

2014

VALUES AND SERVICES OF A PROTECTED RIVERINE ESTUARY IN EAST AFRICA: THE WAMI RIVER AND SAADANI NATIONAL PARK

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VALUES AND SERVICES OF A PROTECTED RIVERINE ESTUARY IN EAST AFRICA:

THE WAMI RIVER AND SAADANI NATIONAL PARK

BY

CATHERINE GRACE McNALLY

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ENVIRONMENTAL SCIENCES

UNIVERSITY OF RHODE ISLAND

2014

DOCTOR OF PHILOSOPHY DISSERTATION

OF

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2014

ABSTRACT

The dialogue pertaining to the management of riverine and coastal ecosystems has evolved over the past decade to consider ecosystem goods and services due to their ability to link ecosystem structure and function to human well-being. Ecosystem services are “a wide range of conditions and processes through which natural ecosystems, and the species that are part of them, help sustain and fulfill human life” (Daily et al. 1997 p.2). Ecosystem goods emerge from ecosystem services and are defined as “organisms and their parts and products that grow in the wild and ... are used directly for human benefits” (Daily et al. 1997 p.4). Protected areas, such as national parks, and environmental flow regimes that identify critical aspects of river flow, are increasingly being utilized as management measures to enhance resiliency, protect biodiversity, and preserve the delivery of ecosystem goods and services.

Recently it been proposed that aquatic ecosystem goods and services can serve as a common currency to account for the benefits and losses associated with altered flow regimes and define the risks in a transparent manner since they provide immense value to all stakeholders (Arthington 2012). Adopting this idea, my dissertation research comprises three studies focused on the ecosystem goods and services related to the protected portion of the Wami River and Estuary encompassed within Saadani National Park (SANAPA), Tanzania. The first study investigates the use and perception by different groups of downstream stakeholders of the value of ecosystem goods and services. The second study examines the effect of SANAPA on the tradeoff between two specific ecosystem services and whether the local surrounding communities fell into a

poverty trap as a result of the restrictive measures put in place when the park was created. The third study assesses how proposed water withdrawals for a large scale irrigation project located just upstream of the park's boundary would alter the freshwater inflow regime and potentially impact the delivery of ecosystem goods and services to SANAPA and the neighboring local communities.

The need for enhanced understanding of how different stakeholders perceive and depend upon an array of ecosystem goods and services is a critical research priority. In our first study, we employ a mixed methods approach comprised of focus groups and face-to-face surveys to examine the specific ecosystem goods utilized by residents and compare and contrast the perceived value of 30 ecosystem services held by upstream residents, downstream residents, tourism officials, and conservation organizations. Our key finding is that a good deal of consensus exists among these groups in regards to which ecosystem services are deemed most and least valuable. Each group places a high value on the provision of domestic water, habitat for wild plants and animals, tourism, and erosion control, and a relatively low value on the prevention of saltwater intrusion, refuge from predators, spiritual fulfillment, non-recreational hunting, and the provision of traditional medications and inorganic materials for construction. Differences emerge, however, between the groups in the value assigned to the conservation of riverine and estuarine fauna, intrinsic value, and the provision of raw materials for building and handicrafts. The fact that residents assigned a higher priority to raw materials and a lower priority to the intrinsic value and conservation of riverine and estuarine fauna than the tourism and conservation officials suggests that they are

very reliant upon the resources of the Wami River and Estuary for their sustenance and income.

The findings from our first study fall in line with the larger pattern observed around the world, namely, that many coastal communities in developing countries, especially the rural poor, rely heavily upon natural resources for their subsistence and livelihoods. Their access to these resources, however, often changes when protected areas are established. The short- and long-term gains and losses to local residents associated with protected areas remain largely unexplored, especially empirically. In our second study, we integrate remote sensing data of mangrove cover with georeferenced household survey data in an econometric framework to assess the environmental and economic impacts of enhanced mangrove protection efforts undertaken to preserve biodiversity in SANAPA on the neighboring local communities. Specifically, we examine the effect of strengthened enforcement of the prohibition of mangrove harvesting on the tradeoff between two specific ecosystem services (i.e., the short-term benefits from cutting mangroves and the long-term benefits from harvesting the fish and shrimp that thrive if mangroves are not cut), and whether households fell into a poverty trap as a result. Our findings suggest that many households experienced an immediate loss in the consumption of mangrove firewood with the loss most prevalent in richer households. However, all wealth classes appear to benefit from long-term sustainability gains in shrimping and fishing which result from mangrove protection. Overall, the households that have stopped using mangroves for firewood can be considered the “losers” from establishment of SANAPA, while those who started

fishing/shrimping (or making more revenue out of it) are the “winners.” Our data suggest that there are more “winners” than “losers” with the proportion of households that newly engaged in mangrove-related income activities after SANAPA outweighing the proportion of households that no longer use mangroves for their firewood. The creation of SANAPA shifted the future trajectory of the area from one in which mangroves were experiencing uncontrolled cutting to one in which mangrove conservation is providing gains in income for the local villages due to the preservation of nursery habitat and biodiversity.

While the results of our second study are encouraging, the health of the mangroves, existence of the mangrove reliant fish and shrimp species, and continued delivery of the other ecosystem goods and services valued by the stakeholders in our first study, are dependent upon sustained freshwater flows into the lower reaches of the Wami River and Estuary. Upstream anthropogenic activities can alter the magnitude, frequency, duration, timing and quality of freshwater inflows. These alterations to the natural flow regime can cause abiotic and biotic changes within the downstream riverine, estuarine, and coastal ecosystems affecting the availability of the ecosystem goods and services, and in turn, the overall well-being of the stakeholders reliant upon them. In our third study, we examine the potential effects of water withdrawal (i.e., abstraction) from a proposed 10,500 hectare irrigated biofuel project on the Wami River on the delivery of ecosystem goods and services to SANAPA and the neighboring local communities. We utilize daily flow data collected from 1954 to 1978 to derive a number of low flow and extreme low flow parameters for flow durations

ranging from 1 to 90 days to characterize the historic and post-irrigation freshwater flow regime of the Wami River. Our findings demonstrate that the proposed withdrawals during the dry season would dramatically alter the flow regime of the lower Wami River and create conditions unlike any observed over the 24 year period of flow records analyzed. Under the abstraction scenario, there is a 10-fold increase in the occurrence of low flow values observed historically. Moreover, the incidences of zero flow days over the 24 year period of record rise from 15 to 300, creating extended periods of no-flow conditions that would completely dry out lower portions of the Wami River. These changes would have profound effects on the habitats, wildlife, fisheries, and human values and functions that constitute Saadani National Park. Therefore, it is essential that large scale water withdrawals must be approached with caution in perennial, free-flowing rivers draining arid watersheds of eastern Africa to sustain the critical riverine and estuarine linked ecosystem goods and services of downstream protected areas.

ACKNOWLEDGEMENTS

As the saying goes, it takes a village, and I am profoundly grateful for all of the individuals who guided, assisted, and/or supported me throughout my very rewarding Ph.D. journey. My work in Tanzania began in 2007, when the Coastal Resources Center at the University of Rhode Island and the Tanzania Coastal Management Partnership hosted me for my IGERT internship. I was warmly welcomed to Tanzania by the dedicated and hardworking TCMP staff, and became very interested in the ecological and human facets of Saadani National Park and the field of environmental flows after having the opportunity to work on two rapid assessments and the initial environmental flow assessment for the Wami River. Upon my return, I enthusiastically shared all of my experiences with my advisor, Art Gold, and expressed my interest in continuing to work in Tanzania. For all that know Art, it comes as no surprise that he went far above and beyond to help me continue working in Tanzania. He taught me a great deal about hydrology, and together we learned more about environmental flows, ecosystem goods and services, and poverty traps as he helped me craft three interdisciplinary studies. He has been an extraordinary mentor, and I cannot thank him enough for his incredible generosity in terms of knowledge, time, and funding, as well as his steadfast support and cheerful nature. It has truly been an honor to be your student.

I am also extremely grateful for my committee members; Y.Q. Wang, Richard Pollnac, Peter August, and Judith Swift, who not only taught me so much in their classes, but also shared their insights and expertise throughout my research, and exhibited remarkable patience and kindness when medical issues periodically forced me to the sideline. Y.Q. taught me about remote sensing and graciously shared his expertise, as well as his 1990 and

2000 satellite imagery for our second study. Dr. Pollnac taught me a great deal about research methods and statistics, and was instrumental in the development of the research design and survey instrument for our first study. Pete taught me so much about GIS, as well as the art of building strong bridges between scientists, managers, and stakeholders, and I am very thankful for his cheerful support, thoughtful insights, and GIS tips. Judith taught me about environmental justice and her IGERT class gave me a great appreciation for the role of humanities in bridging the realms of science and policy. Throughout my Ph.D. program, she helped me grow both professionally and personally by challenging me to step outside of my comfort zone, and I greatly appreciate her public speaking lessons, keen interest in my research and Tanzania, and words of encouragement along the way.

I am also very thankful for the two communities that I was a part of during my Ph.D. program – the Natural Resources Science Department and the IGERT Program. I learned so much from the faculty and my fellow students, and am especially grateful to Deb Bourassa and Deb Coty for all of their assistance processing the paperwork for my assistantships and trips to Tanzania.

I would also like to thank Christopher Barrett and Alex Travis for the wonderful opportunity to participate in the Biodiversity Conservation and Poverty Traps workshop at Cornell University. I enjoyed interacting with all of the workshop participants and valued having the opportunity to work closely with Emi Uchida on our second study. She introduced me to the field of econometrics, taught me more about the development of survey instruments, and gave me the opportunity to be part of an interdisciplinary team further exploring the linkages between ecosystem services and poverty traps. I am grateful to Stan Cobb for generously sharing his knowledge on fisheries, as well as his many words of

wisdom, and treasure the friendship that developed on our rides to and from URI. I would also like to thank Lesley Squillante, Brian Crawford, Elin Torell, Don Robadue, Jim Tobey, Kim Kaine, and Woodi Woodring for not only giving me the incredible opportunity to work in Tanzania, but for providing so much intellectual and logistical support along the way. I would also like to thank Elizabeth Anderson for teaching me about environmental flows and allowing me to participate in the Wami River environmental flow workshops.

I am tremendously thankful to everyone at the Tanzania Coastal Management Partnership. Without their thoughtful guidance and immense help, none of this would have been possible. They all made me feel incredibly welcome when I first arrived in Tanzania, and with each subsequent trip, our friendships grew deeper as they became my family away from home. I thank Jeremiah Daffa for sharing his extensive knowledge accrued over many years of working with so many different stakeholders in Tanzania and introducing me to many of them; Baraka Kalangahe for his thoughtful insights, his assistance in identifying many of the NGO stakeholders surveyed in our first study, and for hosting Art on his visit; Appa Mandari for accompanying me in the field, introducing our projects to the District and local government leaders, and always making the community members feel at ease with her warm smile and gentle manner; Gratian Luhikula for translating our survey instruments; Wilbard Mkama for his assistance gathering all of the fish and shrimp species information in our first study and overseeing the fieldwork for our second study; Salim Ngomuo for helping me conduct the tourism and NGO stakeholder surveys in our first study and overseeing the fieldwork for our second study; Safarani Msuya, Gumbo Majubwa, and Jumanne Mohamed for their dedicated effort in the field and perseverance in tracking down government documents; Esther Kapinga for all of her assistance in processing the necessary paperwork

for our fieldwork expenses; Andrew Macha for his assistance in arranging many of my meetings with various NGOs and helping to photocopy our survey instruments; and Jacob Mlula and Ayoub Nanjale for their expert driving on the wet and muddy roads in Saadani National Park and many Swahili lessons as we waited in the long traffic jams in Dar.

I am deeply grateful to my very hardworking, thorough, and enthusiastic field teams. It was such a pleasure working with Wilbard Mkama, Salim Ngomuo, Gerald Jacob, Halima Kiwango, Winnie Kikoka, Bahati Joshua, Daniel Kisaka, Alberto Benedicto, Gumbo Majumbwa, Safarani Msuya, Alieth Mutatina, Helena Peter, Grite Nelson, and Gregory Godfrey. I truly cannot thank them enough for the great care they took in collecting our survey data; I am very thankful to Gerry for helping to meticulously enter our survey data into Excel. I also want to thank all of our survey respondents and focus group participants for sharing their knowledge and perceptions with us. I was continuously struck by how generous our respondents were with their valuable time, and am thankful for being welcomed so warmly into their communities, offices, hotels, and businesses.

I also extend my deep appreciation to the village executive officers, District Officers, Mr. Mposo and Zuberi Ramadhani, and Saadani National Park personnel for their logistical support. Special thanks go to Halima Kiwango and Angela Nyaki for their assistance in arranging the field logistics for our work within Saadani National Park and to Festo Mbiliyini for taking us on SANAPA's boat to Porokanya and along the Wami River. I also thank Dr. Patrick Valimba and the Wami Ruvu Water Basin Office for sharing their water flow data, and thank Mr. Ernest Lema for helping us track down the most recent flow data available at the Manderu gauge.

I am very thankful for the special friendships forged along this journey with Julia Royster, Q Kellogg, Kelly Addy, Peg Pelletier, Julia Hyman, Eivy Monroy, Elizabeth McClean, Sam Ayebare, Tiffany Smythe, Karen Sullivan, and Tingting Liu, and would like to thank Lola Herrera, Carissa Lord, Beth Statkus, Christy McManus, Marie Naef and Sue Horst for their continued support and words of encouragement.

Finally, I would like to thank my family for their tremendous amount of support. My Mom and Dad nurtured my love of science from a young age, instilled a sense of adventure, and have always encouraged me to follow my heart. Nana, Megan, Patrick, and Aaron all took a genuine interest in my research and provided much needed comic relief during long days of data analysis and writing while my husband, Pat, has been simply amazing throughout this entire adventure. His ardent support helped to keep me inspired, optimistic and determined, and I am deeply appreciative of the many sacrifices that he made so that I could pursue this degree. He took a leave of absence from work to join me during part of my first trip to Tanzania and kept things running smoothly at home during my other extended trips to Tanzania. Additionally, he shared many helpful Excel tips, put in many hours of proofreading, and always exhibited sincere understanding when my studies kept me late at school or home over the weekends. His encouragement, reassurance during my thyroid difficulties, sense of humor, and love throughout this journey mean so very much, and I could not have done this without him.

PREFACE

This dissertation is written in manuscript format with three main chapters corresponding to the format of journal articles.

The following research questions are addressed in my dissertation:

1. Is there a difference in the perceived value of the categories of ecosystem services within and between the stakeholder groups?
2. Which regulating, supporting, cultural and provisioning ecosystem services provided by the Wami River and its estuary are valued most and least among our targeted stakeholder groups?
3. How do the upstream and downstream residents utilize the Wami River and Estuary in their daily lives and which ecosystem goods are deemed most important for their subsistence and livelihoods?
4. What potential synergies and tensions may exist among these stakeholder groups with regard to the values placed on the ecosystem services?
5. What are the main concerns of these stakeholders regarding the future conditions of the Wami River and its estuary?
6. Did the enhanced enforcement of the prohibition of mangrove harvesting within SANAPA affect the rate of mangrove habitat loss?
7. Did the tradeoff between two provisioning ecosystem services from mangrove forests (i.e., the short-run benefits from cutting the above ground biomass of mangroves for fuelwood and charcoal production versus the long-run benefits from harvesting the fish and shrimp that thrive in the prop roots of uncut mangroves) result in a poverty trap for the local communities surrounding SANAPA?
8. What are the characteristics of the historic/pre-altered flow regime that have supported the ecosystem goods and services currently provided by the Wami River and its estuary?
9. How will proposed upstream irrigation withdrawals for biofuel production change the Wami River's flow regime?

10. How might the altered flow regime impact the ecosystem goods and ecosystem services utilized and valued by the different groups of downstream stakeholders?

The first manuscript addresses research questions 1-5, and will be submitted to the journal *Ecosystem Services*.

The second manuscript addresses research questions 6 and 7, and was published in 2011 in PNAS (citation is below).

McNally, CG, Uchida E, Gold AJ (2011) The Effect of a Protected Area on the Tradeoffs Between Short-run and Long-run Benefits from Mangrove Ecosystems. *Proceedings of the National Academy of Sciences* 108(34):13945-13950.

N.B. The econometric techniques used to explore the causal linkages between mangrove protection and poverty in our PNAS manuscript is the work of Dr. Emi Uchida and is not a component of my own dissertation research.

The third manuscript addresses research questions 8-10, and will be submitted to the journal *River Research and Applications*.

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Stakeholder Perceptions of Ecosystem Goods and Services of the Wami River Estuary

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Abstract

Management of riverine and coastal ecosystems warrants enhanced understanding of how different stakeholders perceive and depend upon different kinds of ecosystem services. Employing a mixed methods approach, this study compares and contrasts the use and perceptions of upstream residents, downstream residents, tourism officials, and conservation organizations regarding the value of 30 ecosystem services provided by the Wami River and its estuary in Tanzania, and investigates their perceptions of the main threats to this system. Our findings reveal that all of the stakeholder groups place a high value on the provision of domestic water, habitat for wild plants and animals, tourism, and erosion control, and a relatively low value on the prevention of saltwater intrusion, refuge from predators, spiritual fulfillment, non-recreational hunting, and the provision of traditional medications and inorganic materials for construction.

Differences emerge, however, between the groups in the value assigned to the conservation of riverine and estuarine fauna and the provision of raw materials for building and handicrafts. Declining fish populations and an increasing human population are identified by the residents and conservation employees, respectively, as their prime concerns regarding the future conditions of the Wami River and its estuary. These groups also acknowledge increasing salinity levels and the loss of mangroves as other key concerns. The identification of these mutual interests and shared concerns can help build common ground among stakeholders while the recognition of potential tensions can assist managers in balancing and reconciling the multiple needs and values of these different groups.

Introduction

The dialogue pertaining to the management of riverine and coastal ecosystems has evolved over the past decade to increasingly consider ecosystem goods and services due to their ability to link ecosystem structure and function to human well-being. However, as highlighted in a recent review article (Liquete et al. 2013), 95% of the studies conducted to date have focused on the biophysical and/or economic aspects of ecosystem services. While this information is critical to informing management decisions, experience has shown that conflicts and disenchantment can arise when stakeholder values and the potential tradeoffs arising from differing values within and among stakeholder groups are not properly considered (Adams et al. 2003, McShane et al. 2011, Vira et al. 2012). As a result, the need for enhanced understanding of how different stakeholders perceive and depend upon ecosystem services has been identified as a critical research priority (Pereira et al. 2005, Carpenter et al. 2009, Barbier et al. 2011, Braat and de Groot 2012). The benefits of incorporating stakeholders' needs and values can lead to more balanced and equitable management decisions with greater levels of legitimacy and compliance (Menzel and Teng 2010). This is particularly relevant for the rural poor in developing countries who often disproportionately rely upon the natural environment for their sustenance and livelihoods.

Ecosystem services are “a wide range of conditions and processes through which natural ecosystems, and the species that are part of them, help sustain and fulfill human life” (Daily et al. 1997 p.2). The Millennium Ecosystem Assessment classifies ecosystem

services into four groups: regulating services (e.g., water purification/waste treatment, flood and drought mitigation); supporting services (e.g., habitat for terrestrial, riverine and estuarine flora and fauna, nursery function, nutrient cycling); provisioning services (e.g., food, fiber, fuel); and cultural services (e.g., recreation, tourism, education, aesthetics, and spiritual significance). Ecosystem goods emerge from the ecosystem provisioning services and are defined as “organisms and their parts and products that grow in the wild and ... are used directly for human benefits” (Daily et al. 1997 p.4). Examples of estuarine and riverine ecosystem goods include fish, vegetation for food and medicinal purposes, and timber for construction and fuel.

Empirical studies conducted to date have employed a number of different approaches to examine stakeholder perceptions of ecosystem services including i) recognition and identification; ii) rating; and iii) ranking perceived levels of importance. The first type of approach asks stakeholders to either answer “yes”, “no”, or “do not know” in response to whether a predefined set of ecosystem services are important (e.g., Sodhi et al. 2010), or to self-identify ecosystem services they deem as important (e.g., Hartter 2010). The second approach asks stakeholders to rate the importance of pre-defined ecosystem services using a Likert scale (i.e., 1 = low importance, 2 = important, and 3 = very important) (e.g., Rönnbäck et al. 2007, Warren-Rhodes 2011). The third approach asks stakeholders to either identify the three most important services overall (e.g., Iftekhhar and Takama 2008) or to distribute a fixed number of counters (e.g., marbles or pebbles) to rank numerous ecosystem services in relation to one another (e.g., Agbenyega et al. 2008, Brown et al. 2008, Adekola et al. 2012, Hicks

et al. 2013). A benefit of the third approach is that it requires the stakeholder to prioritize among a number of different ecosystem services. With the other approaches, a stakeholder could, in theory, state that everything is important/very important to their overall well-being, whereas in a ranking exercise they are forced to either pick their top three or distribute a finite number of counters among many services, providing insightful information on tradeoffs. The need for explicit and systematic assessments of tradeoffs has been identified by numerous researchers as imperative for more informed management decisions (Granek et al. 2010, McShane et al. 2011, Needles et al. 2013, Vira et al. 2012). Many studies have focused specifically on local residents value of ecosystem goods and services, but only a few have examined multiple stakeholder groups simultaneously to ascertain potential synergies and tradeoffs (e.g., Agbenyega et al. 2008, Martín-López et al. 2012, Hicks et al. 2013). Having multiple stakeholder groups rank the same set of ecosystem services provides a method for identifying mutual interests, as well as potential conflicts, which is critical in helping managers balance and reconcile multiple needs and values.

Tanzania, and Saadani National Park in particular, serve as an interesting setting for examining how different groups of stakeholders directly and indirectly use and value the ecosystem goods and services provided by a protected riverine and coastal area.

Approximately 32% (i.e., 304,836.55 km²) of Tanzania's land is protected, which is the second highest total area in Africa (WDPA 2013). These protected areas, which include national parks, games reserves and forest reserves, harbor high levels of biodiversity that attract thousands of tourists each year. Tourism has become one of Tanzania's

most important economic sectors, and from 2000 to 2010, the recorded number of international visitors to Tanzania rose 56% (Nelson 2012, MNRT 2012). Yet, despite Tanzania's wealth of biodiversity and increasing levels of tourism, it remains one of the world's 25 poorest countries (Global Finance 2013).

The Eastern Arc Mountains and Coastal Forests of Tanzania were identified as one of the world's biodiversity hotspots (i.e., "areas featuring exceptional concentrations of endemic species and experiencing exceptional loss of habitat" p. 853) in the Myers et al. seminal article published in *Nature* in 2000. This designation resulted in international NGOs such as Conservation International, World Wide Fund for Nature, and Birdlife International placing a very high priority on their conservation (Republic of Tanzania/UNDP/GEF, undated) augmenting earlier efforts by the Tanzanian government and western donors focused on conserving mangrove ecosystems that had been identified as undergoing rapid decline (Mangora 2011). Saadani National Park contains approximately 30 km² of coastal forest, which along with the Wami River, Estuary, and mangrove forests within the park were classified as exceptional resource values¹. Its location on the coast offers tourists the unique opportunity to enjoy traditional walking and driving wildlife safaris as well as a boat safari and time at the beach within one destination. Many communities surrounding the park have been established in the area for centuries (i.e., Saadani village is one of the oldest Swahili communities in East Africa), and rely heavily upon natural resources for their subsistence and livelihoods.

¹Exceptional resource values are defined as the "biophysical features of a national park that are assessed as being especially important to maintaining the unique ecological character and functions of the park and that provide outstanding social, economic and aesthetic benefits to local, national, and international stakeholders" (SANAPA 2009, p. 8).

Despite this dependence, the majority of biodiversity conservation efforts undertaken in Tanzania within the past fifty years have adopted a top-down approach with limited attention to local residents' needs and priorities (Mangora 2011, Sigalla 2013). Information is warranted on the perspectives and needs of poorer local residents since their dependence on goods and services from the natural environment may foster priorities that differ from those of international conservation organizations, and tourism operators catering to wealthy international tourists (Roe and Walpole 2010). The values of these different stakeholder groups can emerge from historical context as well as past, present, and future needs and interests (Dick et al. 2011). Here we describe a study conducted in the Wami River estuary river/estuarine complex of East Africa that is dominated by a protected national park and surrounded by villages with high levels of poverty.

We compare and contrast the use and perceptions of four different stakeholder groups (i.e., upstream residents living adjacent to the Wami River, downstream residents living adjacent to the Wami River Estuary and coast, tourism officials, and conservation organizations) regarding the value of ecosystem goods and services provided by the Wami River and its estuary, and determine what they perceive as the main threats to this system. This study seeks to address key information gaps identified by Sarmett and Anderson (2008) that can be useful for future management efforts within the Wami River Estuary.

Specifically, we examine the following research questions:

1. Is there a difference in the perceived value of the categories of ecosystem services within and between the stakeholder groups?
2. Which regulating, supporting, cultural and provisioning ecosystem services provided by the Wami River and its estuary are valued most and least among our targeted stakeholder groups?
3. How do the upstream and downstream residents utilize the Wami River and Estuary in their daily lives and which ecosystem goods are deemed most important for their subsistence and livelihoods?
4. What potential synergies and tensions may exist among these stakeholder groups with regard to the values placed on the ecosystem services?
5. What are the main concerns of these stakeholders regarding the future conditions of the Wami River and its estuary?

Site Description

Saadani National Park (SANAPA), Tanzania's only national park to bridge terrestrial and marine environments, is located approximately 80 km north of Dar es Salaam and 27 km west of Zanzibar within the Districts of Pangani and Bagamoyo (latitude 5° 20' - 6° 17'S; longitude 38° 45' - 39° 02'E) (Figure 1). Initially created as a 200 km² game reserve in 1969, following consultation with the elders in Saadani village and compensation for the loss of cultivated land incorporated into the reserve's boundary, it was expanded to 1,137 km² and upgraded to a national park in November 2005 (Baldus et al. 2001, SANAPA 2005, Baldus et al. 2007). The downstream reaches of the Wami River and

Estuary, which were not part of the initial reserve, were incorporated into SANAPA since the area was being subjected to high levels of mangrove cutting for charcoal production, firewood, and building materials (SANAPA 2005, Baldus et al. 2007, McNally et al. 2011). SANAPA protects a range of different habitats including acacia woodlands, open grasslands, coastal forests, riparian vegetation, mangroves, and coral reefs, and encompasses the final 20 kilometers of the Wami River and its estuary.

The Wami River and Estuary are keystones of the Saadani National Park ecosystem as their riparian and estuarine areas support riverine forests and mangrove stands that are extremely diverse both in floral and faunal species (Baldus et al. 2007, McNally et al. 2007, SANAPA 2009). The abundant and diverse bird population associated with the mangrove forests at the mouth of the Wami River Estuary is a major tourist attraction, and the Wami River and adjacent riparian vegetation provides important habitat for crocodiles (*Crocodylus niloticus*), hippopotami (*Hippopotamus amphibious*), and black and white colobus monkeys (*Colobus angolensis*). Moreover, since it is the only perennial river within SANAPA's boundaries, it serves as a critical source of drinking water for the terrestrial animals and residents during the dry season (Tobey 2008). Although the levels of ecotourism are still low in comparison to many of Tanzania's other national parks (SANAPA 2009), it is expected to continue to increase with improvements in transportation and park infrastructure.

