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A Dynamic Model to Assess Carrying Capacity of a Defined System

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Abstract

A system dynamics method to assess carrying capacity of a defined natural environment is presented. The proposed method seeks to relate *per capita* resource usage to ranges of population and *per capita* consumption beyond which the system is not viable relative to population dependent resource constraints. It provides a platform to investigate system behavior through system dynamics simulations where populations change, natural resources decay due to stressor impacts, and feedback occurs via implementation of policy. Application of the model to a case study of Total Maximum Daily Load (TMDL) of phosphorous in Bear Lake, a Lake Michigan estuary (USA), shows the major total phosphorous (P) loading contribution is anthropogenic land use development. Three *scenarios* are quantitatively explored by assuming changes in land use and/or loading rates. Simulation results show tradeoffs between reduction of total P and land use; economic development can be flexibly evaluated against targets of loading reduction trajectories.

Keywords: carrying capacity, dynamic systems model, environmental stressors, Great Lakes, sustainable development, Total Maximum Daily Load (TMDL), viability

1. Introduction

This study develops a modeling methodology that can be used to assess the carrying capacity metric of a defined natural environment. The method models the causal relationships governing natural resource consumption and long-term responses of the natural environment to public policies shaped by stakeholder preferences. Stakeholders include: (1) the public who directly draw economic benefits from the system, (2) policymakers who develop and implement policy that directly impacts the system, and (3) domain experts (e.g. environmental scientists) who provide the knowledge base from which policy is designed, and to the extent possible, Coupled Human and Natural Systems (CHANS) are understood and maintained. Priorities of stakeholder groups often vary significantly, ranging from efforts that emphasize conservation to efforts that emphasize economic growth. As a result, policymakers are often left with the difficult task of balancing conflicting priorities without depleting the natural resources of a region. The problem is further magnified because policies that emphasize either economic growth or conservation often result in unintended feedback that makes the region environmentally and/or economically unsustainable. Therefore, a policy should be considered in the context of how it adapts to long-term changes in available natural resources and stakeholder priorities. It is also worth noting the importance of having accurate locally-scaled models described in this study that capture the relationship between the information embodied in these policies (namely people's hope for their communities now and into the future) and the thermodynamics of physical systems (carrying capacity is essentially a thermodynamic parameter that aggregates the capacity of an ecosystem to procure and utilize energy as well as processes waste streams). Understanding these types of relationships is essential to devising scalable methods through which complex local, regional, and larger CHANS can be studied (Scheffer, Carpenter, Foley, Folk, & Walker, 2001; Walker, Holling, Carpenter, & Kinzig, 2004; Mayer, Pawlowski, Fath, & Cabezas, 2007; Zurlini *et al*., 2006; Brondizio, Ostrom, & Young, 2009; Angelstam *et al*. 2013). Over time, these policies must adapt to regulate consumption practices within the limits of available natural resources. Figure 1 illustrates the constant participation and involvement of different stakeholders in this process.

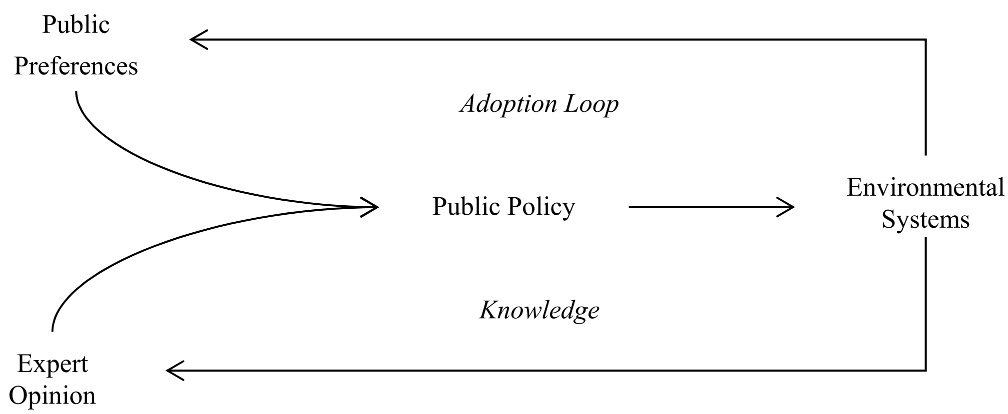

Figure 1. Idealized conceptual view of interactions leading to policy adaptation

The proposed method uses the carrying capacity of a system as a control parameter to indicate the overall environmental and socioeconomic health of the system. The goal of this model is to provide policymakers with a method that enables analysis of long-term impacts of policy as relationships between stakeholder behavior and natural resource consumption change. It uses a simulation framework to compare the outcomes of competing policies.

Therefore, the challenge is to develop an integrated definition of the natural resource system including the following components:

- resource constraints and relationships,
- stakeholder priorities,
- the value and impact of natural resource usage.

The carrying capacity metric is formally defined so that the system dynamics can be simulated to assess outcomes of alternatives from competing polices. This builds on previous work: a focus group of the general public, which included survey instruments to evaluate stressors to the Great Lakes Environment, was conducted to investigate attitudes, concerns, and preferences of the public about such stressors (Breffle *et al*., 2013). Pollution ranked the highest. Other stressors that might be interrelated include the availability of fresh water, recreation, and wetlands preservation or restoration, among others. Research addressing these stressors has been extensively documented in the literature. For example, eutrophication management through models that simulate mass changes of nitrogen (N) and phosphorous (*P*) in water bodies due to nutrient loadings have been extensively studied. Carpenter, Ludwig, & Brock (1999) propose a model with one state variable and one control variable that describes the state of a lake's eutrophication due to changes in phosphorus loading and management inventions. They present three thresholds that classify how lakes respond to reductions in *P* inputs: reversible (recovery is proportional to the *P* reduction), hysteretic (recovery requires substantial amount of *P* reduction in a given time period), and irreversible (recovery cannot be reached by reducing *P* loading alone). They used an input and output mass balance model to evaluate the changes of *P* in the body caused by the changes of inputs under the two scenarios: (1) when either *P* inputs are constant or stochastic, and (2) when there is or is not a time lag between implementing *P* input policy. Relevant conclusions were drawn based on each simulation.

