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Hydrologic Modeling of the Downstream Impacts of Land Use Change in the Mau Forest

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A significant portion of the forest within the upper Njoro River drainage basin was converted to agriculture between 1995 and 2003. This portion of the watershed lies within the Mau Forest, a significant water tower in Kenya that supplies both surface runoff and groundwater recharge within the Rift Valley. The Njoro River is a key contributor to Lake Nakuru National Park, which provides a host of ecological and economic services to the region. Previous research in the upper portion of the basin has identified deforestation as significantly altering the hydrologic regime of the river, but was limited to a local analysis where relatively rich data were available. In this research project, a hydrologic model was used to identify how the changes in the upper part of the watershed would be manifest in changes to the amount, timing, and apportionment of water both in terms of the riverine discharge and groundwater recharge. Findings show that the overall amount of water delivered to the river terminus (Lake Nakuru) was relatively unchanged, while the ratio of surface flow to groundwater recharge was significantly changed, that the timing of water flow was altered, and that the number of low flow days increased. These findings have implications for both human and ecological stability in the region, and are intended to provide guidance to planners tasked with watershed management and community development.

Background

Prior to a change in policy regarding forest management that took place in the early 2000's, the upper portion of the Njoro River watershed, located in the Rift Valley of Kenya (Figure 1) was dominated by mixed forest with some grassy areas and agriculture in the extreme upper portion of the watershed. Plantation forests dominated the lower reaches of the forested area, while the upper and steeper sections were indigenous forests. Previous research by SUMAWA has quantified the extent of the conversion of these forests to small-scale agriculture (Baldyga et al., 2007); the watershed changed from a dominant forested region (>80% forested) to a mixed-use region with 63% forested. This transition has resulted in changes to the hydrology of the upper watershed, primarily through changes in the timing and amount of surface runoff. Previous efforts at understanding and modeling the hydrological system in the Njoro River focused on the upper watershed because of the relatively rich historical data set that allowed for a better quantification and calibration of the effects. This research extends previous work by simulating runoff and groundwater recharge throughout the entire basin as it extends to Lake Nakuru at its terminus.

Lake Nakuru is an important economic and ecologic site within the Rift Valley. The Lake itself is highly dependent on both surface water discharge from the Njoro and other small rivers and groundwater influx from the regional water table. There is concern that changes in runoff, both in terms of timing and amount, will negatively affect the lake by changing water quality (especially sediment loading) and volume. Furthermore, if the rate of groundwater recharge to the regional aquifer is reduced, there is the increased potential for lake instability. In addition to these ecological effects, changes in hydrology have potential serious consequences for humans reliant on both groundwater and surface water. People within the Njoro watershed rely on both surface and groundwater for domestic and animal use. Groundwater reserves are particularly important for human use because they have higher water quality and reduced pathogen loadings, with the notable trade-off of being higher in fluoride, which increases the risk of fluorosis (a health condition hindering tooth development, generally in young children). However, people rely on surface discharge as well for both household use and for stock watering throughout the year, and if the timing of river discharges is altered or flows are significantly reduced during the dry season, this places additional stress on these families due to lowered access and reduced water quality.

Major Findings

A hydrologic model was built for the entire Njoro watershed that drains the Mau Forest water tower and empties into Lake Nakuru (Figure 1). The Soil and Water Assessment Tool (SWAT) was used to simulate

Table 1. Average annual values for hydrologic characteristics simulated using the SWAT hydrologic model with implications for human consumption.

Category	Water Yield	Surface Runoff	Groundwater Recharge
1995 Vegetation	148	108	127
2003 Vegetation	151	118	118
Change from 1995-2003 (mm)	+3	+10	-9
Change from 1995-2003 (%)	+2	+9	-7
Change from 1995-2203 in water available for domestic water use, assuming 150 liters per day per person	+15,000	+50,000	-44,509

hydrologic processes within the Automated Geospatial Watershed Assessment (AGWA; Miller et al., 2007) model. AGWA has a Geographic Information System (GIS)-driven interface that allows the user to calibrate and optimize the model by changing the ways in which rainfall-runoff ratios are calculated. The model was calibrated using historical data collected at a runoff station located halfway down the watershed and land cover and soils data constructed by SUMAWA researchers. Researchers investigated changes to the hydrology of the River by looking at simulated changes in the amounts and timing of evapotranspiration, surface runoff, groundwater recharge, and total water yield delivered on a daily basis for 12 years. These results were evaluated both at the outlet of the River and spatially within the watershed using GIS.