SANAPA is surrounded by rural villages with persisting high poverty rates (Research and Analysis Working Group, 2005). Forty percent of the village inhabitants live below the poverty line, 89% do not have access to a piped or protected water source, and 94%

do not have electricity. Additionally, there is high population growth, high infant mortality rates (i.e., 105 deaths per 1000 births), low investment, and most households lack access to markets, credit, and insurance (Research and Analysis Working Group, 2005).

For the local stakeholders within this study, we focused on an upstream and downstream village that are in close proximity to the Wami River and its estuary. The upstream village of Matipwili is located approximately 20km upstream of the Wami River Estuary, and is bordered on the north and south by SANAPA and the Wami River, respectively. The village is comprised of six sub-villages with a total population of 2,149 (506 households), and the primary livelihoods for the residents are small scale agriculture and fishing (NBS 2012). The downstream village of Saadani village primarily has settlements located approximately 9km north of the Wami River Estuary, and is bordered on the north, south, and west by SANAPA and the Indian Ocean on the east. The village is comprised of 13 sub-villages with a total population of 1,433 individuals (444 households) (NBS 2012). Among the sub-villages of Saadani are Kajanjo, which is situated directly on the coast approximately 3km north of the Estuary's mouth, and the sub-village of Porokanya, which lies along the bank of the Estuary approximately 0.5km upstream of the mouth. Fishing is the main livelihood activity in Saadani, Kajajano and Porokanya. The other two stakeholder groups included the domestic and international hotel owners and tourism operators who bring tourists to SANAPA, as well as domestic and international conservation employees who either work within/around SANAPA or are familiar with the Wami River and Estuary ecosystems. The hotel owners and

tourism operators bringing visitors to SANAPA are located in the villages of Saadani, Matipwili, Mkwaja, and Ushongo, and the towns/cities of Bagamoyo, Stone Town, Pangani, Tanga, Lushoto, Moshi, Arusha and Dar es Salaam. The conservation employees who work within/around SANAPA or are familiar with the area are based in Saadani, Bagamoyo, Pangani, Tanga, Dar es Salaam and Zanzibar and represent organizations and agencies that include the World Wide Fund for Nature, the Wildlife Conservation Society, IUCN, the Tanga Coastal Zone Center, the Institute for Marine Sciences, etc. (Figure 1).

Methods

Our study employed a mixed methods approach comprised of face-to-face surveys and focus groups to gather extensive qualitative and quantitative data on the stakeholders use and perceived value of ecosystem goods and services, as well as their main concerns regarding future conditions of the Wami River and its estuary. The survey instrument included separate sections for ecosystem goods, ecosystem services, and stakeholder concerns while the focus group questions focused specifically on the types of ecosystem goods utilized by the local communities. The appropriateness and clarity of the focus group discussion and survey questions were evaluated in pilot testing with a community in Tanzania before commencing data collection.

Forty-one upstream community members (8% of the total households), 44 downstream community members (10% of the total households), 30 tourism operators, and 30 conservation organization employees completed the survey. Among the

downstream residents, twenty-two were randomly selected from the seven sub-villages located in the heart of Saadani, eleven were randomly selected from Kajanjo, and eleven were randomly selected from Porokanya. A total of nineteen focus group discussions were convened within upstream and downstream communities. The number of participants ranged from 3-10 individuals per focus group, and separate focus groups were convened for men and women. A total of 31 upstream (12 males, 19 females) and 47 downstream (33 males, 14 females) community members participated.

A stratified sampling strategy design was used to collect data on a random sample of upstream and downstream community members while a snowball technique was used to identify the tourism operators and conservation organization employees (Pollnac and Crawford 2000, Babbie and Benaquisto 2009). The focus group participants were selected with the assistance of key informants from each village to ensure that we were reaching a wide array of users. All of the focus group discussions were conducted in August 2009, and the survey data were collected between July 29 and September 19, 2009, by means of face-to-face interviews.

Prior to commencing data collection, the lead author conducted two days of thorough training with seven Tanzanian enumerators to ensure data quality control. The majority of the enumerators had previous survey experience in rural coastal communities. As a group, the enumerators and lead author went through each survey instrument question by question. In the event where there was either confusion over a scientific term or it was deemed that the survey respondent may need additional clarification to answer the question, a list of standard definitions, word for word

translations, and short explanations were created to assist the enumerators in relaying the identical information to all survey respondents. In addition to reviewing each survey question, the enumerators also practiced the survey instruments on one another with the most experienced enumerators paired with the least experienced enumerators. To further ensure quality control of the survey data, the lead author stayed in the field with the survey team throughout the data collection, reviewed the survey data collected by each enumerator each day to identify any issues with the data (i.e., missing data, incomplete responses, etc.) so that it could be corrected immediately, and held daily debriefing meetings with the field team.

The Tanzanian enumerators conducted the focus group discussions and community surveys while the main author along with one other enumerator from Tanzania conducted the tourism operator and conservation organization surveys. The interviews with the community members were conducted at the homes of the survey respondents in Swahili while the interviews with the tourism operators and conservation employees were conducted in English at their place of business. On average, the surveys took approximately 1 hour for the tourism officials and conservation employees to complete, and 1.5-2.5 hours for the residents to complete. The latter took longer due to the inclusion of the ecosystem goods section and a greater number of open-ended questions. The focus groups took 2 to 3.5 hours to complete depending upon the size of the group.

The ecosystem services and stakeholder concerns portions of the survey instrument were used for all of the stakeholder groups; the ecosystem goods section was only used

for the local residents in the upstream and downstream communities. The ecosystem services section adapted the methods developed by Agbenyega et al. (2008). Similar to their study, four tables were created, each corresponding to one of the Millennium Ecosystem Assessment ecosystem services categories (i.e., regulating, supporting, cultural, and provisioning). The specific services listed in each table were compiled from the literature drawing predominantly upon Daily et al. (1997), De Groot et al. (2002), Millennium Ecosystem Assessment (2005), Korsgaard (2006), and Agbenyega et al. (2008) (see Table 1 for a list of the specific ecosystem services included within each category). Although these prior studies included nutrient cycling and soil formation as separate types of supporting services, we used habitat as a catch all since the overall quality of the latter is affected by changes in the former (Twilley and Rivera-Monroy 2009). Within each ecosystem service category, each respondent was given 25 marbles (counters) and asked to allocate them among the list of specific ecosystem services provided by the Wami River and Estuary according to their personal perceptions of their relative importance. After completing this activity for each of the ecosystem categories, each respondent was then asked to consider the full suite of ecosystem services listed in each individual table together and allocate the 25 marbles (counters) according to their perceptions of the relative importance of each complete set in relation to the other sets (i.e., permitting comparisons among the four basic ecosystem categories).

Given that there were an unequal number of services within each category, we calculated an expected value (i.e., 25 divided by the total number of services within each category) to permit relative comparisons between the services of the different

categories. In addition, we drew attention to those services where the values fell either 50% above or below the expected values. The values assigned to each individual service by the different stakeholder groups were analyzed for differences with Kruskal-Wallis and Mann-Whitney U tests. For comparisons among the ecosystem service categories as a whole, Kruskal-Wallis and Mann-Whitney U tests were employed to examine whether statistically significant differences existed between the different stakeholder groups as well as within each individual stakeholder group. For all of the Mann-Whitney U results discussed in the text, we display the significance value (p values) as well as the effect size statistic, denoted by d , which estimates the magnitude of an effect and serves as a measure of practical significance (Nakagawa and Cuthill 2007). Values of $d < 0.3$ signify a small effect, ≥ 0.3 to < 0.5 signify a medium effect, and ≥ 0.5 signify a large effect (Cohen 1988).

In the main concerns section of the survey, each respondent was asked, “What do you see as possible problems for the Wami River and Wami River Estuary?” The responses were classified into different groups, and the overall percentages of each stakeholder group identifying the specific categories were calculated. Chi-Square tests for equality of proportions were employed to examine whether the perceived problems differed across the stakeholder groups and Cramer’s V were calculated to measure effect size. Values < 0.3 signify a small effect, ≥ 0.3 to < 0.5 signify a medium effect, and ≥ 0.5 signify a large effect (Gravetter and Wallnau 2004).

The ecosystem goods section, which was only given to the local residents, was designed to augment the information gathered in the focus group discussions, and

included questions to gather information on the most common activities conducted at the Wami River and Estuary, the sources of water for drinking, cooking, and bathing as well as the quantity of water collected per day. Each respondent was asked whether they visit the Wami River and Estuary, and if so, how often and for what purposes. The resulting data were analyzed with descriptive statistics.

The focus group discussions were convened for the local residents within upstream and downstream communities to gather specific information on the fish and crustacean species captured in the river and adjacent coastal waters for food and livelihoods as well as the specific mangrove and riparian species utilized for medicinal purposes, fuelwood, and building materials. Once the species lists were compiled, the focus group participants were asked to collectively rate each species overall importance on a scale of 1 (not very important) to 4 (very important).

Results

Stakeholders Perceptions of the Relative Importance of each Category of Ecosystem Services

The relative importance assigned to each of the ecosystem service categories by the stakeholder groups ranged from 17 to 37% (Figure 2). Looking across groups, the median value assigned to the entire set of provisioning services by the upstream and downstream residents was significantly higher than the median values assigned by the tourism officials ($p=0.008$, $d=0.32$ and $p=0.003$, $d=0.35$, respectively) and conservation employees ($p=0.017$, $d=0.29$ and $p=0.011$, $d=0.30$, respectively) (Table 2). The perceived level of importance for the supporting services was similar among the four stakeholder

groups while the upstream residents valued the regulating services significantly lower than the tourism officials ($p=0.016$, $d=0.29$) and conservation employees ($p=0.023$, $d=0.28$) (Table 2). Similarly, the upstream residents also valued the cultural services significantly lower than the tourism officials ($p=0.008$, $d=0.32$) and conservation employees ($p=0.011$, $d=0.31$) (Table 2).

Examining results within each stakeholder group, the upstream and downstream residents placed a significantly higher level of importance on provisioning ecosystem services than the other services ($p<0.0001$, d ranged from 0.40 to 0.63). Both groups of residents placed a significantly lower level of importance on the cultural ecosystem services ($p<0.05$, d ranged from 0.27 to 0.63) (Table 2). The tourism officials also perceived the cultural ecosystem services as significantly less valuable than provisioning ($p =0.006$, $d =0.37$) and regulating services ($p=0.012$, $d =0.34$) while the conservation employees assigned similar levels of importance to all four categories (Table 2).

Stakeholders Perceptions of the Relative Importance of the Individual Ecosystem Services within each Category²

Regulating Services

All four of the stakeholder groups surveyed in this study perceived erosion control as a valuable regulatory ecosystem service while the prevention of saltwater intrusion was not valued highly by any group (Table 3). In addition to erosion control, the

² Given that statistically significant differences between upstream and downstream residents were observed only for some of the specific provisioning services, the upstream and downstream residents were collapsed into one resident category for all of the other individual ecosystem services.

residents placed high value on the delivery of water and sediments to maintain nursery habitats and water purification. Similarly, tourism operators placed high value on water purification. Overall, the conservation employees distributed their counters more evenly among the regulatory services than the other stakeholder groups. The perceived importance of the Wami River and Estuary in maintaining nursery habitats was significantly higher for the residents and conservation employees than the tourism operators ($p < 0.0001$, $d = 0.43$ and $p = 0.003$, $d = 0.4$, respectively) (Table 3).

Supporting Services

At the group level, all four of the stakeholder groups surveyed perceived the existence of healthy ecosystems/habitat for wild plants and animals as the most valuable supporting service followed by plant and terrestrial animal conservation (Table 4). None of the stakeholder groups perceived refugium function as a particularly valuable service, and as seen within the regulating services, the tourism officials did not place a high value on nursery habitat. Although all of the stakeholder groups surveyed in this study identified habitat for wild plants and animals as the most valuable supporting service, the residents' median value was significantly higher than the conservation employees ($p = 0.011$, $d = 0.24$) and tourism operators ($p < 0.0001$, $d = 0.36$). The perceived importance of the Wami River and Estuary in riverine/estuarine animal conservation was significantly higher for the tourism and conservation employees than the residents ($p < 0.0001$, $d = 0.39$ and $p = 0.002$, $d = 0.29$, respectively).

Cultural Services

All four of the stakeholder groups surveyed in this study perceived tourism as a valuable cultural ecosystem service while spiritual fulfillment in connection with the Wami River and Estuary was not perceived as important by any of them (Table 5). The tourism officials placed the highest value on tourism while the conservation employees placed the highest value on the intrinsic value of biodiversity conservation. In both cases, the median values were 50% higher than the expected value. In addition to tourism, the residents placed high value on science and education as well as a significantly higher value on aesthetics than both the tourism officials ($p < 0.001$, $d = 0.36$) and conservation employees ($p = 0.015$, $d = 0.23$). The tourism officials perceived aesthetics as significantly less important than the conservation employees ($p = 0.043$, $d = 0.36$), but placed a significantly higher value on recreation than the conservation employees ($p = 0.008$, $d = 0.41$) and residents ($p = 0.001$, $d = 0.31$) (Table 5).

Provisioning Services

At the group level, all four of the stakeholder groups surveyed perceived domestic water as a very valuable provisioning ecosystem service as exemplified by median values twice as high as the expected value (Table 6). However, there were significant differences in the values placed on specific types of provisioning services based upon the residents' proximity to the freshwater and estuarine ecosystems within the Wami River and Estuary. The upstream residents placed a significantly higher value on flood recession agriculture than the downstream residents ($p = 0.001$, $d = 0.38$) while the downstream residents placed a significantly higher value on fish and shrimp for

subsistence and commercial fisheries than the upstream residents ($p=0.015$, $d=0.26$). While all stakeholder groups perceived traditional medicinal plants and inorganic raw materials as relatively unimportant, the downstream residents placed a significantly lower value on vegetable and fruit production than the other stakeholder groups ($p<0.05$, d ranged from 0.29 to 0.37). Furthermore, they also placed a significantly higher value on organic raw materials for building and handicrafts than the tourism officials ($p=0.014$, $d=0.29$) and conservation employees ($p=0.006$, $d=0.32$).

Ecosystem Goods

Given the significantly high value assigned to the provisioning ecosystem services by the upstream and downstream residents, we decided to further examine the reasons the local residents visit the Wami River and Estuary. There was substantial variability between subvillages in the extent of water collection for drinking and cooking that did not relate to their upstream or downstream locations, but appear to link to availability of alternative water sources. Several sub-villages (Matipwili, an upstream village, and Porokanya, a downstream village) obtain virtually all of their domestic needs from direct collection from the river. These villages have no alternative sources. Where alternative sources exist, 12 out of 33 surveyed households directly use the river for their major water needs. These estimates are conservative because residents often purchase water from peddlers who obtain water from local rivers. Additionally, during the dry season Wami River usage can expand due the loss of wells and drying of intermittent rivers. Of the residents gathering their own water, the average amount collected per visit for the residents ranged from 46L to 106L.

In addition to the important role that the Wami River serves in providing water for domestic uses, 38 out of 85 surveyed households within the sub-villages reported visiting the Wami River, estuary, and nearshore coastal waters for artisanal fishing. A total of 63 fish species were identified by the focus group participants as being caught for food with 42 of them (67%) rated as very important. The two downstream sub-villages located in closest proximity to the estuary had 13 of the 22 surveyed respondents visiting the river, estuary, and nearshore coastal waters for commercial fishing. A total of 29 fish species are harvested for income, and of those 16 (55%) were rated as very important. Interestingly, only two species (*Epinephelus coeruleopunctatus* (whitespotted grouper) and *Epinephelus tauvina* (greasy grouper)) were identified as very important sources of food and income. Visits to the Wami Estuary and nearshore coastal waters for shrimping were reported by 18 out of 44 surveyed downstream respondents with *Acetes erythraeus*, *Fenneropenaeus indicus*, *Penaeus monodon*, *Penaeus semisulcatus*, and *Periclimenes holthuisi* all rated as very important.

The upstream residents stressed the critical role the Wami River serves in their flood recession agriculture. Corn, rice, peas and potatoes were identified as the greatest sources of food and cash income. Millet was also identified as an important source of food while tomatoes are often grown for income. Residents also noted visiting the Wami River and Estuary to gather building materials and medicinal plants. Residents indicated that the most important mangrove species for building materials are *Avicennia marina*, *Bruguiera gymnorrhiza*, *Ceriops tagal*, *Rhizophora mucronata*, and *Xylocarpus granatum*, and the most important riparian species are *Grewia bicolor*,

Spirostachys africanas, *Olea europaea spp. africana*, and *Ficus sur*. Although the ranking of medicinal plants by upstream and downstream residents overall was quite low in comparison to some of the other provisional ecosystem services, it is important to note that the residents identified the fruit of *R. mucronata* and *X. granatum* as very important for treating a variety of medical ailments.

Main Concerns

Seventy-three percent of upstream and downstream residents identified declining fish populations as a prime concern regarding the future conditions of the Wami River and its estuary (Table 7). Fifty percent or more of the downstream residents also identified increasing salinity levels, declining shrimp populations, and the loss of mangroves as key concerns. The second most common concern voiced by the upstream residents was increasing human population, which was the most frequent concern identified by the conservation employees. Forty percent of the conservation employees also identified declining fish populations, increasing salinity levels, and the loss of mangroves as primary concerns. Additional water abstractions from the Wami River for upstream agriculture as well as proposed irrigation withdrawals for a biofuel project just upstream of the park boundary were causes of concern for at least one-third of the conservation employees and 29% of the upstream residents. In comparison to the other stakeholder groups, many of the tourism officials noted during the surveys that it was very difficult to predict foreseeable problems since they only visit the Wami River and Estuary on occasion.

Discussion

Synergies and Tensions among the Stakeholder Groups

As expected, the upstream and downstream residents placed a high priority on the provisioning services tightly linked to their sustenance and main sources of income. Likewise, the tourism officials highly valued tourism while the conservation employees assigned a high priority to intrinsic values. However, the results of our survey also revealed a good deal of consensus among the stakeholder groups in regards to specific ecosystem services deemed important and unimportant. Each of the stakeholder groups placed a high value on the provision of domestic water, habitat for wild plants and animals, tourism, and erosion control, and a relatively low value on the prevention of saltwater intrusion, refuge from predators, spiritual fulfillment, non-recreational hunting, the provision of traditional medications and inorganic materials for construction.

It is particularly noteworthy that the supply of domestic water from the Wami River was perceived as the most important provisioning service by the all the surveyed groups, even though $\frac{3}{4}$ of the downstream residents live in villages with some access to alternative sources of domestic water and the tourism trade and conservation employees do not use the Wami River for domestic water. This is a strong indication that all stakeholder groups are concerned about the welfare of those local residents who rely heavily on the Wami for such critical services. Flood recession agriculture, subsistence and commercial fisheries, vegetable and fruit production, and employment were all perceived as the next most valuable provisioning services by the tourism

officials and conservation employees. Although many of Tanzania's past biodiversity conservation efforts have not adequately taken into account the needs and values of local users, this recognition suggests that there may be growing awareness and appreciation. Roe and Walpole (2010) draw attention to the recent trend of many conservation organizations trying to expand their missions to also consider poverty alleviation and genuinely incorporate local communities. The local residents placed a high priority on habitat and tourism, and assigned similar priorities to nursery habitat and the conservation of riparian and mangrove flora and terrestrial fauna as the conservation employees. This combined with the overlap in many aforementioned provisioning services suggests that there is common ground among the groups that future management efforts within the Wami River and Estuary can build upon.

In addition to identifying potential areas of mutual interest, the results of our survey also highlighted possible tensions among the stakeholder groups that managers need to bear in mind and account for in future management efforts. While both the upstream and downstream residents concurred with conservation and tourism stakeholders on the importance of habitat, they placed a significantly lower value on intrinsic values (i.e., conserving an element of biodiversity for its own sake without the intention of using it) and conservation of riverine and estuarine fauna. Additionally, the downstream residents placed a significantly higher value on the provision of raw materials for building and handicrafts than the other groups. The results of our focus group discussions highlighted that they rely on a number of mangrove species for these materials (i.e., *A. marina*, *B. gymnorrhiza*, *C. tagal*, *R. mucronata*, and *X.granatum*).

However, if not managed properly, overharvesting could lead to tradeoffs with many of the other highly valued ecosystem services associated with mangroves (e.g., erosion control, coastal protection, habitat provision, aesthetics, tourism etc.).

The Prioritization of Ecosystem Services by Each Stakeholder Group

The high and low level of importance assigned by local residents to the categories of provisioning and cultural services as a whole, respectively, aligns with the results of other studies conducted in developing countries (Brown et al. 2008, Iftekhar and Takama 2008, Warren-Rhodes et al. 2011). To our surprise, the tourism officials placed a significantly lower value on cultural services as a whole than the groups of provisioning services and regulating services. This was unexpected since tourism, recreation, aesthetics, and intrinsic values all fall under the umbrella of cultural services. In contrast to the other stakeholder groups that placed a lower value on the cultural services as a whole, the conservation employees ranked all four of the ecosystem categories similarly. The more uniform distribution of the marbles (counters) among a suite of different ecosystem services by conservation practitioners is similar to the findings of Hicks et al. (2013). Their study, which asked fishermen, scientists, and managers living and working in Tanzania, Kenya, and Madagascar, to distribute counters between eight types of services (i.e., fishery, habitat, coastal protection, sanitation, tourism, education, cultural, and bequest), also found that managers were more inclined to assign similar levels of priority among an array of different types of services than local users and scientists.

The high priority placed on domestic water, flood recession agriculture, and subsistence and commercial fisheries by the residents underscores the vital role of these specific provisioning services to the subsistence and economic well-being of the residents living in close proximity to the Wami River and Estuary, and parallels the recognition, rating, and/or ranking assigned by local communities in comparable empirical studies (Rönnbäck et al. 2007, Brown et al. 2008, Iftekhhar and Takama 2008, Hussain et al. 2010, Sodhi et al. 2010, Vilarity et al. 2011, Adekola et al. 2012, Berbés-Blázquez 2012, Kari and Korhonen-Kurki 2013). The high priority placed on habitat for riverine and estuarine flora and fauna versus the low priority assigned to the conservation of riverine and estuarine fauna further suggests that the residents are very reliant upon the natural capital. This follows the pattern noted by Roe and Walpole (2010) in which poorer individuals tend to focus on the direct use values of biodiversity versus the sustained presence of threatened species. Interestingly, however, the residents placed significantly higher values on aesthetics than the tourism officials and conservation employees. The appreciation of the beauty of mangrove ecosystems by local residents and fishermen has been noted in other studies (e.g., Rönnbäck et al. 2007, Iftekhhar and Takama 2008, López-Medellín et al. 2011), but comparisons between urban and rural respondents have found that the former place greater value on aesthetics and the existence value of biodiversity (Martín-López et al. 2012).

The high priority given to the delivery of water and sediment to maintain nursery habitats is similar to the findings by Vilarity et al. (2011) and Warren-Rhodes (2011), and highlights the residents understanding of the nexus with the abiotic factors influencing

the composition and abundance of the fish and crustacean species they rely upon for their subsistence and livelihoods. An interesting disconnect, however, was the identification of increasing salinity levels as a main concern regarding the future conditions of the Wami River and its estuary by the residents and conservation employees juxtaposed against the very low levels of importance placed on the river's role in preventing the intrusion of saltwater upstream by all of the stakeholder groups. This, along with the low values assigned to the provision and maintenance of nursery habitats by tourism officials, exemplifies potential education outreach opportunities.

References

1. Adams, W.M., D. Brockington, J. Dyson, and B. Vira (2003) Managing Tragedies: Understanding Conflict over Common Pool Resources. *Science* 302: 1915–1916.
2. Adekola, O., S. Morardet, R. de Groot, and F. Grelot (2012) Contribution of Provisioning Services of the Ga-Mampa Wetland, South Africa, to Local Livelihoods. *International Journal of Biodiversity Science, Ecosystem Services & Management* 8(3): 248–264.
3. Agbenyega, O., P.J. Burgess, M. Cook, and J. Morris (2008) Application of an Ecosystem Function Framework to Perceptions of Community Woodlands. *Land Use Policy* 26(3): 551–557.
4. Babbie, E.R., and L. Benaquisto (2009) Fundamentals of Social Research. Second Canadian Edition. Toronto, Canada: Nelson Education Ltd.
5. Baldus, R.D., V. Beddoe, and J. Jafferji (2007) Saadani National Park. Zanzibar: Gallery Publications.
6. Baldus, R.D., K. Roettcher, and D. Broska (2001) Saadani: An Introduction to Tanzania's Future 13th National Park. Dar es Salaam, Tanzania: GTZ Wildlife Programme in Tanzania.
7. Barbier, E.B., S.D. Hacker, C. Kennedy, et al. (2011) The Value of Estuarine and Coastal Ecosystem Services. *Ecological Monographs* 81(2): 169–193.
8. Berbés-Blázquez, M. (2012) A Participatory Assessment of Ecosystem Services and Human Wellbeing in Rural Costa Rica Using Photo-Voice. *Environmental Management* 49(4): 862–875.
9. Braat, L.C., and R. de Groot (2012) The Ecosystem Services Agenda: Bridging the Worlds of Natural Science and Economics, Conservation and Development, and Public and Private Policy. *Ecosystem Services* 1(1): 4–15.
10. Brown, K., T. Daw, S. Rosendo, M. Bunce, and N. Cherrett (2008) Ecosystem Services for Poverty Alleviation: Marine & Coastal Situational Analysis.
11. Carpenter, S.R., H.A. Mooney, J. Agard, et al. (2009) Science for Managing Ecosystem Services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences* 106(5): 1305–1312.

12. Cohen, J.W. (1988) *Statistical Power Analysis for the Behavioral Sciences*. 2nd edn. Hillsdale, NJ: Lawrence Erlbaum Associates.
13. Daily, G.C., and et al (1997) Ecosystem Services: Benefits Supplied to Human Societies by Natural Ecosystems. *Issues in Ecology* 2: 1–16.
14. De Groot, R.S., M.A. Wilson, and R.M.J Boumans (2002) A Typology for the Classification, Description and Valuation of Ecosystem Functions, Goods and Services. *Ecological Economics* 41(3): 393–408.
15. Dick, J.M., R.I. Smith, and E.M Scott (2011) Ecosystem Services and Associated Concepts. *Environmetrics* 22(5): 598–607.
16. Granek, E.F., S. Polasky, C.V. Kappel, et al. (2010) Ecosystem Services as a Common Language for Coastal Ecosystem-Based Management. *Conservation Biology* 24(1): 207–216.
17. Gravetter, F.J., and L.B. Wallnau (2004) *Statistics for the Behavioral Sciences*. 6th edn. Belmont, CA: Wadsworth.
18. Hartter, J. (2010) Resource Use and Ecosystem Services in a Forest Park Landscape. *Society & Natural Resources* 23(3): 207–223.
19. Hicks, C.C., N.A.J. Graham, and J.E. Cinner (2013) Synergies and Tradeoffs in How Managers, Scientists, and Fishers Value Coral Reef Ecosystem Services. *Global Environmental Change* 23(6): 1444-1453.
20. Hussain, S.A., and R. Badola (2010) Valuing Mangrove Benefits: Contribution of Mangrove Forests to Local Livelihoods in Bhitarkanika Conservation Area, East Coast of India. *Wetlands Ecology and Management* 18(3): 321–331.
21. Iftekhar, M.S., and T. Takama (2008) Perceptions of Biodiversity, Environmental Services, and Conservation of Planted Mangroves: A Case Study on Nijhum Dwip Island, Bangladesh. *Wetlands Ecology and Management* 16(2): 119–137.
22. Kari, S., and K. Korhonen-Kurki (2013) Framing Local Outcomes of Biodiversity Conservation through Ecosystem Services: A Case Study from Ranomafana, Madagascar. *Ecosystem Services* 3: 32–39.

