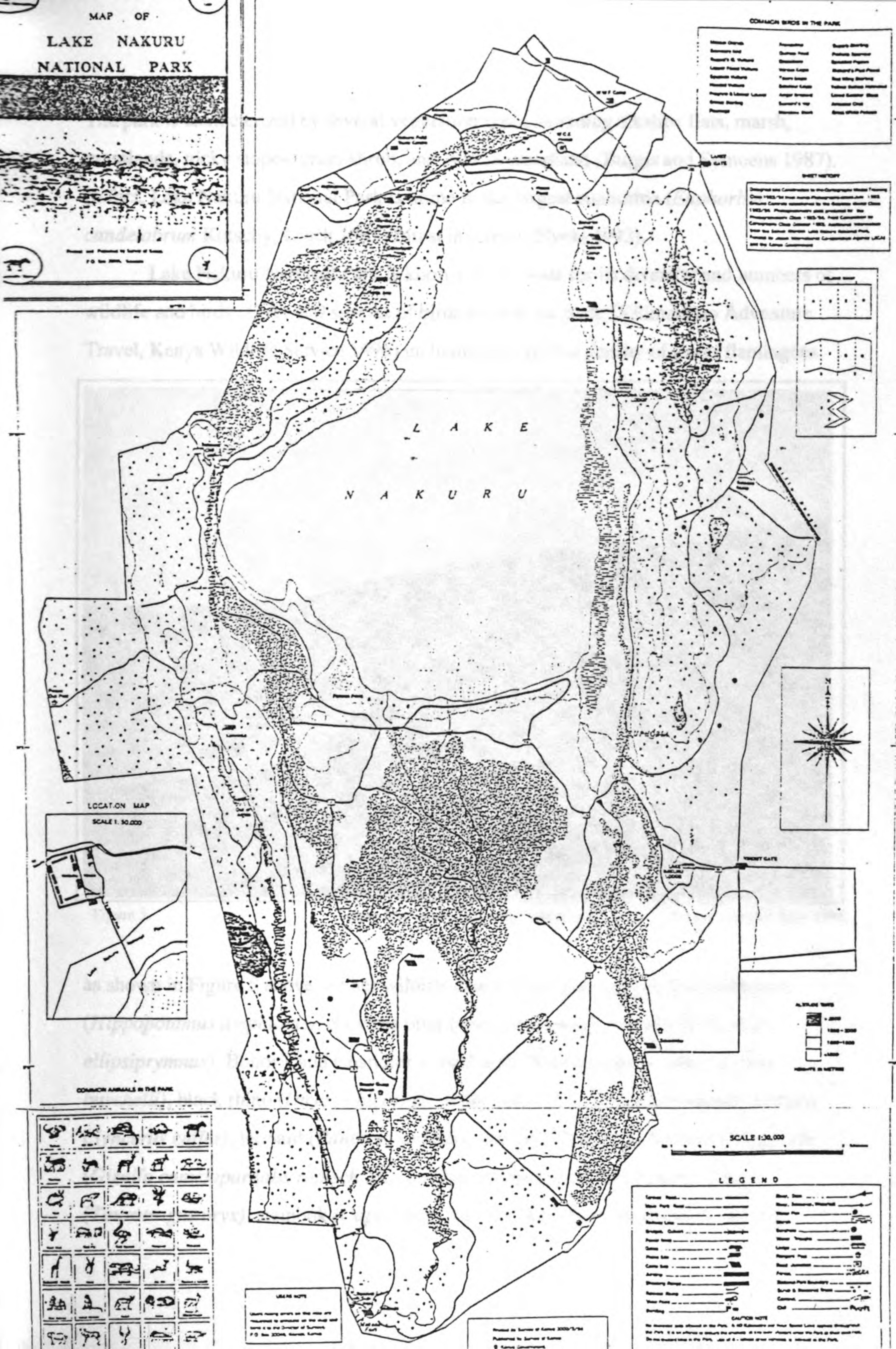


Figure 3. Lake Nakuru Area
Source: http://www.kerdownysafari.com/virtual.html


MAP OF
LAKE NAKURU
NATIONAL PARK
COMMON BIRDS IN THE PARK
SHEET HISTORY
LAKE
NAKURU
LOCATION MAP
SCALE 1:50,000
ALTITUDE TINTS
HEIGHTS IN METRES
COMMON ANIMALS IN THE PARK
SCALE 1:30,000
LEGEND
USERS NOTE
CAUTION NOTE

The park is characterized by several vegetation types including alkaline flats, marsh, grasslands, rocky slopes, grass-shrub, and Acacia woodland (Burgis and Symoens 1987). In fact, Lake Nakuru National Park is home to the largest euphorbia (*Euphorbia candelabrum* Kotschy, Leach 1985) forest in Africa (Nyeki 1993).

Lake Nakuru National Park is known world wide for its diversity and numbers of wildlife and birds. Over 400 species of birds exist in the park, (Kilimanjaro Adventure Travel, Kenya Wildlife Service 1996) including an extreme density of lesser flamingoes

Figure 5. Lake Nakuru and its lesser flamingoes. Voorheis-Madill June 1996.

as shown in Figure 5 above. Other wildlife assets to the park include hippopotamus (*Hippopotamus amphibius)*, clawless otter (*Anoyx capensis)*, waterbuck (*Kobus ellipsiprymnus)*, Bohor's and Chandler's reedbucks (*Redunca spp.)*, zebra (*Equus burchelli)*, black rhino (*Diceros bicornis),* white rhino (*Ceratotherium simum)*, buffalo (*Syncerus caffer)*, leopard (*Panthera pardus*), lion (*Panthera leo)*, Rothschild's giraffe (*Giraffa camelopardalis rothschildi)*, colobus monkey (*Colobus badius)*, eland (*Taurotragus oryx)*, steinbok (*Capra ibex)*, impala (*Aepyceros melampus)*, dik dik

(*Madoqua kirki)*, rock hyrax (*Heterohyrax brucei)*, klipspringer (*Oreotragus oreotragus*), and baboon (*Papio Anubis*) (Kilimanjaro Adventure Travel, Kenya Wildlife Service 1996).

