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Unravelling complex interactions between urbanisation and coastal fisheries using a system dynamics approach

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INTRODUCTION

Coastal zones are amongst the most heavily populated and exploited areas in many parts of the world. Burgeoning coastal urbanization and resource use is increasingly giving rise to conflict among users of coastal resources. One such conflict arises from wastewater disposal in urban areas causing degradation of coastal water quality and pollution impacts on other uses, such as fishing. This is especially significant in developing countries, where subsistence fishing is very important to coastal communities that rely on their catches as a source of food and for their livelihoods.

Thus urbanisation in coastal areas is often a factor contributing to devaluing of ecosystem goods and services, and can impact other uses, such as subsistence fisheries. Natural questions which arise are how severe is this impact, and what could be done to mitigate, or at least minimize it? In this project we aim to develop a decision-support tool to support non-technical decision-makers in data poor environments to reach realistic solutions in these complex socio-ecological systems without having to rely on detailed data and information. Specifically, we focus on potential conflict between land-based wastewater inputs from a city on a coastal fishery. This paper presents a simplified conceptualization of the key elements in this conflict situation, and proposes a preliminary design of a system dynamics model. This model will be refined in an expert workshop forum as part of the next stage in this project. Once calibrated, the model will be used to test various wastewater scenarios, so as to assist in unravelling this complex interaction and, most importantly, inform future mitigation needs.

METHOD

The model was developed in Vensim® PLE for Windows Version 6.4E software from Ventana Systems, Inc. Because the intention of this study was to implement this type of tool in data poor environments, where detailed data and information can be sparse (e.g. in developing countries), secondary data sources (available information) and expert knowledge were used for the population of the model parameters.

We chose the City of Durban (urban area) and the Port of Durban (a commercial port that also supports recreational and subsistence fisheries), situated along the South African east coast, as case study. River inflows into the Silt canal, containing runoff and wastewater from the city have affected water quality in the port for many years (Begg, 1978) and have potentially detrimental impacts on this fishery (Guastella, 1994).

Conceptualization of Conflict Situation

The Port of Durban is situated in an estuarine embayment (Durban Bay) and is roughly divided into to a shallow water area (the Silt Canal) and a deep water basin (the Main Basin) (Figure 1). The Main Basin is well-flushed as a result of strong diurnal tidal exchange, but flushing of the Silt Canal is much weaker. Stormwater discharges enter the port at various locations along the port perimeter, but the major land-based inputs flow into the upper reaches of the Silt Canal where tidal exchanges are lowest and retention rates are highest. These inflows are from contaminated rivers and include wastewater treatment work (WWTW) effluents from the adjacent City of Durban.

In the port significant recreational and subsistence fisheries target various species. Spotted Grunter (*Pomadasys commersonnii*), an estuarine dependent, marine spawning fish, is the most targeted species. It is a species that is common in artisanal, recreational and industrial fisheries in other parts of the world (Man et al. 2002, Al-Nahdi et al. 2010). Adults spawn at sea but larvae and early stage juveniles recruit to estuaries for 1-3 years before reaching adulthood (Whitfield 1999). These juveniles are strongly dependent on estuaries for their survival. Although the Port of Durban is regarded as a marine embayment, it retains an estuarine function as a nursery for many species of estuarine fishes (Cyrus and Forbes, 1996) including Spotted Grunter. Juveniles of this species (< 3 years) typically occupy the more sheltered and freshwater influenced area of the Silt Canal as preferred habitat. Adults prefer the Main Basin, predominantly as foraging area where their main food source (sand prawns) occurs plentifully on the shallow tidal areas in this area. Spotted Grunter are targeted by both recreational and subsidence anglers, and therefore have considerable economic and social importance. Most of the fishing activity occurs in the lower reaches of the port, in the Main Basin, and targets adult fish.