23. Korsgaard, L. (2006) Environmental Flows in Integrated Water Resources Management: Linking Flows, Services and Values. Lyngby, Denmark: Institute of Environment and Resources, Technical University of Denmark.
24. Liqueste, C., C. Piroddi, E.G. Drakou, et al. (2013) Current Status and Future Prospects for the Assessment of Marine and Coastal Ecosystem Services: A Systematic Review. *PLoS ONE* 8(7): e67737.
25. López-Medellín, X., A. Castillo, and E. Ezcurra (2011) Contrasting Perspectives on Mangroves in Arid Northwestern Mexico: Implications for Integrated Coastal Management. *Ocean & Coastal Management* 54(4): 318–329.
26. Mangora, M.M. (2011) Poverty and Institutional Management Stand-off: A Restoration and Conservation Dilemma for Mangrove Forests of Tanzania. *Wetlands Ecology and Management* 19(6): 533–543.
27. Martín-López, B., I. Iniesta-Arandia, M. García-Llorente, et al. (2012) Uncovering Ecosystem Service Bundles through Social Preferences. Kamal Bawa, ed. *PLoS ONE* 7(6): e38970.
28. McNally, C.G., E. Uchida, and A.J. Gold (2011) The Effect of a Protected Area on the Tradeoffs between Short-Run and Long-Run Benefits from Mangrove Ecosystems. *Proceedings of the National Academy of Sciences* 108(34): 13945–13950.
29. McShane, T.O., P.D. Hirsch, T.C. Trung, et al. (2011) Hard Choices: Making Trade-Offs between Biodiversity Conservation and Human Well-Being. *Biological Conservation* 144(3): 966–972.
30. Menzel, S., and J. Teng (2010) Ecosystem Services as a Stakeholder-Driven Concept for Conservation Science: Participative Ecosystem Services. *Conservation Biology* 24(3): 907–909.
31. Millenium Ecosystem Assessment (2005) Ecosystems and Human Well-Being: Wetlands and Water Synthesis. Washington DC: World Resources Institute.
32. MNRT (2012) Tourism Statistical Bulletin 1995-2010. Ministry of Natural Resources and Tourism, Tourism Division.

33. Myers, N., R.A. Mittermeier, C.G. Mittermeier, G.A.B Da Fonseca, and J. Kent (2000) Biodiversity Hotspots for Conservation Priorities. *Nature* 403(6772): 853–858.
34. Nakagawa, S., and I.C. Cuthill (2007) Effect Size, Confidence Interval and Statistical Significance: A Practical Guide for Biologists. *Biological Reviews* 82(4): 591–605.
35. Needles, L. A., S.E. Lester, R. Ambrose, et al. (2013) Managing Bay and Estuarine Ecosystems for Multiple Services. *Estuaries and Coasts*
36. Nelson, F. (2012) Blessing or Curse? The Political Economy of Tourism Development in Tanzania. *Journal of Sustainable Tourism* 20(3): 359–375.
37. Pereira, E., C. Queiroz, H.M. Pereira, and L. Vicente (2005) Ecosystem Services and Human Well-Being: A Participatory Study in a Mountain Community in Portugal. *Ecology and Society* 10(2): 14.
38. Pollnac, R.B., and B.R. Crawford (2000) Assessing Behavioral Aspects of Coastal Resource Use. Narragansett, RI: Coastal Resources Center, University of Rhode Island.
39. Republic of Tanzania, United Nations Development Programme, and Global Environment Facility undated. Extending the Coastal Forest Protected Area Subsystem in Tanzania.
40. Research and Analysis Working Group (2005) Poverty and Human Development Report. Dar es Salaam: Mkuki na Nyota Publishers.
41. Roe, D., and M.J. Walpole (2010) Whose Value Counts? Trade-Offs between Biodiversity Conservation and Poverty Reduction. In *Trade-Offs in Conservation: Deciding What to Save*. N. Leader-Williams, W.M. Adams, and R.J. Smith, eds. pp. 157–174. Conservation Science and Practice Series, No. 8. Oxford: Wiley-Blackwell.
42. Rönnbäck, P., B. Crona, and L. Ingwall (2007) The Return of Ecosystem Goods and Services in Replanted Mangrove Forests: Perspectives from Local Communities in Kenya. *Environmental Conservation* 34(4):313-324.
43. SANAPA (2005) Saadani National Park Management Zone Plan.

44. SANAPA (2009) Saadani National Park General Management Plan.
45. Sarmett, J., and E.P. Anderson (2008) Wami River Initial Environmental Flow Assessment Synthesis Report. Coastal Resources Center, University of Rhode Island, Wami Ruvu Water Basin Office, and Florida International University.
46. Sigalla, H.L. (2013) Trade-Offs between Wildlife Conservation and Local Livelihood: Evidence from Tanzania. *African Review* 40(1): 155–178.
47. Sodhi, N.S., T.M. Lee, C.H. Sekercioglu, et al. (2010) Local People Value Environmental Services Provided by Forested Parks. *Biodiversity and Conservation* 19(4): 1175–1188.
48. Tobey, J. (2008) A Profile of the Wami River Sub-Basin. Coastal Resources Center, University of Rhode Island.
49. Twilley, R.R., and V.H. Rivera-Monroy (2009) Ecogeomorphic Models of Nutrient Biogeochemistry for Mangrove Wetlands in Coastal Wetlands: An Integrated Ecosystem Approach. Elsevier, Amsterdam: 641–683.
50. Vilarity, S.P., J.A. González, B. Martín-López, and C. Montes (2011) Relationships between Hydrological Regime and Ecosystem Services Supply in a Caribbean Coastal Wetland: A Social-Ecological Approach. *Hydrological Sciences Journal* 56(8): 1423–1435.
51. Vira, B., B. Adams, C. Agarwal, et al. (2012) Negotiating Trade-Offs. *Economic & Political Weekly* 47(9): 67.
52. Warren-Rhodes, K., A. Schwarz, L.N. Boyle, et al. (2011) Mangrove Ecosystem Services and the Potential for Carbon Revenue Programmes in Solomon Islands. *Environmental Conservation* 38(04): 485–496.

Table 1: Ecosystem Services the Survey Respondents were Asked to Rank

Ecosystem Service Category	Ecosystem Services
Regulating	Water Purification (clean water) Flood mitigation (water retention capacity) Minimizing drought Erosion control/stabilization of land by vegetation Coastal protection of beach and coastlines from storm surges, waves, and floods Prevention of saltwater intrusion Delivery of water and sediments to maintain nursery areas
Supporting	Habitat for wild riverine and estuarine plant animal species (e.g., fish, hippos, migratory birds, etc.) Plant conservation (riparian and mangrove species) Riverine/estuarine species conservation Terrestrial species conservation (drinking water provided by the river during the dry season) Nursery habitats (i.e., places/locations for food and protection for juveniles) Refugium function (i.e., places/locations that provide shelter and protection for animals from their predators)
Cultural	Recreation Tourism Intrinsic value Spiritual and inspirational information (religious significance/spiritual-sacred sites) Aesthetic (appreciation of natural features) Science and education (opportunities for formal and informal education and training) Historic information
Provisioning	Water for domestic uses (drinking, cooking, bathing) Fish/shrimp for subsistence and commercial fisheries Fertile land for flood-recession agriculture and grazing Wildlife for hunting (non-recreational) Vegetables and fruit production Fiber/organic raw material for building/handicrafts Fuelwood/charcoal production Traditional medicinal plants Inorganic raw materials for construction (gravel, sand, clay) Employment

Table 2. Relative importance of overall categories of ecosystem services provided by the Wami River and Estuary as perceived by 41 upstream residents, 44 downstream residents, 28 tourism operators, and 26 conservation employees.

The survey respondents distributed 25 marbles among the four categories.

Ecosystem Services Categories	Residents		Tourism	Conservation
	Upstream (n=41)	Downstream (n=44)	Officials (n=28)	Employees (n=26)
	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Regulating Services	^b 5 ^z (3)	^b 6 ^{y,z} (2)	^a 6.25 ^y (1.75)	6 ^y (3)
Supporting Services	^b 6 (2)	^b 6 (2.75)	^{a,b} 6 (2)	5 (3.25)
Cultural Services	^c 4 ^z (2.5)	^c 4 ^{y,z} (3)	^b 5 ^y (1)	5.5 ^y (3.25)
Provisioning Services	^a 8 ^y (5.5)	^a 8.15 ^y (3.75)	^a 7 ^z (2)	7 ^z (2)

Significant at <0.05. The letters a, b and c are used to connote differences within stakeholder groups (looking down a column) and letters y and z are used to connote differences between stakeholder groups (looking across a column).

Table 3. Relative importance of regulating ecosystem services provided by the Wami River and Estuary as perceived by 85 local residents, 28 tourism operators, and 26 conservation employees.

The survey respondents distributed 25 marbles among 7 regulation ES (expected value = 3.6).

The values in the table are median (interquartile range).

Regulation Ecosystem Services	Residents (n=85)	Tourism (n=28)	Conservation (n=26)
	Median (IQR)	Median (IQR)	Median (IQR)
Water purification	4 (3)	5 (3)	3.7 (3)
Flood mitigation	3 (3)	3 (1)	3 (2)
Drought minimization	3 (4)	3 (2.5)	4 (4)
Erosion control	4 (2)	4 (2)	4 (2)
Coastal Protection	3 (3)	3 (3.5)	3.7 (3)
Prevention of saltwater intrusion	2 (4)	3 (2.5)	2 (1)
Maintenance of nursery habitats	5 ^a (3)	3 ^{b**} (2)	4 ^a (2)

Kruskal-Wallis and Mann-Whitney U tests were conducted. Statistical differences between group values with rows that have a different letter are significantly different based on **: p<0.01.

Table 4. Relative importance of supporting ecosystem services provided by the Wami River and Estuary as perceived by 85 local residents, 28 tourism operators, and 26 conservation employees.

The survey respondents distributed 25 marbles among 6 regulation ES (expected value = 4.2).

The values in the table are median (interquartile range). Those in bold and italics denote values 50% higher and lower, respectively, than the expected value.

Habitat Ecosystem Services	Residents (n=85)	Tourism (n=28)	Conservation (n=26)
	Median (IQR)	Median (IQR)	Median (IQR)
Habitat for wild plants and animals	8^{a*} (2)	6 ^b (1.5)	6 ^b (4)
Nursery habitat	4 ^{a*} (2)	3 ^b (1)	4 ^{a,b} (2)
Refuge from predators	2.1 (3)	3 (2)	3 (3)
Plant conservation (riparian/mangrove spp.)	4 (2)	4 (0.5)	4 (2)
Riverine/estuarine animal conservation	3 ^{b**} (3)	4 ^a (2)	4 ^a (2)
Terrestrial animal conservation (drinking water)	4 (2.5)	4 (2)	4 (2)

Kruskal-Wallis and Mann-Whitney U tests were conducted. Statistical differences between group values with rows that have a different letter are significantly different based on *: $p < 0.05$, **: $p < 0.01$.

Table 5. Relative importance of cultural ecosystem services provided by the Wami River and Estuary as perceived by 85 local residents, 28 tourism operators, and 26 conservation employees.

The survey respondents distributed 25 marbles among 7 cultural ES (expected value = 3.6). The values in the table are median (interquartile range). Those in bold denote values 50% higher than the expected value.

Cultural Ecosystem Services	Residents (n=85) Median (IQR)	Tourism (n=28) Median (IQR)	Conservation (n=26) Median (IQR)
Intrinsic value	3 ^{c*} (2.5)	4 ^{b*} (2)	6^{a*} (3)
Aesthetics	4 ^{a*} (2.5)	2 ^{c*} (3.5)	3 ^{b*} (2)
Spiritual fulfillment	2 (4)	2 (2)	2 (3)
Tourism	5 ^b (3)	6^{a*} (2.5)	5 ^{a,b} (2)
Recreation	2 ^b (4)	4 ^{a**} (2.5)	3 ^b (2)
Science and education	5 ^{a*} (3)	4 ^b (2.5)	4 ^{a,b} (2)
Historic information	3(2.5)	3(2)	3(3)

Kruskal-Wallis and Mann-Whitney U tests were conducted. Statistical differences between group values with rows that have a different letter are significantly different based on *: $p < 0.05$, **: $p < 0.01$ and *** $p < 0.001$.

Table 6. Relative importance of provisioning ecosystem services provided by the Wami River and Estuary as perceived by 41 upstream residents, 44 downstream residents, 28 tourism operators, and 26 conservation employees.

The survey respondents distributed 25 marbles among 7 regulation ES (expected value = 2.5).

The values in the table are median (interquartile range). Those in bold and italics denote values 50% higher and lower, respectively, than the expected value.

Provisioning Ecosystem Services	Residents		Tourism	Conservation
	Upstream (n=41)	Downstream (n=44)	Officials (n=28)	Employees (n=26)
	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Domestic water	5 (2)	5 (2)	5 (2)	5 (2)
Subsistence/commercial fisheries	3 ^b (2.5)	4^{a*} (3.75)	3 ^b (2)	3 ^{a,b} (1)
Flood recession agriculture	4^a (2)	2.5 ^{b**} (3)	4^a (2)	3 ^{a,b} (1)
Non-recreational hunting	0 (2)	2 (3)	2 (3)	<i>1</i> (2)
Fruit production	3 ^a (1.5)	1.5 ^{b*} (3)	3 ^a (1.5)	3 ^a (2)
Traditional medicinal plants	<i>1</i> (2)	<i>1</i> (2)	<i>1</i> (2)	<i>1</i> (2)
Fuelwood/charcoal	2 (3)	1.5 (3)	<i>1</i> (2)	<i>1</i> (2)
Organic raw materials for building and handicrafts	2 ^{a,b} (3)	2.45 ^{a*} (1.75)	<i>1^b</i> (1.5)	<i>1^b</i> (2)
Inorganic raw materials for construction	<i>1</i> (2)	<i>1</i> (2)	2 (1)	<i>1</i> (2)
Employment	2 (2)	2 (4.75)	3 (1)	3 (1)

Kruskal-Wallis and Mann-Whitney U tests were conducted. Statistical differences between group values with rows that have a different letter are significantly different based on *: $p < 0.05$, **: $p < 0.01$.

Table 7. Main Concerns of Each Stakeholder Group Regarding the Future Conditions of the Wami River and Estuary.

Stakeholders' Main Concerns	Stakeholder Group				χ^2 (3, 145) (Cramer's V)
	Upstream Residents (n=44) (%)	Downstream Residents (n=41) (%)	Tourism Officials (n=30) (%)	Conservation Employees (n=30) (%)	
Decline in Fish	73.2	72.7	13.3	40	34.59, p < 0.0001 (0.488 ^b)
Decline in Shrimp	39	59.1	3.3	36.7	23.81, p < 0.0001, (0.405 ^b)
Increasing Salinity	46.3	63.6	16.7	40	16.26, p = 0.001 (0.335 ^b)
Increasing Human Population	51.2	38.6	13.3	46.7	11.66, p = 0.009, (0.284 ^a)
Loss of Mangroves	34.1	50	13.3	40	10.72, p = 0.013, (0.272 ^a)
Water Abstractions for Biofuel production	29.3	13.6	10	33.3	7.95, p = 0.047, (0.234 ^a)
Water Abstractions for Domestic Use	29.3	15.9	10	16.7	4.83, p = 0.185, (0.182)
Water Abstractions for Upstream Agriculture	29.3	15.9	13.3	36.7	6.8, p = 0.079, (0.217)
Other	39	15.9	30	46.7	9.22, p = 0.026, (0.252 ^a)

^a small effect size, ^b medium effect size



Figure 1. Study Sites

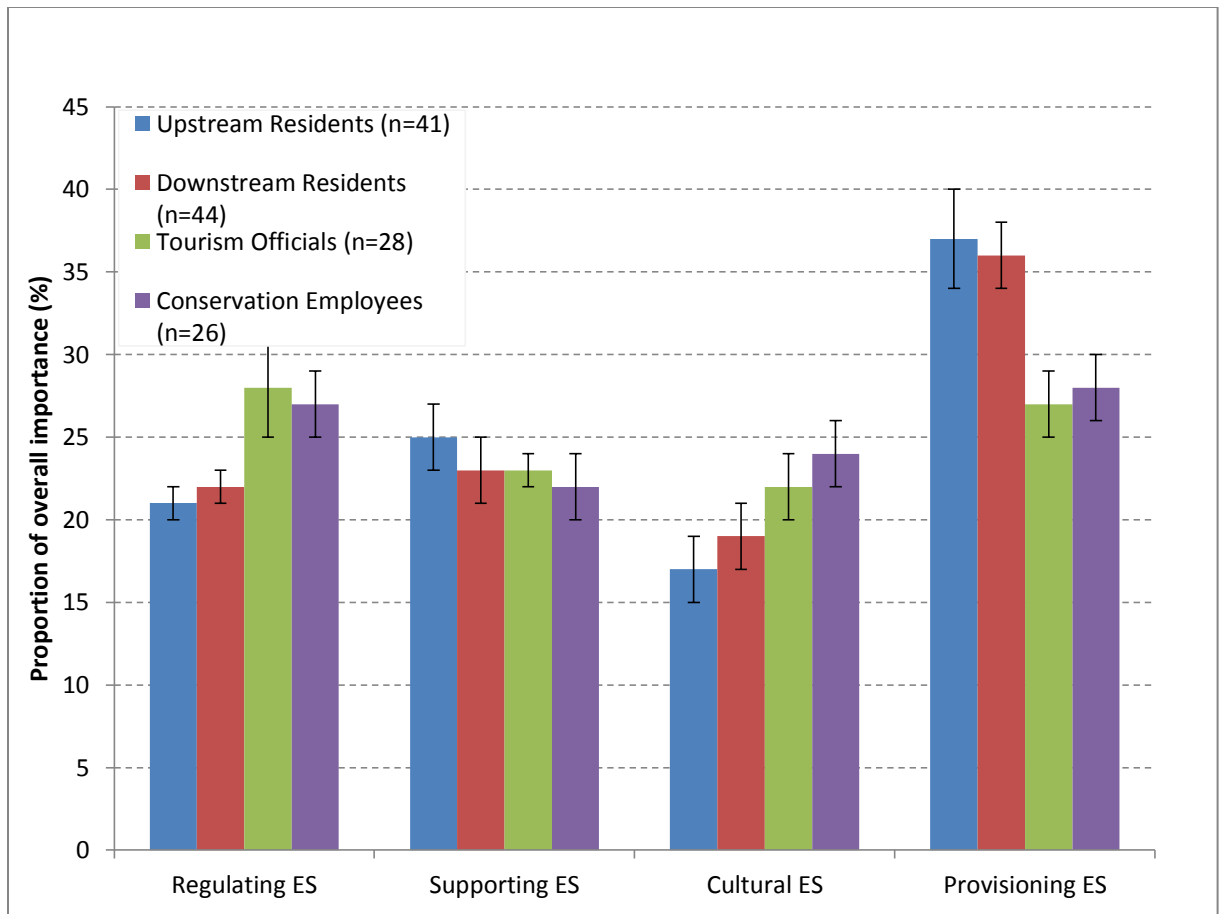


Figure 2. Relative Valuation Assigned to each Category of Ecosystem Services by Residents, Tourism, and Conservation Stakeholders

The Effect of a Protected Area on the Tradeoffs Between Short-run and Long-run Benefits from Mangrove Ecosystems

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*Published in the journal Proceedings of the National Academy of Sciences
Volume 108, Number 34, pages 13945-13950, 2011*

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Abstract

Protected areas are used to sustain biodiversity and ecosystem services. However, protected areas can create tradeoffs spatially and temporally among ecosystem services, which can affect the welfare of dependent local communities. This study examines the effect of a protected area on the tradeoff between two extractive ecosystem services from mangrove forests: cutting mangroves (fuelwood) and harvesting the shrimp and fish that thrive if mangroves are not cut. We demonstrate the effect in the context of Saadani National Park (SANAPA) in Tanzania, where enforcement of prohibition of mangrove harvesting was strengthened to preserve biodiversity. Remote sensing data of mangrove cover over time are integrated with georeferenced household survey data in an econometric framework to identify the causal effect of mangrove protection on income components directly linked to mangrove ecosystem services. Our findings suggest that many households experienced an immediate loss in the consumption of mangrove firewood with the loss most prevalent in richer households. However, all wealth classes appear to benefit from long-term sustainability gains in shrimping and fishing that result from mangrove protection. On average, we find that a 10% increase in the mangrove cover within SANAPA boundaries in a 5-km² radius of the subvillage increases shrimping income by approximately twofold. The creation of SANAPA shifted the future trajectory of the area from one in which mangroves were experiencing uncontrolled cutting to one in which mangrove conservation is providing gains in income for the local villages as a result of the preservation of nursery habitat and biodiversity.

Introduction

Mangrove forests comprise only 0.12% of the world's total land area, but are highly productive ecosystems that underpin a major portion of the world's fisheries (1,2). Mangroves thrive where many other species cannot survive, and are important habitat for associated flora and aquatic and terrestrial fauna (1,3-5), with more than 1,500 faunal species inhabiting mangroves in the Indo-Malaysian region (3,4).

Many coastal communities in developing countries, especially the rural poor, rely upon extraction of mangrove forests for their subsistence and livelihoods (6-7). Overexploitation for fuelwood, charcoal, and timber production has degraded more than one quarter of the world's mangrove habitats (8). The direct harvest of mangroves not only affects biodiversity levels and species interactions, but also causes physical changes that can cause propagules and saplings to be washed away with the retreating tides. Mangrove extraction adversely impacts nursery habitat for fish and shrimp vital to the subsistence and livelihoods of coastal communities. Approximately 80% of worldwide fish catches are estimated to depend directly or indirectly on mangroves (9), and almost 100% of the shrimp catch in the Association of Southeast Asian Nations (ASEAN) countries depend upon mangroves for at least part of their life cycle (10). Penaeid shrimp production decreases precipitously as the remaining mangrove area is reduced (11).

The rapid destruction of mangrove forests has spawned a host of protected areas across the world. However, given the reliance of many local communities on mangrove forests for fuelwood, charcoal, and other uses from harvested mangroves,

protection efforts that sustain the long-term viability of these ecosystems – including their value for fisheries – could pose an immediate threat to livelihoods of the rural poor. Without some mechanism to compensate the affected households, protected areas can place them in a poverty trap, i.e., a mechanism that causes poverty to persist (12). However, if protected areas can enhance long-run livelihood opportunities for the poor, they can potentially be a win-win solution for conservation and poverty alleviation. This question underlies the literature in integrated conservation and development projects and their variants, which are recent efforts to conserve biodiversity and alleviate poverty together (13-15). However, there has been little empirical evidence of successful delivery of both goals (16).

This article demonstrates that improvements in mangrove ecosystems that result from a protected area have resulted in tangible improvements in incomes for the poor. The impact of protected areas on the natural resources and the local communities' livelihood, and the variation of the impact among households in different wealth groups remain largely unexplored (17-19). Protected areas often create tradeoffs among multiple ecosystem services, making it challenging to quantify and assess the linkage between the human and natural systems. Previous studies do not show strong linkages between changes in natural resources and use patterns at the household level. In the context of mangrove conservation, although previous studies linked variations in mangrove areas to potential benefits from fisheries (e.g., refs. 20-23), they do not observe actual changes in mangroves and their effects on tangible benefits in the form of income or consumption. Moreover, most studies do not clearly identify the causal

link between protected areas and poverty because they fail to use direct measures of well-being and fail to control for potential confounding effects of baseline characteristics (17,18). Protected areas in developing countries are often established in remote areas with high poverty rates and few alternative livelihood strategies (24). To identify whether protected areas create tradeoffs among different benefits from mangrove forests, the appropriate comparison would be between households living near protected areas and households with similar characteristics and trends that are not affected by protected areas (18).

The overall goal of this study is to assess the environmental and economic impacts of a major mangrove protection effort undertaken to preserve biodiversity in Saadani National Park (SANAPA) in Tanzania. This region has mangrove forests, which sustain a rich biodiversity, but the local communities suffer from persisting poverty. Specifically, we examine the effect of strengthened enforcement of prohibition of mangrove harvesting in the protected area on the tradeoff between short-term benefits from cutting mangroves and long-term benefits from harvesting the fish and shrimp that thrive if mangroves are not cut, and whether households fell in a poverty trap as a result. There are several mechanisms through which SANAPA can affect the livelihoods of the local households. First, after the establishment of SANAPA, they are prohibited from harvesting mangroves for fuelwood and other uses. Second, there are penalties imposed for infringing within the park boundaries. Third, park protection and monitoring of mangroves increase the mangrove cover, causing recovery of shrimp and fish populations, and hence increasing incomes from shrimping and fishing activities.

Finally, there are opportunities for new non-agricultural employment (largely with SANAPA). The first two impose negative effects on villagers and the last two generate positive gains, at least for those who fish or shrimp or attain jobs with the park service.

To meet these objectives, we coupled geospatial and georeferenced household survey data to examine local changes in mangrove cover and socioeconomic impacts of SANAPA. In an effort to overcome some of the previous limitations in protected areas and poverty studies, we assessed the components of income that are directly linked to ecosystem services from mangrove forests. We also used econometric techniques to explore causal linkages between mangrove protection and poverty. In addition, we extended the model to understand how the establishment of the protected area affected households from the three wealth segments (poorer, middle, richer), which were defined based on the total value per capita of productive and consumable asset levels in 2004.

Site Description and Mangrove Protection Efforts

SANAPA, Tanzania's only coastal national park, is located approximately 80 km north of Dar es Salaam and 27 km west of Zanzibar within the Districts of Pangani and Bagamoyo (latitude 5° 20' - 6° 17'S; longitude 38° 45' - 39° 02'E). It was established in 2005, and spans across 1100 km² (Fig. 1a) (25,26). It protects a range of different habitats, including coastal forests, mangroves, and coral reefs, and encompasses the Wami River Estuary, a critical habitat for many species of fish, shrimp, and birds (25). The Estuary provides extensive lengths of mangrove-lined habitat edge, where juvenile shrimp have access to the mangroves. This type of configuration has been shown to be a

more important indicator of shrimp densities, as there is a direct relationship between length of mangrove-lined habitat edge and density of juvenile shrimp (27). Also, the abundant and diverse bird population associated with these mangrove forests are a draw for ecotourism.