Lake Nakuru is the sink of a catchment area of 1800 km^2 (Burgis and Symoens 1987, Berger 1988). This drainage basin includes many types of landforms, one of the most prominent being the Chyulu Hills. No rivers flow out of these hills, which supply the catchment area with recharge water into the groundwater table and feed the springs at the foothills (Berger 1988). Nderi River flows into Lake Nakuru from the southeast, Makalia River flows in from the south, along with Enjoro River, a seasonal river, that flows in from the northwest. In addition, approximately a dozen seasonal streams may flow into the lake at some point or another during the year (Map of Lake Nakuru National Park 1994). For all of these rivers and streams, Lake Nakuru is the last stop on the waters hydrologic journey. Lake Nakuru has no outlet.

It is for this reason that it is even more important to also understand what is happening around the lake. Since Lake Nakuru has no outlet, all water, sediment,

Figure 6. Photo displays the surrounding dominant land use of agriculture. Voorheis-Madill June 1996.

pollution, etc. from contributing sources has the potential of remaining in Lake Nakuru. It is crucial to understand the processes that bring those materials into the lake in order to interpret solutions for enhancing water quality. There are two sewers that empty into Lake Nakuru: one at the north end and some along with the Enjoro River. The land use percentages around the area are as follows: 5% towns, 35% bush, and 60% cultivation/ rangeland. (Burgis and Symoens 1987). Agriculture and cattle ranching are prevalent in much of the area, including the majority of land from Nairobi to Nakuru (Figure 6, page 10). The town of Nakuru is located northwest of the lake, and almost abuts the fenced

Figure 7. One of the open storm and effluent drains. Voorheis-Madill June 1996.

National Park boundaries. Its population in 1987 was thought to be near 60,000 persons (Burgis and Symoens 1987). Assuming that the growth rate is comparable to that of Kenya's 4% (Olindo 1996), the projected population in 1996 was 85,400. However, one source claims that the 1970 population was near 50,000 and 150,000 by 1990 (Kenyan Study Area 1996). Most of the city's effluents and storm water runoff flow directly through open storm drains into the lake (Figure 7, page 11). When I visited Lake Nakuru in June, 1996, however, it was noted that the effluents from the city of Nakuru appeared to have gone through some type of minimal oxidation treatment before flowing into Lake Nakuru (Olindo 1996). Oxidation is the process of treating effluents with aeration techniques to promote quicker decomposition of materials, thereby decreasing water pollution.

Lake Nakuru has several demands on its water and landscape. First, because of the fence around Lake Nakuru National Park, it is part of a somewhat "closed" environment. Birds, fish, and other animals use its water for drinking, bathing, and as their dwelling in some cases. These uses alone put a severe strain on the quality of the water, especially when considering that between one and two million flamingoes may utilize it at any one time. Second, human water consumption is rapidly affecting the lake in a variety of ways. The city of Nakuru (Figure 9, page 13) not only uses it for effluent and storm water drainage, but it also draws its drinking water supply from these same waters. Nakuru's population has increased dramatically in the 1980's and continues to grow; only increasing the strain on the lake. The areas surrounding Lake Nakuru heavily rely on agriculture and ranching for its economic vitality. Pesticide and fertilizer pollution and soil erosion are resultant negative impacts on the lake. Increased tourism into Lake Nakuru National Park is also a human use that is taking a toll on the Lake Nakuru ecosystem primarily because of the increased demand on the water supply and effluents created. Finally, there are also natural, physical factors such as high evapotranspiration, low precipitation, lack of outlets, and a shallow water basin that influence the lake's water quality.

Figure 8. The City of Nakuru from Baboon Cliffs in Lake Nakuru National Park Voorheis-Madill June 1996.

All of these factors combine to put a tremendous strain on water quality, water levels, and Lake Nakuru's biological environment. These are all issues that are facing the city of Nakuru and the Kenya Wildlife Service, which is trying to manage Lake Nakuru National Park and the wildlife inside of it. In addition, Berger (1988) cites issues facing Lake Nakuru as pressure from the city of Nakuru to annex the park, soil erosion from overgrazing, clearing of natural vegetation for cultivation up to the park boundaries, domestic waste from Nakuru, and food that is being grown within park boundaries that may be accumulating toxins from the water that is being used to grow it. *SciFinder News Net* (1996) states that flamingo population declines are due to deforestation, climate change, urbanization, and lake "dryouts." Finally, World Wildlife Foundation (1996) indicates that farming and urban development are major threats to Lake Nakuru's environment. Problems related to these activities are extensive deforestation, increased sediment content, soil erosion, and pollution.

Methodology

The method of inquiry for this paper is based upon site observations and discussions that I experienced while visiting Kenya's Lake Nakuru in June of 1996. After discovering the challenges that faced Lake Nakuru's managers, I soon realized that the same dilemmas occur in the Great Lakes region of the United States, where I reside, and in many places in North America and probably worldwide as well. In an attempt to present possible solutions for the complex scenarios involving Lake Nakuru, I reviewed techniques used in the U.S. to assess water quality and how to manage water bodies with degrading water quality issues. By combining my personal experience of Lake Nakuru with a literature review of applicable techniques, I could then assess the appropriateness of the technology to an African application.