This paper is similar to the work by Carpenter *et al*. (1999), in as much as it attempts to assess the impact of policy on lake eutrophication. However, it fundamentally differs from Carpenter *et al*. (1999) by explicitly accounting for stakeholder opinion and participation in the management of natural resources, thus modeling the socioeconomic roots of the human stressors. The model presented in this study uses Breffle *et al.* (2013) as a platform to explore system behavior by simulating scenarios for population growth and natural resources decay due to the impact of these stressors. Within this context, the policies considered in this paper are directly tied to the different kinds of associated land use.

The method presented herein uses a population dynamics model in conjunction with ideas from viability theory. Using the ecological concept of carrying capacity as an indicator, this model and theory will be used to simulate the outcomes of a policy over time by recognizing the coupled relationship between *per capita* consumption and the total population in a limited resource domain. In this case, the model is used to describe the relationship between eutrophication of water bodies and the socioeconomic roots of the stressors. It identifies the tradeoffs that should inform policy development. The outcome is the carrying capacity metric that presents the tradeoff to decision-makers in an easy and intuitive fashion that can be used to support decision-making.

In summary, the fundamental contributions of the present paper are as follows:

1) the method uses a system dynamics model in conjugation with ideas from viability theory to address the tradeoffs between *per capita* consumption and population in a limited resource domain. It furthers the idea of the carrying capacity metric to provide practical decision-support;

2) the model explicitly ties stakeholder preferences and their impact on consumption and sustainable use of public resources to policy;

3) the model allows dynamic simulation to explore the outcomes of a policy over a period of time.

The methods developed in this paper can be extended to study different problems of sustainability in a broader context of differing levels of economic development that can be formulated within the limited resource consumption framework.

2. Underlying Theory

A system is defined as a group of interacting, interrelated, or interdependent elements performing as a whole. It is “complex” when the elements interact to create multi-loop, non-linear feedback. Forrester, considered the father of the field of system dynamics, defines it as a combination of the theory, methods, and philosophy needed to analyze the behavior of complex systems using a common foundation that can be applied whenever we want to understand and influence the change of behavior over time (Forrester, 1991 and 1994). System dynamics involves modeling real-life scenarios in computer simulation models that allow us to understand how the structure creates its behavior. It explains that systems thinking approaches can provide a way of understanding the emergent behavior of complex interactions that involves a continuum of activities, ranging from the conceptual to the technical (Richmond, 1991 and 1994).

Support for applying this dynamic systems approach to natural resource management can be found in viability theory (Eisnack, Ludeke, Petschel-Held, Scheffran, & Kropp, 2007). The control theoretic approach proposed by viability theory naturally applies to natural resource management because environmental systems can be represented in terms of resource relationships, constraints and dynamically evolving stakeholder preferences associated with economic activity and use of resources. Figure 1 depicts the high level view of feedback loops that constitute such a coupled system. It shows the adoption loop in which public preferences modify and influence policy. The knowledge loop represents the influence of expert knowledge in shaping policy. The adoption and knowledge loops define a dynamic system that remains viable when the carrying capacity metric remains below a defined threshold C; beyond this level, carrying capacity is exceeded and natural resource stocks (or their quality) will decrease. In this manner the carrying capacity parameter is used as a metric to define the limits within which a system is viable. Policy measures can be modeled as top-down control to manage the evolution of the system in order to keep it viable. In addition, as discussed by Eisnack *et al.* (2007), inclusion of stakeholder priorities and the dynamic feedback allows modeling of decentralized bottom-up control. Capturing these feedbacks in a rational manner is particularly important to accurately simulate complex system performance in the presence of environmental stressors that not only impact internal system performance but also impact the boundary conditions constraining system behavior (Mayer, Donovan, & Pawlowski, 2014). A simulation of the complex dynamics of such a system allows the exploration and comparison of alternative priorities and policies, which has been successfully applied in the management of infrastructure systems (Mukherjee, Johnson, Jin, & Kieckhafer, 2009; Jin, 2013).

This approach requires a definition for carrying capacity appropriate for this study. The carrying capacity is a guiding principle; it is *a metric defined such that, when a system is viable per associated viability criteria, it can be ensured that critical constraints will be sustained*. The definition of the carrying capacity metric is developed so that it does not significantly depart from the conceptual definitions described in our previous paper (Breffle *et al*., 2013), and at the same time can be used to identify viable system equilibria. Given the problem at hand, the carrying capacity metric C will have to be defined along with a set of viability criteria. The system viability will be defined for values of C belonging to the range $[c_1,c_2]$ within which the criteria are fulfilled.

2.1 System Dynamics Modeling: Population Dynamics

Growth in population is limited by a given set of natural resources. The time rate of change of population is defined as the difference between the number of births and number of deaths per unit of time. The number of births and deaths are in turn a function of the rates calculated as a fraction of the population. Thus, as the population increases, the number of births and deaths increase, thus setting in motion two feedback loops, one balancing or reducing it over time through deaths and the other reinforcing or increasing it over time through births.

Within a Malthusian system where natural resources are finite and limited, two more feedback loops are included. The first one is due to the propensity of a population to grow and reproduce. This increases the fractional birth rate and reinforces the population stock. The second one is the increasing fractional death rate when the growing population approaches or passes the carrying capacity of the system. This is a balancing loop, and over time, it reduces the population stock. These two competing feedbacks monitored by the ratio of population (P) to carrying capacity (C), or (P/C), ensure that as time approaches infinity, the population asymptotically approaches the carrying capacity of the system after exhibiting S-shaped growth over time. Analytically, population P as a function of time t is described as follows:

$$P(t) = CP_o e^{gt} / [C + P_o(e^{gt} - 1)] \tag{1}$$

where C is the carrying capacity of the system, g is a rate representing the increase of the population P in one unit of time and P_o is the initial population. A more complex formulation in which the carrying capacity is itself a function of the population is certainly possible, but Equation 1 is adequate for the purposes of our study. In addition, the very definition of the carrying capacity is itself a function of the people's behavior or choices the model is intending to explain or predict. For our model, we assume C is a neither a function of P nor do we provide explicitly for coupling system behavior to user preference with respect to a fundamental indicator like C.