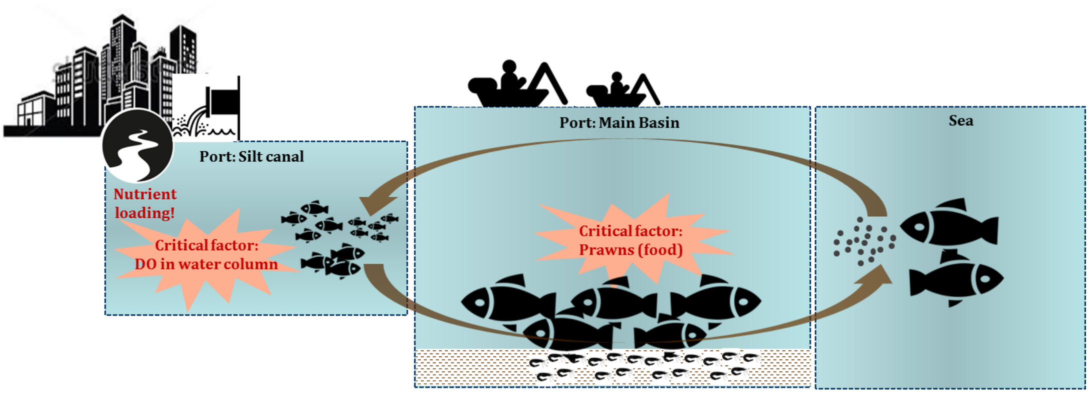

Figure 1. Conceptualization of key pathways linking land-based urban runoff to subsistence fishery in the Port of Durban

Critical factors affecting populations of Spotted Grunter in the Port of Durban can be identified at both juvenile and adult life stages, and these come into play in different areas in the port. A critical factor in the Silt Canal is low dissolved oxygen (DO) concentrations in the water column, driven by eutrophication and organic loading from the land-based pollution and wastewater inputs (Taljaard et al. 2017). Here juvenile Spotted Grunter are especially vulnerable to low DO levels, and significant mortalities have been noted to occur in recent fish kill events. Adult Spotted Grunter, prefer the well-flushed Main Basin where land-based inflows do not affect DO levels to the same degree as occurs in the Silt Canal. Here prey (sand prawn) abundance (food availability) becomes the most important factor affecting fish abundance (and fishery catches). Inflows from the surround city, therefore, are not the most critical factor to consider here. Port activities, such as dredging or quay development, become more relevant. Of course, the fishers themselves can also contribute to the decline in their fishery resource through over-exploitation (Guastella, 1994). However, in our preliminary model design we focus on resolving the critical factors influenced by land-based wastewater inputs (that is DO in the Silt Canal), initially assuming dredging and port development (in the Main Basin) to remain constant, and without consideration of fishing pressure itself.

RESULTS

Preliminary Model Design

The preliminary stock-and-flow model design is presented in Figure 2. In this simplified model, the juvenile life stages are grouped together, i.e. the juvenile stock contains a mixed population of newly recruited early life stage juveniles to 3 year old sub-adults. The “recruitment rate” symbolizes the recruitment of late larvae and juveniles into the Silt Canal. We assumed that females constitute 50% of the adult population based on the findings of Al-Nahdi et al. (2010), with 90% of the females spawning during the spawning season. A skewed normal distribution represented the typical spawning season occurring predominantly from June to December, peaking in October, but lasting into late February. This distribution was derived based on observed larval recruitment rates into the Port of Durban (Harris and Cyrus, 1999) as well as monthly gonadosomatic indices presented for the species by Al-Nahdi et al. (2010). Larval survival rate was assumed to be 0.001%. A 5% emigration loss per year (juveniles leaving the Silt Canal) and 2.5% mortality per month under normal circumstances was assumed.