Results

It has been established that "changes in water quality for mid-continental North American lakes are directly related to changes in watershed land uses" (Burley 1990). Likewise, Garn and Parrott (1977) attest that all management programs within a lake watershed may impact the lake. It is for this reason that the water quality assessment and management technologies at a watershed level are vitally important. Common coverages used in case studies are roads (including width and length), property boundaries, soils, surface and groundwater hydrology, vegetation cover types, faunal distributions, land use/cover, drainage patterns, topography, surface temperature, radiation balance, sensible heat flux, soil moisture, snow, surface water quality, groundwater transport, building density, source area fractions, rooftop pitch, hydrologic soil group, elevation, flooding extent, stream temperature, stormwater control device specifications, precipitation, lake evaporation estimates, surface area, and mean lake depth (Engman 1995, Haney and Power 1996, Haubner and Joeres 1996, Hession et al 1996, Taylor 1996).

Prediction models are just what they appear to be. They may be computer modeling or simulation programs and/or equations that are used to predict such things as phosphorus levels and sources in a watershed. Most of them are designed to create a variety of scenarios or outcomes that may occur in the future under certain circumstances or goals that are predetermined. This tool helps managers and planners decide on the appropriate course of actions that need to be taken once the problem is properly defined and options are identified. Bettinger, Johnson, and Sessions (1996) point out three distinct advantages to this type of approach: reduction in the time spent in searching for problem-solving activities, solutions to problems can be identified within a limited computing time, and provision of good solutions to difficult problems easily and quickly.

Examining problems within a watershed perspective is critical in order to fully understand hydrologic and related processes and to manage for them. It is not only hydrologically sound to proceed in this manner, but politically as well. Oftentimes, several communities may exist within a watershed and share its resources. By approaching issues from a landscape perspective, the communities may be able to work together for the good of the region and make complementary and congruent decisions within that watershed.

Spatial analysis techniques are valuable to researchers for several reasons. The large land areas covered for analyses and the large databases that programs can manipulate allow for the measurement of entire system conditions (Engman 1995). The shear number of potential scenarios or outcomes that can be created from these processes are also increasingly important for making sound management decisions. Montgomery, Grant, and Sullivan (1995) point out several distinct advantages that analysis at a watershed level can create. Watershed analyses incorporate scientific input from the beginning of the project or study, which may decrease crisis or reactive management and also decrease the likelihood of unanticipated conflicts. The inter-agency and inter-disciplinary approach of these types of analysis reinforces the previously mentioned component of cooperation across political boundaries. They may also carry a certain level of public accountability.

The main spatial analysis tools for computing water quality at watershed levels include Geographic Information Systems (GIS), remote sensing, and mathematical prediction models. They are used to identify sources of pollution and to offer insights into potential management solutions. Within this body of knowledge, I would like to introduce three approaches that drive these types of processes and projects. In addition, I present information concerning GIS, related management techniques used, and the variables required to assess the landscape. I also describe why these procedures are important to water quality assessment projects, advantages and disadvantages, and common protocol procedures.

The three management approaches or styles that apparently have influenced water quality assessment projects and research, GIS, remote sensing, and prediction methods at a watershed level are ecosystem management, adaptive management, and landscape ecology. All three philosophies will be treated simultaneously as many times they are in the literature, since they share common principles.

As evidenced by landscape ecology, which has been a school of thought and research since 1939, these types of management approaches have been in academic circles for literally decades (Jensen et al. 1996). These management styles may be considered exploratory problem-solving techniques that couple science with social values to promote the sustainable management of natural systems (Haney and Power 1996). They are based on the idea of learning by doing. They incorporate scientific thought, experiments, and research into planning. Actually, it is believed that science must precede planning and decision-making in order for sound management to take place (Montgomery, Grant, and Sullivan 1995). It is in this manner that science is used as a tool to learn from and also as knowledge that may be applied to management decisions or plans. The goal of ecosystem management-type approaches is to "preserve ecosystem integrity, while maintaining sustainable benefits for human populations" (Montgomery, Grant, and Sullivan 1995). This defining goal introduces three overarching principles of thought for these management approaches: to combine social and ecological values, large scale thinking, and inter-generationalism.

The above management approaches try to balance the impacts of the urban civilization and the needs of an ecosystem. They are based on the fundamental assumption that the two entities can successfully be balanced and in fact, that by combining the two, a more realistic and holistic approach is taken. By approaching management problems from a landscape perspective, a more comprehensive planning and decision making process may be achieved. While smaller scale managing may be coupled with the larger perspective, landscape planning allows managers of ecosystems to tailor management to landscape features, potential, and processes (Montgomery, Grant, and Sullivan 1995). Lastly, the idea of inter-generational ecology is part of these approaches. Not only do they consider current conditions, they also take into consideration the future's resources and needs. In this manner, these styles may truly be said to have comprehensive qualities.

Harwell (1996) presents nine defining principles of ecosystem management that help to clarify their positions further:

- uses an ecological approach that would recover and maintain the biological diversity, ecological function and defining characteristics of natural ecosystems
- recognizes that humans are part of ecosystems
- adopts a management approach that recognizes ecosystems and institutions as characteristically heterogeneous in time and space
- integrates sustainable economic and community activity into the management of ecosystems
- develops a shared vision of desired ecosystem conditions
- provides for ecosystem governance at appropriate ecological and institutional scales
- uses adaptive management as the mechanism for reaching desired outcomes and critical new understandings regarding ecosystem conditions
- integrates the best science available to form the basis of the decision-making process, while continuing to improve the basic scientific understanding of ecosystems
- implements ecosystem management principles through coordinated government and non-government activities.