The net effect of land cover conversion was an overall slight increase in water yield, expressed as the total discharge from the outlet of the river resulting from both surface runoff and river flow supported by water migrating to the river from the soil, which occurs when the soil is relatively well saturated. While the overall effect on water yield was relatively small (an increase from 148 mm/yr to 151 mm/yr), the proportion of water yield resulting from surface runoff increased significantly at the expense of soil water and subsurface flow. Surface runoff increased by 9% while lateral flow was reduced by approximately 2%. The increase in surface water was offset by a commensurate decline in groundwater recharge (Table 1), which declined by 7%. These changes are the result of two factors: 1) declines in evapotranspiration due to the reduction in forest cover, and 2) a higher proportion of rainfall being converted into surface runoff instead of infiltrating into the soil and migrating to the regional aquifer. This effect is well documented throughout the scientific literature, and these results are reasonable given the SUMAWA experience in hydrologic modeling of the upper watershed. The implications, however, are very important.

The spatial distribution of changes in surface runoff and groundwater recharge are nearly mirror images of one another. Inspecting Figure 1 reveals that the upper-middle part of the watershed experienced the highest rate of change in surface runoff due to the conversion of forest to agriculture, while the uppermost and middle reaches of the watershed were relatively stable. The greatest increase (40-50%) occurred where plantation forests had previously been present; as Baldyga et al. (2007) showed; almost the entire plantation forest was harvested, while the indigenous forest remained more or less intact, though subject to small incursions.

