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Water Resources Policy Development Using Hydrologic And Systems Dynamics Modeling – A Case Study For East Africa

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WATER RESOURCES POLICY DEVELOPMENT USING HYDROLOGIC AND SYSTEMS DYNAMICS MODELING – A CASE STUDY FOR EAST AFRICA

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Drought is a natural disaster that affects millions of people across the globe. Lack of rainfall reduces crop yields and livestock productivity and in turn, food availability and income. In developing countries, these effects are even more detrimental. As droughts become more frequent, adaptation is a fundamental concern for countries and their policy makers. Hydrologic and system dynamics models were developed for a region in East Africa, focused on the Horn of Africa (ie. a region bordering Kenya, Somalia, and Ethiopia), an area well-known for frequent droughts due to unpredictable rainfall and high temperatures. The models simulate the interdependencies between water availability, land degradation, food availability, socio-economic welfare and the impact new adaptation policies can have on the region over a 10 year simulation. It was found that a combination of increased hydraulic infrastructure and innovative agricultural practice policy can reduce domestic water deficits by 54-100% while increasing the income per capita up to 285% over the 10 years. By innovatively combining hydrologic and system dynamics modeling, realistic simulation of the effects water scarcity has on natural systems can be observed. Implementation of policies within the model aids the selection process by evaluating multiple options, quantifying the effectiveness the policies have on individual stakeholder livelihood, and analyzing the overall outcome to ensure equitable costs and benefits.

INTRODUCTION

Natural disasters such as droughts and floods pose a complex challenge to decision makers in helping the affected population to regain control of their normal life as well as protect them from future disasters. Most developing nations depend on outside aid during a natural disaster. Dependence on outside aid is not a viable solution to avoid potentially catastrophic outcomes; policymakers strive to implement innovative and supportive strategies to reduce these effects. Ideally, proper drought adaptation measures would results in a resilient population, sustaining themselves through times of drought by means of adaptive measures and a reliable infrastructure. Towards this end, a system dynamics framework is developed for policymakers that will help in the understanding of interdependencies across multiple systems affected by drought: physically, biologically, and socio-economically. Hydrologic modeling can simulate the water cycle for a given region using climate and geological data. Using water availability data from the hydrologic model, system dynamics modeling can be used to show different effects and interdependencies due to water availability and scarcity over time. Additionally, the systems dynamic model has the ability to incorporate new adaptation measures and compare the impacts between scenarios in order to measure improvements or breakdowns within the systems. Many of the of the systems effected by drought have been studied, but they have not been modeled and simulated in order to introduce and evaluate mitigation policies that may drastically improve the well-being of the populations suffering through drought. By understanding these complex relationships and evaluating different scenarios for drought adaptation, the system dynamics modeling can be a powerful tool for policymakers when they are selecting the best solution or combination of solutions for drought adaptation.

STUDY AREA

Over the past few decades, the Horn of Africa has been struck by multiple droughts, leaving a majority of the population in a food crisis. They have become dependent on outside aid to sustain their populations. Additionally, Somalia has been under political turmoil and civil war, resulting in a large migratory refugee population spilling in to Ethiopia and Kenya. Because drought is an expected occurrence in East Africa, it is selected as the test bed for this study. It is part of the Juba River Basin and encompasses parts of Southern Ethiopia, Eastern Kenya and Southern Somalia. The study area is centered on the Mandera Triangle in the Horn of Africa as seen in Figure 2.1. The modeled watershed has an area of approximately 537,023 sq km, extending from 36.2 to 45.0 east latitude and 7.5 north longitude to -2.5 south longitude. The watershed for this region is broken up into 11 subwatersheds and covers roughly 203,260 sq km of Kenya, 170,008 sq km of Somalia, and 163,755 sq km of Ethiopia. The outlet of the basin is the culmination of the Juba and Shabelle Rivers, located in southern Somalia and discharges into the Indian Ocean.

METHODOLOGY

The methodology involves creating a system dynamics model that will simulate the complex interdependencies between water availability, land degradation, livestock and agriculture production, and socioeconomic impacts. This is accomplished by using the system dynamics modeling program called Vensim. The model contains over 1300 dynamic variables representing different environmental and economic systems within this East African region. Drought has a strong effect on water availability which is directly related to land, livestock, and population dynamics. The resulting socio-economic welfare is measured based on the effected systems. The model is run on a monthly time step for a period of 10 years (2001-2010). One of the main components of this dynamics model is the availability of water, which is simulated by using the Soil Water Assessment Tool (SWAT). The systems modeling framework for water availability is shown in Figure 1.