If one is using one of the management approaches presented above; GIS, remote sensing, and prediction models make excellent tools whereby data can be collected and analyzed for management plans and decisions. Landscape management approaches and these techniques make logical companions. Since GIS and remote sensing are hailed for their abilities to represent large land areas with several variables, it would seem automatic to use these capabilities in a management project that is exploring large-scale and comprehensive perspectives.

Essentially, GIS and remote sensing are used to create large databases of information. Most times, they are the "science" that precedes management decisions. GIS can then layer as many coverages as desired to produce the necessary maps for analysis. GIS's main strength is not its capability of combining a limitless amount of databases and maps, but in its ability to present these combinations for analysis purposes. One of the most important aspects about this is that those maps can become baselines of information from which trend analyses may be performed. As in most studies, the comparison of baselines with many points in time is crucial in understanding certain processes, linking impacts to human activity, and managing for them (Montgomery, Grant, Sullivan 1995).

However, Montgomery, Grant, and Sullivan (1995) also point out a few of the disadvantages too. Management and political commitment to a watershed level project must be reliable and lasting because GIS related undertakings are both time-consuming and costly. They also require highly trained resource specialists. A watershed analysis done poorly is a waste of time, money, and does not maximize the potential aid in sound decision-making or planning.

GIS and prediction models are powerful tools used to analyze many characteristics about or in a watershed. Burley's (1990) study of Lake Itasca, Minnesota was conducted in order to "predict the amount of development that can occur within a watershed without compromising water quality." GIS/EPPL7 and SAUKBIT3.BAS were the programs used to predict the carrying capacity of a lake, which was based on climate, land use, soil features, and lake morphology (Burley 1990). Garn and Parrott's (1977) goals of a project in the Ottawa National Forest were to avoid water quality deterioration, to determine lake water quality problem areas, and to recommend courses of actions. A case study involving forest planning in Oregon used spatial analysis techniques to meet five goals: "to manage for high quality fish habitat, maintain elk habitat, restore forest condition within natural range of viability, maintain forest condition within natural range of viability, and contribute to community economic stability" (Bettinger, Johnson, and Sessions 1996). SNAP II++, "a series of criteria with network analysis to develop solutions for spatially constrained forest planning problems" was used in this study (Bettinger, Johnson, and Sessions 1996). Two related case studies involving GIS techniques both deal with phosphorus loading. One determined wetland characteristics that affect phosphorus loading from a lake basin spanning Vermont, New York, and the Canadian Province of Quebec (Weller, Watzin, and Wang 1996). The other examined lake impairment level and major phosphorus sources in an Oklahoma lake (Hession et al 1996). The latter project utilized a computer program, EUTROMOD, which is a nutrient loading and lake response model accompanied by GIS/GRASS (Hession et al. 1996). One study near West Lafayette, Indiana utilized the WEPP (Water Erosion Prediction Project) program along with the GIS/GRASS program. WEPP is a powerful tool that can predict "water-induced soil erosion, storm runoff, root zone soil water, evapotranspiration, plant-growth and snowmelt on cropland, rangeland, and forestland watersheds" (Savabi 1995). The last case study occurred in a watershed near Plymouth, Minnesota and used spatial analysis techniques "to assist in the assessment of stormwater runoff pollution at the municipal level" (Haubner and Joeres 1996). This included strategies to increase water clarity, decrease weed growth and also decrease algal growth (Haubner and Joeres 1996). This study utilized another powerful prediction tool, Source Loading and Management Model (SLAMM). This model estimates source areas of pollutant loadings for urban areas (Haubner and Joeres 1996).

Like scientific research, spatial analysis techniques and water quality assessment projects follow definite pre-determined courses of action. There are several methodologies available when exploring watershed modeling studies, however, there appear to be common steps along the way in several of the case studies reviewed. Three phases are generally recognized for these approaches. The first phase, which I will refer to as model design, deals with preliminary and start-up procedures such as deigning a model to use or gathering data. The second phase, data collection and manipulation, involves the manipulation of the gathered data sets. This may be through layering coverages in a GIS or using prediction models to prepare future, potential scenarios. The last phase, results, relies upon results from previous steps. For example, this phase weighs outcome implications and may allow for a course of actions to be chosen. It is important to explain that some tasks are continued for the life of the project. The exchange of information and inventories should be continued throughout the entire process of the project, especially when multiple owners, agencies, and disciplines are involved (Haney and Power 1996). Also necessary at various steps throughout a project is public education and input. By encouraging public participation from the onset of the study, conflicts and issues of cooperation, which may plague or terminate a project, may be avoided at later stages of the study. Lastly, re-evaluation, remodeling, and further reassessing is important to ensure that the methodology produces the desired information for the desired goals. A monitoring program needs to be created with the first steps of the project through to completion and beyond in order to link effectiveness of goals with methodology, determine if further study is needed, and to monitor impacts of management decisions and plans.

Phase One: Model Design

♦Step one, logically, is to define the watershed in need of analysis (Burley 1990). This should be accomplished by using environmental criteria, such as hydrology, topography, and geology.

