SYSTEM DYNAMIC MODEL APPROACH FOR URBAN WATERSHED SUSTAINABILITY STUDY

Huan Feng [a], Danlin Yu [b], Yang Deng [c], Michael P. Weinstein [d], George Martin [e]
[a, b, c] Department of Earth and Environmental Studies,
Montclair State University, Montclair, New Jersey 07043, USA
[d] PSEG Institute for Sustainability Studies, Montclair State University, Montclair, New Jersey 07043, USA.
[e] Department of Sociology, Montclair State University, Montclair, New Jersey 07043, USA.
[a] Corresponding author: fengh@mail.montclair.edu

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Abstract: Over a century of rapid urbanization and industrialization in New Jersey brought visible impacts on the watershed. Consequently, it puts ever-increasing stress on the resource and environmental capacities of the region. This research focuses on an urban industrial coastal area in New Jersey (Water Management Areas 4, 5, 6 and 7), USA, an ecology heavily impacted by human activities. The objective of this research is to investigate the dynamic interactions between natural environment and human society and to model long-term trends in environmental impact and sustainable development. The data include 21 environmental, social and economic indicators for five counties (Bergen, Essex, Hudson, Morris, and Passaic Counties) collected for years between1980and 2010 (Some indicators have data only from 1990 to 2010). The data show that within the study area, population has increased by an annual average of 6.4% with a range from -7.9% to 20.7% over 30 years , and per capital GDP increased from $11,836 to $53,362 , while unemployment rates fluctuated from 4.4% to 10% over 20 years . The environmental investment increased steadily from $143 million to $247 million from 1990 to 2010. To project the future of environmental sustainability, a system dynamic model was established based on the 21 indicators. Results suggest that population will remain stable, reaching 3.35 million in 2025 from 3.3 million in 2010, and per capita GDP will reach $71,990 with an annual growth rate of 1.7%. A continued increase of environmental investment is also predicted, as per capita GDP growth is forecast to be reasonably strong. The average value of the Pb hazard quotient, which is a pollution indicator, is projected to drop from 5.0 in 1999 to 2.46 in 2025. However, this value will remain within the moderate hazard range. The research indicates that environmental pollution in this urbanized area will remain as a consequence of historical urbanization and industrialization. The system dynamic model suggests that we will be walking a finely-balanced line in Northern New Jersey as the environment continues to suffer from the consequences of long term industrialization and urbanization at the same time that climate change may present new challenges.

Keywords: Environmental pollution; Sustainability; System dynamics; Urbanization and industrialization; Watershed

INTRODUCTION

Urbanization and associated land use change have had profound environmental impacts at local, regional and global scales, especially in coastal areas. Better identifying and quantifying these impacts, including contamination through the rapidly-growing system dynamic modeling technique is critical to effective watershed environmental management and restoration. In the state of New Jersey, the northern urban watershed (closely coincides with Watershed Management Areas 4, 5, 6 and 7) is located within the New York/New Jersey metropolitan area, and is part of the New York/New Jersey Harbor Estuary system. The basin has a high concentration of former refining and manufacturing activities [1]. This area was once a rich collection of ecological systems supporting enormous biological diversity that provided former native peoples with abundant environmental and human-use services. Like many urban river watersheds throughout the world, industrial development, population growth, urbanization and land use change have resulted in many changes in the area including habitat destruction, wetland drainage, land alteration, and release of hazardous substances into the environment [2]. Excessive nutrient discharge from agricultural farming and runoff, waste and sewage disposal, and industrial toxic chemicals spills have significantly affected the aquatic system. To address this degradation and its future, it is necessary to examine the interaction between socioeconomic development and the environmental quality. This study investigates the socioeconomic impacts on sustainability, and the interaction between urbanization and environmental pollution in a New Jersey urban watershed.

MATERIALS AND METHODS

Study area

Our study area is a northern New Jersey urban watershed specifically within New Jersey Water Management Areas (WMA) 4, 5, 6 and 7 (Fig. 1). The area includes five counties and the lower Passaic River and the Saddle River. Land in this study area is extensively developed and contains many older cities and industrial centers including Newark. Within our study area, an extremely urbanized and polluted subwatershed is the Lower Passaic River Watershed from the confluence of the Pompton River downstream to the Newark Bay. This 53-km section meanders through Bergen, Hudson, Passaic and Essex Counties, and includes a number of falls, culminating with the Great Falls in Paterson. The watershed has a drainage area of approximately 334 km^2. The major tributaries to this section of the Passaic River are the Saddle River, Preakness Brook, Second River and Third River. The Saddle River is one of the larger tributaries to the Lower Passaic River. The Saddle River Watershed has a drainage area of approximately 132 km^2.