2.2 Model to Assess Carrying Capacity

The next step is to extend this population dynamics model by linking it to the available stock of natural resources in a system. In Breffle *et al.* (2013), carrying capacity of the system was considered constant, which in turn reflects the assumption that natural resources available are finite and limited. In an uncontrolled system, this assumption is appropriate. However, it is more typical that the following occur: (1) invention of innovative technology that can reduce the *per capita* natural resource usage, (2) implementation of policies that can control and monitor the rate of this use, and (3) changes in preferences and behavior of individual stakeholders. The resulting levels of complexity are significantly higher and to accommodate this it becomes necessary to introduce a stock of natural resources into the system model. Just as the population increases or decreases due to changes in birth and death rates, similarly the stock of natural resources increases or decreases because of changes in gain and loss rates. These rates are directly influenced by stressors in the environment, which in turn, directly reflect *per capita* usage of resources. Here, given a set of natural resources (N), the system viability and dynamics becomes a function of the population (P) and the impact of the stressors on N. Given the stocks of population and natural resources, the *per capita* resource usage, R, is generally defined as:

$$R = N/P \tag{2}$$

Hence, as the population increases, the *per capita* amount of available natural resources decreases. It is important to understand that R in Equation 2 is not necessarily the actual *per capita* resource consumption of the system. In practice, the difference from the actual *per capita* resource consumption can be used as a metric to estimate whether the system is viable. In addition, increases in population directly increase consumption, which in turn increases the impact of stressors on natural resources. The nature of the stressor and its relationship to other stressors determine the rate at which the gain or loss in the natural resource is increased or decreased. This allows the integration of the population stock with the natural resource stock directly through *per capita* consumption and its impact through the stressors. This approach is similar to Ehrlich and Holdren (1971), where environmental impact is the product of population, affluence, and technology.

The population P times the metric R is always equal to the available natural resources in the system N. However, the population P times the actual *per capita* resource consumption (defined as R') denotes the demand for natural resources in the system. Hence, the following system constraint can be established for the system to be viable:

$$P \times R' < N \tag{3}$$

This constraint can be satisfied through reducing the population or the *per capita* resource consumption to maintain viability. This requires further definition of ranges within which the values of population and R need to be constrained to fully develop all viability constraints. Consider the plot of P *versus* the metric R (Figure 2). For a given level of natural resources in the system N, Equation 2 is a function that will result in hyperbolic curves relating the population to the allowable *per capita* natural resources. In other words, all the points on the curve are limiting values of (P, R) couples that satisfy the condition in Equation 3. In effect, each of the values of P is the carrying capacity of the system given the available natural resources N and the *per capita* resource consumption R. Because all the points on the curve are equivalent, the curves are system isoclines; each point on an isocline is presumed to represent equivalent system behavior. As the net available natural resource in the system changes by ΔN, the isoclines move either to the left or the right according to the direction of change. ΔN and the dotted line represent an increase in the natural resource availability. The viability constraint in Equation 3 is represented by the region to the left of the curve. This of course implies that conditions can arguably exist with zero *per capita* resource consumption and an infinite population, which is unrealistic. Therefore the shaded area in Figure 2 defines the viable region. This establishes two more viability constraints:

$$P_1 \leq P \leq P_2; \text{ and } R_1 \leq R \leq R_2 \tag{4}$$

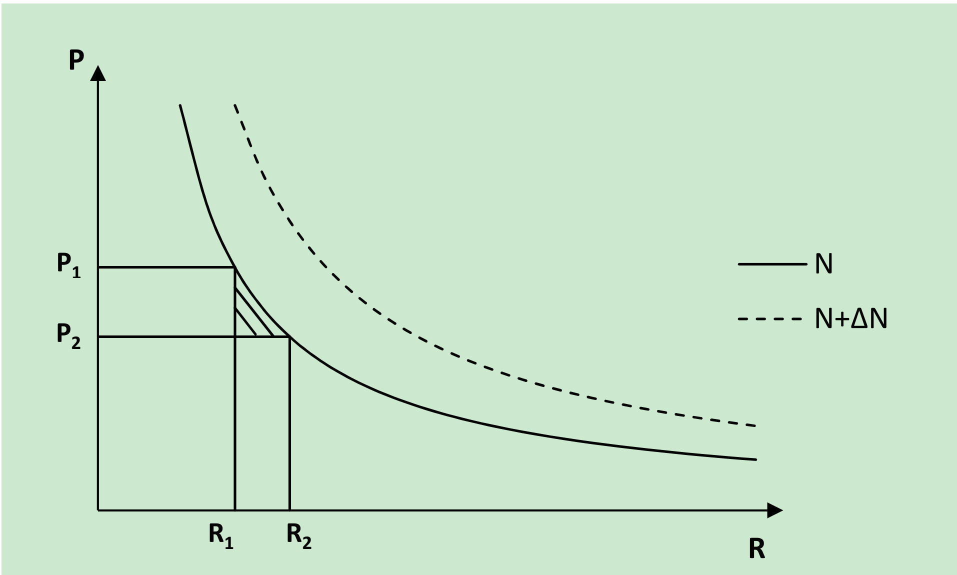

Figure 2. Interaction of population, P, *per capita* natural resource consumption, R, and available natural resource, N.

These define the ranges within which the population and per capita consumption need to be constrained for the system to be viable at all times. Control measures and policies are defined to ensure that the constraints in Equations 3 and 4 are met, and the system remains in the shaded region for a given level of available natural resources N.

The foundation supporting this model is compelling and can indeed further the application of a control theoretic approach rooted in system dynamics and viability theory to managing natural resources. As with any model it provides a platform to further explore system behavior by simulating scenarios for different growth trends in population and decay in natural resources due to the impact of stressors. The following section outlines a method that incorporates stakeholder opinion and participation in the management of natural resources.

2.3 Demonstration and Application to Bear Lake Case Study

The focus group results from our previous work clearly indicate that one of the primary issues of water resource concern for the public is pollution and contamination (Breffle *et al.* 2013). It is therefore not surprising that this is also one of the foremost areas where a willingness to take action and allocate remediation funds was reported in the results of that survey. This information is used to determine variables of interest in the system dynamics model, and in the choice of Bear Lake as an example in the system dynamics model. Bear Lake is an estuary (of approximately 415 acres) on the western shore of Lake Michigan located in Muskegon County in the state of Michigan (latitude: 43.25776, longitude: -86.28009). It is a popular destination for recreation and a possible source of drinking water. Thus, Bear Lake is a small enough body of water with specific enough problems that it makes a good candidate for this pilot study, while its location near Lake Michigan renders its results relevant to the larger aquatic systems. To study this issue, two parameters are chosen as the focus of interest: precipitation and land use. Both contribute to the total phosphorous loading of the lake. The total external loading can be expressed as a function of precipitation and land use types. In the following sections, we discuss each parameter in detail.