♦Step two is to classify the lake that is being focused on in the watershed in terms of trophic condition so that a baseline may be determined (Haubner and Joeres 1996). From the baseline, trend analyses and/or monitoring may proceed. This may be done by using Carlson's Lake Index, which is based upon three variables: chlorophyll a concentration, Secchi disk transparency, and total phosphorus levels (Garn and Parrott 1977). See Carlson (1977) for further explanation of trophic state indices. Other valuable baselines include lake sensitivity and carrying capacity (Garn and Parrott 1977).

♦Step three may involve several things all related to a type of data collection. Before goals can be set (Step four), a compilation of information concerning ecological, socioeconomic, institutional, and cultural issues needs to be gathered (Haney and Power 1996). At this time it is also appropriate to identify stakeholders' desires and needs (Jensen and Everett 1994). Furthermore, definition and clarification of critical issues is also necessary (Montgomery, Grant, and Sullivan 1995). Along with the social issues and data that needs compilation, physical data and sources can be gathered as well. For example, inventories such as biotic surveys, literature reviews, public surveys, market analyses, databases, and maps are all examples of appropriate information (Montgomery, Grant, and Sullivan 1995). In other words, all available baseline material needs to be collected.

♦Step four then defines the goals and proceeds with the technical model creation. It is important at this phase to plan out resolution and scale of the project including the variables that will be used and to classify the similar land units by groups if necessary (Haubner and Joeres 1996). It is during this step that the real mechanics of the model are decided upon.

Phase Two: Data Collection and Manipulation

♦Step five involves actually creating GIS databases with previously gathered data. These data sets can then be layered to produce maps and analyses. These maps and analyses may be ready for examination for insights into problems, issues, resource potentials and limitations, and other essential information. For example, phosphorus levels and land use data sets may have been layered in order to produce a map that can then be examined in order to identify where potential phosphorus loading is occurring within a watershed. Depending on the goals set forth at the beginning of the project, this may be the extent of examination necessary. Often times, however, much thorough investigative research is required.

♦Step six may be manipulating the GIS databases further and/or applying prediction models and equations to produce more significant parts of the puzzle.

Phase Three: Results

♦Step seven, if future conditions and outcomes are created, is scenario consequence analysis or the weighing of implications of each of the future conditions generated (Harwell 1996). It is from here that decision-making and planning for specified goals proceeds. Upon completion of decision-making and subsequent plans, implementation strategies are applied.

Discussion

There may be one of several potential explanations for Lake Nakuru's existing water condition. There may be natural or man-made influences or a combination of both affecting its quality. Natural influences affecting water quality, including the rate of evaporation, amount of rainfall, soil type, and wildlife tend to be difficult to manage the effects of. Man-made influences are more than likely linked to land uses. The probability of any one of these factors or any combination of them contributing to the decreasing water quality is high. Assuming a GIS study similar to one presented above yielded several potential scenarios of contributing sources for contamination, this section examines potential solutions.

For example, if the rate of evaporation exceeds the amount of rainfall or input from the contributing tributaries (which occurs in most years) lake levels will fall. The recession of water then increases the concentration of elements within it. This would include the elements that affect water quality; bacteria, nutrients, and sediment. There is no natural solution if the contributing factor to decreasing water quality is in fact tied to the amount of rainfall occurring.

One solution to this dilemma, however, is to increase the amount of water entering the lake by one of its two contributing processes; rainfall or flow from rivers and streams. Since we can not influence the amount of rainfall, the only other option would be to increase the flow of contributing waters. Water could be imported to the rivers and streams before they enter Lake Nakuru. However, increasing the amount of water that these flowing water bodies carries may have other adverse impacts on Lake Nakuru's watershed. Increased bank erosion and stream-bed scouring may only make more sediment available to travel into Lake Nakuru, resulting in sediment loading which could exacerbate the water quality issue. Ultimately, solutions need to be considered in the context of the entire environment, not piecemeal.

If the desire is to increase the amount of water in Lake Nakuru, the most direct route may be the most beneficial i.e. import water from elsewhere and deposit it into the Lake itself. This would avoid potential problems with increased flow from its contributing rivers and streams. However, as in most places in Africa, the question of where to get *excess* water becomes the limiting factor in this scenario. Furthermore, if water is being imported into the lake, why wouldn't the city of Nakuru simply use that water for its own use and consumption rather than drain water from the lake. This might then allow for a natural lake level stabilization to occur.

Another solution is to examine other potential sources contributing to the degrading water quality. While in reality there is probably not one source, but many contributing sources to the water quality problem, solutions must then come from a variety of areas. For example, limit the amount of water that can be drained from the lake or limit the amount of effluents and quality of them being dumped into it.

This also appears to be the answer to the question regarding the scenario if soils appear to be contributors of nutrients into the lake. Some soil types naturally are high in phosphorus and nutrient levels and tend to leach them into surrounding areas, including nearby water bodies and groundwater. There is little that can be done in these situations except to examine the nutrient budget of the lake, i.e. account for all loading and consumption of nutrients, and target management strategies at other sources that are contributing nutrients. For example, assuming that the amount of nutrients being loaded into the lake from soils is constant, the amount of water that can be drained from the lake was limited, and the amount of effluents and quality of them being dumped into the lake were minimized, the desirable net amount of nutrients in the lake may be attained without managing for the natural nutrient inputs from the soils.

The other potential solution to the soil contributing scenario mentioned above would be to apply a buffer strip along the lake. Soils underneath the lake that contribute nutrients directly to lake waters would be unaffected by this effort, but if runoff into the lake is carrying water high in nutrients from the soils uphill, then a buffer zone of vegetation that consumes nutrients may be beneficial.