System analysis

One of the practical approaches to analyze a complex system such as the coupled human-environment system is to construct an indicator system which attempts to capture the measurable aspects of various components in the system. From an environmental sustainability perspective, we separated the system based on the indicators into two fundamental subsystems which we call the carrier and the user subsystems. The carrier indicators represent resources in their broader meaning, such as water/sediment quality, land resources, and social and economic resources. Increases of the carrier indicators (either by locating new resources or increasing human investment that makes utilizing old resources more effective) presumably will increase the sustainability of the watershed system. User indicators mainly consist of human activities that consume environmental services. They generally represent the pressure that human beings and human activities impose upon the environment and resources through rapid population growth, resources consumption, and pollutant discharge loadings in the watershed [4]. In this study, we established a tentative set of parameters that contain 21 different indicators (Table 1) and follow the carrier/user dichotomy. It is worth noting here that the parameters in Table 1 are by no means a complete list. Instead, the list is developed from a practical perspective as many of the original indicators had to be removed from the list due the data availability issues (either no data were available at all or the recorded data did not have a sufficient time series).

Data collection and processing

With appropriate indicators identified as shown in Table 1, the research team set to collect data from various public sources that include the New Jersey Department of Environmental Protection, US Environmental Protection Agency, and National Priorities List (NPL). Our primary data, including the socioeconomic, demographic, resource data were obtained from these reliable sources and then processed. Environmental pollution data were obtained from both those public sources and our previous field work; it was processed to produce the environmental pollution index for the system dynamic modeling purpose.

System dynamic model design

One of the goals of scientific research is to predict or forecast a future trend based on currently available information. For environmental sustainability within a system, the forecast is often much more complex than prediction of one or two key components in the system (such as waste disposal, remediation costs, or anthropogenic activities). This is because an individual indicator that belongs to either the carrying or the using camp creates **interaction** between them that is also an inseparable part of the environmental system. From our previous experience [5], we found a developed method, the system dynamic (SD) modeling scheme, might serve the purpose. SD modeling has had a wide range of applications since it was first promoted by Forrester (2007) in the later 1960s.

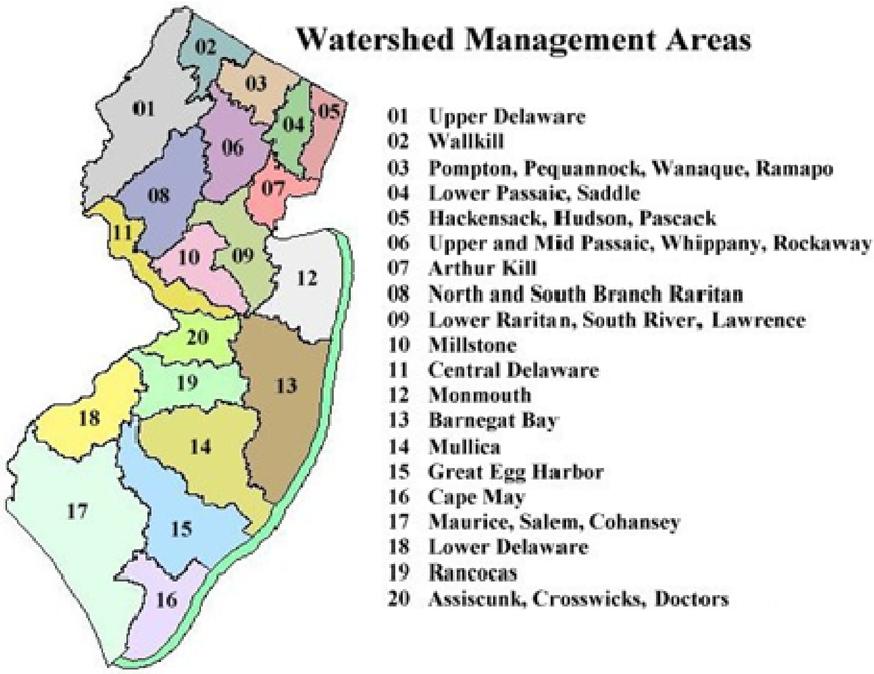

Figure 1: Map showing the northern New Jersey urban watershed Management Area (WMA 4, 5, 6 and 7) [3].