In the majority of lakes in Michigan, phosphorous is regarded as a critical algal nutrient that leads to eutrophication (Michigan Department of Environmental Quality, 2008). A Total Maximum Daily Load (TMDL) of total phosphorous is an important indicator of water quality in estuaries where excess phosphorous can cause a host of well-known problems. Figure 3 illustrates the control problem pertaining to the management of water quality; i.e., how to constrain TMDL within acceptable limits. Best Management Practices (BMP), land use practices, and precipitation are three important factors that directly influence the loading. Note that two of these factors involve human activity and intervention, and furthermore, most climate change models predict that the anthropomorphic influence on climate change will almost certainly affect the third as well. Hence, if the expected loading from each of these human activities is less than or equal to the TMDL, then to increase economic activity, land use practices and BMPs will be adjusted to allow for higher phosphorous loading. This feedback loop needs to be accounted for when policies controlling the loading are considered.

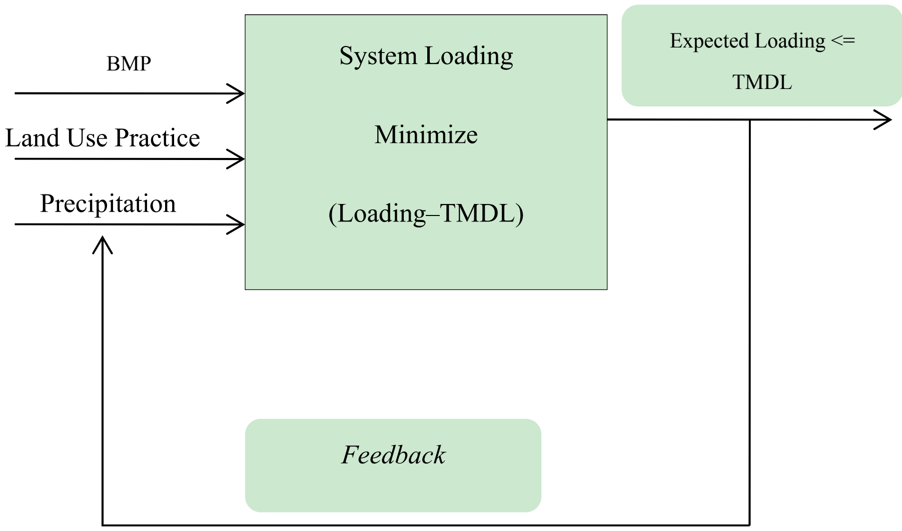

Figure 3. Illustration of TMDL (Total Maximum Daily Load) control problem with Best Management Practices (BMP)

2.3.1 Precipitation

Figure 4 displays the average annual precipitation trend for Muskegon County. It can be seen that in general, more loading is expected during summer (precipitation is almost twice the average amount of that from January to March) and directly influences the instantaneous concentration of phosphorus in the lake. Although compared to loading from other external sources (such as residential land use), direct loading from precipitation is relatively small. The exact phosphorus input is difficult to quantify accurately; however, it can be estimated reasonably well from data in literature. A typical lake has a loading rate of 0.156 lbs/acre/yr (U.S. Environmental Protection Agency, 1974). When this precipitation loading is multiplied by the total lake area, the total loading is estimated to be about 64 lbs/yr (Michigan Department of Environmental Quality, 2008).

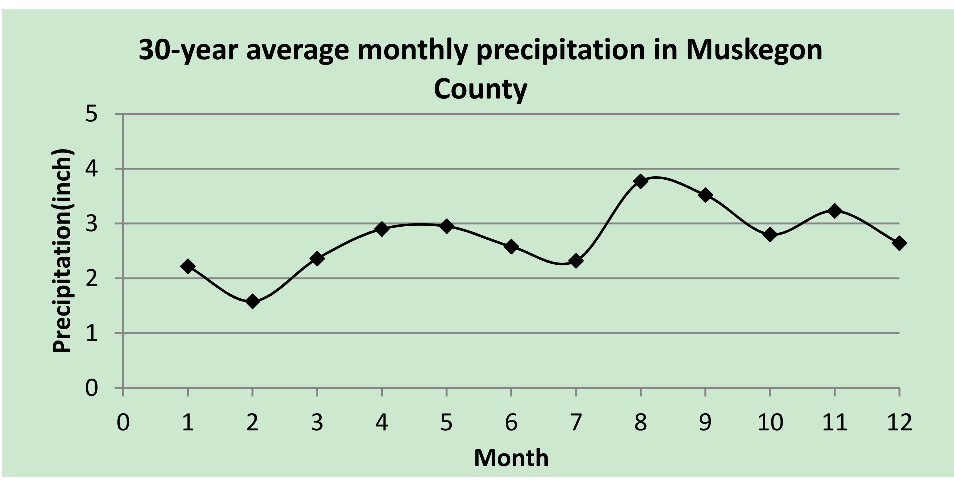

Figure 4. 30-year average monthly precipitation in Muskegon County, MI

2.3.2 Land Use

Most external phosphorus loading comes from point and non-point pollution sources in different land use categories. The total external annual phosphorous loading is estimated to be 1,839 lbs/yr to the lake (Michigan Department of Environmental Quality, 2008), where 1,488 lbs are contributed from various land uses in the area of interest. Table 1 lists estimated phosphorus loading from each land use. Based upon the average loading, the Total Loading from Land Use (TLLU) is given by Equation 5:

$$TLLU=0.507\times A1+0.192\times A2+ 0.251\times A3 +0.821\times A4 +0.002\times A5+0.003\times A6 \quad (5)$$

where A1 through A6 are areas for commercial, industrial, residential, agricultural, forest, and grass/pasture land uses, respectively. Equation 5 can be used to calculate the differences in phosphorous loading when decisions regarding land use reallocation are made. For example, if ten acres of forest site were converted to residential use, then phosphorous loading will increase by:

$$\Delta(TLLU)=0.251\times 10 - 0.002\times 10=2.49 \text{ lbs/yr} \quad (6)$$

Table 1. Estimates of phosphorus loads and percent load contribution from the various land use types in the total contribution area

Land use category	**Acres**	**Load Estimates (lbs/yr)**	**Load Estimates (lbs/acre)**	**Percent Load Contribution**
Commercial	248.3	126	0.507	8.5%
Industrial	156.3	30	0.192	2.0%
Residential	2713.9	680	0.251	45.7%
Agricultural	756.4	621	0.821	41.7%
Forest	10250.7	17.3	0.002	1.1%
Grass/Pasture	4365.7	13.2	0.003	0.9%
Water/Wetlands	564.6	0	0.000	0.0%
Total	19058	1488	-	100%

Source: revised from Michigan Department of Environmental Quality, 2008.