If the major contributing factor to degraded water quality is discovered to be wildlife related, there may be several wildlife management options available to explore. Wildlife influences could be many including contributing nutrients into the lake, use and consumption, and in the case of the flamingoes, covering it enough to potentially affect the solar processes involved with primary production in the lake.

Since flamingo populations have been participants in the Lake Nakuru ecology for centuries, it may be wise to examine solutions that do not directly affect their behavior or well-being. Flamingoes have inhabited this region for many more years than humans have. Therefore, it would be difficult to state that flamingo use is the sole contributor to the existing water quality condition. There probably has been a certain level of contamination from flamingo populations for long periods of time. The *combination* of flamingo populations with other factors, however, may be the determinant that is contributing to degrading water quality. One option that was previously discussed, would be to import water into the lake. Essentially, this would dilute the concentration of pollutants present and increase the surface area available for wildlife use. The other potential solution would be to mitigate the impact that flamingoes have on water quality by reducing nutrient inputs from other sources, as was discussed in the soil scenario. Both of these options would have minimal impacts on waterfowl, yet address the problems associated with water quality in the lake.

Another option would be to create another or numerous waterholes inside the Park boundaries that animals would be able to access. This may lessen the intensity of use upon Lake Nakuru by offering wildlife another option for drinking, eating, and bathing. While, this may alleviate stress on the lake from wildlife other than flamingoes, the majority of the water quality problems that are contributed to flamingo populations would still be present. Depending on the size and location of the waterholes, changes in watershed hydrology would need to be carefully planned for and monitored intensely. Again, the concept of ecosystem/watershed management comes into effect. When making decisions, it is vitally important to consider impacts across the entire watershed so as to minimally disrupt the balance within it.

The question of how to cope with the massive numbers of flamingoes that flock to Lake Nakuru every year seems to be an extremely difficult one. The impact that flamingoes have on Lake Nakuru is massive, simply due to their shear numbers. The assumption that they contribute their share of nutrients is probably realistic and one that needs attention. However, it is highly sensitive. Like other solutions that could have impacts on other aspects of the watershed, solutions to the flamingo problem should not disrupt or influence the behavior of the birds or related biological systems.

If by using a spatial analysis technique similar to one described previously, it is determined that one of the main culprits for decreasing water quality is in fact effluents from the city of Nakuru, a potential application technique may be the use of either natural or constructed wetland treatment systems (CWTS). These facilities could be used to divert the city of Nakuru's effluents and storm drainage runoff to better purify the water before it enters Lake Nakuru.

The practice of using either natural or constructed wetlands to treat wastewater is relatively new and still considered highly experimental. In 1989, a total of 100 constructed wetlands existed in the United States, all of them only two or three years in age (Dawson 1989). This means that now, even the oldest of facilities is only ten years old, the typical age to which they're built to last (James 1995). The long-term effects and impacts of these facilities are still missing pieces of this complex puzzle, and of course, those factors are vital to implementation and management practices. Schutz (1990) points out that there is still disagreement among interested parties on their construction and management practices.

Today in the U.S., wetland systems operate in all types of climates. U.S. facilities range in treatment capacity from 10,000 gallons per day to 20 million gallons per day (Schutz 1990). Not only are they used to treat municipal wastewater, but there are several other valuable uses as well, including treating industrial discharges, landfill leachate, acid mine drainage, and for agriculture and stormwater runoff control (James 1995).

While the mechanics of these facilities may still be considered to be in infant stages, positive feedback is already returning from those in use. Two of the most promising features of these wetlands are the cost to build and maintain them and the quality of the water after passing through them.

Dawson (1989) claims that the construction cost of one of these facilities is approximately $300,000. when comparing this figure to the average cost of a traditional wastewater treatment facility ($3-4 million), the difference is staggering. James (1995) reiterates the savings as typically being 25% less than traditional facilities. Not only are construction costs drastically reduced, but maintenance and operational fees as well. Dawson (1989) again states that CWTS's are self-maintaining after 2-3 seasons, thereby reducing staffing and maintenance costs. James (1995) restates this theme and claims that operation and maintenance costs are cut by 10-30%.

The resultant water quality from improved CWTS techniques appears to be increasing. Suspended solids, biological oxygen demand (BOD), and fecal coliform levels are all below standards set for "purified" water that passes through a treatment facility (Dawson 1989). Other positive impacts include reduced nutrient (nitrogen, phosphorus, and ammonia-nitrogen), heavy metal, and pesticide and other organic chemical levels (James 1995).

There are some drawbacks to CWTS facilities, however. Primarily, they require a large land area (Dawson 1989). Secondly, plants within these facilities tend to accumulate the heavy metals that pass through in the water (Dawson 1989). Disposal of these heavy metal-laden plant materials would be another issue that the Nakuru area would have to address. Potentially, the solution of disposing of these toxic materials may pose more problems than the original issue of poor water quality. Lastly, the wetland facilities require a minimum of upstream primary treatment for BOD and solids removal in order to prevent clogging in the wetlands (Schutz 1990). So, a minimum of one facility would also be required to enhance water quality later.

For example in Benton, Kentucky, there are 4700 people, who produce one million gallons of wastewater per day. This particular facility, like others, uses three different cells, one of bulrush, cattails, and one mixture grown in four to six inches of water, to pass the wastewater through to increase the quality of the (Dawson 1989). Assuming that the people of the city of Nakuru consumed and produced the wastewater at the same rates and amounts per person in Benton and assuming a population of 85,400 persons; Nakuru would need a facility with a capacity for over 18 million gallons per day. Assuming that the living conditions are the same, Nakuru's 18 million gallon per day treatment facility would require a maximum of 792 acres of land. This is likely larger than necessary because the rates of consumption are probably lower in Nakuru than they are in Benton.