When the original modeling scheme was promoted, it was intended to solve a potential sustainable development problem – to predict how the world would progress under the then conditions. The book, *The Limits to Growth* [6], is a direct application of the SD modeling scheme and the results are still widely discussed today. The most appealing characteristics of the SD modeling scheme are that it is based on an indicator system and takes into consideration interactions among indicators [4, 7-8]. Although the SD model cannot "predict" the dynamics of an environmental system, the results generated can provide a basis for informed decision making and reduce possible pitfalls due to an inability to incorporate system interactions. In a typical system dynamic model, we can roughly divide indicators and their interactions into four primary groups: the stock, the process, the auxiliary variables, and the flow (Fig. 2). The stock variable stores the basic (and core) states of the environmental system. It is governed by in- and out-rates that are often impacted by the process and/or auxiliary variables. The processes (or ongoing activity) in the system determine the contents of the stock. Auxiliary variables are system variables that often dictate the rates at which processes operate. Flow (or inter-relationship) represents the intricate connections among all components of a system [9]. This terminology is partially borrowed from a commercial system thinking software package, STELLA®. STELLA (ISEE System, Inc.) is one of the first dynamic modeling software packages to achieve broad recognition, due in large part to its user-friendly graphic interface that has an iconographic interface to facilitate building of dynamic systems and has components that are intuitively assembled to simulate the dynamic processes [10-11].

For years, we have been developing a system dynamic model that can serve as a framework and starting point for understanding the dynamics of a coastal urban watershed's environmental sustainability. The model is based on a slightly different indicator system than the one proposed in Table 1. In a nutshell, the model includes three primary modules, i.e., population and production module, land use module, and environmental protection and pollution module. In these modules, there are indicators that belong to both the carrying and using categories. Relationships among various indicators are determined by verification and rectification of data analysis.

Table 1: Tentative indicators for sustainability system analysis

Sub-system level	Sub-category level	Individual indicator level
Service providers and enhancers	Natural resources	Available industrial quality and above water resources
		Available non-urban land areas
		Average air quality (pollution resistance)
	Quality of life	Median household income
		Employment rate
		Percentage of people above poverty line
	Environmental investment / protection	Remediation investment
		Solid waste disposal facilities' capacities
		Waste water treatment facilities' capacities
		Environmental education programs (from elementary to high school curricula in local schools)
	Societal development	Education level (percentage of bachelor and above degree holders)
		Ethnic diversity
Service consumers	Industrial growth	Growth rate of local industrial section (output or number of factories that produces potential environmental pollutants)
	Resources consumption	Average daily water consumption rate
		Average daily energy consumption rate
	Population growth	Total population
		Population growth rate (natural and immigration)
	Land use deterioration	Increase rate of urban land uses
		Loss rate of wetlands
	Environmental pollution	Brownfield and/or superfund sites (remediation cost)
		Pollutant index (in water, sediments, soil and air)

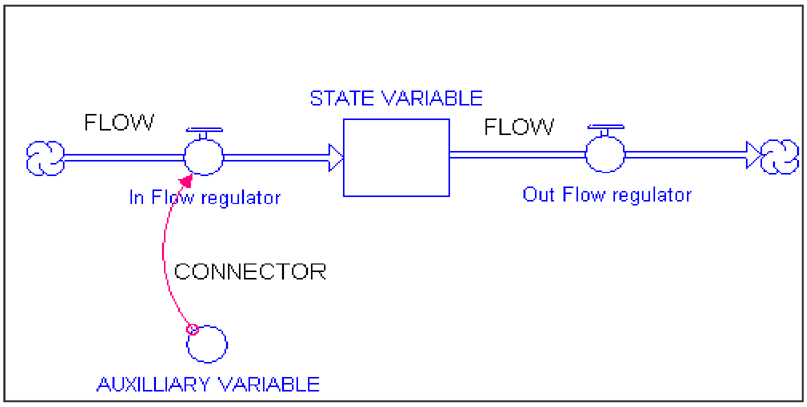

Figure 2: A very basic unit diagram showing visual dynamic linkages of STELLA system dynamic model. The main components in STELLA model consist of state variables, auxiliary variables, flows and connectors, and have computer simulation application.