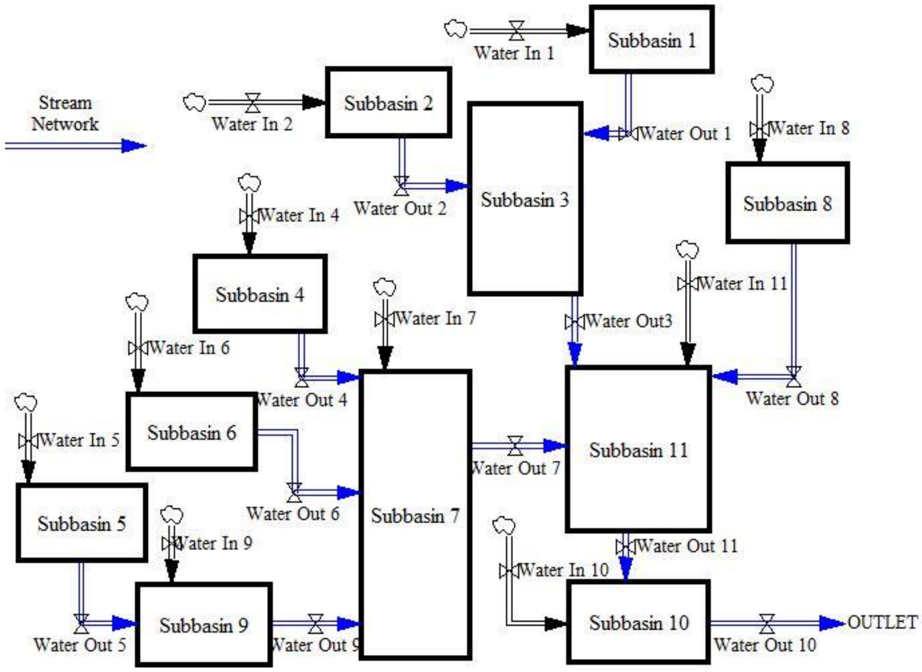

Figure 1: Framework of watershed dynamics implemented in system dynamics model

The output from SWAT, which is basically the amount of water available on surface and sub-surface is then linked to models created for land change dynamics, livestock and agriculture production, and socioeconomic impacts. The policy component of the system dynamics is included by incorporating the use of hydraulic policy such as installation of sand dams, wells and rain water harvesting structures, improved agricultural practices policy and a combination of both.

RESULTS

Figures 2-4 show how the water availability or deficit, crop production and per capita income are affected from rainfall during a 10 years simulation for Kenya, one of the study regions. As seen in Figure 2, the water deficit increased during the dry season, and the crop yield is directly related to the amount of rainfall. Similarly, the increase in crop yield is directly related to increase in per capita income for the region. Figures 2-4 present a baseline scenario for Kenya, and similar results are obtained for Ethiopia and Somalia, while the results are slightly different, but the overall trend is similar for all regions. After establishing the baseline scenario, the hydraulic and agricultural policies are implemented to see how the policies affect the water availability, and in turn the overall dynamics. Table 1 show the results for the Kenyan region. It is noticeable that with the new infrastructure, the magnitude of the deficits is reduced. The most successful infrastructure is the wells which reduce the number of total as well as the overall magnitude of deficits. Ponds and sand dams reduce the magnitude of the water deficits, but are not as successful at eliminating them completely. Finally, the rain water harvesting (RWH) tanks are the least successful; they do not add enough water to the system to change the baseline deficits.