These figures were derived from Schutz's (1990) calculations of 176 acres treating 4 million gallons per day.

Wetland treatment systems obtain their high water quality by using the attributes of several wetland plant types. Common plant species used in American systems are cattail (*Typha* J. St. Hil) (Beal 1904), soft-stem bulrush (*Scirpus validus* Vahl) (Voss 1972), *Pontederia* Dumort (Beal 1904), water hyacinth (*Eichhornia crassipes* Mart. Solms) (Berg 1961), duckweeds (*Lemna* L. and *Spirodela* Schleid) (Beal 1904), reed grass (*Phragmites communis* Trin) (Beal 1904), and pickerel weeds (Dawson 1989, Schutz 1990, Gover 1993, James 1995). Use of native plant species is highly recommended.

There are two types of wetlands that are used for wastewater treatment that are characterized by the type of flow passing through them: a free - surface or free water wetland and a subsurface flow wetland. The free or surface flow wetland offers two distinct advantages: less odor and fewer mosquitoes (Dawson 1989). One hundred seventy-six acres can treat 4 million gallons per day at a cost of $.99 per million gallon per day. It can treat between 60,000 and 20 million gallons per day at a construction cost of $22,200 per acre (Schutz 1990). Assuming Schutz's numbers, it would cost Nakuru $17,582,400 in construction costs to build the facility and $17.82 per day for operation.

While, the subsurface flow wetlands are more efficient at removing nitrogen during colder months, the rates of nitrogen removal also decrease over time (Gover 1993). Three acres of the subsurface facility can treat 483,000 gallons per day at a cost of $.53 per gallon per day and can treat between 10,000 and 3,500,000 gallons per day. The average construction cost is $87,218 per acre (Schutz 1990). More communities prefer these almost two to one and larger communities tend to use them more because of their cost effectiveness and the fact that wastewater flow is seven times greater than the free surface wetlands (Schutz 1990).

Another human activity that threatens Lake Nakuru with elements that could degrade its water quality is agricultural practices. Berger (1988) already cited soil erosion from overgrazing and clearing of natural vegetation for cultivation as major issues facing the Nakuru area. The World Wildlife Foundation indicates that farming and urban development are major threats to Lake Nakuru's environment (1996). Water quality problems associated with farming activities include increased sediment content from soil erosion and nutrient loading from fertilizer use.

Soil erosion is a common problem in farming areas where large amounts of soil may be exposed and/or saturated. Increased sediment content in lakes or streams that are located in foothills oftentimes occurs because of soil erosion. During storm events, or even in non-dramatic rainfall events, large amounts of water can run off sloping land. This runoff water frequently carries any elements in its path downslope with it. All too often, soil particles are swept with the water downslope and deposited wherever the water eventually stops moving. In the case of Lake Nakuru, which is the sink for a catchment area, this means that runoff water carrying sediment and nutrients from fertilizers becomes deposited in its waters.

Runoff water from soil erosion may occur under a variety of conditions including an area's topography, soil type, and amount and types of vegetation. If the topography in the area is sloped, the soil type is a variety of clay materials, and vegetation is sparse, there is a good chance that soil erosion will be rampant. All of these characteristics are common to Lake Nakuru's catchment area. While there is little that can be done to change those natural existing conditions, there are many actions that can be taken to lessen the impact that soil erosion has on the landscape.

Essentially there are two approaches that may counteract the impact of soil erosion on land surrounding Lake Nakuru: biological and mechanical strategies. Herbaceous vegetation strategies offer several counterattacks on the processes of soil erosion. Grasses provide root reinforcement through the restraint of soil particles, absorption of rainfall energy, prevention of soil compaction, filtration of sediment from runoff water, maintenance of soil porosity and permeability, and delay of soil saturation (a condition highly conducive to runoff situations) through infiltration (Gray and Leiser 1982).

All of these processes may be accomplished through a buffer zone of native, herbaceous vegetation surrounding the lake, a vegetated settling pond, or a CWTS as described previously. A buffer zone simply would supply a vegetated strip where runoff water from upslope could be filtered in a limited amount of time before it enters the lake. Settling or retention ponds could offer more time for physical and chemical processes to take place than a buffer zone because the water remains static for a certain amount of time, which allows sediment and other elements to settle or separate from the water. CWTS's essentially would offer the same processes and impacts, only at a larger, more complex scale.

Mechanical strategies employ structures such as rip-rap, settling ponds, diversions, check dams, and cut slopes to offer protection from slope movement and soil erosion. This is accomplished primarily by slowing the velocity of the moving water down so as to minimize erosion activity (Gray and Leiser 1982). Rip-rap are simply rocks placed strategically on a slope to offer some stability from sheer forces, gravitational and weight forces pulling soil downhill. Settling ponds were already highlighted, however, they may be either vegetated or non-vegetated. It should be noted that vegetation in the vegetated ponds may promote uptake of nutrients traveling in runoff water. Diversions are channels on a sloping land surface (Gray and Leiser 1982). These structures would carry water to a desired specific location rather than by haphazard runoff down a slope. Another strategy that may be employed jointly with diversions are check dams. Check dams are barriers in channels that serve to slow water velocity down further. Cut or terraced slopes are another potential solution to lessening the impact that soil erosion has on water quality. Terraces would act as temporary water diversions which may allow enough time for absorption of the runoff into the soil.