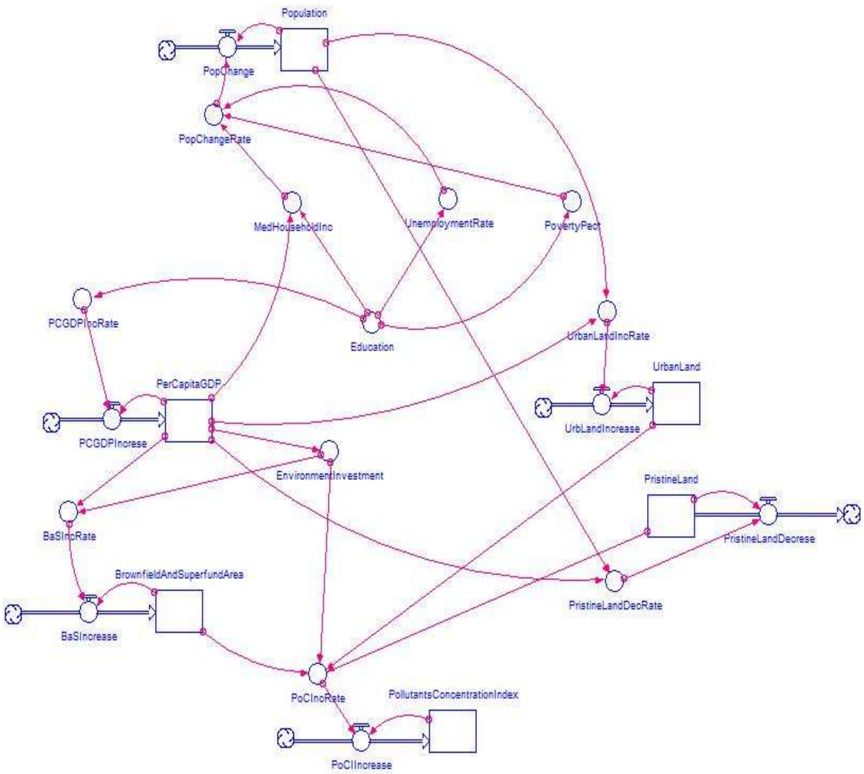

Figure 3: A flow diagram and relationship between the parameters in the system dynamic model.

The population and production module includes a population stock and a per capita GDP stock. Median household income, unemployment rate, poverty rate and education are included as auxiliary variables that provide input for the changing rates of population and/or per capita GDP. Population and per capita GDP, on the other hand, are designed to have significant impact upon environmental investment, and land use changes. The land use module contains an urban land and a pristine land stock variable. Not surprisingly, we found both stock variables were highly correlated (with a nearly perfect negative correlation). This was expected since urban land had been largely converted from pristine land (which includes forest, wetland, and barren categories). To investigate the dynamics of how environmental degradation might impact different land use categories, we intentionally maintained these two categories in this module. This module is directly linked with both the environmental protection and pollution module, and the population and production module. The environmental protection and pollution module contains a brownfield and superfund site information stock and a pollution index stock variable. The environmental investment auxiliary variable, which uses the annual budget from New Jersey's Department of Environmental Protection as a proxy, is linked with the population and production module. Data from 1990 – 2010 were collected and assembled for all these indicators. Relationships among various indicators were tested using the data and the model structure was revised based on data verification. After the data were plugged in and the model performance reached satisfaction, the final model structure was produced (Fig. 3).

RESULTS AND DISCUSSION

This pilot study investigated environmental sustainability and its dynamics. The research will enable us to better understand the relationship between current environmental status and economic development and land use change in a coastal urban watershed. Based on our data analysis and system dynamic modeling, we have come to some interesting results.

Urban Passaic River watershed contamination and socioeconomic development

It is well known that the urban area of Northern New Jersey (specifically, Bergen, Essex, Hudson, Morris, and Passaic Counties) has witnessed tremendous socioeconomic development and ecological-environmental damage. Due to its long-term industrialization and urbanization, the primary causes of water and sediment contamination originated from waste disposal, atmospheric deposition, and industrial sewage and toxic chemicals spills [12]. Our data analysis as well as the previous studies indicate that, for example, the lower reach of the Passaic River is heavily polluted by dioxins, PAHs, PCBs and heavy metals from historically uncontrolled agricultural and industrial activities and urbanization [13-14. Table 2 shows selected metal concentrations in sediments of the lower reach of Passaic River 10 km up from the mouth of the river. Meanwhile, excessive nutrient discharge and waste and sewage disposal have significantly contaminated the Passaic River aquatic system. Phosphorus load is one example of environmental concern (Fig. 4). High mercury (Hg) concentration in the sediments is another example of serious anthropogenic impact on the aquatic environment (Fig. 5). Such environmental degradation and contamination are also associated with rapid socioeconomic gains. The socioeconomic development status in the study area in the last half century (1969-2006) is shown in Fig 6, which integrates population growth, personal income increase, and proprietor business change. During the past 40 years, Northern New Jersey has experienced intensive economic growth, especially personal income and non-farm proprietors (industries). It is clear that this economic growth and environmental degradation are inherently related to each other. To fully understand the relationship between environmental protection/degradation and economic gains requires a systematic view that takes into consideration all relevant (or at least all recognized) components in an inter-related dynamic system, such as the results produced from a system dynamic model.