Current phosphorous loading to the lake is beyond the threshold of criteria established under the Clean Water Act requirement. The total internal and external loads are estimated to be 3,387 lbs/yr, while the loading capacity (maximum allowed loading under current policy) is calculated to be around 1,458 lbs/yr (Michigan Department of Environmental Quality, 2008). Therefore, it is necessary to develop and implement policies that can reduce the load. In terms of policy, long-term changes in designation of land use are the most effective way of controlling the load. In the short term, it is most important to reduce current loading from each specific land use type. Human activity is directly associated with land use and may need to be accounted for if the situation is grim enough to endanger the health of the regional economies. Therefore, in addition to a scientific approach to reduce the existing amount of P, mandatory policies need to be implemented to reduce the actual discharge amount within the limit in order to meet water quality standards.

2.3.3 Policy implementation

As shown in Figure 5, the total P loading from agricultural land use is the highest, followed by commercial, residential, and industrial land uses. Equation 5 illustrates the total phosphorous loading estimated based on the current situation. It can be seen that two variables are essential: rates of P loading for different land uses, and total area. One possible strategy is to modify the composition of land use categories. For example, forests have a small contribution to the load, but when forested land is converted to commercial use, loading will increase. In the long run, such policies directly impact the growth and development of land use and its direct impact on the economy. For example, agricultural lands discharge the most phosphorous per unit area. However, strategically decreasing the total agricultural land (which is an important stressor in previous sections) to decrease the total P loading is not an immediate option. Instead, in the short run it is more reasonable to reduce the loading rates from each land use category, without changing the land use distribution.

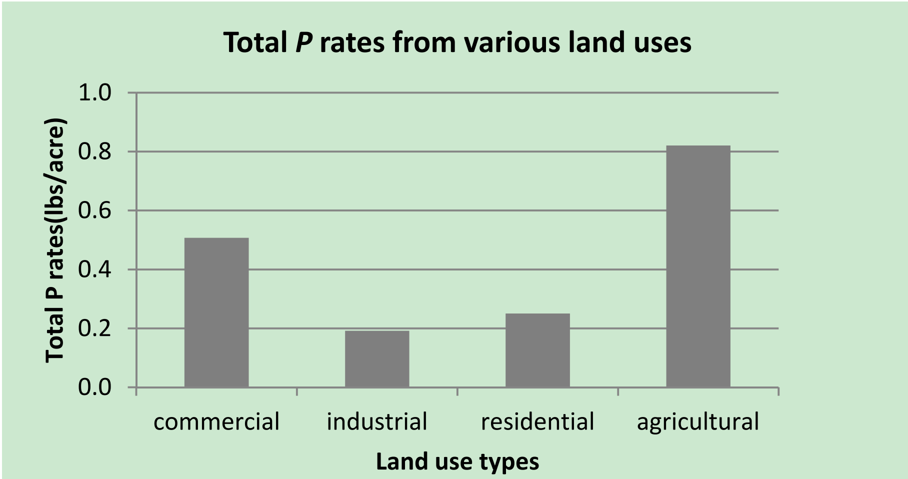

Figure 5. Annual *P* loading rates from different land use types

Both point and non-point sources contribute to total *P* loading. For discharge from point sources, regulation needs to be enforced to reduce the total *P* amount with pre-treatment before discharge. In terms of non-point sources, runoff carries all kinds of pollutants to the natural water bodies in general. To respond to these situations, BMPs (e.g., simple structural methods, such as silt fences, rock dams, and sediment basins; or more sophisticated methods such as bio-retention basins or constructed wetlands) assist in improvement of water quality in general. Figure 6 illustrates the decision-making flow chart considering the reduction of *P*. To see how the dynamic model can be used for policy decisions, consider the impact of general policies aiming to reduce the phosphorous loading under the following *scenarios*:

1) Assume that there are no changes in land use, but loading rates are reduced;
2) Assume that loading rates are constant, but there is a change in land use;
3) Assume that loading rates and/or land use vary (develop control policies).