All of these practices would greatly enhance the land's capacity to control the deleterious effects of soil erosion. They are also capable of influencing the impacts that fertilizers have on the water quality through many of the same principles. Excess fertilizer that is not consumed by crops and vegetation or absorbed by the soil often becomes one of the elements swept away with the runoff water. The biological strategies of a buffer zone, a settling pond, or a CWTS could propose positive impacts on the water quality of the lake. The vegetation associated with each of these solutions would benefit greatly from the presence of increased nutrient levels, while those nutrient levels would be decreased from the water content of the lake downslope from farming fields.

Another solution to managing the fertilizer issue may be crop rotation. By rotating crops, the soil is less likely to become saturated with any one element or component. For example, if members of the legume family are cultivated cyclically, nitrogen in the soil would be consumed and become unavailable to be swept away by runoff water. The possible limiting factor in this scenario is the climate and growing conditions. I am certain that because of the semi-arid climate, the variety of crops that are capable of flourishing there are limited. Since agriculture/rangeland is the dominant land use (60%) from Nairobi to Nakuru, this could influence the economic livelihood of many people who depend on agriculture and grazing for survival.

Conclusion

It is apparent that the situation in Lake Nakuru's watershed is complex. The variety of land uses and natural influences surrounding the degrading water quality are many and the inter-relationships between them are vital to understand and difficult to manage. It would seem that by using spatial analysis techniques and modeling and prediction tools that sources contributing to the existing water quality condition could be properly identified. With the knowledge of what and where the sources are that govern water quality, ecosystem management principles could then be applied to manage and remedy the problem.

Realistically, all of the potential scenarios of contributing sources I mentioned in the discussion section probably factor into the water quality condition equation. Also as was previously discussed, the problem of managing for all contributing sources becomes even more difficult when balance in the watershed is maintained. It is for this reason that the use of ecosystem management, adaptive management, and landscape ecology principles would be highly beneficial. The large-scale thinking associated with these management approaches is exactly the thinking needed to accomplish set water quality goals. The inter-generational approach to those methods is needed as well in the Lake Nakuru scenario to ensure that the lake survives through and for generations of use by humans and wildlife. Lastly, the combination of social and scientific solutions is of vast relevance to the Nakuru watershed situation.

Addressing the last principle of ecosystem management (a social interaction with the problem at hand) is especially important in the issues facing Lake Nakuru for two reasons. One reason the social element is so critical to the questions surrounding the water quality of Lake Nakuru is because human consumption, use, and dumping is probably a major influence on its water quality. Considering that only 5% of the surrounding land use is designated as "towns," this problem can only intensify as more land is set aside for urban purposes.

The other reason revolves around the concept of public participation. In recent years, the Kenya Wildlife Service (KWS) has launched a vigorous campaign to educate the people living near Lake Nakuru National Park about its resources, wildlife, and the role they play in each. These efforts would need to be continued and enhanced to ensure that the public has a voice in the process, understands decisions that are being made, and how those decisions might affect them and the watershed.

Using spatial analysis and prediction techniques similar to those presented earlier would be an excellent vehicle in the pursuit of answers to Lake Nakuru's water quality questions. Large-scale areas could be used in order to represent the entire watershed appropriately. Potential sources of contamination may be identified in order to manage for them. While this may appear to be the technical solution to the methodology of such a project, there are also several limitations that need to be pointed out.

In Kenya in the past, much of the research that was conducted was done so by visiting scientists. Unfortunately, when the scientists left, they had a tendency to take their research with them and would leave very little information or knowledge behind. Justifiably, not only is there skepticism about outside researchers conducting research, but there is little base information available. Assuming that I was to undertake a GIS project to identify the sources that are contributing to the degrading water quality of Lake Nakuru, the lack of baseline information could become a large limiting factor when considering that large and diverse databases would be required for the watershed analysis. In many instances, the databases that in North America could be downloaded from an appropriate agency in a matter of hours, would in Nakuru, have to be created. While this could be done, it would be highly time consuming, cumbersome, and increase the project time length. Time would appear to be of the essence, especially if authorities are simply trying to maintain water quality levels without it worsening.

Political systems are another factor that might play heavily into a project as proposed. An intense study of the existing political system in the Nakuru area and the country as well would be beneficial in understanding how to carry out the methodology, gather information, and make decisions. This would also be a major factor if some management plan were decided upon that would affect wildlife. Because Kenya's economy is highly dependent on the wildlife tourism industry, the management of wildlife parks and systems often becomes highly polifical. Care would need to be taken in any management decision so that the interests of the watershed would be of top priority.

Two other limiting factors, which are common in North America, present themselves. Lack of amount and continued funding appears to factor into almost every proposed and in-progress project today. Also, since watershed management often crosses political boundaries, the question of inter-governmental and inter-agency involvement becomes key to the success of a study of Lake Nakuru's water quality from a landscape perspective.

Keeping all of the limiting factors in mind, a GIS project with the goals of understanding degrading water quality and identifying sources of pollution would be difficult, but necessary. Currently, I believe that little is being done to correct the present situation. If continued demand on water and little rainfall continues, the life of the lake may be in jeopardy. This would only make future endeavors to enhance water quality and use more water increasingly difficult.

With all of the variables that are participants in the watershed ecosystem, this would be a challenging and exciting undertaking. By examining techniques and technologies currently being called upon in North America to help find solutions to intricate problems such as this, potential applications to the African counterpart may be discovered. It may also be discovered that solutions to complex problems with similar issues are not worlds apart.

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