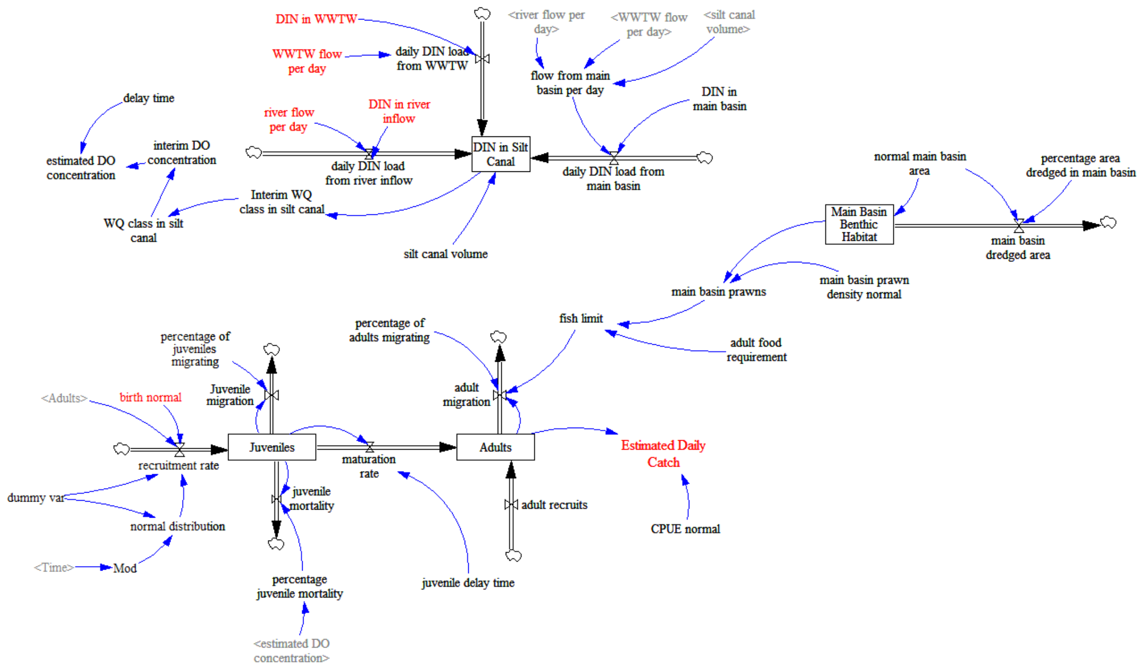

Figure 2. Preliminary model design depicting the key relationships in potential conflicts between urban waste inflows and the Spotted Grunter fishery the Port of Durban

Since the Juvenile stock contains a mixed population of early juveniles to sub-adults, a time delay was built into the "maturation rate". We used a Delay1 function with a time delay of 3 years. Adults were assumed to live 15 years, with an average of three adults recruiting into the Main Basin per day and 10% emigrating out of the Main Basin per year. At this stage no fishing pressures are imposed and only the estimated daily catch, based on an estimated catch per unit effort (CPUE) of 5% of adult population, are noted as output.

To estimate food availability (sand prawn abundance) in the Main Basin, benthic habitat area (Allan et al. 1999) and an assumed estimated prawn density were used. Assuming an adult food requirement of five sand prawns per day it was estimated that the Basin could sustain between 20,000 and 23,000 adults on average per day. For this preliminary model no dredging or development activities were assumed, and this carrying capacity remained constant. When the adult fish population goes beyond this limit, prey abundance becomes limiting, and excess Spotted Grunter emigrate out of the Main Basin, as search for other foraging areas.

The model is driven by estimated daily volumes and nutrient inputs from land-based sources into the Silt Canal. The box model approach of Taljaard et al. (2017) was used to estimate DO levels in the silt canal. According to this model, the silt canal can be treated as a basin where a water quality rating can be derived from estimated daily volumes and nutrient inputs from river inflows (land-based sources) using dissolved inorganic nitrogen (DIN) as a proxy, and from the sea, together with the estimated volume of water in the Silt Canal. Assuming the daily volume of the basin remains constant, the fraction of basin volume not accounted for by land-based inflows must be made up by seawater entering via the adjacent Main Basin (with an assumed DIN concentration of 0.05 mg/ℓ). Volumes and nutrient levels in land-based inflows vary depending on rainfall, wastewater flows and levels of pollution. The resultant WQ ratings derived for the Silt Canal (using Taljaard et al. 2017, Table 3) were then patterned with expected DO response levels, based on expert judgement, using the following formula:

$$\textit{Estimated DO concentration } (mg/\ell) = 13.4 \textit{ lin } (\textit{WQ rating}) + 9.03 \qquad (1)$$