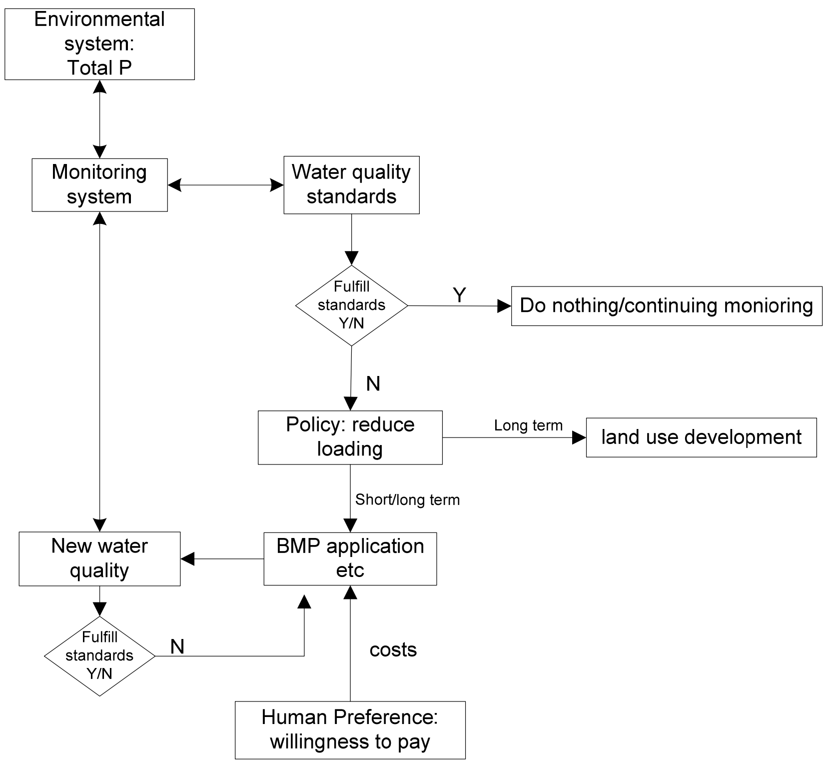

Figure 6. Flow chart for adoption and evaluation of BMP applications

Under the *first scenario*, the following two example policies can be considered: (a) decrease the total phosphorus loading by 10% *per* year from the commercial land use; or (b) decrease the total phosphorus from all major land uses by 10% *per* year. Again, the maximum load allowed from both internal and external sources is estimated for the lake to be 1,458 lbs/yr. The estimated loading limits from various internal land uses are around 590 lbs/yr (but currently are in actuality 1,488 lbs/yr; Table 1). Reductions in loading due to the above policies over a period of 20 years were simulated using Vensim (Vensim, 2013). Figure 7 illustrates that with the first policy, no substantive decrease can be noticed on the total phosphorous loading. However, if there were further investment to reduce the loading from all land use types by 10% as in Figure 8, by building retention basins or constructing wetlands, then it can be seen that at the end of the ninth year, the total P loading will be reduced to below the limit. This is a significant improvement compared to original high loading level of P.

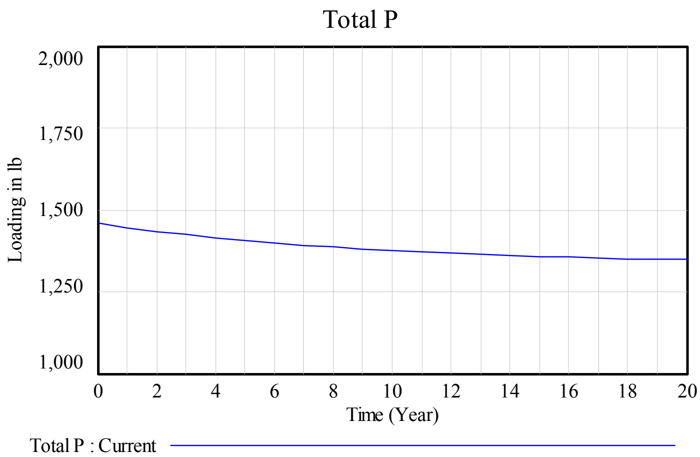

Figure 7. Total external phosphorus loading trend for *Scenario 1*: 10% reduction in commercial loading rate only

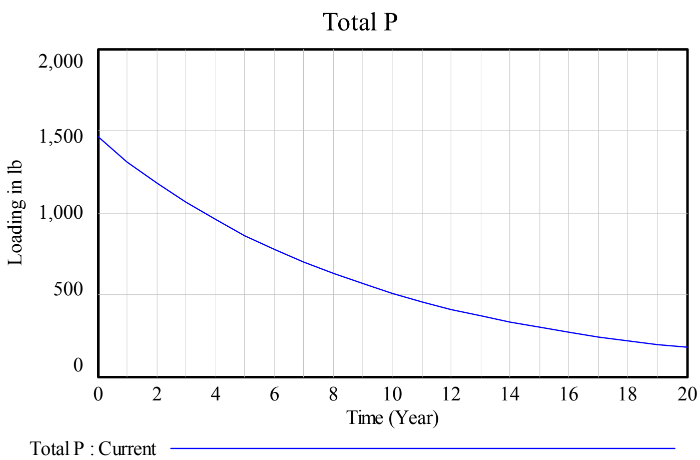

Figure 8. Total external phosphorus loading trend for *Scenario 1*: 10% loading rate reduction for all land use types

Per the *second scenario*, a constant loading rate is used, and load mitigation policies are determined in terms of long-term land use development. An instance of a change in land use is directly related to increases in population, due to incoming migrants to the region. Under such circumstances, more forestland is converted to residential, industrial, commercial, and agricultural land use. Assuming the rate per population increase is 1% per year, the change of additional P loading was simulated. As shown in Figure 9 and estimated from Equations 5 and 6, total phosphorus loading increases with time and at the end of the 20th year, an additional loading of 321 lbs/yr will be released, which is unsustainable.

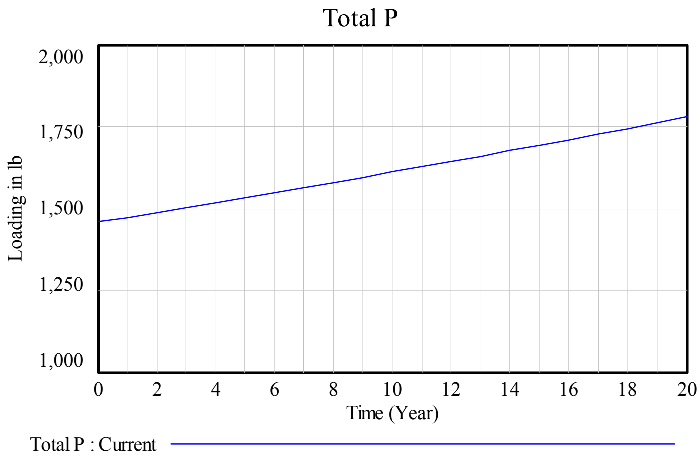

Figure 9. Total external phosphorus loading trend for *Scenario 2*: Additional total phosphorous discharge from assumed land use development versus time caused by 1% growth in population per year

The *third scenario* considered allows for understanding these dynamic variations in total loading rate per land use type and the total area of each land use type. In certain cases, the two variations balance or reinforce each other to influence the final reduction in phosphorous levels. To further examine this dynamic system, the following narrative is developed:

1) Population growth adheres to a logistic model for a given carrying capacity;

2) As the population grows, consumption increases, which in turn increases or decreases different land uses;

3) As the land use increases, it creates a feedback loop that reinforces or balances usage. For example, if commercial land use goes up because of an increasing population, it reduces the forested land. The associated loading rates also show relevant changes;

4) The total *P* loading from a particular land use becomes a product of the loading rate and the total land area, each of which are changing.

The interactions among variables are shown in Figure 10. Three control policies, each reducing the loading rate across all land use types by 5%, 10% and 20% respectively, are considered. In accordance with the theory developed in the previous sections, the simulated couples of area and loading rate, $(Al)_{sim}$, are plotted in an l-A plot along with the isoclines for $(Al)_{theo} = L_o$, (for L_o = 1500 lbs, 1000 lbs, 590 lbs, and 100 lbs). The critical *P* loading (viability constraint) defining the load capacity is set to $Al < 590$ lbs. The results are illustrated in Figure 11.