System dynamic modelling

In this preliminary study, we developed a system dynamic model to reflect the interaction between natural environment and anthropogenic activities. During the data analysis that covered a 21-year period, we found some of the data, such as brownfield, superfund sites, and population, showed quite irregular patterns. For brownfield and superfund site data, this may be due to the identification process of their sites. Although the population showed a general increasing trend, total population of the five counties fluctuated rather irregularly during the 21-year period. To accommodate such an irregularity into the system dynamic modeling scheme, we attempted to apply a so-called grey-system time series simulation technique [17]. This technique has been employed in many system analysis problems and has been found to perform well in sorting out regularity from seemingly irregular patterns/series. In this study, we found that the incorporation of the grey-system time series simulation technique increased the system dynamic model's performance quite dramatically.

Table 2: Maximum and average concentrations of selected metals in Passaic River sediments. Concentration is in µg g^{-1}. (S.D. is standard deviation and n is sample size.) [14]

Year	Sediment	Chromium				Lead				Mercury				Nickel				Zinc			
		Max	Mean	SD	n	Max	Mean	SD	n	Max	Mean	SD	n	Max	Mean	SD	n	Max	Mean	SD	n
1991	Upper layer	402	152	98	33	2200	412	382	33	12.4	4.4	3.0	28	118	50.7	22.2	14	740	562	191	11
	Deep core	1230	188	215	142	3000	359	472	102	29.6	6.1	7.5	102	269	52.7	49.5	102	10200	553	982	142
1993	Upper layer	397	151	97	25	777	340	182	21	6.7	2.6	1.5	21	178	50.8	37.8	25	1800	568	381	25
	Deep core	1530	292	325	55	7860	581	1071	55	28.1	4.3	5.0	54	143	51.5	26.4	55	8630	802	1204	55
1995	Upper layer	589	153	100	95	751	334	147	90	10.7	3.3	1.9	92	369	47.7	42.9	64	1620	596	235	71
	Deep core	2160	334	314	490	22000	505	1286	490	28.3	6.5	5.4	490	309	58.2	35.8	490	3110	788	531	490
1999	Upper layer	202	124	38	58	515	224	98	58	5.8	2.3	1.2	58	57.7	39.2	7	30	680	523	69	30

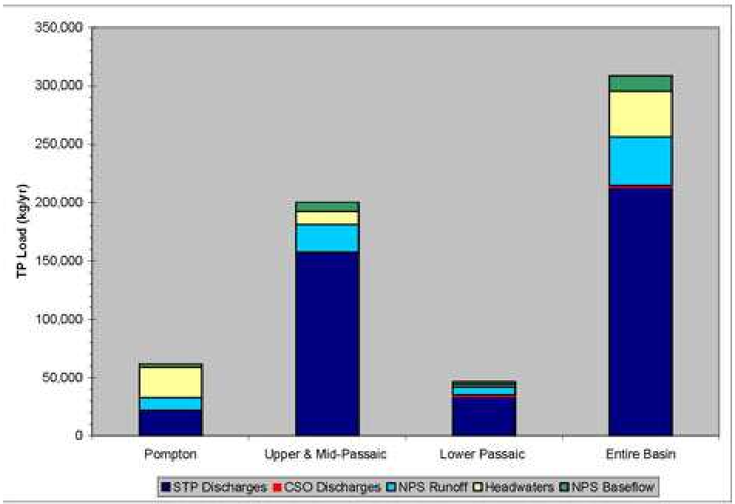

Figure 4: Average annual phosphorus loads by basin within and around the Passaic River watershed [15].