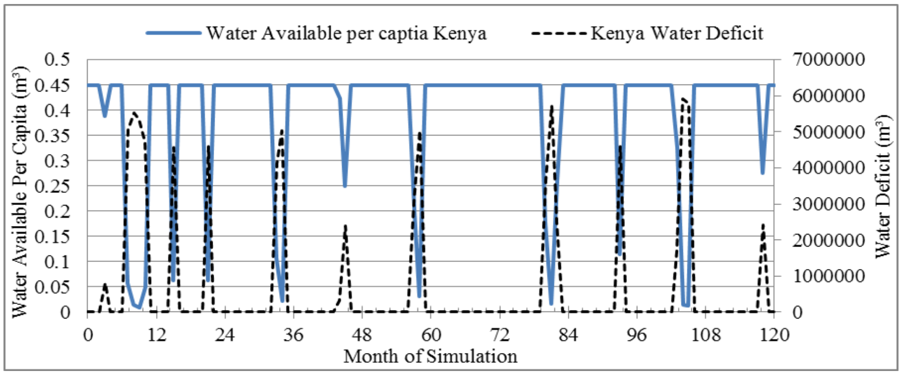

Figure 2: Water deficit and water availability per capita for Kenyan region

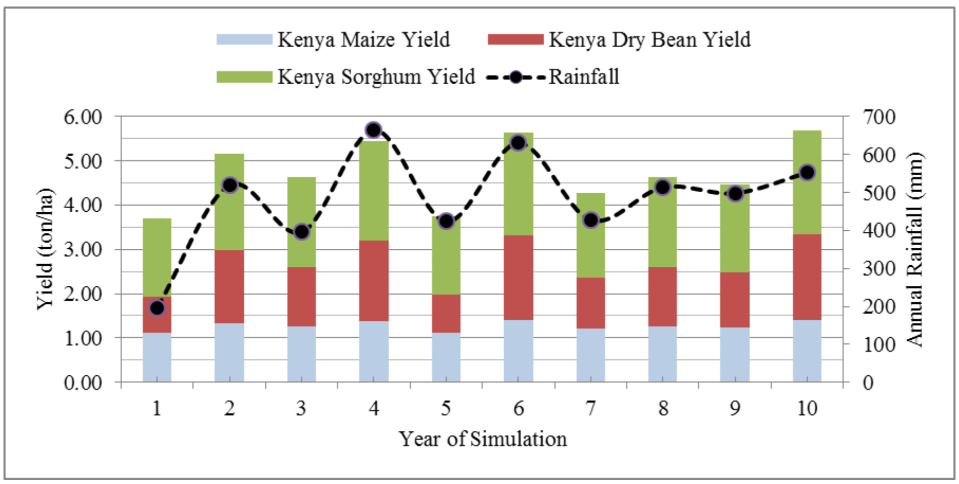

Figure 3: Kenyan region crop yield in relation to annual rainfall

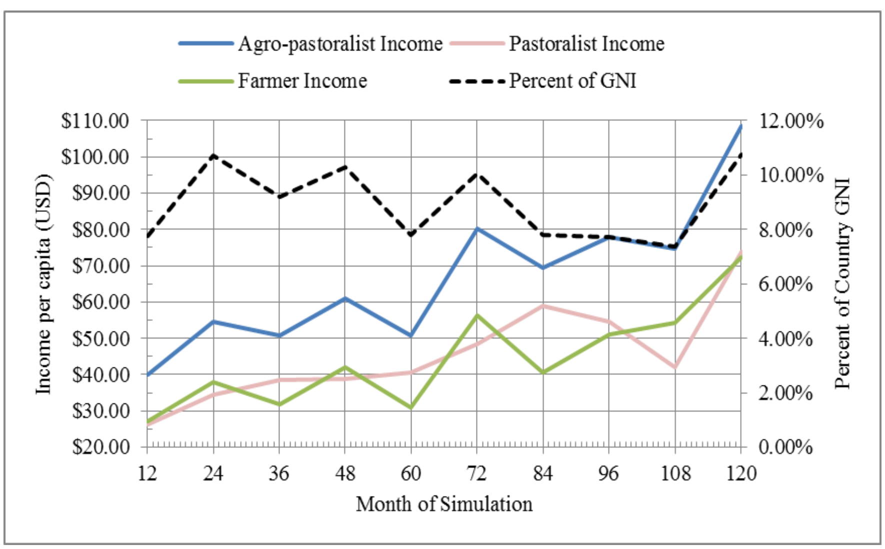

Figure 4: Kenyan region income per capita

Table 1: Months with water deficits in Kenya under various hydraulic infrastructures

Water Deficit	Baseline	Sand Dams	RWH tanks	Ponds	Shallow Wells	Boreholes
Number of months with Deficits	21	19	21	17	16	12
< 1,000,000 m³	2	2	2	3	3	6
1,000,001 - 2,000,000 m³	1	3	1	1	4	4
2,000,001 - 3,000,000 m³	3	2	3	1	2	2
3,000,001 - 4,000,000 m³	2	5	2	4	2	0
> 4,000,000 m³	13	7	13	8	5	0

Similarly, effect of agricultural policies in the form of improved irrigation and agroforestry are shown in Table 2.