Before the establishment of the park, very high levels of mangrove cutting for charcoal production, firewood, and building materials threatened both the local artisanal fisheries and the biodiversity of the area (7, 25, 26). This rapid degradation of mangrove forests was in part caused by weak property rights and enforcement (28). Between 1995 and 2005, the total mangrove area within the current park boundaries decreased by 27% (Table 1). The creation of SANAPA prohibited the consumptive use of all mangrove resources within the park's boundaries (26). Authority vested to SANAPA enforcement personnel allows them to arrest and fine any individuals caught harvesting mangroves. The penalties are strict: imprisonment for 3-5 years and fines of 50,000 Tanzanian Shillings (Tsh approximately \$34). Park personnel actively enforce any charcoal-related activity in the general vicinity of SANAPA, and will stop and arrest crews that are transporting charcoal between the mainland and Zanzibar. Based on our interviews with SANAPA enforcement officials, approximately sixty individuals were fined and/or arrested between 2005 and 2010. Based on surveys with numerous village residents, it appears that enforcement of the ban on mangrove fuelwood harvest occurs beyond park boundaries; many villagers are now afraid to harvest mangroves from areas within and surrounding SANAPA. In addition to enhanced enforcement, some

collaborative community mangrove forest management initiatives outside of SANAPA's boundaries, but within our study area, commenced in the mid-1990s (29).

SANAPA is surrounded by rural villages with persisting high poverty rates (7, 30). In Bagamoyo district, 40% of the village inhabitants lived below the poverty line in 2000. The region lacks basic needs (89% do not have access to a piped or protected water source and 94% do not have electricity) and suffers from one of the highest infant mortality rates in Tanzania. Additionally, there is high population growth [i.e., total population increased on average by more than 2% per year between 1998 and 2009 (7, 31)] and low investment, and most households lack access to credit and insurance markets. The rural poor living in the vicinity of SANAPA largely depend on and earn their livings from natural resources, and their livelihoods are tightly linked to the ecosystem services provided by the mangrove forests. For example, focus groups conducted in our study area revealed that, for many households, shrimping and fishing were the only lucrative income activities, and in some areas, mangroves are still the only fuel source.

Results

Changes in Mangrove Cove. The loss of mangroves within SANAPA slowed considerably following the park's establishment in 2005 (Fig. 1c and Table 1). The mean loss from 1990 to 2005 was 27.3 ha/yr, versus 1.8 ha/yr from 2005 to 2010. The rate of harvest also decreased outside of the park's boundaries, and a mean regrowth of 11.9 ha/yr was observed. Four additional mangrove patches were observed within the park's boundaries in 2010, whereas no additional patches were observed during that time period outside of the park's boundaries. Loss caused by natural events may have

contributed to the changes observed, but we note that there were no tropical cyclones in the study region between 1990 and 2010 (32, 33).

Although we have clear evidence that management practices are protecting and enhancing mangrove cover within SANAPA, more site specific data on improvements in biodiversity and the response of dependent fauna within the Wami River Estuary will require concentrated monitoring efforts (*SI Published Literature Table S1*).

Changes in Mangrove Use for Fuel Source. The most direct and common use of mangroves in the study area is for cooking and heating fuel (Table 2). Between 1990 and 2009, the use of mangroves as primary household fuel decreased from 42% to 34%, but the largest decrease took place between 2004 (39%; before SANAPA) and 2009 (34%; after SANAPA). These figures suggest that, with SANAPA, a number of households in the area lost a key extractive ecosystem service from mangroves. Still, more than one third of the households in the sample rely on mangroves as the primary fuel source. The actual figure could even be higher, as households may have been reluctant to report mangrove extraction in the survey (*SI Survey*). Most households that no longer use mangroves have switched to other trees, which may result in biodiversity impacts yet to be explored.

When we stratify the sample households into three wealth groups based on terciles of per capita assets, a larger proportion of the richer group has switched to other fuel sources (12%). In contrast, only 2% of the households in the poorer group changed to other fuel sources, suggesting that the poor may have limited alternative fuel sources. In addition to subsistence uses, there is a high urban demand for mangrove

charcoal (7, 34, 35), but few households in our sample reported engagement in charcoal production. The charcoal market requires well-organized networks with boats and trade connections that may be centered outside of the local villages.

Changes in Mangrove-Related Income. To assess the impact of SANAPA on income, we focus on two major income sources related to mangroves: shrimping and fishing.

Combined, they were the most important income source in 2009 for nearly 40% of the sample, far exceeding the proportion of households who reported that agriculture or off-farm occupations were their most important income source. Moreover, households are increasingly engaged in shrimping and fishing (Table 3, columns 1 and 2).

Households engaging in shrimping increased from 16% of the sample in 2004 to 23% in 2009. Households engaging in fishing increased even more, from 27% in 2004 to 43% in 2009. Interestingly, the majority of the households that started shrimping and fishing between 2004 and 2009 were from the poorest segment of our sample, suggesting that these mangrove-related income sources are pro-poor. Our data also show an increase in the proportion of households engaged in agriculture, charcoal production, and other income sources, suggesting that households are diversifying their income sources. Some of the occupations in 'other sources' include ecotourism, which are jobs associated with SANAPA.

The household data show that shrimping and fishing incomes have increased over time (Table 3, column 5). In particular, annual fishing income increased on average by 161,000 Tsh (approximately \$107) per household per year; shrimping income also showed a modest increase of 7,000 Tsh (approximately \$4.70) per household per year.

Importantly, the magnitude of increase in both shrimping and fishing incomes was the largest for the poorest segment of the sample, again underscoring the importance of mangrove-related income sources for the poor.

Effect of SANAPA on Mangrove-Related Income. Point estimates from the regression models reveal that the establishment of SANAPA increased mangrove-related incomes (Table 4). As mangrove cover increased within SANAPA, there was an increase in incomes from shrimping (Table 4, models 1-3) and from fishing (Table 4, models 4-6). Specifically, a 1-km² increase in mangrove cover within SANAPA increased the shrimping income by 19.5 million Tsh (approximately \$13,000) per year, an estimate that is significant at the 5 percent level (Table 4, model 3, row 1). We found that the average SANAPA mangrove cover in a 5-km² radius around each village in 2005 was 0.71 km². Thus, our model result implies that an approximate 10% increase in SANAPA mangrove cover within a 5-km² radius of the villages increases shrimping income by twofold. In contrast, a 1-km² increase in mangrove cover outside SANAPA increased shrimping income by only 626,000 Tsh (approximately \$417; Table 4, row 2). Qualitatively, we find a similar result for fishing income (Table 4, models 4-6). A 1-km² increase in mangrove cover within SANAPA increased fishing income by 13.87 million Tsh (approximately \$9,450). On the contrary, a 1-km² increase in mangrove outside SANAPA increased fishing income by only 323,000 Tsh (approximately \$220). The changes in these incomes are a result of an increase in number of shrimping and fishing days, earnings per day, and, in the case of fishing, increase in consumption per day as well. The differences in the results between mangrove cover within and outside SANAPA may also reflect the

greater fisheries productivity expected from mangroves located along the edge of riverine estuaries as occurs with the Wami River Estuary of SANAPA. We acknowledge, however, that, in theory, the same effect may also arise independently of the protected area, e.g., as a result of a price increase or improvements in harvesting technology, for which we cannot control in our analysis because of a lack of data (*SI: Materials and Methods*).

The results also reveal that degree of monitoring for enforcement, as proxied by the distance to boat ramp, has had an effect on shrimping income, but not on fishing income. Specifically, the interaction term between change in mangrove area outside SANAPA and distance to boat ramp is negative and significant for changes in shrimping income per capita, meaning that the closer the mangrove area is to the enforcement officers' base, the larger the increase in shrimping income. This finding suggests that there may be some spillover effect of enforcement beyond the park boundaries. This coefficient was negative but insignificant for fishing income.

In addition, we find that, although the new entrants to shrimping and fishing were in the poorest group, the effect of the increase in mangrove area within SANAPA on incomes does not particularly favor the poor (Table 4, models 3 and 6). Although most coefficients related to the wealth groups are insignificant (Tables, rows 5-10), the effect of SANAPA on shrimping income is lower for the poorest third of the sample compared to the richest third of the households. Wealth represents a few factors that affect incomes from shrimping and fishing, such as quantity/size of shrimping gear and

boats, search capacity, and, potentially, skills. There is no difference across wealth groups for the effect on fishing income.

Overall, the households that have stopped using mangroves for firewood can be considered the “losers” from establishment of SANAPA, whereas those who started fishing/shrimping (or making more revenue out of it) are the “winners.” Our data suggest that there are more “winners” than “losers”: the proportion of households that newly engaged in mangrove-related income activities after SANAPA outweighs the proportion of households that no longer used mangroves for their firewood. In our sample, the proportion of households that used mangroves for firewood decreased by 5%. In contrast, during the same time period, households that newly engaged in shrimping increased by 7% and those who engaged in fishing increased by 16%.

Mangrove Protection vs. Poverty Trap

The expansion of mangrove protection through the creation of SANAPA and enhanced enforcement led to a markedly different future for the mangrove forest species and the biodiversity within that habitat. It also influenced the welfare of the adjacent communities that have been relying on these forests for their livelihood. The trajectory shifted from one in which the mangroves were experiencing uncontrolled cutting, which was destroying the foundation of a critical ecosystem, to one in which mangrove conservation is providing gains in income for the local communities through the preservation of nursery habitat and biodiversity. Our findings suggest that SANAPA has created a tradeoff between the short-run benefits from cutting mangrove forests and potential long-run benefits from not cutting mangroves – and these tradeoffs

appear to differ somewhat by household wealth. Many households have experienced an immediate loss in the consumption of mangrove firewood, with the loss most prevalent in richer households.

The households that have entered the fisheries since 2005 were in the poorest group of our sample, suggesting that they have benefited considerably from protection of mangrove forests. At the same time, all wealth classes appear to benefit from long-term sustainability or gains in shrimping and fishing that result from mangrove protection in the Wami River Estuary. This is in contrast to other studies that found that the impact of protected areas was not uniform across households, or that nonpoor households captured most of the welfare gains (7, 17, 36).

However, it is not clear whether the continued protection of mangrove cover would avoid a poverty trap in the long run. Only 2% of the households in the poorer group changed to a different source of fuel since 2005, suggesting the need for some support to transition to alternative fuel sources. Another concern is that there exists no formal mechanism for the “winners” of the protected area (i.e., those who enjoy increased fishing opportunities) to compensate the “losers” (i.e., those who lost access to mangroves for firewood and other uses). Without such mechanism, tensions may arise in the future. Furthermore, the sparse data environment for artisanal fisheries in Tanzania precludes us from assessing whether the current rate of harvest is sustainable. Even if it were at a sustainable level, the long-term sustainability of shrimp and other fisheries is contingent not only upon the continued existence of nursery habitat, but also sustainable levels of harvest, which requires appropriate institutions and property rights

to manage the fisheries effectively. Although the artisanal fisheries have been given a temporary lifeline as a result of mangrove protection and the recent countrywide banning of commercial trawlers in 2008, there is a strong need for sustainable fisheries management, as well as improvements in storage facilities within the villages and greater accessibility to markets (*SI Fisheries*). To help prevent excessive pressure on the fisheries, especially if the population levels continue to increase, efforts may be needed to further generate other livelihood options such as ecotourism, which is now possible as a result of the creation of SANAPA. In fact, several respondents said that their job in ecotourism was now their most important income source.

Our field work and survey data show that SANAPA already generates a number of new direct and indirect benefits to the local communities. If these benefits grow with the expansion of ecotourism, there is potential for further poverty alleviation (Table S2). As an example of direct benefits, SANAPA directs a portion of the park fees to local communities for building schools, dispensaries, and mosques. In addition, park personnel assist in supplying drinking water to the communities through the construction of pumps and collection of non-saline river water, and help to transport ill community members to regional hospitals. SANAPA can also provide indirect benefits to the communities through improving roads and cellular phone towers and the creation of temporary and permanent employment opportunities in tourism. Our survey confirmed that these factors were perceived as benefits by the local communities, especially among those who live closer to SANAPA. Together with increases in mangrove related incomes, these benefits may turn SANAPA into a win-win strategy.

Materials and Methods

Geospatial Data and Household Surveys. The present study focused on mangrove habitat cover in 1990 (before park establishment), 2005 (time of park establishment), and 2010 within and immediately adjacent to SANAPA (Fig. 1). Landsat images were manually interpreted and delineated within ArcGIS (ESRI) at a scale of 1:17,000 (*SI Materials and Methods*). ArcGIS was used to calculate mangrove area per time period inside and outside of the SANAPA boundaries. It was also used to identify the mean center point for each subvillage and create circular land cover analysis zones. The latter extended in a 5-km radius around each mean center point to quantify mangrove forest cover located within these zones that was inside or outside the boundaries of SANAPA in 2005 and 2010 (Fig. 1a). We selected an area encompassed within a 5-km radius of each subvillage to reflect the likely travel distance for subvillage fishermen. The continental shelf in this area extends less than 5 km offshore, and most small-scale fishermen do not have access to the technology (e.g., outboard or inboard engines and cooling or freezing facilities) and the capital needed to fish in waters greater than 5 km offshore (7, 37).

We next combined the geographic information systems mangrove data with a survey data set obtained from georeferenced households. We administered the survey in April 2010 to evaluate the livelihood impact of SANAPA. The survey instrument was approved by the University of Rhode Island Institutional Review Board on Human Subjects. The household survey used a stratified sampling strategy designed to collect

data on a random sample of 150 households in the SANAPA area. From 15 subvillages in the SANAPA area (Fig. 1a), which are of varying distances from the park boundary, 10 households per subvillage were randomly selected. Our sampling frame includes only subvillages that have some access (i.e., by roads or water) to mangroves, some of which are within the park boundaries. By using the survey data, we were able to produce information on mangrove-related income (shrimping and fishing) for both before (in 2004) and after (in 2009) the establishment of SANAPA. The survey also included detailed information on primary fuel source for 1990, 2000, 2004, and 2009, asset holdings and income earnings for 2004 and 2009, and perceptions of the positive and negative impacts of SANAPA (*SI Survey*).

To identify the impact of SANAPA on mangrove-related incomes from fishing and shrimping, we used the variation across households in the changes in mangrove area within SANAPA boundaries. Specifically, we first use the GPS coordinates of the central location of each subvillage to draw a 5-km radius circle around each subvillage (Fig. 1a). We then calculate the changes in mangrove cover (in km²) in each 5-km-radius circle between 2005 and 2010. If enforcement is effective, we should expect an increase in mangrove-related incomes (from fishing and shrimping) where mangrove cover within SANAPA boundaries has increased. We use this variable as the key treatment variable and as a tool for identifying the effect of SANAPA.

Econometric Methods. In identifying a causal linkage between the establishment of SANAPA and mangrove-related incomes, we used econometric methods to address concerns that changes in mangrove-related incomes could be caused by factors other

than the establishment of SANAPA and stronger enforcement of regulations on mangrove harvest (*SI Material and Methods*). For example, stocks of shrimp and fish could have increased between 2004 and 2009 all along the coast of the study area as a result of more favorable weather or ecological conditions. Changes in mangrove-related incomes could also be caused by changes in mangrove areas outside SANAPA.

Moreover, they also could result from unobservable factors that affect both mangroves and mangrove-related income (e.g., a community's ability in managing mangroves) and location-specific factors that affect productivity of mangroves. To evaluate convincingly the impact of the protected area on mangrove-related incomes, we need to control for time effect and unobservable factors to the extent possible. We also had a sample selection issue in which a large proportion of respondents reported zero income for certain income categories. If we did not deal with these issues, the estimates of the impact of establishing SANAPA could have been biased.

Our identification strategy attempted to deal with these issues through several different econometric methods. First, we used data on two periods - before and after the establishment of SANAPA - and applied a method to control for sample selection for panel data (38). Specifically, we used a first-differenced model, which is equivalent to a fixed-effects model with two periods, with inverse Mills ratios (IMRs) for each period (*SI Materials and Methods*). This approach allowed us to control for time trends, time-invariant unobservable factors, and sample selection. We acknowledge the shortcoming, however, that this approach does not allow us to control for time-varying factors that could affect fishing and shrimping income, such as prices and fish stock.

Second, to address the potential confounding effect of changes in mangrove cover outside the protected area, we controlled for changes in mangrove cover outside SANAPA within 5 km from each subvillage. We expected a smaller coefficient on this variable compared with within-SANAPA mangrove cover for the following two reasons. First, there is a placement effect, i.e., SANAPA protects the areas that are key shrimp and fish breeding areas. Second, there could be quality differences in mangroves; presumably, mangroves within the park boundaries have better protection and hence are more productive as a habitat. We also created a variable to proxy the degree of enforcement by calculating the distance between each subvillage and the park's boat ramp at which the park enforcement agents periodically reside. We explored whether subvillage proximity to the boat ramp is associated with stronger enforcement. As anecdotal evidence suggests there could be some spillover effect of enforcement to areas outside the park boundaries, we attempted to capture this effect by interacting the distance to the boat ramp and the mangrove area outside the park boundaries. A positive coefficient would indicate that an increase in mangrove area outside the park boundaries is associated with a larger increase in shrimping or fishing income if the subvillage is closer to the boat ramp and is subject to stronger enforcement.

In sum, we estimate the following empirical model:

$$y_{it} = x_{it}\beta + \alpha_i + \lambda_{it}\gamma + \varepsilon_{it} \quad (1)$$

where y_{it} is the outcome variables of interest (i.e., shrimping and fishing income) for individual i in year t ; x_{it} is a vector of time-variant observables, including the distance from the boat ramp (measure of enforcement after establishment of SANAPA) and the

interaction term between mangrove cover outside the park boundaries and the distance from the boat ramp; α_i is an individual fixed effects; λ_{it} is a vector of IMR from a probit model for each year; and ε_{it} is the error term. We report a robust SE that corrects for heteroskedasticity (*SI Materials and Methods*, Table S3).

In addition, we extended the model to understand how the establishment of the protected area affected households from the three wealth segments (poorer, middle, richer) differently. Specifically, we divided the sample into terciles (i.e., three groups of equal size) based on the value of productive and consumable asset per capita (*SI Survey*). We then added to Eq. (1) dummy variables for the poorer and middle groups (richer group as the base category) and the interaction terms between the dummy variables and the variables for mangrove areas. Intuitively, coefficients on these variables measure how the impact of increased area in mangroves in SANAPA differs for the two groups relative to the richer group. Descriptive statistics for the variables are available in Table S4.

Acknowledgments

We thank C. Barrett and A. Travis for organizing the Biodiversity Conservation and Poverty Traps workshop. We greatly appreciate the assistance of J. Daffa, A. Mandari, W. Mkama, S. Ngomuo, J. Mohamed, and S. Msuya, and other individuals for their dedicated effort in fieldwork. Our appreciation extends to the survey respondents for sharing their time and knowledge, A. Kafle and H. Wakamatsu for their research assistance, S. Cobb, K. Castro, and Coastal Resources Center staff for sharing their expertise, and the Editor and the four anonymous reviewers for their helpful comments. This work was partially funded through the Coastal Institute of the University of Rhode Island.

References

1. Polidoro BA, et al. (2010) The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS One* 5:e10095.
2. Mitch WJ, Gosselink JG (2000) Mangrove Swamps. *Wetlands* (Wiley, New York), pp 335-373.
3. Kathiresan K, Rajendran N (2005) Mangrove ecosystems of the Indian Ocean region. *Indian J Mar Sci* 34:104-113.
4. Spalding MD, Blasco F, Field CD (1997) *World Mangrove Atlas*, (The International Society for Mangrove Ecosystems, Okinawa, Japan).
5. Nagelkerken I, et al. (2008) The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquat Bot* 89:155-185.
6. Walters BB, et al. (2008) Ethnobiology, socio-economics and management of mangrove forests: A review. *Aquat Bot* 89:220-236.
7. Semesi et al. (1998) Coastal resources utilization and conservation issues in Bagamoyo, Tanzania. *Royal Swedish Acad Sci* 27:635-644.
8. Valiela I, Bowen JL, York JK (2001) Mangrove forests: One of the world's threatened major tropical environments. *Bioscience* 51:807-815.
9. Ellison AM (2008) Managing mangroves with benthic biodiversity in mind: Moving beyond roving banditry. *J Sea Res* 59:2-15.
10. Singh HR, Chong VC, Sasekumar A, Lim KH (1994) Value of mangroves as nursery and feeding grounds. Status Reviews. Proceedings of the third ASEAN-Australia symposium on living coastal resources, eds Wilkinson CR, Suraphol S, Chou LM (Chulalongkorn Univ, Bangkok), Vol 1, pp 105-122.
11. Robertson AL, Blaber SJM (1992) Plankton, epibenthos and fish communities. *Tropical Mangrove Ecosystems*, eds Robertson AI, Alongi DM (American Geophysical Union, Washington DC), pp 173-224.

12. Azariadis C, Stachurski J (2005) Poverty Traps. *Handbook of Economic Growth*, eds Aghion P, Durlauf S (Elsevier, Amsterdam), pp 295-384.
13. Agrawal A, Redford K (2006) Poverty, Development, and Biodiversity Conservation: Shooting in the Dark? (Wildlife Conservation Society, Bronx, NY).
14. Hughes R, Flintan F (2001) *Integrating conservation and development experience: A review and bibliography of the ICDP literature*, (International Institute for Environment and Development, London).
15. Salafsky N, Wollenberg E (2000) Linking livelihoods and conservation: A conceptual framework and scale for assessing the integration of human needs and biodiversity. *World Dev* 28: 1421-1438.
16. Campbell et al. (2001) Assessing the performance of natural resource systems. *Conserv Ecol* 5:22
17. Andam KS, Ferraro PJ, Sims KRE, Healy A, Holland MB (2010) Protected areas reduced poverty in Costa Rica and Thailand. *Proc Natl Acad Sci USA* 107:9996-1001.
18. Wilkie DS, et al. (2006) Parks and people: Assessing the human welfare effects of establishing protected areas for biodiversity conservation. *Conserv Biol* 20:247-249.
19. Adams WM, et al. (2004) Biodiversity conservation and the eradication of poverty. *Science* 306:1146-1149.
20. Aburto-Oropeza O, et al. (2008) Mangroves in the Gulf of California increase fishery yields. *Proc Natl Acad Sci USA* 105: 10456-10459.
21. Miththapala S (2008) *Mangroves: Coastal Ecosystem Series* (IUCN Ecosystems and Livelihoods Group, Colombo, Sri Lanka), Vol 2.
22. Baig SP, Iftikhar UA (2005) *Are the mangroves for the future? Empirical evidence of the value of Miani Hor mangrove ecosystem as the basis for investments* (International Union for the Conservation of Nature, Karachi, Pakistan).
23. Iftikhar U (2002) in *Sea Intrusion in the Coastal and Riverine Tracts of the Indus Delta - A Case Study* (International Union for the Conservation of Nature, Karachi, Pakistan).

24. de Sherbinin A (2008) Is poverty more acute near parks? An assessment of infant mortality rates around protected areas in developing countries. *Oryx* 42:26-35.
25. Baldus RD, Beddoe V, Jafferji J (2007) *Saadani National Park* (Gallery Publications, Arusha, Tanzania).
26. Tanzania National Parks Department of Planning and Projects Development (2003) *Saadani National Park Management Zone Plan* (Arusha, Tanzania).
27. Staples DJ, Vance DJ, Heales DS (1985) Habitat requirements of juvenile penaeid prawns and their relationship to offshore fisheries. *Second Australian National Prawn Seminar*, eds Rothlisberg PC, Hill BJ, Staples DS (CSIRO, Cleveland, Australia), pp 47-54.
28. Katoomba Ecosystem Services Incubator (2009) *Getting Started on REDD in Tanzania: A Scoping Study for the Katoomba Ecosystem Services Incubator* (Forest Trends, Washington, DC).
29. Nurse M, Kabamba J (2000) *Defining Institutions for Collaborative Mangrove Management: A Case Study from Tanga, Tanzania* (International Union for Conservation of Nature Eastern African Regional Office, Nairobi).
30. Research and Analysis Working Group of the United Republic of Tanzania (2005) *Poverty and Human Development Report* (Mkuki na Nyota Publishers, Dar es Salaam, Tanzania).
31. Bagamoyo District Planning Department (2006) Bagamoyo District Profile (Bagamoyo District Planning Department, Bagamoyo, Tanzania).
32. Wang YQ et al., (2010) in *Remote Sensing of Coastal Environments*, ed Wang YQ (CRC Press, Boca Raton), pp. 395-411.
33. World Meteorological Organization WMO annual statements on the status of the global climate 1995-2010 (World Meteorological Organization, Geneva). Available at www.wmo.int/pages/prog/wcp/wcdmp/wmostatement_en.html. Accessed June 8, 2011.

34. Ahrends A, et al. (2010) Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. *Proc Natl Acad Sci USA* 107:14556-14561.
35. Mwampamba TH (2007) Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability. *Energy Policy* 35:4221-4234.
36. Bandyopadhyay S, Tembo G (2010) Household consumption and natural resource management around national parks in Zambia. *J Nat Resources Policy Res* 2:39-55.
37. Jiddawi NS, Öhman MC (2002) Marine fisheries in Tanzania. *Ambio* 31:518-527.
38. Wooldridge JM (1995) Selection corrections for panel data models under conditional mean independence assumptions. *J Econom* 68:115-132.

Table 1. Changes in mangrove forest area within and outside of SANAPA borders, 1990 to 2010.

Time Period	Annualized mangrove change within SANAPA, ha/yr	Mangrove change within SANAPA, %/yr	Annualized mangrove change outside SANAPA, ha/yr	Mangrove change outside SANAPA, %/yr
1990 → 2005	-27.3	-1.79%	-20.8	-0.66%
2005 → 2010	-1.8	-0.16%	+11.9	0.42%

Table 2. Changes in proportion of households that used mangroves as a primary source of cooking/heating fuel, 1990 to 2009.

	1990	2000	2004	2009
Total	42%	43%	39%	34%
Poorer group	35%	35%	35%	33%
Middle group	38%	38%	35%	29%
Richer group	52%	57%	46%	40%

Note: Group category is based on tercile of total value per capita of productive and consumable assets in 2004.

Table 3. Income source and changes in real income per capita, 2004 and 2009.

Income Activity	Engaging in mangrove related and other income activities, %		Changes in real income per capita (unit: 1,000 Tanzanian Shillings)		
	2004 (before SANAPA)	2009 (after SANAPA)	2004 (before SANAPA)	2009 (after SANAPA)	Mean change, 2004-2009
Shrimping	16	23	944.03 (1014.49)	674.03 (930.90)	+7.43 (848.34)
Fishing	27	43	686.93 (826.14)	599.21 (851.35)	+160.96 (1043.24)
Agriculture	19	34	146.39 (158.31)	972.88 (124.24)	+12.14 (148.46)
Aquaculture	1	1	-	-	-
Charcoal (Mostly not mangrove)	6	11	534.76 (647.74)	354.93 (743.06)	+41.24 (881.28)
Firewood (Mostly not mangrove)	3	3	756.10 (1495.94)	289.34 (470.89)	-225.39 (1287.68)
Other sources	45	79	202.54 (358.67)	189.47 (308.20)	+72.98 (181.11)

Notes: Mean of changes between the two years are calculated by first subtracting the 2004 value from the 2009 value for each household and then taking the mean. Values for 2009 are adjusted for inflation using consumer price index generated by the National Bureau of Statistics. Values in parentheses are SDs. * Unit of measurement is 1,000 Tanzanian Shillings; \$1 is equivalent to approximately 1,500 Tanzanian Shillings.