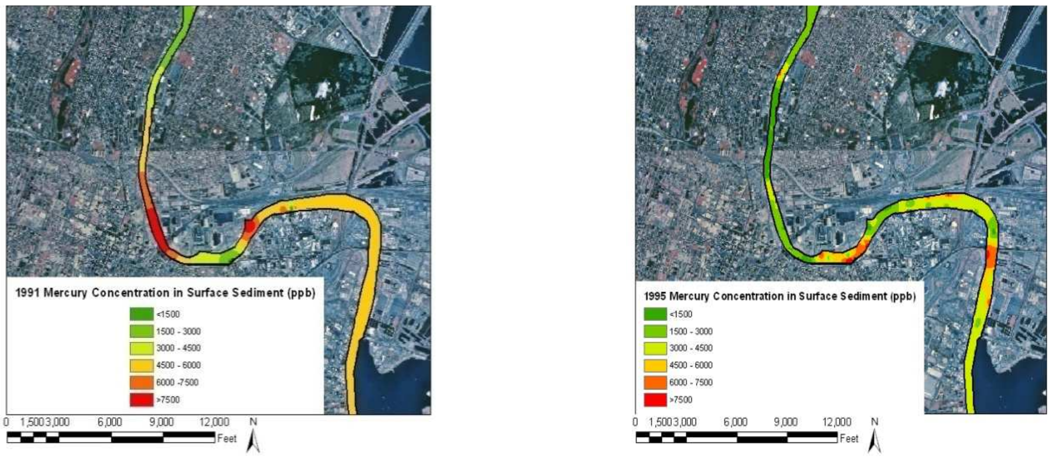

Figure 5: Spatial and temporal variations in mercury (Hg) concentration in the Lower Passaic River surface sediments (<15 cm). Map showing Hg concentration distributions from the 1991 sampling (left), and the 1995 sampling (right).

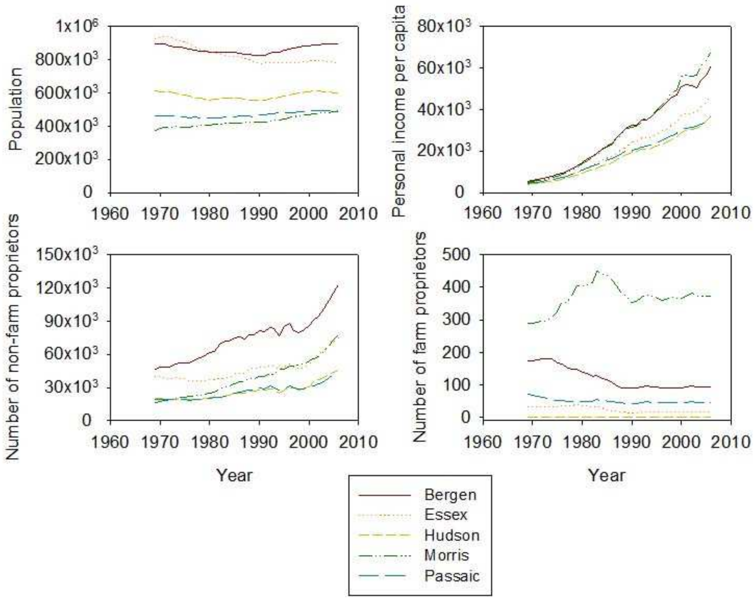

Figure 6: The annual socio-economic development trend in the study area from 1969-2006. The area includes five counties (Bergen, Essex, Hudson, Morris, and Passaic Counties). (Data source: [16])

In analyzing the data collected from 1990 – 2010, our modified system dynamic model gave a general prediction error (against the actual data) from 5% to 50%. Large errors appear, unsurprisingly, in the irregular indicators (population growth, brownfield and superfund site area, etc.). Compared to the unmodified system dynamic model, which produces prediction errors from 5% to 200%, we deem the modified model an acceptable increase in model performance.

In principle, the system dynamic model can be used to make prediction forward for as long as the modeler desires (at least the software, STELLA®, has such capability). In practice, however, with a large error of nearly 50%, any prediction period longer than 15 years will not be reliable [18]. Even prediction longer than 10 years should be treated with extreme caution. Because of this, we have parsed our prediction period of 2011 to 2025. We deem the first 5 years of prediction is relatively reliable and can be used for supporting policy and planning for urban sustainable development, years 6 – 10 (2016 – 2020)'s prediction can provide some guidance for decision support, while years 11 – 15 (2021 – 2025)'s prediction can be used only as reference. It is seen that our model is able to predict values of each individual indicator. To keep the narrative concise, however, we report here only the predicted results of six indicators from the three modules, which also demonstrate a smooth and gradual changing trend, and relatively small prediction error (within 20% against the actual data). These indicators include population, per capita GDP (dollar), unemployment rate (%), urban land area (square kilometers), environmental investment (thousand dollars), and Pb hazard quotient (as the proxy of pollution index) (Fig. 7).