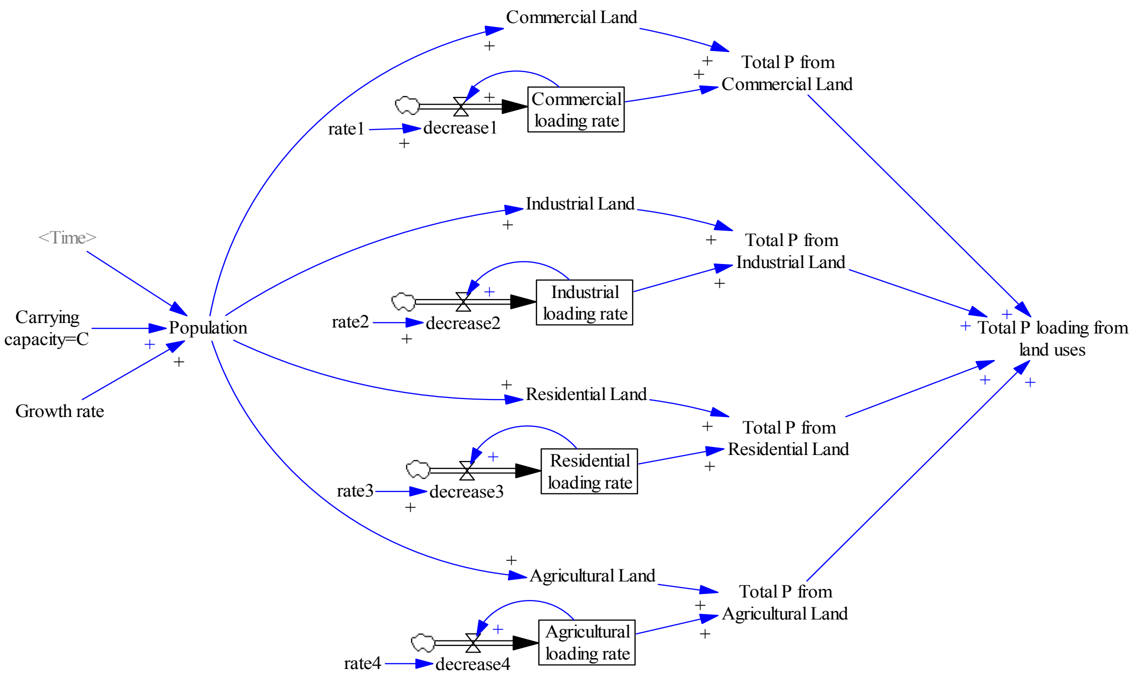

Figure 10. Interaction diagram for *Scenario 3*

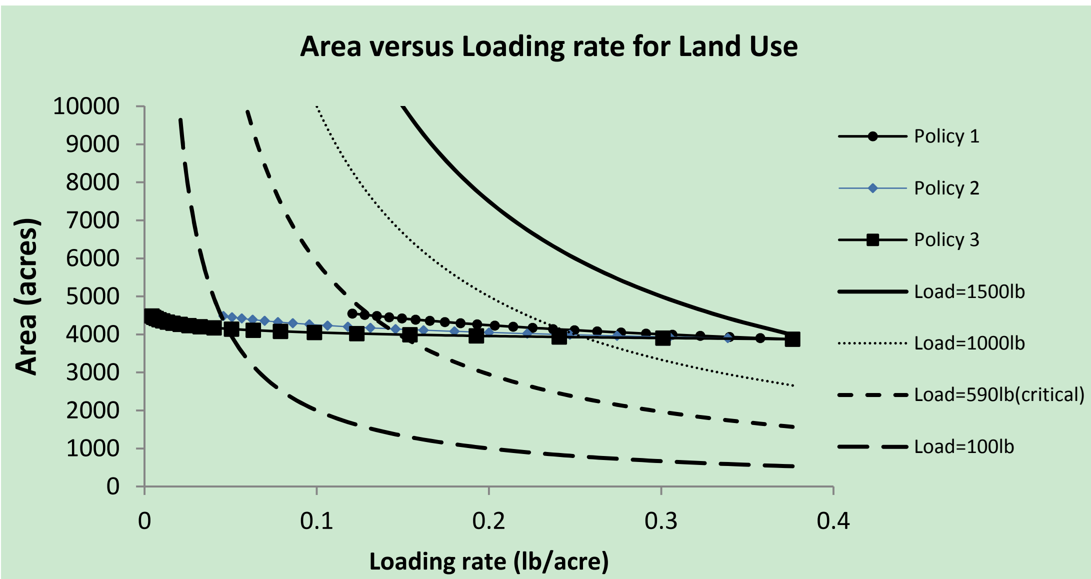

Figure 11. *Scenario 3* –Simulated and analytical results for three policies: 5%, 10%, and 20% reduction in *P* loading rate

Given that the initial loading is well above the allowable level, the simulated point moves from right to left; i.e., over time the policies result in a reduction in loading rate and possible increase in the total land area being used. It can be seen that Policy 1, which is the 5% reduction in loading rate, does not keep the system viable because the plot of $(Al)_{sim}$ is entirely to the right of L_o = 590 lbs. In comparison, Policies 2 and 3 do eventually move to a region left of the Al = 590 lbs curve, where the system becomes viable.

Table 2 illustrates the performance of each of the policies. Policy 1 does not satisfy the $[(Al)_{sim} < L_o]$ condition, though after 21 years it does reach the limiting value and just satisfies $[(Al)_{sim} = L_o]$. However, this duration makes the policy infeasible. Policies 2 and 3 both meet the condition $[(Al)_{sim} < L_o]$ in 10 years and in less than 5 years, respectively, after which a continuance of the policy will allow a reduction in the critical loading rate while increasing the total available land usage. For Policy 2, the critical loading rate weighted by land use type is 0.142 lbs/acre/year, allowing a total land use greater than 4,165 acres; and for Policy 3, the critical loading rate weighted by land use type is 0.146 lbs/acre/year, allowing a total land use greater than 4,013 acres. This suggests that land available for growth could increase by 7.5% to 16.7%. The second policy may be the most favorable, as it lowers the loading rate and eventually allows for more land use for economic growth. The tradeoff is that it takes almost twice as much time as the third policy. The third policy reduces the phosphorous load more aggressively in the first five or six years and eventually provides a much higher reduction. The tradeoff is that it allows less land use for economic growth. Figure 12 further establishes these trends on a time plot. It is very critical to note that both Policies 2 and 3 will have to be continued well after the TMDL target is met so that the reduction trajectory can be maintained. If the policies are abandoned, the system will very quickly lose viability.