Table 4. Regression results of the primary equation.

Explanatory Variables	Dependent Variables					
	Change in shrimping income per capita			Change in fishing income per capita		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Change in mangrove area within SANAPA	6,052.34 (1.75)*	14,872.23 (2.88)***	19,429.28 (2.83)**	5,475.83 (2.37)**	9,366.99 (2.10)**	13,873.98 (2.12)**
Change in mangrove area outside SANAPA	127.78 (1.56)	510.11 (2.99)***	626.15 (2.88)***	85.67 (2.14)**	178.757 (1.32)	322.99 (1.70)*
Change in mangrove area outside SANAPA * Distance to boat ramp		-8.16 (2.57)**	-12.46 (2.51)**		-2.73 (1.05)	-5.55 (1.36)
Distance to boat ramp		-3.23 (0.64)	0.62 (0.07)		7.817 (1.65)	13.41 (1.25)
Poorer Group			-269.37 (0.57)			-368.68 (0.83)
Middle Group			22.224 (0.04)			-404.59 (0.83)
Change in mangrove area within SANAPA * Poorer Group			-12,924.48 (1.76)*			3,664.04 (0.45)
Change in mangrove area within SANAPA * Middle Group			3,277.62 (0.40)			881.57 (0.11)
Change in mangrove area outside SANAPA * Poorer Group			4.59 (0.02)			-0.31 (0.00)
Change in mangrove area outside SANAPA * Middle Group			125.93 (0.80)			33.66 (0.19)
R ²	0.26	0.46	0.56	0.39	0.43	0.46
N	31	31	31	59	59	59

Notes: Robust *t* statistics are in parentheses. All regression models also control for IMR in 2004 and 2009 and income levels in 2004 of respective income sources. Significant differences at *10%, **5 %, and *** 1%.

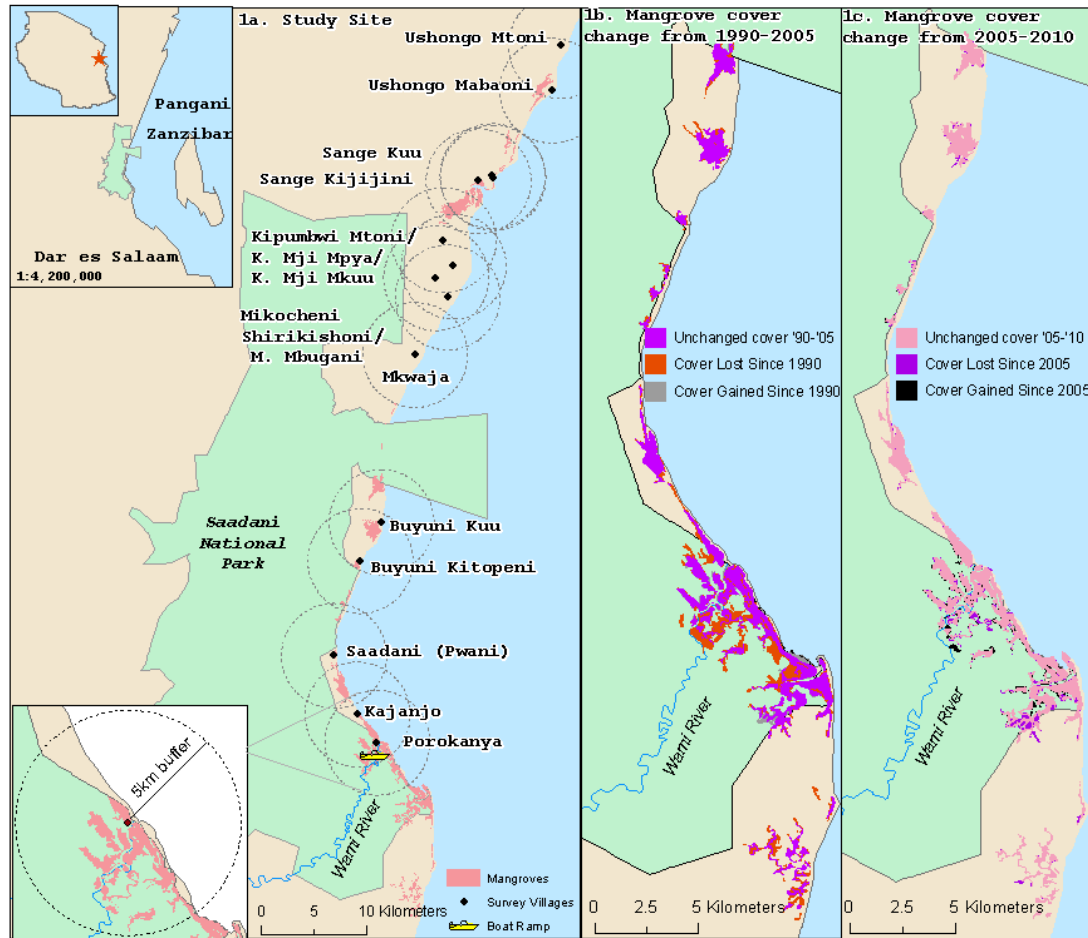


Figure 1a. Study site of Saadani National Park, Tanzania and villages used in econometric analyses. Inset illustrates the 5 km radius around each village that was used to assess mangrove cover change per village within and outside Saadani NP; 1b./1c. Mangrove forest cover from 1990 to 2005, and 2005 to 2010, respectively.

Supporting Information

Published Literature

Rönnbäck et al. (1) found high structural complexity and penaeid shrimp density in five to six year old replanted habitat. Mangrove plantations studied in Gazi Bay, Kenya were found to exhibit similar, and in certain instances, greater species richness, abundance, and biomass in sediment-infauna, macrobenthic fauna, epibiotic flora and fauna, postlarval and juvenile shrimp, and juvenile and adult fish populations to natural stands five to eight years after planting (2-6) (Table S1). However, mangrove replanting does not always result in the same level of fish and benthic macrobiota species diversity found in natural cover due to lower accretion rates of fine and organically rich sediments and differences in the types of habitat abutting natural versus replanted sites (7). Therefore, when possible, emphasis should be placed on protecting natural mangrove habitat.

Survey

The survey collected information on all income categories and on major categories for productive and consumable assets. Income categories include agriculture, fishing, shrimping, aquaculture, firewood and charcoal, livestock, self-employed businesses not covered in other sections, wage jobs, pensions, remittances from relatives or others, assistance/support from NGOs or other institutions (not credit), and other (specified by the respondent). Productive assets include farming and fishing equipment, livestock, and transportation vehicles. Land was not included as part of productive assets as there

is no well-functioning land rental market. Consumable assets include furniture, electronics, mosquito nets, mobile phone, and current value of housing.

The study relies on information for 1990, 2000, 2004, and 2009 that was collected in 2010. We acknowledge the potential problems inherent in recall data, especially regarding the pre-SANAPA period. Unfortunately, government agencies in Tanzania did not collect information from the local communities prior to the park establishment. We addressed concerns about recall bias through the design of the survey, for example, by reminding the respondent that 2004 refers to pre-SANAPA period. We also trained the enumerators to ensure that respondents produced their best recollections of past amounts and activities. At the same time, if all of the households have the same degree of recall bias, at least a part of it is captured through the first-differenced model (a version with constant terms which absorbs the time effect). In addition, to the extent that the degree of recall bias is correlated with wealth (e.g., the poor may have more diverse income sources and hence have a more severe recall bias), we also partly control for these differences through the wealth categories which we include in the full model.

In addition to recall bias, we are concerned about the potential bias in the data regarding mangrove firewood collection because of the perceived risk of reporting an illegal behavior. To solicit information that is as accurate as possible, we did explain to the respondents at the outset of the survey that any information we collect will remain confidential, that it will not be shared with any other entities, and that they may refuse

to respond to any question. Based on information from focus groups that we conducted after the survey, we have some indication that there could have been cases of underreporting among households who live in or adjacent to the park. However, our data show that there are few households who switched from mangrove to other types of firewood from 1990 to 2004 among households who live in or adjacent to the park. Therefore, although the absolute level of proportion of those who use mangrove firewood may be biased downwards, the switch information contains less bias.

In this study, we linked household survey data with mangrove cover data within a 5 km radius circle around each subvillage. Since all households are georeferenced, we could technically create the same variable at the household level. However, since most households are clustered within each subvillage, there is little variation in the location of the circular 5 km radius land cover analysis zone (and hence mangrove area). We therefore use the subvillage-level variable.

Materials and Methods

Geospatial Data and Methods

Landsat TM scenes acquired between 1988 and 1990, and Landsat-7 ETM+ scenes acquired in 2005 and 2010 (path/row numbers of P166/R164) were used to extract the mangrove forest area and quantify changes in mangrove area cover. The data selection was dictated by available cloud free coverages, and variations in the tidal range are a potential source of error. Both the Landsat TM and Landsat ETM+ images have a spatial resolution of 30 m. The frame and fill program (v.1) created and distributed by NASA in

2009, was utilized to fill the gaps in the 2005 and 2010 Landsat ETM+ imagery caused by the Landsat 7 Scan Line Corrector-Off (SLC-off) malfunction in 2003. The Landsat images were manually interpreted and delineated within ESRI ArcGIS at a scale of 1:17,000, and manual interpretation was selected over supervised classification because the former enables more precise extraction of the mangrove vegetation boundary. One researcher conducted all image interpretation for the three time periods to minimize inconsistencies in the image interpretation process. The classification of mangrove cover area focused on dense stands and those that changed over time from a scattered pattern associated with colonization to denser growth, but did not delineate new scattered growth.

Econometric Method

In identifying a causal linkage between the establishment of SANAPA and mangrove-related incomes, we use econometric methods to address concerns that changes in mangrove-related incomes could be due to factors other than the establishment of SANAPA and stronger enforcement of regulations on mangrove harvest. For example, households may be shrimping and fishing more in 2009 in response to increasing demand for shrimp and fish. Alternatively, stocks of shrimp and fish could have increased between 2004 and 2009 all along the coast of the study area due to more favorable weather or ecological conditions. Changes in mangrove-related incomes could also be due to changes in mangrove areas outside SANAPA areas. Moreover, they also could be due to unobservable factors that affect both mangroves and mangrove-related

income (such as community's ability in managing mangroves, shrimp, and fish) and location-specific factors that affect productivity of mangroves. We also need to control for selection bias in income activities.

To address these challenges, we employ Heckman's sample selection model for panel data (8). In general, a key advantage of the selection model is to control for sample selection biases that could otherwise arise from the existence of unobservable variables that determine both the discrete and continuous choices pertaining to income generation. Such biases may emerge from the possibility that the determinants of income activities are not random. The sample selection model for panel data allows us to control for time trends (e.g., the trawling ban or changes in output prices, to the extent that they do not vary across households in the study area), time-invariant unobservable factors (e.g., biophysical factors that affect the productivity of shrimp and fish that do not change over time), and sample selection (i.e., factors that are inherently different about those households who engage in shrimping and those who do not). We acknowledge the shortcoming, however, that this approach does not allow us to control for time-varying factors that could affect fishing and shrimping income such as prices and fish stock. Unfortunately, we do not have the data to control for these time-variant factors.

To implement the Heckman's sample selection model for panel data, we utilize the data from pre-SANAPA (2004) and post-SANAPA (2009) to form a panel data set in a two-step estimation procedure. Here we explain in the context of fishing income; we

repeat the same procedure for shrimping income. The first step is to estimate the selection model for whether or not the household earns income from shrimping in each year (2004, 2009). Let the equation that determines the sample selection be:

$$z_{it}^* = w_{it}'\gamma_t + u_{it}, t=2004, 2009$$

where z_{it}^* is a latent variable for fishing income in year t for household i , $z_{it}=1$ if $z_{it}^* > 0$ and 0 otherwise, w_{it} denotes the determinant of this status, γ_t is associated parameter estimates, and u_{it} is an error term. The canonical specification for this relationship is a probit regression of the form:

$$\text{Prob}(z_{it} = 1 | w) = \Phi(w_{it}'\gamma_t)$$

where Φ is the cumulative distribution function of the standard normal distribution. In our specification, the explanatory variables in Z_{it} are all time-invariant variables, including household size, household head's age, gender, education, whether or not the household can borrow from a commercial bank in times of need, and productive and consumable asset per capita in 2004. We estimate two probits on selection into fishing income in each year (2004 and 2009). As an example, the selection into fishing in 2004 is shown in Table S3. From the probit model estimates we compute the Inverse Mills Ratios (IMRs) for each year, defined as:

$$\hat{\lambda}_{it} = \phi(w_{it}'\hat{\gamma}_t) / \Phi(w_{it}'\hat{\gamma}_t)$$

where ϕ denotes the standard normal density function.

The second step is to use the IMRs to estimate the equation of primary interest (outcome equation):

$$y_{it} = x_{it}'\beta + \varepsilon_{it}$$

where y_{it} is income from fishing, x_{it} are determinants of fishing income including mangrove cover, β are associated parameter estimates, and ε_{it} is an error term. In estimating this equation, we employ the first-differenced model with IMRs, which is equivalent to fixed effects for two periods. Under assumptions explained in Wooldridge (8), we can control for the sample selection by including the IMRs in estimating this outcome equation. The advantage of the first-differenced model is that we are able to control for all time-invariant, unobserved variables at the household level which can potentially bias the coefficient estimates. To do so, we take the difference of the time-variant variables and measure the changes between pre- and post-SANAPA, including changes in mangrove cover in 5km radius within the SANAPA boundaries and outside the boundaries and the IMRs. We then include interaction terms between these variables and the distance to boat ramp as well as the income categories. We report the robust t-statistics in Table 4.

Moreover, by adding a constant term to the first-differenced model, we can control for time-variant, unobservable variables that are common across households, such as the trawling ban that took place between 2004 and 2009. This type of effect gets absorbed in the constant term along with all other time effects. We ran all six

models with a constant term and found that the difference in the magnitude and the significance of the coefficients of interest are negligible.

What we cannot control for through this approach are time-variant, unobservable, potentially-confounding variables which vary across households. For example, output prices of fish and shrimp changed over time in the region and this price effect could be different across households depending on which species the fishermen harvested in each year. Moreover, the effects may also be confounded by improvements in the harvesting technology, for which we also do not have household-specific data (although we are not too concerned based on our field observation). Unfortunately, since we only have information on net earnings from fishing as a lump sum and not for specific species, we cannot control for these effects. We note that for this reason, most fisheries analysis will look for 'fishery independent' estimates of abundance change [e.g., a series of standardized stock surveys, (9)]. However, a critical advantage for this study of using income data is that we can directly observe the changes in households' welfare.

Unfortunately, our survey did not include direct questions about the reasons behind the behavioral change in effort allocation. The information we do have are qualitative information on the respondents' perceptions of the positive and negative effects of SANAPA. We do not attempt to identify causality using the answers to these questions partly because of lack of observations, lack of a convincing strategy, and high collinearity among questions. However, based on simple correlation coefficients, we

find that those who lost land to crops due to establishment of SANAPA are associated with larger gains in fishing income between 2004 and 2009. We know through our focus groups that fishing and shrimping are some of the few (in some cases, the only) income-generating activities available in the area. This suggests that households could be changing effort allocation partly out of necessity when there are changes in other income sources, which could be driven by the establishment of a protected area. However, because we cannot convincingly demonstrate this causality, we will refrain from speculating this in the main text.

Fisheries

Commercial and Artisanal Fisheries in Tanzania

The shrimp and fish species typically caught by the commercial trawlers and the artisanal fishermen varied due to the types of fishing gear employed. Double-rigged side trawlers were used in the commercial fishery, and the preferred fish species harvested included grunters, groupers, kingfish, catfish, cobia, and spiny turbot (10). The most common shrimp species harvested by the trawlers included *Fenneropenaeus indicus* (74.8%), *Metapenaeus monoceros* (17.2%), *Penaeus monodon* (3.8%), *P. semisulcatus* (3.8%), and *M. stebbingi* (0.4%) (10).

Artisanal fishermen with access to boats use dhows, dugout canoes, outrigger canoes, and small boats propelled by sails or oars. Those using hook and line catch barracuda, bream, emperor, kingfish, and needle fish. Kingfish, queen fish, rays, sharks, and tuna are typically caught with shark nets and gillnets, while marlin and sailfish are

targeted with long lines and drift nets. Fishermen purse seining at night with pressure lamps typically harvest anchovies, mackerels, and sardines (10, 11). However, the majority of fishermen in our study area rely on seine nets (which are dragged off the beach at low tide) cast nets, mesh nets, mosquito nets, and fish traps. The seine-net fishery typically yields emperor, mackerel, parrotfish, rabbit fish, and sardines (10). Research by Jiddawi et al. (12) found coral reef fishes such as emperors, goatfish, groupers, parrotfish, rabbit fish, snappers, surgeonfish, and sweetlips particularly important to the artisanal fishermen since they can access and harvest these species with their traditional fishing gear and crafts. The most common shrimp species harvested by the artisanal fishermen are *P. monodon*, *P. semisulcatus*, and *F. indicus* with the latter most prevalent when mesh nets are employed near river mouths or within the intertidal zone (10, 13).

Ecosystem Impacts of Commercial Shrimping

Prior to the outright ban in January 2008, a series of regulations were created by the Tanzanian government in an attempt to reduce the impact of commercial shrimp trawling on the ecosystem: (i) limitations on commercial vessels (i.e., a maximum of 500 HP engine power, 150 Gross Registered Tonnage, two nets, and a minimum cod-end mesh of 50mm); (ii) a minimum depth requirement of 5 meters and a closed season extending from December 1st through February 28th to help protect juvenile shrimp populations; (iii) prohibition of night trawling to minimize conflicts with artisanal fishermen setting their nets or fishing in the same grounds at night; (iv) creation of three

zones and rotation of commercial vessels throughout them to try to evenly disperse fishing effort; and (v) a bycatch policy mandating the retention of all bycatch species for marketing and processing at the landing sites (14-16). In addition, TAFIRI put forth maximum sustainable yield (MSY) recommendations, but harvesting levels were twice the recommended amounts (17).

Although the prohibition of night trawling was meant to reduce conflict with artisanal fishermen, an unintended consequence of this policy was exacerbated damage to the bottom habitats as trawlers conducted heavier sweeps with tickler chains to dig up *Penaeus semisulcatus*, a nocturnal shrimp species (18). Regulations did not require turtle exclusion devices (TEDs) and bycatch reduction devices (BRDs). The net result was the harvesting of many unintended marine and estuarine species, as well as increased turbidity and habitat damage (14, 16, 18, 19). To address these issues and concerns related to overfishing of the shrimp stock, trawling was banned outright in 2008 (20).

Bycatch species included seagrasses, sponges, sea cucumbers, starfish, crabs, fish, squid, sharks, rays, and sea turtles. Common bycatch fish species include *Arius* spp. (catfish), *Chirocentrus* spp. (wolf herring), *Gazza minuta* (toothpony), *Hilsa kelee* (kelee shad), numerous *Leiognathidae* spp. (pony fish), *Mugil* spp. (mullet), *Pellona ditchela* (Indian pellona), *Trichiurus lepturus* (largehead hairtail), *Thryssa vitrirostris* (orangemouth anchovy) and immature valuable commercial species such as *Gerres filamentosus* (whipfin silver-biddy), *Johnieops sina* and *Otolithes ruber* (croakers), *Sphyrna obtusata* (barracuda), and *Terapon theraps* (largescale grunter) (10, 14, 16,

21). Clearly one would expect trophic interactions among the species. It is entirely possible that removal of a key species by one fishery could have significant effects in the other. However we have no empirical evidence or data which would allow us to identify such interactions.

Artisanal Catch Levels within Bagamoyo District

In Tanzania, all artisanal catch is supposed to be recorded at the District level. Yet, data collection is not always systematic due to budgetary and logistical constraints. In the case of Bagamoyo District, only two of the eight landing stations (i.e., Nchi Pana and Custom) systematically record landings (10). Based on a very limited data set provided by the Bagamoyo District Natural Resource Office, the total artisanal catch in the district declined from a high point of approximately 4200 tonnes in 1995 to approximately 1250 tonnes in 2005, but then rose to 3875 tonnes by 2009 (Figure S1). The data also reveal that the number of licensed fishermen within Bagamoyo District rose from approximately 900 to 1,751 individuals from 1994 to 2010, with the largest increase occurring between 2004 and 2005 (Figure S1). These data, however, should be interpreted with caution. Semesi et al. (10) found that many of the District's official records underestimated the actual quantities of shrimp and fish harvested since fishermen often do not take their catch to the landing sites to avoid paying taxes. Furthermore, the number of licensed fishermen may not reflect the actual number of fishermen since they may have been encouraged to register in certain years. Moreover, there is no information on the MSY with which we can compare the harvest data. We

therefore cannot infer any conclusions about the sustainability of the current rate of harvest.

To understand how the artisanal catch levels reported by the District compare with the national trends, we plotted the total artisanal catch for Bagamoyo District with the national-level total shrimp and marine fish capture statistics compiled and submitted by the government of Tanzania to the Food and Agricultural Organization of the United Nations (FAO). The countrywide total catch declined and then leveled off from 2004 to 2008, while the total artisanal catch within Bagamoyo District has increased since 2005 (Figure S2). The nationwide ban on commercial bottom trawling in 2008 could be a large contributor to the fisheries resources and their availability to the subsistence and artisanal fisheries, as evidenced by the increase in Bagamoyo District catch in 2008 and 2009 (Figures S1 and S2). Further, the increase observed within Bagamoyo District may in part be due to the establishment of SANAPA and the subsequent protection of important nursery habitats; however we cannot draw any firm conclusions from the available fisheries data.

Future Monitoring

Given the lack of fisheries independent monitoring data, we could only infer the relationship between mangrove protection and increased fisheries production. Therefore, we recommend the implementation of a series of standardized surveys to monitor changes in fish and shrimp abundance in the riverine and coastal mangrove habitat protected along the Wami River and Estuary over time so that future studies can

base analyses on empirical evidence. Precise details will be site specific, but important components to consider when designing and executing a fisheries monitoring program include a sound experimental and statistical design that is pragmatic (e.g., costs, sustainable funding, logistics), and encourages improvements in local assessment capacity.

Fisheries monitoring methods need to be reliable, repeatable, and conducted consistently over time for intra- and interannual temporal comparisons (22). To make these efforts comparable to other studies carried out in the Western Indian Ocean region, sampling regimes should be linked to life histories and habits of the species of interest during neap spring tides with stake nets (23-25). In addition, appropriate sample sizes for stock assessments and the inclusion of spatial and temporal controls are important considerations. The collection of other important physiochemical aquatic variables and mangrove characteristics such as structural complexity of the root system to track the extent of nursery habitat over time are also recommended.

References

1. Rönnbäck P, Troell M, Kautsky N, Primavera JH (1999) Distribution pattern of shrimps and fish among *Avicennia* and *Rhizophora* microhabitats in the Pagbilao Mangroves, Philippines. *Estuar Coast Shelf Sci* 48:223-234.
2. Bosire JO, Dahdouh-Guebas F, Kairo JG, Cannicci S, Koedam N (2004) Spatial variations in macrobenthic fauna recolonisation in a tropical mangrove bay. *Biodivers Conserv* 13:1059-1074.
3. Huxham M, Kimani E, Augley J (2004) Mangrove fish: a comparison of community structure between forested and cleared habitats. *Estuar Coast Shelf Sci* 60:637-647.
4. Crona BI, Rönnbäck P (2005) Use of replanted mangroves as nursery grounds by shrimp communities in Gazi Bay, Kenya. *Estuar Coast Shelf Sci* 65:535-544.
5. Crona BI, Holmgren S, Rönnbäck P (2006) Re-establishment of epibiotic communities in reforested mangroves of Gazi Bay, Kenya. *Wetlands Ecol Manage* 14:527-538.
6. Crona BI, Rönnbäck P (2007) Community structure and temporal variability of juvenile fish assemblages in natural and replanted mangroves, *Sonneratia alba* Sm., of Gazi Bay, Kenya. *Estuar Coast Shelf Sci* 74:44-52.
7. Al-Khayat JA, Jones DA (1999) A comparison of the macrofauna of natural and replanted mangroves in Qatar. *Estuar Coast Shelf Sci* 49:55-63.
8. Wooldridge JM (1995) Selection corrections for panel data models under conditional mean independence assumptions. *J Econom* 68:115-32.
9. Seber GAF (1992) A review of estimating animal abundance II. *Int Stat Rev* 60: 129-166.
10. Semesi et al. (1998) Coastal resources utilization and conservation issues in Bagamoyo, Tanzania. *Royal Swedish Acad Sci* 27:635-644.
11. Amir OA, Berggren P, Jiddawi NS (2002) The incidental catch of dolphins in gillnet fisheries in Zanzibar, Tanzania. *Western Indian Ocean J Marine Sci* 1:155-162.
12. Jiddawi NS, Öhman MC (2002) Marine fisheries in Tanzania. *Ambio* 31:518-527.
13. Chande AI, Mhitu HA (2003) *Size structure, maturity status and relative abundance of prawns in different fishing areas during pre-season (2003)*. (Tanzania Fisheries Research Institute, Dar es Salaam, Tanzania).
14. Haule WV (2001) Tropical Shrimp Fisheries and Their Impact on Living Resources *FAO Fisheries Circular No. 974* (Food and Agriculture Organization, Rome), pp 216-233.

15. Bwathondi PJ, et al. (2002) *Investigations on the abundance and distribution of prawns at Bagamoyo and Rufiji Delta*. (Tanzania Fisheries Research Institute, Dar es Salaam, Tanzania).
16. Sookocheff W, Muir C (2007) *A literature review of marine fisheries bycatch data in the United Republic of Tanzania*. (Sea Sense, Dar es Salaam, Tanzania).
17. Tanzania Coastal Management Partnership (2009) *Community based fisheries management plan Bagamoyo District, Tanzania*. (Tanzania Coastal Management Partnership, Dar es Salaam, Tanzania).
18. Castro K, Parker L (2008) *Rapid assessment of the Tanzania commercial trawl fisheries: Management issues and by-catch reduction strategies*. (Tanzania Coastal Management Partnership, Dar es Salaam, Tanzania).
19. Lema RE (2005) *Concerns over prawn trawling in the territorial waters of Tanzania mainland*. (Tanzania Coastal Management Partnership, Dar es Salaam, Tanzania).
20. West L (2010) *Indian Ocean Turtle Newsletter*, eds Schauble C, Shanker K (Medknow, Bombay), No. 11.
21. Nhwani LB, Mwaiko SP, Chande AI, Mwamsojo GJ, Mhitu HA (1993) *Crustacean resource assessment in Rufiji and by-catch studies of prawn trawlers. Consultant report to National Environment Management Council* (National Environment Management Council, Dar es Salaam, Tanzania).
22. Krebs, CJ (1989) *Ecological Methodology*, eds Wilson C, Pisano S (Harper and Row, New York).
23. Huxham M, Kimani E, Augley J (2004) Mangrove fish: a comparison of community structure between forested and cleared habitats. *Estuar Coast Shelf Sci* 60:637-647.
24. Crona BI, Rönnbäck P (2005) Use of replanted mangroves as nursery grounds by shrimp communities in Gazi Bay, Kenya. *Estuar Coast Shelf Sci* 65:535-544.
25. Crona BI, Rönnbäck P (2007) Community structure and temporal variability of juvenile fish assemblages in natural and replanted mangroves, *Sonneratia alba* Sm., of Gazi Bay, Kenya. *Estuar Coast Shelf Sci* 74:44-52.