Table 2: Regional profitability of agricultural systems over 10 year simulation

	Ethiopia	Somalia	Kenya
Drip Irrigation			
Area of Ag Land (ha)	357,743	18,700	157,772
Initial Investment cost ($/ha)	$15,000	$15,000	$15,000
Total Investment	$5,366,155,500	$280,501,200	$2,366,587,500
Increase in Income From Crops*	$655,974,500	$328,658,610	$1,512,947,500
NPV Profit	-$3,652,253,130	-$37,037,190	-$1,000,294,720
NPV profit (per ha)	-$10,210	-$1,980	-$6,340
Agroforestry			
Area of Ag Land (ha)	396,618	18,700	157,772
Initial Investment cost ($/ha)	$90	$90	$90
Total Investment Cost	$35,695,620	$1,683,010	$14,199,530
Increase in Income From Crops*	$337,812,200	$183,718,670	$1,270,943,800
Income From Tree Products*	$891,278,340	$41,313,270	$348,089,710
NPV profit	$76,324,920	$68,691,680	$545,603,610
NPV profit (per ha)	$190	$3,670	$3,460

*over 10 years

From this analysis, Agroforestry is successful at returning a profit for the farmer investing. Because drip irrigation has such a high initial investment cost, when applying it to such a large area, the resulting income due to increased yield of the staple crops is not enough to justify the high cost of implementation. In all regions, there is no positive return. Additionally, the increase in water demand that drip irrigation adds is immense and creates a negative effect on the pastoral population as livestock income decreases. When the hydraulic and agricultural policies are combined, there are increased profits for all sources of income when compared to the baseline simulation (Table 3). For the first few years, the staple crops do not produce as high of yields, but as the trees mature in the agroforestry agricultural land, yields do increase above baseline harvests. After the 10 year period, the total net present value (NPV) profit based on initial investment costs (with drip irrigation occurring at year 0 and year 5) and the resulting profit cash flows (net change in income from the baseline scenario for each year of simulation) it is evident that the combination policy results in a positive annualized return on investment (ROI). Moreover, the increased income extends across all livelihoods (crops and livestock) and would benefit the entire population.

Table 3: Cost and profits from combined policy model over 10 year simulation

	Ethiopia	Somalia	Kenya
Sand Dams	$1,120,000	$880,000	$1,520,000
Shallow Wells	$597,600	$432,000	$720,000
Ponds	$1,320,000	$1,000,000	$1,360,000
Boreholes	$450,000	$405,000	$660,000
Drip Irrigated Land** (ha)	$2,413,270	$1,379,340	$2,275,4230
Agroforestry Land (ha)	$3,665,760	$167,270	$1,418,250
Total Policy Costs	-$9,566,630	-$4,263,610	-$7,953,670
Income Gained - Agroforestry	$53,105,970	$4,105,030	$34,765,770
Income Gained - Cash Crops	$618,409,900	$363,457,800	$576,834,700
Income Gained - Livestock	$128,225,900	$115,775,100	$140,118,000
Income Gained - Staple Crops	$117,855,830	$13,315,280	$91,013,030
NPV Profit	$456,170,430	$254,040,340	$424,247,790
Annualized Return on Investment	477%	596%	533%

** (drip irrigation has a 5 year lifespan)

SUMMARY AND CONCLUSIONS

Through system dynamics and hydrologic modeling, the effects of different policies are explored and analyzed for an East African region known to be chronically effected by drought. For the study area, this modeling highlights the relationships between water availability, livestock and crop production, and the socio-economic effects on the people within the region. An understanding of these complex relationships is essential when determining strategies to alleviate potential undesirable consequences due to water shortages. The hydrologic model effectively determines water availability for the region based on historical weather data. Through literature and system dynamics modeling, it is possible to explore alternative policy options that could potentially lessen the effects of drought within the region and improve the overall livelihood of the population. Based on the three policies explored, it is found that a combination of hydraulic infrastructure to improve water availability and introducing new agricultural practice to increase crop production would be the most beneficial for all livelihood categories within the study region in East Africa.

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