Fig. 7 shows two interesting results. Firstly, not surprisingly, population, per capita GDP, environmental investment, and urban land area are all predicted to increase for the next 15 years, provided that the current socioeconomic, policy, industrialization and urbanization conditions remain constant. Population increase is quite small; only 50,000 more is predicted in the 15-year period. This is to be expected as Northern New Jersey is a mature urbanized region with an urbanization rate close to 90%. Per capita GDP increase is slow but steady with a predicted annual increase rate of 1.7%, indicating that the region will continue to grow in wealth and prosperity. The unemployment rate seems to show a linear trend, which is somewhat troubling. However, considering the system dynamic model's prediction capability, this trend might remain true for the first five years, indicating a slight increase, but still not a seriously high unemployment rate (less than 6%). The trend beyond 2015 should be treated with caution. It gives a 7% unemployment rate.

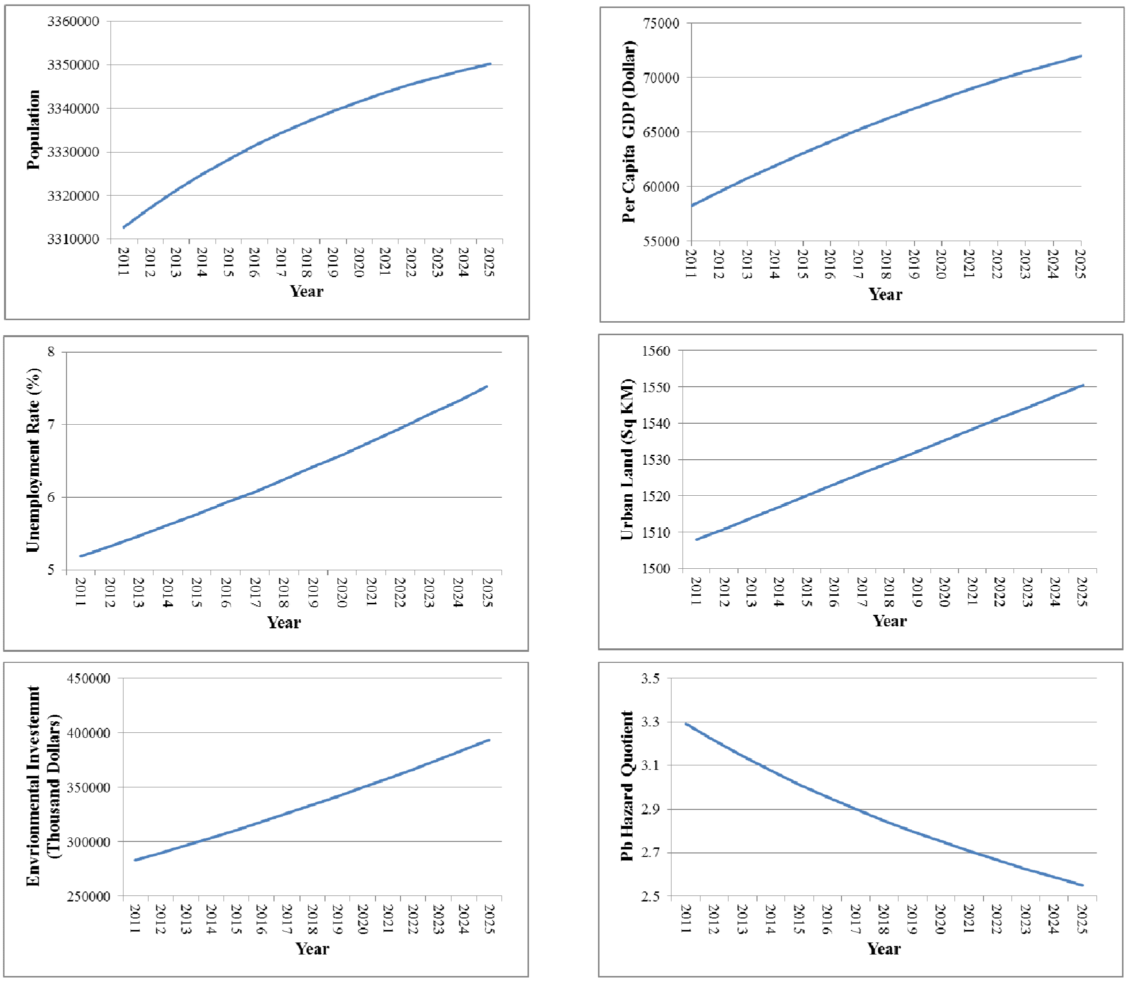

Figure 7: System dynamic model predicted results for selected indicators from the three modules.