Table S1. Summaries of research articles pertinent to our study.

<p>Al-Khayat and Jones, 1999. A comparison of the macrofauna of natural and replanted mangroves in Qatar</p> <p><u>Study Location:</u> Qatar. <u>Date of Study:</u> June 1993-June 1994. <u>Purpose:</u> To quantify decapod and fish biodiversity in a natural <i>Avicenna marina</i> mangrove, a ten-year old <i>A. marina</i> mangrove plantation, and a salt marsh to ascertain if pelagic biota recolonize replanted mangroves. <u>Methods:</u> Hand net fishing to capture juvenile and small fish, gill net (20m x 1.5m with 7cm mesh) and seine net (15m x 1.5 m with 5cm mesh) fishing to capture adults. <u>Main relevant findings:</u> 1) Natural mangrove areas had smaller sediment grain size and higher levels of organic material and substrate moisture in comparison to the planted mangrove areas 2) Overall species diversity ranged from 33-34 spp. among the natural sites, 27-33 spp. among the replanted sites, and 24 spp. in the salt marsh sites. 3) 26-30 spp. of juvenile fish and 17 spp. of adult fish were captured in the natural sites versus 13-22 spp. of juvenile fish and 9-14 spp. of adult fish in the replanted sites. 4) <i>P. semisulcatus</i> was present in both the natural and replanted sites. 5) The natural and replanted sites demonstrated 61% similarity. <u>Relevant study conclusions:</u> Difference in species diversity and abundance between the natural and replanted sites was due to the slow accretion rates of organically rich, fine sediment and differences in bordering vegetation types.</p>
<p>Rönnbäck et al., 1999. Distribution pattern of shrimps and fish among <i>Avicennia</i> and <i>Rhizophora</i> microhabitats in the Pagbilao Mangroves, Philippines</p> <p><u>Study location:</u> Pagbilao Bay, Philippines. <u>Date of study:</u> 1996. <u>Purpose:</u> To determine the shrimp and fish species composition and distribution in natural stands of <i>Avicennia officinalis</i>, <i>A. marina</i> and <i>Rhizophora opiculata</i> and 5-6 year old restored <i>R. opiculata</i>. <u>Methods:</u> Stake netting (2-3mm mesh) to capture post larvae penaeid shrimp and fish. <u>Main relevant findings:</u> 1) The most abundant shrimp were Palaemonidae (53.5%) followed by <i>Acetes spp.</i> (31.7%). 2) Fish from 37 taxa were caught with <i>Ambassis urotaenia</i>, <i>A. kopsi</i> and <i>Atherinomorus balabacensis</i> comprising more than 92% of the total abundance. 3) The replanted <i>Rhizophora</i> site, which had the greatest structural complexity, exhibited the highest shrimp density whereas the highest small-sized fish density and biomass were observed in <i>Avicennia</i> sites located furthest inland. <u>Relevant study conclusions:</u> The successful shrimp and fish recolonization of the replanted <i>Rhizophora</i> habitat suggests that mangrove restoration can help to restore depleted fisheries (p. 233).</p>
<p>Bosire et al., 2004. Spatial variations in the macrobenthic fauna recolonisation in a tropical mangrove bay</p> <p><u>Study location:</u> Gazi Bay, Kenya. <u>Date of study:</u> Not specified, but the research was conducted five years after mangrove replanting. <u>Purpose:</u> To study the recolonization of macrobenthic fauna in replanted <i>Avicennia marina</i>, <i>Rhizophora mucronata</i>, and <i>Sonneratia alba</i> mangrove plantations. <u>Methods:</u> Crabs and sediment infauna were collected from randomly placed quadrats, identified, and counted. <u>Main relevant findings:</u> 1) Natural sites had the highest sediment infauna density with the exception of the reforested <i>A. marina</i> site. 2) The <i>R. mucronata</i> and <i>A. marina</i> reforested sites had higher crab densities than the natural forests, but the reverse pattern was observed within <i>S. alba</i> sites. <u>Relevant study conclusions:</u> Similarities in the number of taxa between natural and reforested sites suggests a recovery in habitat provisioning ecosystem services (p.1069).</p>

Huxham et al., 2004. Mangrove fish: a comparison of community structure between forested and cleared habitats

Study location: Gazi Bay, Kenya. Date of study: 2002. Purpose: To compare the fish communities among natural, reforested, and cleared sites of *Sonneratia alba*, and *Rhizophora mucronata*. Methods: Stake netting with single (100m with 1mm mesh) and paired (24m with 1mm mesh) nets to capture fish. Main relevant findings: 1) Site 1, a *S. alba* plantation planted years before the study, had the highest mean abundance, biomass, and species richness of all mangrove sites, the second highest total number of species, and supported several species found only in mangroves. Relevant study conclusions: The findings suggest that reforested sites are capable of providing “suitable (or possibly superior) habitat for fish” (p.644).

Crona and Rönnbäck, 2005. Use of replanted mangroves as nursery grounds by shrimp communities in Gazi Bay, Kenya

Study location: Gazi Bay, Kenya. Date of study: 2002-2003. Purpose: To assess the distribution of post larval and juvenile shrimps in two different 8 year old reforested *Sonneratia alba* stands (IP and MP) and compare these findings to natural and clear cut sites. Methods: Stake netting (2mm mesh enclosing 9m² of intertidal microhabitat). Main relevant findings: 1) A total of 615 individuals from 19 spp/taxa were caught with Penaeids comprising 66% of the catch. 2) ANOSIM (analysis of similarities) found the natural and reforested IP site to have similar shrimp species composition and abundance values. 3) Macrobrachium spp., Acetes spp., and *P. semisulcatus* were mainly found in the natural and reforested IP sites, *P. indicus* was found mainly in the reforested MP site, *M. monoceros* was found in the natural and both reforested sites, and *P. japonicus* was found predominantly in the clear cut site. Relevant study conclusions: The higher diversity of penaeid spp. in the natural and reforested IP sites are likely due to longer periods of inundation and greater heterogeneity in structural complexity (p.543).

Crona et al., 2006. Re-establishment of epibiotic communities in reforested mangroves of Gazi Bay, Kenya

Study location: Gazi Bay, Kenya. Date of study: 2002. Purpose: To examine epibiotic flora and fauna recolonization in 8 year old replanted *Sonneratia alba* pneumatophores and trunks and compare these findings to natural and clear cut sites. Methods: Sampling of all epibiota within randomly placed 0.5m x 0.5m wood frames. Main relevant findings: 1) There were 18 species of algae in the natural site, 23 spp. in the reforested IP site, 10 in the reforested MP site, and 1 in the clear cut site; 2) the highest total algae and sessile fauna biomass occurred in the natural and reforested IP sites.

Crona and Rönnbäck, 2007. Community structure and temporal variability of juvenile fish assemblages in natural and replanted mangroves, *Sonneratia alba* Sm., of Gazi Bay, Kenya

Study location: Gazi Bay, Kenya. Date of study: 2002. Purpose: To determine the abundance and species composition of juvenile fish within two different 8 year old replanted *Sonneratia alba* sites and compare these findings to natural and clear cut sites. Methods: Stake netting (2mm mesh enclosing 9m² of intertidal microhabitat). Main relevant findings: 1) A total of 1800 individuals from 49 taxa and 34 families were caught with five spp/taxa comprising ~70% of the total fish abundance. 2) Margalef's index of species richness ranged from 1.07 at restored site MP to 1.43 at restored site IP, and Shannon-Wiener diversity ranged from 0.66 at the natural site to 1.00 at the clear cut site. There were no statistically significant differences between any of the sites. 3) The clear cut site had the highest fish abundances while restored site MP had the lowest abundance, but highest fish biomass. Relevant study conclusions: 1) The insignificant differences between diversity values suggest that at this spatial scale, temporal patterns play a larger role in juvenile fish assemblages than the presence and type of mangrove (p.50). 2) Similarities in fish density, diversity, and community composition between the natural and replanted sites suggest that the refuge and foraging areas for juvenile fish has been restored in the replanted mangroves (p. 50). 3) Higher fish densities in the clear cut site may be explained by its small size and enclosure by mangrove habitat at a larger spatial scale (p. 50).

Table S2. Perceptions of the effect of SANAPA on livelihood, 2010.

	Mean of households in subvillages which has some mangrove cover within SANAPA in 5km radius	Mean of households in subvillages which has no mangrove cover within SANAPA in 5km radius
Lost access to mangroves used for cooking fuel	-2.38	-3.33
Lost access to mangroves for income (e.g., charcoal)	-3.54	-2.93
Lost access to land to grow crops	-4.08	-3.90
Lost access to fishing grounds	-1.58	-2.31
There has been increase in mangroves	3.36**	2.17
There has been increase in fish stock	0.26	0.49
There has been increase in shrimp stock	-0.35	-0.23
There has been increase in coastal buffer against storms	-0.24	0.46
Better water quality	0.86	0.17
More tourism-related jobs	-0.06	-0.06
Any negative impact of SANAPA on your livelihood (%)	44%***	17%
Any positive impact of SANAPA on your livelihood (%)	24%***	5%

Notes: The respondent was asked whether they agree or disagree with each statement and to rate the response on an 11-point Likert scale. We rescaled the original numbers so that +5 indicated “strongly agree” and -5 indicated “strongly disagree”. The numbers shown in the table are means. The last two rows show the percentage of households agreeing to the statement. ***, ** indicates that the difference between the two groups are statistically significant at the 1% and the 5% level, respectively.

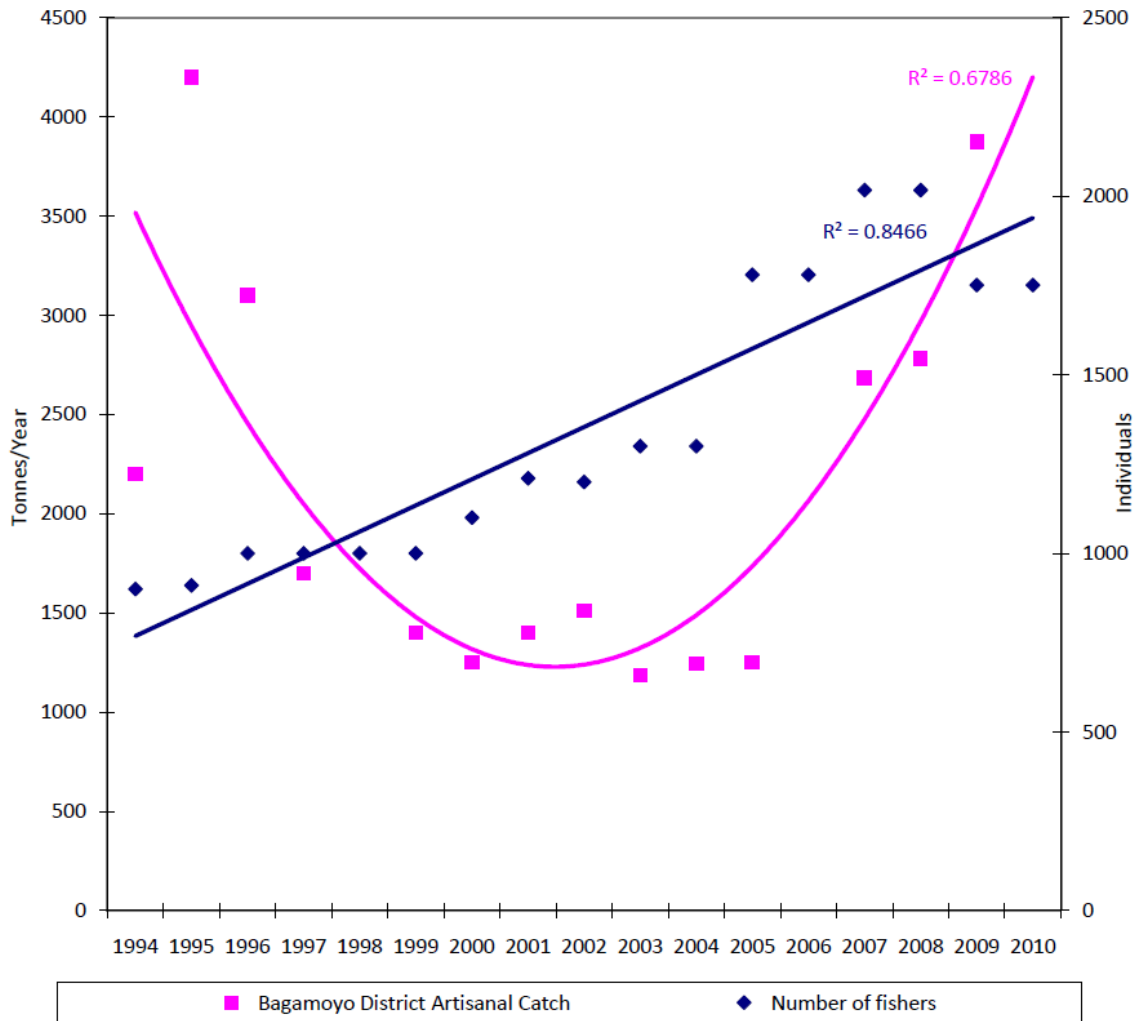
Table S3. Probit model for having fishing income in 2004 or not.

	Dependent variable: Having fishing income in 2004 (=1 if some fishing income in 2004, 0 otherwise)
Household size	0.02 (1.21)
Household head's age	0.00 (0.07)
Gender (=1 if household head is female, 0 otherwise)	-0.29*** (-4.17)
Household head's education dummy (=1 if 3 years)	0.14 (0.57)
Household head's education dummy (=1 if 4 years)	0.28 (0.58)
Household head's education dummy (=1 if 5 years)	0.35 (0.92)
Household head's education dummy (=1 if 6 years)	0.00 (0.01)
Household head's education dummy (=1 if 10 years)	0.55** (2.20)
Credit market access (=1 if cannot borrow from commercial bank in times of need)	0.14 (1.58)
Credit market access (=1 if don't know whether they can borrow from commercial bank in times of need)	-0.08 (-0.39)
Productive and consumable asset per capita in 2004	0.00 (0.12)
Observations	127
Pseudo-R ²	0.11

z-statistics are listed in parentheses. Significant at *** p<0.01, ** p<0.05, * p<0.1

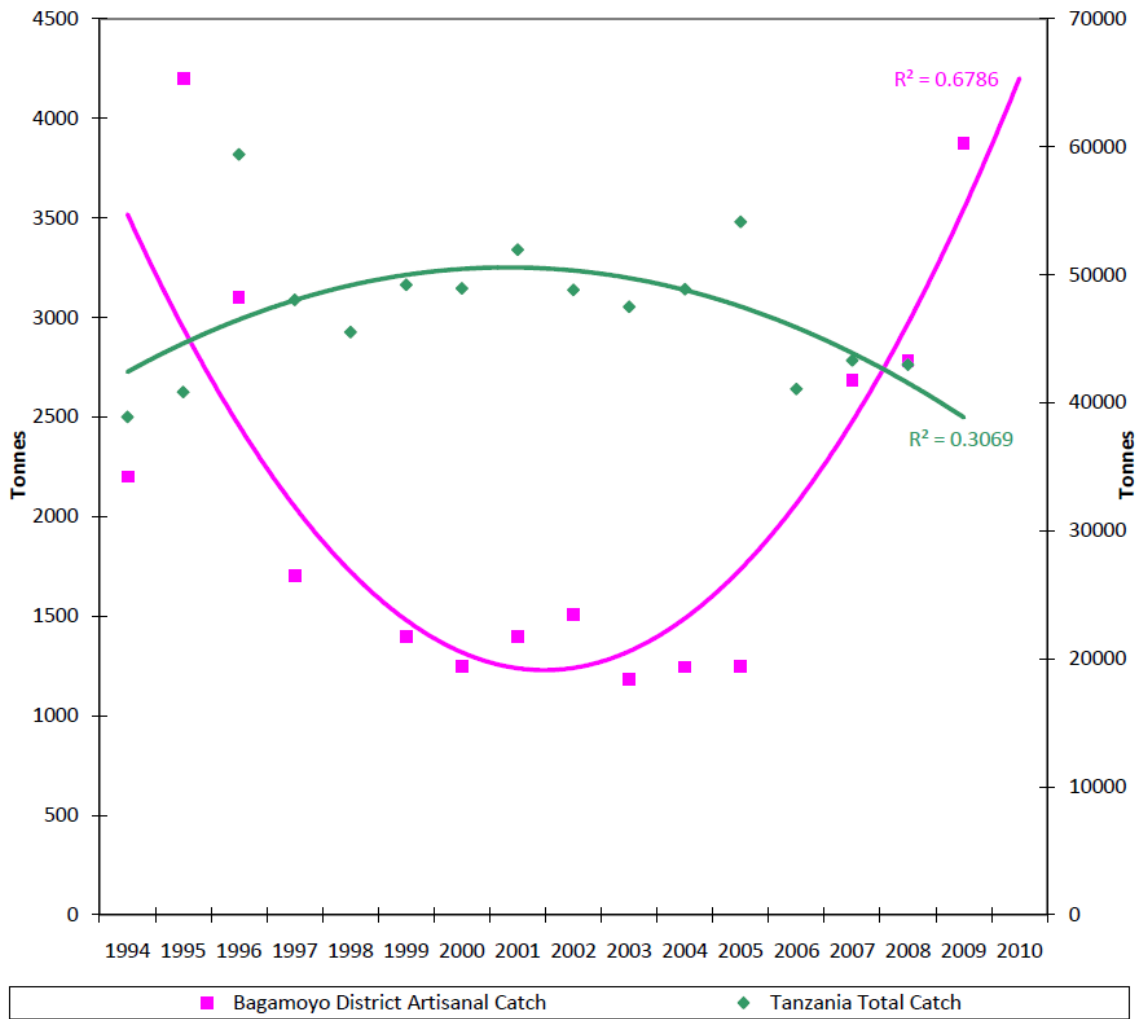
Table S4. Descriptive Statistics.

Variable	Obs	Mean	Std. Dev.
Fishing Income in 2004 (1000 Tanzania Shilling)	65	370.78	641.50
Fishing Income in 2009 (1000 Tanzania Shilling)	65	599.21	851.35
Shrimping Income in 2004 (1000 Tanzania Shilling)	34	659.54	956.86
Shrimping Income in 2009 (1000 Tanzania Shilling)	34	674.03	930.90
Household Size	150	4.68	2.42
Household Head's Age	146	42.32	12.07
Household Head's Gender (=1 if female)	150	0.13	0.33
Household Head's Education (years)	150	5.41	2.35
Credit Market Access (=1 if can borrow from commercial bank in times of need, =0 if cannot borrow)	143	0.26	0.52
Asset Per Capita in 2004 (1000 Tanzania Shilling)	150	421.85	735.40
Asset Per Capita in 2009 (1000 Tanzania Shilling)	150	441.67	618.35
Mangrove Cover in 5km radius circle within SANAPA Boundaries in 2005 (square km)	150	0.71	1.75
Mangrove Cover in 5km radius circle within SANAPA Boundaries in 2010 (square km)	150	0.73	1.79
Mangrove Cover in 5km Buffer outside SANAPA Boundaries in 2005 (square km)	150	2.35	1.89
Mangrove Cover in 5km Buffer outside SANAPA Boundaries in 2010 (square km)	150	2.42	1.93
Distance to SANAPA Boat Ramp (km)	150	39.04	21.59



Source of data: Bagamoyo District Natural Resource Office

Figure S1. Multispecies artisanal catch and number of licensed artisanal fishers in Bagamoyo District from 1994 to 2010.



Source of data: FAO Capture Production Statistics and Bagamoyo District Natural Resource Office

Figure S2. Total shrimp and marine fish catch in Tanzania (1994-2008) compared to the total artisanal catch in Bagamoyo District (1994-2009).

**Irrigation in a Free-Flowing River in East Africa: Impacts on Downstream
Ecosystem Goods and Services Provided by a Coastal Protected Area**

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To be submitted to the journal River Research and Applications

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Abstract

Modifications to the natural flow regime can be particularly damaging to protected areas that have been set aside to sustain biodiversity and ecosystem services that depend on water resources. This study examines the effects of water withdrawal from a proposed 10,500 ha irrigated biofuel project on the Wami River on the delivery of ecosystem goods and services to Saadani National Park and neighboring local communities. We utilize daily flow data collected from 1954 to 1978 to derive a number of low flow and extreme low flow parameters for flow durations ranging from 1 to 90 days to characterize the historic and post-irrigation freshwater flow regime of the Wami River. Our findings demonstrate that the proposed withdrawals during the dry season would dramatically alter the flow regime of the lower Wami River and create conditions unlike any observed over the 24 year period of flow records analyzed. Under the abstraction scenario, flow values that historically occur at the Q99.5 level are observed with a Q95 frequency (i.e., a 10-fold increase in the occurrence of these low flow levels), and the number of years with extended periods of extreme low flow increase. Importantly, the incidences of zero flow days over the 24 year period of record would rise from 15 to 300 creating extended periods of no-flow conditions that would completely dry out lower portions of the Wami River. These changes would have profound effects on the habitats, wildlife, fisheries and human values and functions that constitute Saadani National Park. New large scale water withdrawals must be approached with caution in perennial, free-flowing rivers draining arid watersheds of

eastern Africa to sustain the critical riverine and estuarine linked ecosystem goods and services of downstream protected areas.

Introduction

Protected areas within riverine estuaries are deeply dependent upon the incoming freshwater flow regime and are vulnerable to upstream anthropogenic activities (Estevez 2002, Jameson 2002, Arthington 2012). Numerous examples from around the world document how dam construction, irrigation abstractions, urbanization, and other land-use changes alter the amount, timing, frequency, and quality of freshwater inflows into rivers and estuaries (Alber 2002, Postel and Richter 2003, Dickens 2003, Vorosmarty et al. 2010, Vilarly et al. 2011, de Luz and Genz 2013, Adams 2014). Alterations to the natural flow regime, in turn, can cause abiotic and biotic changes within the downstream riverine, estuarine, and coastal ecosystems (Poff et al. 1997, Loneragan and Bunn 1999, Bunn and Arthington 2002, Robins et al. 2005, Poff and Zimmerman 2010, Bucx et al. 2010, Rolls et al. 2012). These changes can be particularly damaging to protected areas that have been set aside to sustain biodiversity and ecosystem services as alterations in flow regime can affect the distribution and survival of flora and fauna and the delivery of the ecosystem goods and services that the protected areas are designed to preserve (Mtahiko et al. 2006, Elisa et al. 2010, McClain et al. 2014).

Reductions in the quantity of freshwater inflow to estuaries can diminish the effective size of an estuary, increase salinity, reduce dissolved oxygen, nutrient input, and sediment recharge, and alter circulation patterns and increase residence time (Olsen et al. 2006). Furthermore, alterations in the timing of freshwater inflows can

lead to the degradation of habitats adapted to the seasonal freshwater pulses and associated changes in salinity levels as well as the removal of certain estuarine organisms with life history stages tied to particular inflow regimes and biogeochemical conditions (Olsen et al. 2006).

Over the past decade there have been many efforts across the globe to establish environmental flows as a cornerstone for river and estuary management (Postel and Richter 2003, Tharme 2003, Dickens 2011, Arthington 2012, Acreman et al. 2014). An environmental flow is defined as “the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems” (Brisbane Declaration 2007, p.1). It sets a dividing line between the water reserved for ecosystems and water available for other human uses, such as irrigated agriculture. Environmental flow recommendations have emerged as a management tool for proactively minimizing or reactively mitigating the abiotic and biotic repercussions of flow regime alterations by explicitly reserving water for ecosystems (Postel and Richter 2003).

In 2007, an interdisciplinary team comprised of natural and social scientists and water resource managers conducted an initial Environmental Flow Assessment for segments of the Wami River to help operationalize Tanzania’s National Water Policy and inform future water use planning. This initiative was proactive in nature since unlike other rivers within Tanzania (e.g., the Greater Ruaha, Katuma, Pangani, and Ruvu rivers), the Wami River and its upstream watershed have not yet undergone extensive development and are still in a relatively intact state (Tobey 2008, Sarmett and Anderson

2008). The purpose of the estimated initial environmental requirements was to provide decision makers within the Wami Ruvu Water Basin Office scientific information that could be used to ascertain permissible quantities of water for extractive water uses that would still allow for the maintenance of a desired level of protection for the river and its related ecosystems (Dickens 2011). While this initiative resulted in specific flow recommendations for the Wami River (see Sarmett and Anderson 2008 for further details), the terminus of the Wami River that is located within the boundary of Saadani National Park and the Wami River Estuary fell outside the scope of the first initial EFA assessment.

In 2009, the Tanzanian government approved irrigation water withdrawals from the Wami River for a 10,500 hectare biofuel sugarcane plantation located just upstream of Saadani National Park. Increasing water withdrawals from the river, particularly during dry periods, will affect the delivery of freshwater to the downstream sections of the river and estuary located within Saadani National Park. These alterations to the natural flow regime could affect the availability of the ecosystem goods and services, and in turn, the overall well-being of the stakeholders reliant upon them.

In an attempt to further understand the linkages between hydrological alterations, ecological consequences, and ecosystem goods and services, we quantitatively assess how the proposed irrigation withdrawals from the Wami River for biofuel production could alter the freshwater inflow regime (i.e., magnitude, frequency, and duration) into the estuary and qualitatively examine the potential effect of those changes on the ecosystem goods and services utilized and valued by the different downstream

stakeholder groups. This study seeks to address key information gaps identified by Sarmett and Anderson (2008), Gordon-Maclean et al. (2008) and IUCN (2011) that can be useful for helping to inform future water management decisions within the Wami River watershed.

Specifically, we examine the following research questions:

1. What are the characteristics of the historic/pre-altered flow regime that have supported the ecosystem goods and services currently provided by the Wami River and its estuary?
2. How will proposed upstream irrigation withdrawals for biofuel production change the Wami River's flow regime?
3. How might the altered flow regime impact the ecosystem goods and ecosystem services utilized and valued by the different groups of downstream stakeholders?

Because water abstractions for irrigated agriculture are usually most intense during dry periods of the year, our analyses focus on changes in the extent and frequency of low flows.

Site Description

The Wami River originates in the Eastern Arc Mountains and flows through the semi-arid region of Dodoma on to Morogoro and then drains into the Indian Ocean after passing through Saadani National Park (Figure 1). The watershed covers an area of approximately 40,000 km², and is home to approximately 1.8 million people. The Wami River's discharge is related to both climate and land use and exhibits large intra-annual variations between the wet and dry seasons and inter-annual variation. The short rains usually commence in late December or early January and then are followed by the longer rainy season that lasts from March through June. The dry season lasts from July through November, and it is during this time that the flows in the river reach their

lowest levels. The average annual rainfall observed at a rain gauge located near the mouth of the river is ~1200mm, but the monthly amounts range from 25 mm in the dry season to 220 mm in the wet season (Valimba 2007). The annual evaporation ranges between 1200-1500 mm, and plants experience extended periods of water stress in the dry season months when evaporation exceeds precipitation.