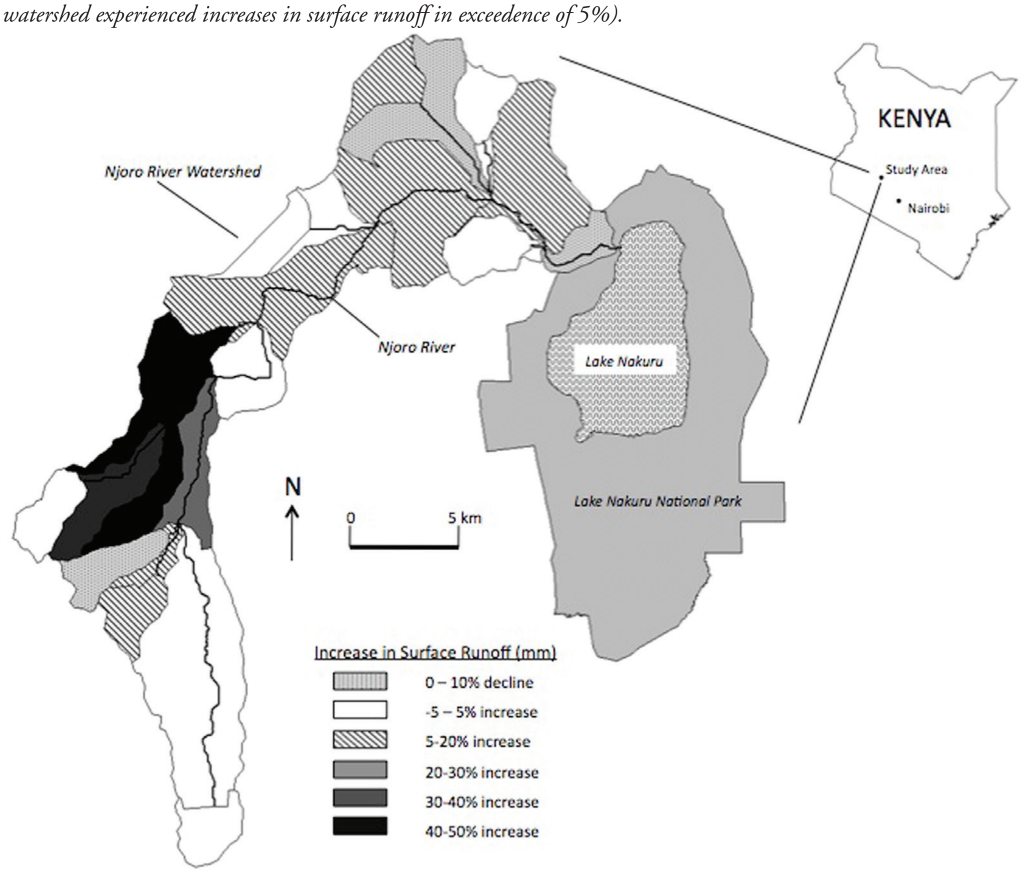
Practical Implications

Humans rely on water for a range of household, animal husbandry, and industrial uses. People within the watershed source their water from both surface and groundwater withdrawal points. There is a trade-off involved in the sourcing of water: groundwater costs more but has higher water quality and lower risk of pathogens and water-borne disease. The groundwater within and around the watershed is, however, relatively high in fluoride, which is undesirable due to potential health concerns regarding the human acquisition of fluorosis. Changes in the apportionment of water have direct implications for human water use; there is a shift from rainfall being recharged into the regional aquifer and converted into direct surface runoff. This has the net effect of reducing groundwater reserves and impacting borehole function. In fact, several boreholes within the watershed have gone dry in recent years, to the point where Egerton University (located in the middle portion of the watershed) has commissioned a task force to respond to a water availability crisis on the campus due to declining borehole function.

Table 1 illustrates the shift in allocations of surface and groundwater recharge with an estimated associated impact on water availability for human use. It is very challenging to identify the minimum human requirements for domestic water consumption. The World Health Organization (WHO) identifies a minimum standard of 15 liters per person per day, but this is strictly for consumption and sanitation. More reasonable estimates for domestic use that include cooking, cleaning, and other household duties range from 100-200 liters per person per day as a minimum. In Table 1, water is converted from units of mm to liters and then divided by 150 liters per person per day to determine the number of people impacted by the change in hydrology. The overall net effect is an increase in water availability due to increases surface runoff and a decline in groundwater availability. However, the amount of water actually available to humans via surface runoff is actually much lower due to the high variability in runoff throughout the year; much of the runoff pulses through the watershed in response to high rainfall events and quickly is lost to the lake. A more stable and reliable source of water throughout the year is groundwater supported by recharge, but the model identifies a net decline of water availability via recharge. Note that these numbers are relatively rough estimates of annual averages and are better used to identify trends and magnitude in change, and do not precisely identify gains or losses.

Ecological effects are primarily negative with this kind of shift in water delivery. While Lake Nakuru relies on river flow to periodically increase its volume, especially in high rainfall years, the shift to surface runoff has several outcomes on the lake that are undesirable from an ecological perspective. First, surface runoff is associated with higher erosion and sediment delivery, and the park has identified siltation and sediment transport as issues of serious concern for lake sustainability. While the researchers did not simulate erosion prediction in this effort, increases in surface runoff are linked to increased surface erosion and loss of topsoil and long-term sustainability. Surface runoff, especially in areas with low vegetation cover, results in concentrated flow and increased sediment transport, resulting in higher sediment delivery rates downstream and reduced water quality. Second, surface runoff is more rapid than flow supported by groundwater and/or soil moisture release, and downstream runoff from these flows tend to be much flashier. A shift to a flashier system impacts the temporal distribution of flow by increasing runoff during the rainy season but reducing it during the dry season, when ecosystems are particularly stressed. Thus, the net effect can be an increase or negligible change in total runoff on an annual basis while the system is put under stress due to a shift in the timing of the delivery of water.

Figure 1. Spatially distributed change in surface runoff in the Njoro River watershed resulting from land cover change (primarily conversion of forest to agriculture) from 1995-2003 simulated with a hydrologic model. (Note that much of the watershed experienced increases in surface runoff in exceedence of 5%).



Further Reading

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The GL-CRSP Sustainable Management of Rural Watersheds (SUMAWA) project was established in 2003 and is a multidisciplinary research effort focusing on biophysical and human-related factors governing health in the River Njoro watershed in Kenya. The Principal Investigators for SUMAWA are Dr. Scott Miller (Email: snmiller@uwyo.edu) and Dr. Patterson Semenye (Email: semenye@sumawa.or.ke).

The Global Livestock CRSP is comprised of multidisciplinary, collaborative projects focused on human nutrition, economic growth, environment and policy related to animal agriculture and linked by a global theme of risk in a changing environment. The program is active in East and West Africa, Central Asia and Latin America.

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