Table 2. *Scenario 3*: Estimated parameters under different policy options that achieve annual simulated loading $(Al)_{sim} <= L_o = 590$ lbs.

Policy number	After number of time steps (years)	Weighted avg. loading rate (lb/acre/yr)	Total area (acre)	Comm. Land (acre)	Indus. Land (acre)	Resi. Land (acre)	Agri. Land (acre)
1 $[(Al)_{sim} = L_o]$	21	0.130	4523	290	182	3167	883
2 $[(Al)_{sim} < L_o]$	10	0.142	4165	267	168	2917	813
3 $[(Al)_{sim} < L_o]$	<5	0.146	4013	257	162	2810	783

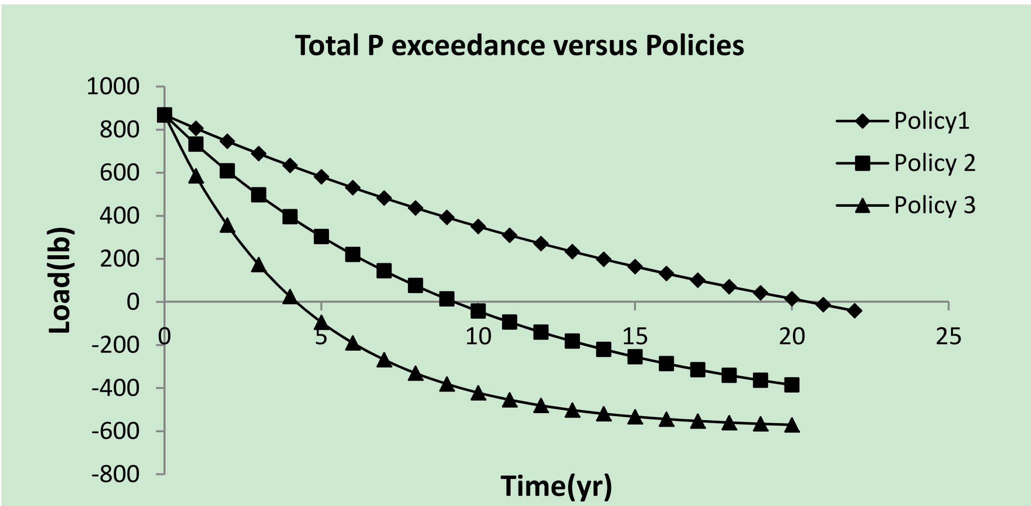

Figure 12. *Scenario 3* – Exceedance as a function time from installation of three different policies: 5%, 10%, and 20% reduction in *P* loading, with population growth

3. Discussions and Conclusions

With regard to pollution, the results from the simulation show that the success of policies to reduce pollution levels in a regional water body strongly depends on land-use patterns. The structure of the system as defined by feedback loops that reinforce growth in a sector that is already flourishing must be considered to develop long-term strategies in reducing contamination.

The public should be informed that their well-being and health are directly dependent on maintaining contaminants within acceptable levels. Increased public awareness will, in turn, influence their willingness to support preventive or remedial measures. Decision makers should be urged to monitor BMP implementations and introduce control measures from time to time to keep the pollution below acceptable thresholds. The control measures should be based on changing conditions; for example, increased precipitation. Encouraging the use of lower-phosphorous fertilizer through educational programs can reduce total *P* loads. A case study performed in Prince George's County (Maryland, USA) illustrates the positive influence of public education programs (Smith, Paul, Collins, Cavacas, & Lahlou, 1994). The survey estimated the connection between pollutant reduction and public usage of fertilizers, detergents, oil, and antifreeze. By assuming 70% of the population followed recommended activities, a significant reduction was noticed in the loading of *P*. Although based on a limited data set, the study did indicate that education programs impact behaviors of residents in terms of recycling, and choosing more sustainable alternatives, thus directly participating in pollution reduction.

An efficient strategy reduces *P* loading while balancing the cost of that reduced usage. Consider the various strategies that use a BMP to control *P* discharge. *Per* acre of runoff treatment area, the cost of a constructed wetland is estimated to be around $1,500 ($US2004); a storm-water infiltration system costs around $25,000 ($US2004) (Jarvis, Coverly, &Auch, 2004). To estimate long-term costs, a present value approach can be adopted to calculate the net present value (NPV) over time, with given discount and inflation rates. With respect to the total *P* in this study, survey results from our previous work (Breffle *et al.*, 2013) reveal that there is high willingness to take action for pollution and contamination; therefore, funding requirements and preferences can be further evaluated in the approval of such projects.

This paper proposes a dynamic model to simulate the relationships among components and assess the carrying capacity metric in a defined system. It allows the exploration and comparison of alternative policies and priorities, while maintaining viability in the system. A TMDL of phosphorous case study in the Bear Lake is then used to demonstrate the complex dynamics of such a system. Performance is simulated under the influences of different policies and alternatives are compared and evaluated quantitatively based on simulation results, which can assist stakeholders in forming strategies and managing resources. The system dynamics approach proposed could readily be generalized, for example, to develop similar dynamic models that could examine the sustainability of woody biomass bioenergy development in the Great Lakes Region. Other stressors that may be less important to the public, but are nonetheless critically important to the proper functioning of a broader ecosystem far into the future, should also be the focus of subsequent modeling efforts. The importance of having rational and accurate subsystem models (like those described in this paper) from which to build these broad ecosystem models become clearer as we consider new understanding of the roles that these subsystems play in the aggregated response of multi-scale diverse ecosystems. For example in Mayer *et al.* (2014), methods are presented for characterizing the direction and strength of feedback in CHANS that are dependent upon rational subsystem models from which thermodynamic indicators and metrics can be identified and quantified. These feedbacks fundamentally govern system response to a wide variety of perturbations and ultimately determine whether a given CHANS can persist.

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