The final 20km of the Wami River and the Wami River Estuary reside within the boundaries of Saadani National Park. Six species of mangroves (i.e., *Sonneratia alba*, *Avicennia marina*, *Rhizophora mucronata*, *Bruguiera gymnorhiza*, *Ceriops tagal*, and *Xylocarpus granatum*) line the shore near the river mouth and dominate both banks of the Wami River up to a distance of approximately 4km from the Indian Ocean. Moving upstream, date palm trees (*Nypa fruticans*) dominate riparian environments along a 2km river segment, which then transition to acacia trees and grassland (Anderson et al. 2007, McNally 2007). The flora and fauna living within and adjacent to the river channel are dependent upon functioning riverine, riparian, and estuarine ecosystems. The riverine and riparian ecosystems provide important habitat for crocodiles, hippopotami, and many different species of birds, all of which attract tourists to Saadani National Park, and the estuarine ecosystem supports one of the most important artisanal shrimp fisheries in Tanzania. Furthermore, the Wami River is the main reliable source of freshwater for wildlife in Saadani National Park during the dry season.

Methods

Hydrological Data Sets

With the assistance of water managers at the Wami Ruvu Water Basin Office, we obtained 24 years of daily flow data to generate a historical data set. The Manderu gauge, the most continuously active downstream gauge on the Wami River, is located at -6.23° latitude, 38.4° longitude (area in $\text{km}^2 = 36,450$) approximately 40 km upstream from the mouth of the Wami River Estuary (Valimba 2007). Daily flow data have been collected from this gauge from 1954 to 1984 and since 2005. For our study, we utilized the daily flow data collected from 1954 to 1978 for the 24 year historical data set since large gaps existed in the data from 1979 to 1984, no data were collected between 1984 and 2004, and the rating curves need to be verified and/or modified for the more recent data collected since 2005. While the gauging station did possess some data gaps and discontinuities from 1954 to 1978, there were only a total of ten events each lasting less than 33 days with the majority lasting less than five days (Table 1). For each gap in the data, we examined the flow values right before the gap began and right after it ended. In all cases, periods of elevated flow existed, and we filled each gap with the mean flow value derived from the two dates on each side of the data gap. Because our analyses focused strictly on low flow events, we felt confident that these mean numbers would not affect the low flow statistics. The post-withdrawal/abstraction data set was created by subtracting the monthly permitted water extractions from the flow values within the historic data set. The monthly permitted water extractions from the proposed biofuel

operation were taken from the Environmental Impact Statement prepared for the project (Orgut Consulting AB 2008, p. 58; Table 2).

Hydrological Analyses

Stream flow data are a continuous variable often summarized by frequency distributions. The values for the streamflow were ranked from smallest to largest and plotted using a Weibull distribution (Weibull, 1951) where:

$$F(x) = \frac{i}{n + 1}$$

where $F(x)$ is the non-exceedance probability, i is the rank of the flow observation, and n is the total number of flow observations. Cumulative distribution functions (CDF), or flow duration curves, show the magnitude of stream flow verses the probability the flow is not exceeded (Figure 2). These statistical flows are frequently expressed in the complementary form; for example, Q99 is the flow magnitude (volume/time) that is equaled or exceeded 99% of the time, which therefore represents the lowest 1% of flow observations.

We calculated a number of low flow and extreme low flow parameters in Microsoft Excel to characterize the historic and post-irrigation freshwater flow regime of the Wami River. These included the number and length of time with zero flow days, and exceedance levels associated with other studies of low flows: Q90, Q95, Q99 and Q99.5 (Smakhtin 2001, Pyrcce 2004, Shokoohi and Hong 2011). The Q99 and Q99.5 are considered to represent more extreme drought conditions (Price et al. 2011). These

flow parameters were developed for a range of flow durations encompassing 1,7,14,30, 60 and 90 days of consecutive days of flow observations. A daily, 24-year flow regime was created that represented the hypothetical conditions that would occur with the proposed biofuel operation (post-irrigation flow regime). This was accomplished by subtracting the expected daily withdrawal rate for each month (Table 2) from the actual historical daily flow rates within that month for each of the 24 years of record.

Given the infancy of the science empirically testing the relationships between changes in the flow regime and ecological responses, it is not possible to know where the exact thresholds exist (e.g., Poff and Zimmerman 2010, Webb et al. 2013, Acreman et al. 2014). Therefore, we also evaluated changes in the median and lower quartile (75th percentile) values that would result from the proposed biofuel operation.

Results

Based on the 24 years of historic data, the average daily flow rate of the Wami River at the Mandera gauging station was found to be 58.9 m³/s, equivalent to a depth of approximately 51 mm/year of flow. On a global scale, large river systems with this rate of runoff are classified as “arid” (Milliman and Farnsworth 2011). On the African continent, large river systems (i.e., watershed areas > 500,000 km²) in this category include the Nile, the Zambesi, and the Niger. The Murray-Darling River of Australia, which received international attention for its unprecedented drought in the first decade of the 21st century, is also in this category.

In addition to its relatively low annual flow, the Wami River exhibits considerable skewness with a coefficient of skewness of 6.6. The ratio of mean daily flow to median

daily flow is 2.3. The incident of small flows is high and the river experiences very large flows on an infrequent basis. The daily flow regime is also highly variable (both seasonally and annually) with an overall coefficient of variability of 1.8. Median monthly flow during April (often the month with highest flows) is approximately 13-fold greater than the median flow during October, the month that usually has the lowest flows (Table 3). The mean annual flow values over the 24 years of record display a coefficient of variation of 0.72 and a skewness coefficient of 2.97, placing the Wami River well above mean values of these characteristics for over 1200 river systems of the globe (McMahon et al. 2007).

To further illustrate the extent of seasonal and interannual variation, we compared high monthly flows to low monthly flows over the 24 years of flow records of the Manderu gauging station. We used the second highest and second lowest monthly values from the period of record to represent high and low flows for these comparisons, rather than the lowest or highest observed values to avoid drawing conclusions from conditions that might represent unusual extremes (e.g., the 100 year drought or flood). For the month of April, which is frequently the month with the highest flow, the second highest monthly flow rate ($369 \text{ m}^3/\text{s}$) is more than eight-fold higher than the second lowest monthly flow rate observed for that month ($46 \text{ m}^3/\text{s}$). For the month of October, often the month with the lowest flow of the year, the second highest monthly flow rate ($37 \text{ m}^3/\text{s}$) is more than nine-fold above the second lowest monthly flow for that month ($4 \text{ m}^3/\text{s}$) (Figure 3). The ratio of the high April flow rate to the low October flow rate is more than 92:1. These large seasonal and annual variations warrant careful

examination of the relative magnitude of the biofuel project abstractions to river flow during the drier months of the year.

During the wetter portions of the year (April and May), the projected monthly withdrawals for the biofuel project were found to represent a relatively modest fraction of the average or median monthly river flows (Table 3). Abstraction requirements during the driest portion of the year (September to November) were comparatively more substantial constituting between 32 and 40% of the median monthly flow (Table 3).

The effects of irrigation withdrawals are particularly compelling when examining low and extremely low flow events. During the 24 years of historic daily flow records analyzed for this study, zero flows were found to occur on 15 days (i.e., 0.16% of the period of record). In contrast, with abstraction due to the proposed biofuel project, the number of zero flow days increased to 300 (i.e., 3.3% of the time). Zero flow was predicted to occur on 35 distinct events (an event is defined as a period of consecutive days where flow is continuously below a given flow threshold) with four of the events each constituting 27 to 29 consecutive days with no flow. Analyzing the 7 day consecutive flow rates, the Q99.5 of the historic data was $1.2 \text{ m}^3/\text{s}$ with zero flow occurring only once for more than 7 days during the extensive drought of 1975. In contrast, with abstractions proposed for the biofuel project, zero flows for 7 consecutive days would increase to a Q99 frequency and occur on 16 different occasions over the 24 years of record (Table 4).

Examining shifts in the low flow indices provides further evidence of the extent of change generated by the proposed project. With the historic flow regime, the Q99.5 for daily flows is $0.8 \text{ m}^3/\text{s}$. That same magnitude of flow, however, would be observed with a Q95 frequency under the abstraction scenario (Table 4). Thus, the proposed irrigation project would shift the frequency of flow of $0.8 \text{ m}^3/\text{s}$ or less from 1 day out of 200 to 5 days out of 100 (i.e., a 10-fold increase in the occurrence of these low flow levels). This same trend in the shift in flow rate is evident for almost all the time increments (i.e., 1, 7, 14, 30, 60 and 90 days; Table 4). The historic Q99.5 flow rate occurs at approximately the Q95 level under the abstraction scenario meaning that the ecosystem would experience very low flows with much higher frequency under the proposed irrigation project.

Examination of the low flow metrics on a yearly basis provides insights into the regularity of changes in low flow that could result from abstractions associated with the biofuel project. It allows one to ascertain if the extreme low flow events would be restricted to just a few years or whether the extreme low flows would occur during many years with major consequences for the resilience and recovery of the ecosystem. Our results demonstrate that the abstractions associated with irrigation would dramatically increase the frequency of drought conditions in a sizeable majority of the years.

At all the time increments analyzed, we ranked the Q99.5 value for each year of record and found that the historic median annual Q99.5 flow rate would occur 20 times more frequently (Q90) if abstraction for irrigation commences (Table 5). Under the

abstraction scenario, daily flow rates of zero were found to occur at a frequency of Q95 (1 out of 20 days) during one out of four years (Table 6). As noted previously, based on historic records, zero flow rates were not even observed at the Q99.5 frequency. So, as well as extreme low flows occurring in more years, the number of years with extended periods of extreme low flows would also increase. From examination of the lower quartile of the distribution of annual flow indices, the 30 day Q95 with abstraction is lower than the 1 day Q99.5. Thus, one of 4 years would experience severe, prolonged droughts with abstraction.

Discussion

Our results demonstrate that new large scale water withdrawals must be approached with caution in free-flowing rivers (i.e., lacking dams and reservoirs) draining watersheds of eastern Africa to sustain riverine-linked ecosystem goods and services of the terminal downstream estuary. High production irrigated cropping systems can generate profound changes in the frequency and severity of drought due to the extreme seasonal variation in flow rates. As evidence, we examined the effects of water withdrawal from the proposed 10,500 ha irrigated biofuel project on the lower Wami River. The required water withdrawals from this single farm, which constitute less than 0.01% of the area of 400,000 km² watershed, would consume only 5.9% of the average daily flow rate. However, because of the high seasonal and interannual variability, withdrawals during the dry season would dramatically alter the flow regime of the lower Wami River and would periodically create extended periods of no-flow -- completely drying out the lower portions of the Wami River for extended periods

resulting in extremely destructive effects on the biota and human populations of Saadani National Park.

Biotic and human communities typically develop adaptive strategies to resist or recover from a predictable range of seasonal low flows that occur annually (Boulton 2003, Lake 2003). However, in intense drought conditions, a riverine ecosystem undergoes a series of predictable responses from isolation of fringing vegetation to cessation of flow and finally elimination of surface waters (Boulton 2003). The transition to each of these stages represents a potential ecological threshold – where a relatively small reduction in flow generates large, often non-linear, responses (Groffman et al. 2006). In the Wami River, these changes could result in a dramatic loss of taxa and biotic diversity. The proposed abstractions for biofuel production would create conditions unlike any observed over the 24 year period of flow records analyzed – potentially generating a dramatic disturbance that exceeds the resistance and recovery strategies of the extant ecosystem and thus degrades the value of ecosystem goods and services associated with the riverine and estuarine system (Humphries and Baldwin 2003). These types of changes would have profound effects on the habitats, wildlife, fisheries and human values and functions that constitute Saadani National Park.

The lower Wami River and Estuary currently provide a host of ecosystem goods and services to Saadani National Park and the adjacent local communities. However, increasing the occurrences of periods with no flow or very low flows will eliminate or sharply limit a number of ecosystem goods and services that are valued by stakeholders. McNally et al., (chapter 1 of this dissertation) surveyed the perceptions of three groups

of stakeholders regarding their valuations of ecosystem services provided by the Wami River and Estuary. The stakeholder groups included local residents, tourism operators and conservation organizations. Out of 30 different ecosystem services evaluated, all three of the stakeholder groups gave high values to domestic water, the sustenance of fish and shrimp for subsistence and commercial harvest, wildlife habitat, and tourism.

Insights on the possible consequences of reduced low flows to the valued ecosystem goods and services can be obtained by examining the fate of two other Tanzanian river systems that have experienced water withdrawals from irrigated agriculture. As with the Wami River, withdrawals are greatest during the dry season when the river flows are the smallest (Elisa et al. 2010). In the Greater Ruaha River, which flows through Ruaha National Park, upstream water withdrawals for large scale irrigation began in the 1990's and caused the river to change from a perennial system (i.e., constant flow) to one with an intermittent flow regime, drying out annually for up to periods of nearly 4 months (Mtahiko et al. 2006). These extended droughts were associated with a host of consequences to the biota. Many water-dependent species either moved out of the park or clustered in very high densities in the areas where water remained. The latter resulted in increases in disease prevalence among the fauna, habitat degradation due to algal blooms, and overutilization of stream bank vegetation that exposed the river banks to erosion in the wet season. Within Saadani National Park, hippos, a favorite of tourists, are found in large pods within the Wami River of Saadani National Park (McNally 2007). Hippos prefer freshwater water depths of 1.5 m (Bruton 1978) and access to fresh drinking water daily (Muller and Erasmus

1995) – features that could be eliminated during the episodes of low flow predicted to occur with the biofuel abstractions.

The Katuma River of Katavi National Park was also a perennial system, but following the onset of upstream irrigation, the river was reduced to a small number of stagnant pools during the dry season (Elisa et al. 2010). Animals were forced to move into surrounding villages in search of water, exposing them to poaching and comprising the safety of the local residents. The lack of river flow also created hardship for adjacent villages, where residents were forced to invest additional time and effort to obtain their domestic water. The Wami River has enormous value as a drinking water source during the dry season. The wildlife within Saadani National Park relies solely on the Wami River for drinking water during the dry season. In addition, McNally et al. (chapter 1 of this dissertation) found that many of the local residents rely on the river for potable water as well. They too will be forced to find other sources during the dry season either through well development or the import and purchase of water supplies.

The lack of flow will also disrupt river continuity, severely limiting the movement of aquatic organisms and disconnecting the estuary from the river system. The riverine and riparian plant communities are likely to experience species shifts that result from changes in salinity as well as hydroperiod causing changes in soil wetness and depth of inundation. The Wami River already experiences regular incursions of saltwater during high tides in the dry season. Based on a synoptic survey of salinity levels within the lower six kilometers of the Wami River in August 2007, notable differences in salinity were found between high and low tide (tidal range is approximately 2-3 meters at the

mouth of the river). During the high tide, a salt wedge was observed approximately four kilometers upstream of the river mouth corresponding to the transition between mangrove and palm forest vegetation (McNally 2007). Salinity in this area ranged from 13 – 22 ppt throughout the water column. In contrast, during low tide, the river was primarily freshwater suggesting that the river flow was able to flush the saline waters rapidly from the channel. Salinity in the river did not exceed 1 ppt within the channel until it entered the Indian Ocean. The daily flow at the Manderu gauge during the synoptic survey was approximately $40 \text{ m}^3/\text{s}$, a flow value equivalent to the historic daily Q32 and much higher than the projected dry season flows under the abstraction scenario. In estuaries that are permanently open to the ocean, a principal effect of extended periods of low flow is an increase in the upstream extent of saltwater (Adams 2014). Therefore, with the additional water abstraction and resultant lower-river flow rates, saltwater intrusion would be expected to move further upstream and this high salinity water will take longer to flush from the river potentially altering estuarine, riverine and riparian habitats.

Mangrove species richness, productivity and height are greater in areas influenced by freshwater (Saenger and Snedaker 1993 as cited in Ewel 2010). Although mangroves are adapted to grow in saline environments, some species are more tolerant of higher salinity levels than others (Duke et al. 1998, Adams et al. 2004). In East Africa, the typical zonation pattern from mean sea level to the high spring tide level is *Sonneratia alba*, *Rhizophora mucronata*, *Xylocarpus granatum*, *Avicennia marina*, *Ceriops tagal*, *Lumnitzera racemosa*, *Brugeria gymnorhiza* and *Heritiera littoralis*

(Richmond 2002). Increases in salinity levels could cause shifts in the distribution of mangrove species along the river channel. For example, *A. marina*, which is capable of tolerating high salinities, would likely colonize further inland while *X. granatum*, which requires the influence of freshwater for survival, would likely be replaced or move further upstream potentially displacing the freshwater dependent Nypa palm (*N. fruticans*) (Gillanders and Kingsford 2002, Richmond 2002). The Nypa palm is indicative of the riparian gallery forest that provides critical habitat for the black and white colobus monkey and wading birds. Flora within the gallery forests are very sensitive to the frequency and depth of inundation, and small changes in flow can cause this habitat to be replaced by the less biodiverse grassland/acacia community (Gritzner and Sumerlin 2007). In addition to altering the distribution and composition of mangrove species, higher levels of salinity can also result in dwarf forms of some of the mangrove species, which have more limited habitat value (Gopal 2014). In the Southern Rufiji Delta, reductions in river flow since the late 1970s have resulted in stunted mangrove growth (Wagner 2008).

Alterations in species composition and mangrove function can affect the provision of specific types of ecosystem goods and services (Ewel et al. 1998). The local communities rely on mangroves for firewood, building poles and furniture construction (McNally et al. chapter 1, Mangora 2011). However, the potential expansion of *A. marina*, which is not widely used due to the soft nature of its wood, and reduction in *X. granatum*, which is used for building furniture, would impact the availability of construction materials.

Changes in the riverine and estuarine vegetation will also alter the condition and availability of nursery habitat. These changes, in turn, will affect the distribution, composition and abundance of juvenile fish and invertebrates with resultant consequences on estuarine trophic interactions and coastal food chains (Ewel 2010). A recent study conducted by Zampatti et al. (2010) in the Coorong estuary, Australia examined the response of fish assemblages to large reductions in freshwater flow due to anthropogenic activities upstream. During their three year study, the amount of freshwater entering the estuary declined and then stopped altogether. The highest level of species richness was recorded during brackish conditions, and the species richness and numbers of estuarine, freshwater and diadromous species declined over time in response to the rising salinity levels. Similar trends have also been observed under natural drought conditions (Martinho et al. 2007, Gillson 2011) along with significant declines in the export of larval fish from estuarine to coastal waters (Dolbeth et al. 2008 as cited in Gillson 2011). Thus increased levels of irrigation will impact fish biodiversity and potentially the livelihoods of the adjacent communities relying on the capture of fish for their sustenance and income.

Finally, when contemplating irrigation withdrawals, it is important to bear in mind that the estimates of water withdrawal were based on the use of drip irrigation and irrigation scheduling – techniques that improve irrigation efficiency (Pereira et al. 2002). Whereas the native flora in this location would be expected to exhibit a number of traits to avoid water use and desiccation during the annual droughts (Kramer and Boyer 1995), irrigation reduces the need for drought avoidance responses in crops such

as sugar cane. The plants are well-watered and do not experience conditions that warrant stomatal closure, thus enhancing the CO₂ exchange that drives biomass production. Well-watered crops typically transpire water at rates comparable to evaporation rates from open water in adjacent locations. We point out that irrigation is projected to constitute almost 90% of the proposed abstraction for the biofuel project on the Wami River. Thus, the vast majority of the water abstraction is strictly linked to water requirements of growing biofuel plants in the climatic conditions of the lower Wami River watershed and is not likely to be reduced with through additional water-saving practices.

Implications

Large, irrigated agricultural developments are likely to be incompatible with downstream protected areas in the arid watersheds of East Africa due to the high interannual and seasonal variability in stream flow. Although a proposed 10,500 ha biofuel operation would constitute less than 0.01% of the watershed, our analyses demonstrated that the water withdrawals will threaten biodiversity and other ecosystems goods and services that are intended to be protected by Saadani National Park, located at the terminus of the Wami River. We note that initial plans for the biofuel development called for a 17,000 ha operation – which would produce even greater impacts on the national park. Decision makers at the local, regional and national levels would ideally have access to tools and data that can provide rapid insights into the trade-offs from different levels of abstraction. In Figure 4, we illustrate the effects of different scales of water abstraction on the extent of zero flow periods

within the Wami River. One hundred percent represents the abstractions associated with the 10,500 ha biofuel operation analyzed in this study. The relative scale simply reflects the withdrawals from a given percent of the full scale operation. Whereas the full scale operation will generate 300 days with zero flow occurring in 35 different events over the 24 years of record, an operation that requires 30% of the required water abstraction will generate 55 days of zero flow ($\sim 1/6^{\text{th}}$ of the amount predicted with the full scale system) over 9 different events. While this lower level of abstraction will generate less impacts than the full scale system, we are not able to estimate the loss of ecosystem services and thus cannot provide the information required by decision makers and stakeholders on the tradeoffs associated with any level of abstraction. In our study, we used the historical dataset as a means for looking at the potential effects of the proposed biofuel water abstractions, but recognize that there has been limited development within the watershed since 1978 that was not captured. We did not have information on the specific location and extent of abstractions in the watershed since 1978, and we did not account for shifts in climate so our results provide perspective.

Estimation approaches such as ELOHA (ecological limits of hydrologic alterations) offer tools to address these information gaps (Arthington et al. 2006, Poff et al. 2010). These approaches recommend developing management guidelines for classes of rivers that share climatic, physiographic and ecological features. Based on reference (unaltered) river systems within a class, flow-ecological relationships can be developed that relate alterations of flow to changes in ecosystem goods and services. ELOHA studies are not available for the Wami River region. However, the analyses conducted

in this study, coupled with the recent losses of ecosystem services in neighboring watersheds provide a very clear message: additional water abstractions from the free-flowing arid watersheds of East Africa risk the loss of critical ecosystem goods and services, particularly for protected areas of high biodiversity.

References

1. Acreman, M.C., I.C. Overton, J. King, et al. (2014) The Changing Role of Ecohydrological Science in Guiding Environmental Flows. *Hydrological Sciences Journal* 59(3-4): 433–450.
2. Adams, J. B. (2014) A Review of Methods and Frameworks Used to Determine the Environmental Water Requirements of Estuaries. *Hydrological Sciences Journal* 59(3-4): 451–465.
3. Alber, M. (2002) A Conceptual Model of Estuarine Freshwater Inflow Management. *Estuaries* 25(6): 1246–1261.
4. Anderson, E. P., C.G. McNally, B. Kalangahe, H. Ramadhani, and H. Mhithu (2007) A Rapid Ecological Assessment of the Wami River Estuary, Tanzania. Global Water for Sustainability Program, Florida International University.
5. Arthington, A.H. (2012) Environmental Flows: Saving Rivers in the Third Millennium. Berkeley, CA: University of California Press.
6. Arthington, A.H., S.E. Bunn, N.L. Poff, and R. J. Naiman (2006) The Challenge of Providing Environmental Flow Rules to Sustain River Ecosystems. *Ecological Applications* 16(4): 1311–1318.
7. Boulton, A.J. (2003) Parallels and Contrasts in the Effects of Drought on Stream Macroinvertebrate Assemblages. *Freshwater Biology* 48(7): 1173–1185.
8. Brisbane Declaration (2007) Available online at http://www.eflownet.org/download_documents/brisbane-declaration-english.pdf, accessed October 1, 2014.
9. Bruton, M.N. (1978) Recent Mammal Records from Eastern Tongaland KwaZulu, with Notes on Hippopotamus in Lake Sibaya. *Lammergeyer* 24: 19–27.
10. Bucx, T., M. Marchand, A. Makaske, and C. Van de Guchte (2010) Comparative Assessment of the Vulnerability and Resilience of 10 Deltas: Synthesis Report. Deltares.

11. Bunn, S.E., and A.H. Arthington (2002) Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* 30(4): 492–507.
12. Dickens, C. (2011) Critical Analysis of Environmental Flow Assessments of Selected Rivers in Tanzania and Kenya. International Union for Conservation of Nature and Natural Resources and Institute of Natural Resources, Nairobi, Kenya.
13. Dolbeth, M., F. Martinho, I. Viegas, H. Cabral, and M.A. Pardal (2008) Estuarine Production of Resident and Nursery Fish Species: Conditioning by Drought Events? *Estuarine, Coastal and Shelf Science* 78: 51–60.
14. Duke, N.C., M.C. Ball, and J.C. Ellison (1998) Factors Influencing Biodiversity and Distributional Gradients in Mangroves. *Global Ecology and Biogeography Letters* 7(1): 27–47.
15. Elisa, M., J.I. Gara, and E. Wolanski (2010) A Review of the Water Crisis in Tanzania's Protected Areas, with Emphasis on the Katuma River—Lake Rukwa Ecosystem. *Ecohydrology & Hydrobiology* 10(2-4): 153–165.
16. Estevez, E.D. (2002) Review and Assessment of Biotic Variables and Analytical Methods Used in Estuarine Inflow Studies. *Estuaries* 25: 1291–1303.
17. Ewel, K.C. (2010) Appreciating Tropical Coastal Wetlands from a Landscape Perspective. *Frontiers in Ecology and the Environment* 8(1): 20–26.
18. Ewel, K.C., and R.R. Twilley (1998) Different Kinds of Mangrove Forests Provide Different Goods and Services. *Global Ecology and Biogeography Letters* 7(1): 83–94.
19. Gillanders, B.M., and M. J. Kingsford (2002) Impact of Changes in Flow of Freshwater on Estuarine and Open Coastal Habitats and the Associated Organisms. In *Oceanography and Marine Biology, An Annual Review* pp. 233–309. London, U.K.: Taylor & Francis.
20. Gillson, J. (2011) Freshwater Flow and Fisheries Production in Estuarine and Coastal Systems: Where a Drop of Rain Is Not Lost. *Reviews in Fisheries Science* 19(3): 168–186.

21. Gopal, B. (2014) Mangrove Ecosystems of Asia. I. Faridah-Hanum, A. Latiff, K.R. Hakeem, and M. Ozturk, eds. New York, NY: Springer New York.
22. Gordon-Maclean, A., J. Laizer, P.J. Harrison, and R. Shemdoe (2008) Biofuel Industry Study, Tanzania. Tanzania & Sweden: World Wide Fund for Nature (WWF).
23. Gritzner, J., and D. Sumerlin (2007) USDA Forest Service Technical Assistance Trip Wami River Resource Assessment.
24. Groffman, P.M., J.S. Baron, T. Blett, et al. (2006) Ecological Thresholds: The Key to Successful Environmental Management or an Important Concept with No Practical Application? *Ecosystems* 9(1): 1–13.
25. Humphries, P., and D.S. Baldwin (2003) Drought and Aquatic Ecosystems: An Introduction. *Freshwater Biology* 48(7): 1141–1146.
26. IUCN (2003) The Essentials of Environmental Flows. Gland, Switzerland and Cambridge, UK: IUCN.
27. Jameson, S.C., M.H. Tupper, and J.M. Ridley (2002) The Three Screen Doors: Can Marine “protected” Areas Be Effective? *Marine Pollution Bulletin* 44(11): 1177–1183.
28. Kramer, P.J., and J.S. Boyer (1995) Water Relations of Plants and Soil. Academic Press.
29. Lake, P.S. (2003) Ecological Effects of Perturbation by Drought in Flowing Waters. *Freshwater Biology* 48(7): 1161–1172.
30. Loneragan, N.R., and S.E. Bunn (1999) River Flows and Estuarine Ecosystems: Implications for Coastal Fisheries from a Review and a Case Study of the Logan River, Southeast Queensland. *Australian Journal of Ecology* 24: 431–440.
31. Da Luz, L.D., and F. Genz (2013) First Essentials Toward Environmental Flows for São Francisco River (Brazil) Recovering Damaged Ecosystems and Meeting Human Needs. World Environmental and Water Resources Congress.