Secondly, the negative relationship between environmental investment (here we use the NJDEP's annual operation budget as a proxy) and the environmental pollution index (again, Pb hazard quotient is used as a proxy) continues as our data suggest. We realize that the two proxies, which are our intended measures of environmental investment and pollution, are by no means perfect (or even complete). Their interaction does support an argument that, although human society has imposed negative impacts on the environment during its development, it is able to invest to improve environmental quality and increase environmental services. Still, as suggested in Fig. 7, while environmental investment reaches almost $400 million in 2025, Pb hazard quotient drops only to about 2.5 (from 5.0 in 1999), which is regarded as medium hazard for the watersheds and their eco-systems. The results seem to suggest that restoration/remediation of a degraded environment costs much more than preventive measures.

CONCLUSIONS

This research investigates the dynamics of the sustainability issue in urban coastal areas in northern New Jersey from a systematic perspective. The historical development and industrialization in the area have made it one of the nation's wealthiest regions. Yet it is also evident that developments have resulted in enormous impacts on the environment and its potential to provide lasting services. Our SD modeling suggests that historical and on-going environmental degradation can be reduced and the region may be able to reach a sustainable level of development. A key factor will be whether or not an appropriate level of investment is reached. The approach adopted in this research provides a holistic understanding of the sustainability issues in coastal urban northern New Jersey. We believe that the knowledge developed through this study can benefit Federal, state and local governments, and public and private environmental managers in decision making for environmental protection and restoration. The results from this study are also vital for developing future environmental management strategies for environmental restoration and urban coastal development. In addition, this project can serve as a methodological model for assessing urban environmental sustainability that can be referenced worldwide.

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ABOUT THE AUTHORS

Huan Feng is a professor of coastal environmental geochemistry at Montclair. His research activities include US-China collaboration to advance understanding of fate and transport of contaminants in coastal marine environments, employing advanced modeling techniques (e.g., GIS, system dynamics) to study urban coastal watersheds, and promoting science-based decision making especially for coastal resource management. Contact Dr. Feng at

Department of Earth and Environmental Studies, Montclair State University, Montclair, New Jersey 07043, USA

Tel: 1-973-655-7549

Fax: 1-973-655-4072

E-mail: fengh@mail.montclair.edu

Danlin Yu is an associate professor of geographic information science and regional studies at Montclair. His major research interests include GIS, spatial analysis, urban/regional studies, environmental sustainability, and remote sensing. His recent research has focused on system dynamic modeling of urban sustainability issues, and geographically weighted regression techniques. Dr. Yu can be reached at Department of Earth and Environmental Studies, Montclair State University, Montclair, New Jersey 07043, USA

Tel: 1-973-655-4313
Fax: 1-973-655-4072

E-mail: yud@mail.montclair.edu

Yang Deng is an assistant professor of water/wastewater treatment and environmental remediation. He is also an active Professorial Engineer (Environmental Engineering). His research covers a broad spectrum of topics in drinking water/wastewater treatment, remediation, hydrology, and water quality. Dr. Deng can be reached at

Department of Earth and Environmental Studies, Montclair State University, Montclair, New Jersey 07043, USA
Tel: 1-973-655-6678
Fax: 1-973-655-4072
E-mail: dengy@mail.montclair.edu

Michael P. Weinstein is Director of PSEG Institute for Sustainability Studies at Montclair State University located in Montclair, New Jersey. He is the former President & CEO of New Jersey Marine Sciences Consortium where he also served as the New Jersey Sea Grant College Program Director. Dr. Weinstein conducts extensive research in the areas of coastal ecology, sustainability science, fisheries science, wetland ecology, and restoration ecology, primarily in salt marshes, sea grass meadows, and mangrove habitats. Dr. Weinstein can be reached at

PSEG Institute for Sustainability Studies, Montclair State University, Montclair, New Jersey 07043, USA
Tel: 1-973-655-3037
Fax: 1-973-655-6810
E-mail: weinsteinm@mail.montclair.edu

George Martin is a professor of environmental sociologist with expertise in urban sociology. In particular, he studies the landscape impacts of urban transportation systems. Dr. Martin can be reached at

Department of Sociology, Montclair State University, Montclair, New Jersey 07043, USA
Tel: 1-973-655-7231
Fax: 1-973-655-5389
E-mail: marting@mail.montclair.edu