The effect of DO on juvenile Spotted Grunter in the Silt Canal was estimated in terms of a mortality rate using an S-shaped response curve (Figure 3) derived from expert judgment, field observations of juvenile Spotted Grunter abundance at different DO concentrations and first hand investigation of fish kills in the Port of Durban.

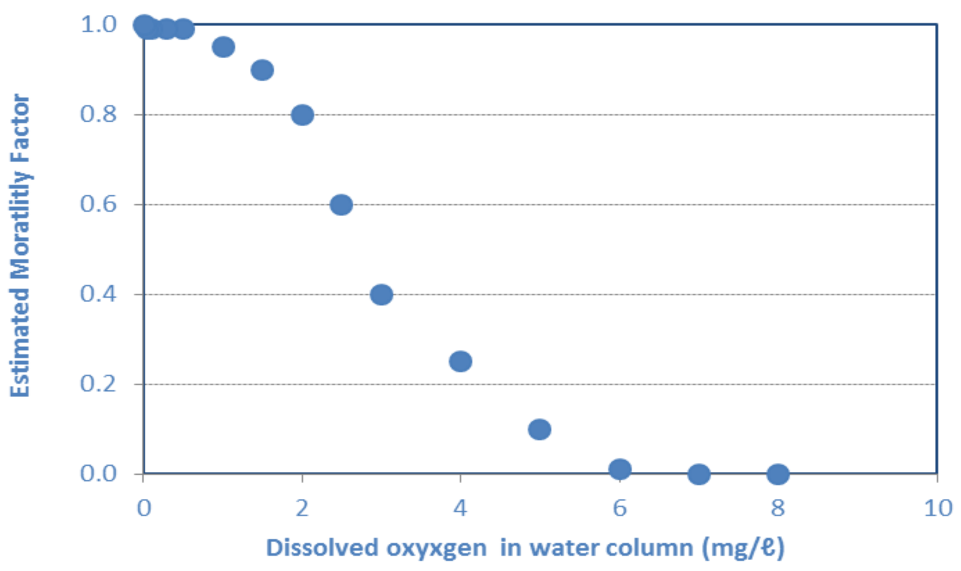

Figure 3. Estimated daily larval mortality factor versus DO levels in Silt Canal

The lower bound of the response curve corresponds to the 2.5% monthly mortality rate under normal circumstances, recalculated to a daily rate of 0.001%. As mentioned above, the model is driven by estimated daily volumes and nutrient inputs from land-based sources. The decision was therefore made to calibrate all response curves to daily rates. Mortality rate is lowest for low DIN concentrations (high DO) and non-linearly increases as the DO decreases.

Preliminary runs of the model, using these hypothetical data, provided promising results following expected trends. For example, in the presence of high DO levels (i.e. relative clean water) and in the absence of fishing activities the Adult population stabilizes to the carrying capacity of the Main Basin. When the DO levels in the Silt Canal decrease, the mortality of Juveniles increases, with a resultant decrease in the Adult population.

CONCLUSIONS

We developed a preliminary stock-and-flow model with the aim of investigating potential conflicts between land-based wastewater inflows from a city on an important coastal recreational and subsistence fishery. Preliminary model set-up and testing produced promising results that will now be further refined. A calibrated model will then be introduced to authorities and managers responsible for environmental issues in the city and port to validate its suitability in unravelling this complex interaction and, most importantly, inform future mitigation needs.

Keywords: Dissolved oxygen, coastal subsistence fishery, port-city interface, system dynamics, wastewater inflow.

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