32. Martinho, F., R. Leitaó, I. Viegas, et al. (2007) The Influence of an Extreme Drought Event in the Fish Community of a Southern Europe Temperate Estuary. *Estuarine, Coastal and Shelf Science* 75: 537–546.
33. McClain, M.E., A.L. Subalusky, E. P. Anderson, et al. (2014) Comparing Flow Regime, Channel Hydraulics, and Biological Communities to Infer Flow–Ecology Relationships in the Mara River of Kenya and Tanzania. *Hydrological Sciences Journal* 59(3-4): 801–819.
34. McMahon, T.A., R.M. Vogel, M.C. Peel, and G.S. Pegram (2007) Global Streamflows – Part 1: Characteristics of Annual Streamflows. *Journal of Hydrology* 347(3-4): 243–259.
35. McNally, C.G., and et al. (2007) A Follow-up Dry Season Rapid Ecological Assessment of the Wami River Estuary, Tanzania. Coastal Resources Center, University of Rhode Island.
36. Milliman, J.D., and K.L. Farnsworth (2011) River Discharges to the Coastal Ocean: A Global Synthesis. Cambridge, U.K.: University Press.
37. Mtahiko, M.G., E. Gereta, A.R. Kajuni, et al. (2006) Towards an Ecohydrology-Based Restoration of the Usangu Wetlands and the Great Ruaha River, Tanzania. *Wetlands Ecology and Management* 14(6): 489–503.
38. Muller, M., and A. Erasmus (1995) Wetland Associated Animals. In *Wetlands of South Africa*. G.I. Cowan, ed. pp. 207–226.
39. Olsen, S.B., P.V. Tiruponithura, and B.D. Richter (2006) Managing Freshwater Inflows to Estuaries: A Methods Guide. Coastal Resources Center, University of Rhode Island and The Nature Conservancy.
40. ORGUT Consulting AB (2008) Environmental and Social Impact Statement of the Proposed BioEthanol Production on the Former Razaba Ranch, Bagamoyo District, Tanzania. Stockholm, Sweden.
41. Periera, L.S., T. Oweis, and A. Zairi (2002) Irrigation Management under Water Scarcity. *Agricultural Water Management* 57: 175–206.

42. Poff, N.L., J. D. Allan, M.B. Bain, et al. (1997) The Natural Flow Regime. *BioScience*: 769–784.
43. Poff, N.L., B.D. Richter, A.H. Arthington, et al. (2010) The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards: Ecological Limits of Hydrologic Alteration. *Freshwater Biology* 55(1): 147–170.
44. Poff, N.L., and J.K.H. Zimmerman (2010) Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. *Freshwater Biology* 55(1): 194–205.
45. Postel, S., and B.D. Richter (2003) Rivers for Life: Managing Water for People and Nature. Washington D.C.: Island Press.
46. Price, K., C.R. Jackson, A.J. Parker, et al. (2011) Effects of Watershed Land Use and Geomorphology on Stream Low Flows during Severe Drought Conditions in the Southern Blue Ridge Mountains, Georgia and North Carolina, United States. *Water Resources Research* 47(2): W02516.
47. Pyrce, R. (2004) Hydrological Low Flow Indices and Their Uses. Watershed Science Centre, WSC Report.
48. Richmond, M.D. (2002) A Field Guide to the Seashores of Eastern Africa and the Western Indian Ocean Islands. Stockholm: SIDA/Department for Research Cooperation, SAREC.
49. Robins, J.B., and et al. (2005) Freshwater-Flow Requirements of Estuarine Fisheries in Tropical Australia: A Review of the State of Knowledge and Application of a Suggested Approach. *Marine and Freshwater Research* 56: 343–360.
50. Rolls, R.J., C. Leigh, and F. Sheldon (2012) Mechanistic Effects of Low-Flow Hydrology on Riverine Ecosystems: Ecological Principles and Consequences of Alteration. *Freshwater Science* 31(4): 1163–1186.
51. Saenger, P., and S.C. Snedaker (1993) Pantropical Trends in Mangrove above-Ground Biomass and Annual Litterfall. *Oecologia* 96(293-299).

52. Sarmett, J., and E.P. Anderson (2008) Wami River Initial Environmental Flow Assessment Synthesis Report. Coastal Resources Center, University of Rhode Island, Wami Ruvu Water Basin Office, and Florida International University.
53. Shokoohi, A., and Y. Hong (2011) Using Hydrologic and Hydraulically Derived Geometric Parameters of Perennial Rivers to Determine Minimum Water Requirements of Ecological Habitats (Case Study: Mazandaran Sea Basin—Iran). *Hydrological Processes* 25(22): 3490–3498.
54. Smakhtin, V.U. (2001) Low Flow Hydrology: A Review. *Journal of Hydrology* 240(3): 147–186.
55. Tharme, R.E. (2003) A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers. *River Research and Applications* 19(5-6): 397–441.
56. Tobey, J. (2008) A Profile of the Wami River Sub-Basin. Coastal Resources Center, University of Rhode Island.
57. Valimba, P. (2007) Environmental Flow Assessment (EFA), Wami River Sub-Basin, Tanzania: The Wami Hydrology. Volume 1 – General Description. Wami-Ruvu Basin Water Office.
58. Vilarly, S.P., J.A. González, B. Martín-López, and C. Montes (2011) Relationships between Hydrological Regime and Ecosystem Services Supply in a Caribbean Coastal Wetland: A Social-Ecological Approach. *Hydrological Sciences Journal* 56(8): 1423–1435.
59. Vörösmarty, C. J., P.B. McIntyre, M.O. Gessner, et al. (2010) Global Threats to Human Water Security and River Biodiversity. *Nature* 467(7315): 555–561.
60. Wagner, G.M. (2008) Baseline Assessment of the Mangrove Ecosystems of Rufiji, Mafia and Kilwa (Tanzania) for Vulnerability to Climate Change. Part of the WWF US/GEF Coastal Resilience to Climate Change Project. Tanzania: University of Dar es Salaam.
61. Webb, J. A., K.A. Miller, E.L. King, et al. (2013) Squeezing the Most out of Existing Literature: A Systematic Re-Analysis of Published Evidence on Ecological Responses to Altered Flows. *Freshwater Biology* 58(12): 2439–2451.

62. Weibull, W. (1951) A Statistical Distribution Function of Wide Applicability. *Journal of Applied Mechanics* 18(3): 293–297.

63. Zampatti, B.P., C.M. Bice, and P.R. Jennings (2010) Temporal Variability in Fish Assemblage Structure and Recruitment in a Freshwater-Deprived Estuary: The Coorong, Australia. *Marine and Freshwater Research* 61(11): 1298.

Table 1. Summary of the daily flow data missing from the Wami River, Mandera gauge (1954-1978)

Dates of missing flow data	Number of missing days	Flow preceding data gap (m³/s)	Flow following data gap (m³/s)	Mean flow value used to fill data gap (m³/s)
5/1/1955 – 5/31/1955	32	104.2	113.5	108.9
3/5/1959	1	47.4	84.1	65.6
3/26/1959 – 3/27/1959	2	34.6	79.2	56.9
11/26/1961 – 11/29/1961	4	114	183	148.5
4/3/1962 – 4/4/1962	2	80.6	67	73.8
10/1/1963 – 10/15/1963	16	13	10.6	11.8
6/2/1968	1	175.3	237.5	206.4
8/16/1970 – 8/27/1970	13	15.9	16.3	16.1
3/31/1974	1	19.4	10.6	15
5/1/1978 – 5/15/1978	16	190	65.2	127.6

Table 2. Water Requirements for 10,500 ha crop area

Month	Irrigation demand (m³/s)	Factory demand (m³/s)	Domestic demand (m³/s)	Total water abstraction demand (m³/s)
January	3.7	0.2	0.2	4.1
February	4.8	0.2	0.2	5.2
March	3.4	0.2	0.2	3.8
April	0.2	0.2	0.2	0.6
May	0.2	0.2	0.2	0.6
June	3.8	0.2	0.2	4.2
July	4.0	0.2	0.2	4.4
August	4.0	0.2	0.2	4.4
September	4.7	0.2	0.2	5.1
October	3.4	0.2	0.2	3.8
November	2.9	0.2	0.2	3.3
December	2.1	0.2	0.2	2.5
Total demand (million m³/year)	97.2	6.0	7.2	110.4

Table 3. Wami River, Mandera Gauge Discharge (1954-1978). Monthly Mean and Median Flows: Historic Flows Versus Projected Flows Following Proposed Biofuel Irrigation Abstractions.

Month	Historic Flows (m ³ /sec)		Post-Abstraction Flows (m ³ /sec)		Percent Change	
	Mean	Median	Mean	Median	Mean	Median
January	59.58	25.4	55.67	21.3	-6.6	-16.1
February	44.42	33.6	39.41	28.4	-11.3	-15.5
March	62.74	40.2	59.01	36.4	-5.9	-9.5
April	190.11	126.95	189.51	126.35	-0.3	-0.5
May	146.61	108.9	146.01	108.3	-0.4	-0.6
June	49.72	37.45	45.52	33.25	-8.4	-11.2
July	26.64	25.4	22.24	21.0	-16.5	-17.3
August	19.93	17.4	15.53	13.0	-22.1	-25.3
September	15.71	12.8	10.65	7.7	-32.2	-39.8
October	13.79	10.3	10.02	6.5	-27.3	-36.9
November	27.93	10.3	24.69	7.0	-11.6	-32.0
December	50.04	17.4	47.61	14.9	-4.9	-14.4
Entire POR	58.92	25.6	55.49	21.6	-5.8	-15.6

Table 4. Wami River, Mandera Gauge Discharge (1954-1978). Statistical Summaries for Cumulative Low Flow Indices: Historic Flows Versus Projected Flows Following Proposed Biofuel Irrigation Abstractions.

Low Flow Indices	Historic			Abstraction Scenario		
	Magnitude (m ³ /sec)	# of Days	# of Events ¹	Magnitude (m ³ /sec)	# of Days	# of Events ¹
1 Day						
Q90	7.0	908	71	3.1	921	80
Q95	4.4	460	41	0.8	454	47
Q99	1.6	89	15	0.0	300	35
Q99.5	0.8	45	7	0.0	300	35
7 Day						
Q90	7.13	912	29	3.34	911	39
Q95	4.74	455	22	1.10	459	24
Q99	1.83	91	5	0.00	154	16
Q99.5	1.20	45	5	0.00	154	16
14 Day						
Q90	7.44	913	24	3.60	912	31
Q95	5.04	460	18	1.44	459	20
Q99	2.14	91	6	0.03	92	9
Q99.5	1.38	46	3	0.00	70	8
30 Day						
Q90	7.83	910	16	4.04	909	16
Q95	5.22	455	12	1.95	457	15
Q99	2.80	93	7	0.20	91	7
Q99.5	2.22	45	4	0.12	45	6
60 Day						
Q90	8.99	907	15	5.09	907	13
Q95	6.00	454	10	2.48	453	11
Q99	3.88	91	3	0.76	95	5
Q99.5	2.96	45	2	0.47	45	3
90 Day						
Q90	9.74	904	14	5.87	905	14
Q95	7.23	452	9	3.52	453	8
Q99	4.04	91	4	1.28	95	5
Q99.5	3.66	45	4	1.06	45	3

¹ An event begins as soon as the criteria are met (i.e., the flow magnitude corresponding to the specific low flow index) and continues until the flow value rises above that threshold. The duration of that event equals the total number of consecutive days that the flow remained below the threshold flow value.

Table 5. Wami River, Mandera Gauge Discharge (1954-1978). Median Annual Values of Selected Low Flow Indices: Historic Flows Versus Projected Flows Following Proposed Biofuel Irrigation Abstractions.

Low Flow Indices	Historic	Abstraction	No. Years \leq Historic Median
	Annual Median Value	Annual Median Value	
1 Day			
Q90	9.75	5.30	19
Q95	7.10	3.90	18
Q99	5.40	2.45	18
Q99.5	5.35	2.15	18
7 Day			
Q90	8.66	5.26	17
Q95	7.04	3.86	18
Q99	5.96	2.81	18
Q99.5	5.78	2.52	18
14 Day			
Q90	8.81	5.55	16
Q95	7.39	4.05	18
Q99	6.33	3.37	18
Q99.5	6.24	3.22	18
30 Day			
Q90	9.72	6.07	16
Q95	8.06	4.81	18
Q99	7.16	4.05	18
Q99.5	6.61	3.55	17
60 Day			
Q90	10.63	6.84	17
Q95	9.36	5.89	16
Q99	8.19	4.58	17
Q99.5	8.16	4.53	17
90 Day			
Q90	11.04	7.00	15
Q95	9.02	5.62	15
Q99	8.66	4.94	16
Q99.5	8.59	4.87	16

Table 6. Wami River, Mandera Gauge Discharge (1954-1978).
 Lower Quartile Annual Values of Selected Low Flow Indices:
 Historic Flows Versus Projected Flows Following Proposed
 Biofuel Irrigation Abstractions.

Low Flow Indices	Historic	Abstraction	
	Annual 75 th Percentile Flow Value	Annual 75 th Percentile Value	No. Years \leq Historic 75 th Percentile
1 Day			
Q90	4.98	1.18	6
Q95	2.88	0.00	7
Q99	2.08	0.00	8
Q99.5	2.03	0.00	8
7 Day			
Q90	5.30	1.44	12
Q95	3.32	0.22	11
Q99	2.58	0.00	11
Q99.5	2.42	0.00	12
14 Day			
Q90	5.04	1.34	12
Q95	3.53	0.36	11
Q99	2.96	0.10	11
Q99.5	2.76	0.04	11
30 Day			
Q90	5.47	1.98	12
Q95	3.90	1.13	10
Q99	3.24	0.28	11
Q99.5	3.18	0.25	11
60 Day			
Q90	6.28	2.59	12
Q95	5.15	1.81	11
Q99	4.49	1.56	12
Q99.5	4.31	1.47	12
90 Day			
Q90	8.06	3.82	13
Q95	6.35	2.61	13
Q99	5.58	2.18	13
Q99.5	5.44	2.12	13

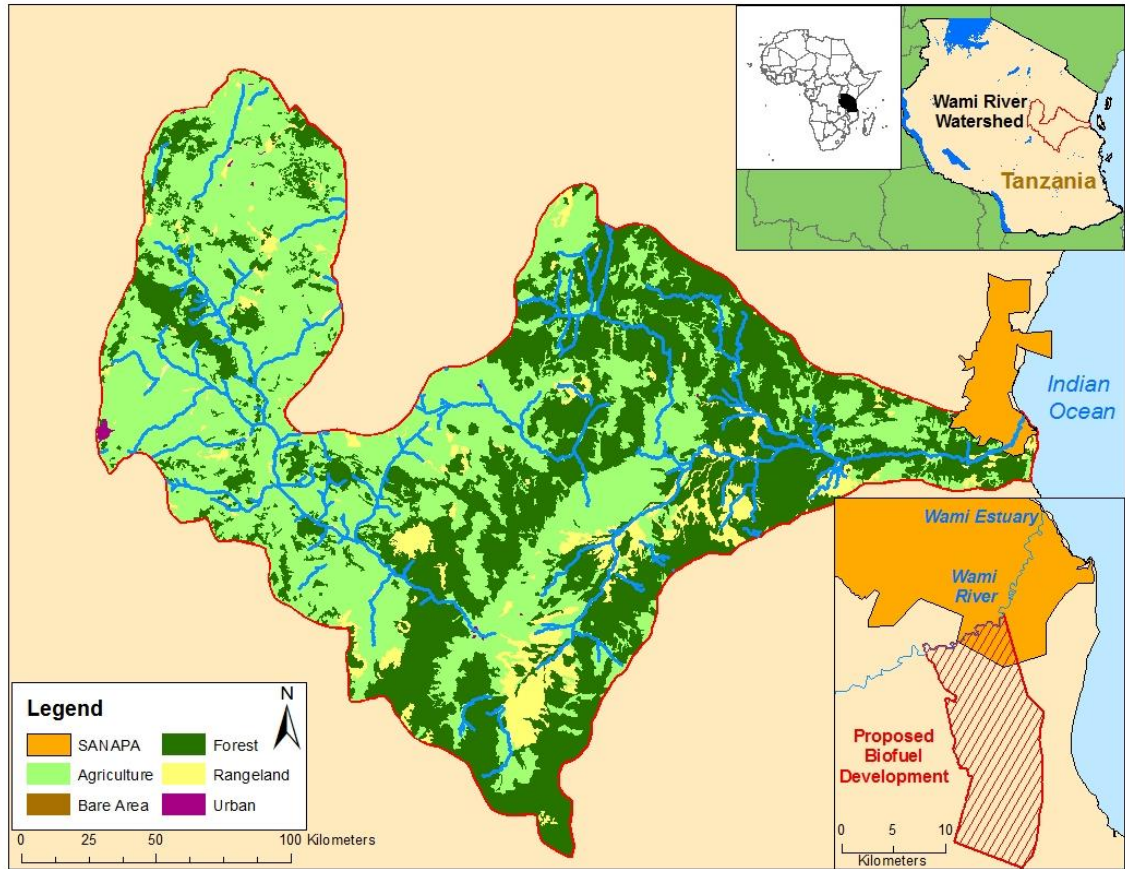


Figure 1. Study Site

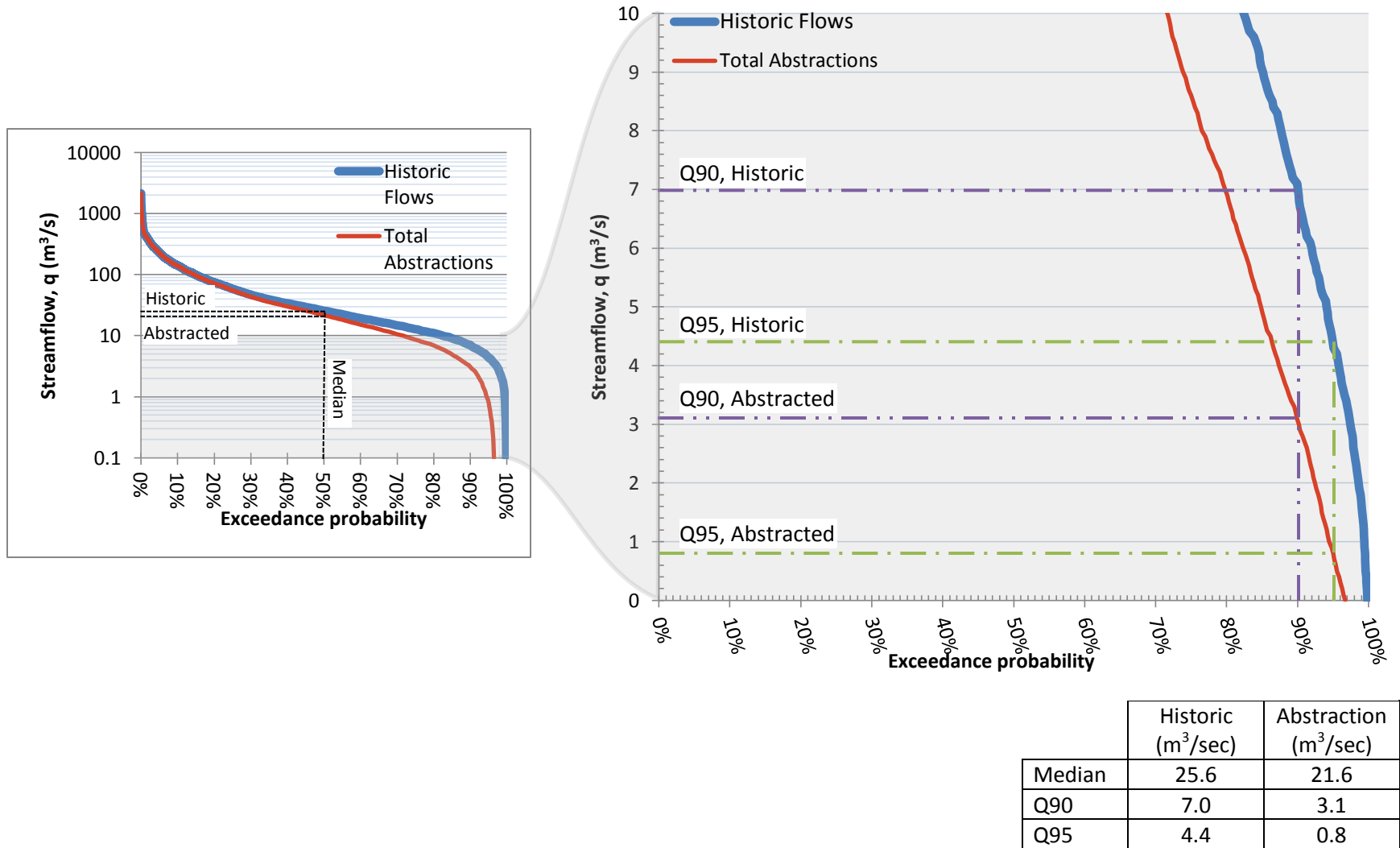


Figure 2. Overall 1 Day Flow Duration Curve of Historic and Abstracted Daily Streamflow (m³/s) for Wami River, 1954-1978.

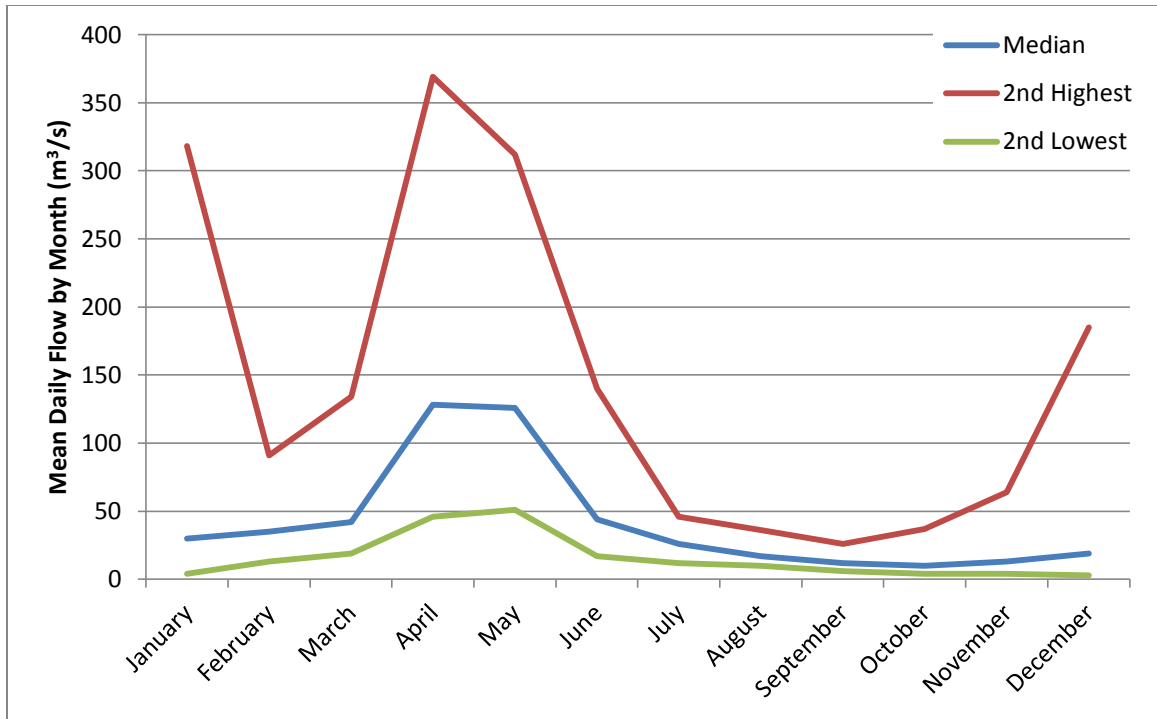


Figure 3. Median Penultimate Flows and Second Highest Median Monthly Flows (m^3/s) for Wami River, 1954-1978.

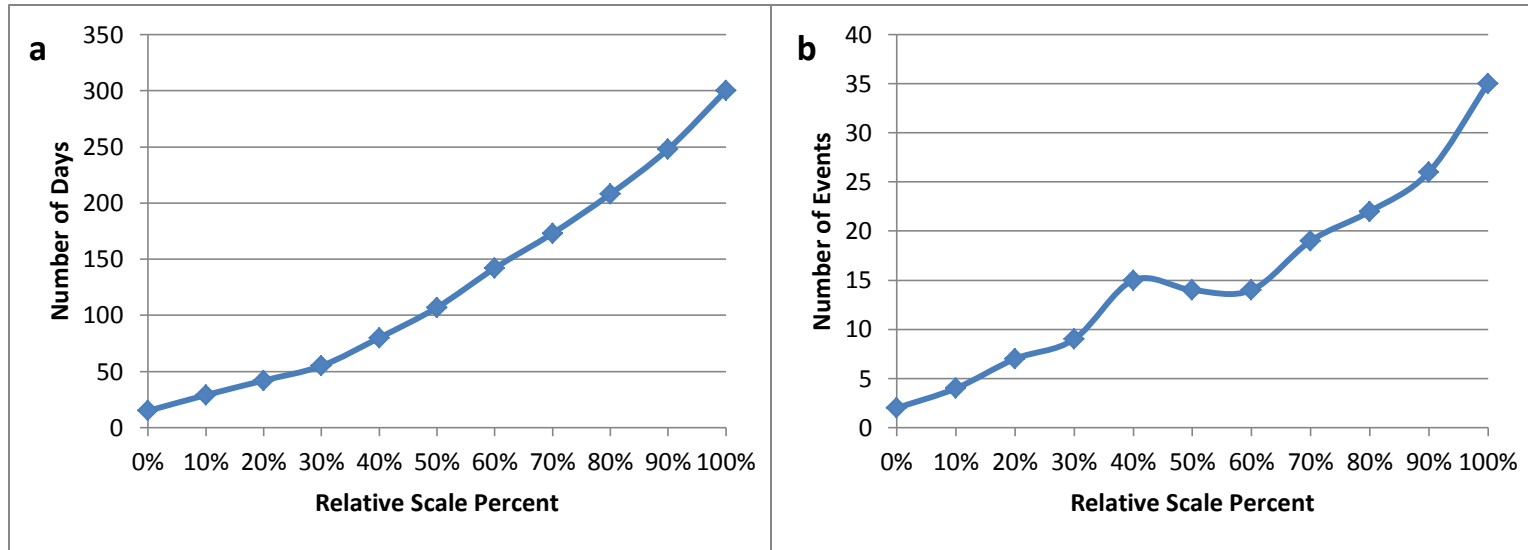


Figure 4. The Total Number of Days (a) and Events (b) with Zero Flow under Scale Percentages of the Total Proposed Biofuel Abstraction