A System Dynamics Model for the Environmental Management of the Sepetiba Bay Watershed, Brazil

Alexandre de C. Leal Neto · Luiz F. L. Legey ·
Marcela Cecilia González-Araya · Silvio Jablonski

Abstract In the recent past, the Sepetiba Bay watershed, located in the Rio de Janeiro State, Brazil has experienced rapid industrial development and population growth, as well as an increase in water pollution and environmental degradation. To analyze the complex interrelationships among the agents affecting the Sepetibza Bay environment, a system dynamics model was developed. The model builds on extensive studies conducted for the watershed, and simulates different hypotheses of economic growth and of demographic expansion. Thus, it can be used as a decision support tool for the identification of investment priorities and policy analyses under various scenarios. In order to provide a comprehensive approach to the environmental management of the Sepetiba Bay watershed, the model had to consider only the most relevant aspects of the behavior and the key interactions among agents operating in the watershed. In this article, the model's structure is presented together with some of its main results.

S. Jablonski (✉)
Department of Oceanography, State University of Rio de Janeiro, Rua São Francisco Xavier, 524, Bl. E, Rio de Janeiro RJ - 20550-013, Brazil
e-mail: jablonski@pobox.com

A. de C. L. Neto · L. F. L. Legey
Energy Planning Programme, COPPE, Federal University of Rio de Janeiro, PO Box 68565, Rio de Janeiro RJ - 21945-970, Brazil

M. C. González-Araya
Departmento de Modelación y Gestión Industrial, Facultad de Ingeniería, Universidad de Talca, Merced No. 437, Curicó, Chile

Introduction

The Sepetiba Bay is located in the Rio de Janeiro State, approximately 50 km to the west of its capital. It is a semiconfined water body, with approximately 305 km^2 of area, bounded at South by the Marambaia sandbank, at North and East by the continent, and at West by the Ilha Grande Bay (Fig. 1).

Small beaches and estuaries, separated by rocky tips, characterize the North shore. The Marambaia sandbank, 40 km long, is a dam of sand that acts as a natural shelter to wave attacks. The connection with the Atlantic Ocean is made through passages and channels between the continent and several islands.

At East, near Barra de Guaratiba, the bay is linked to the sea by a narrow channel. It has about 40 km^2 of preserved mangroves, an important natural nursery of species with great commercial interest. The rivers and channels that flow into the bay drain an extensive watershed of about 2654 km^2, which includes agricultural areas and industrial and urban zones. In addition, the sepetiba watershed receives the water coming from the transposition of the Paraíba do Sul watershed (160 m^3/s). There is also an extensive contribution of sediments to the bay coming from the rivers, provoking an estimated sedimentation rate of 0.3 to 1.0 cm per year (SEMA 1997a). Sepetiba Bay has depths from 2 to 12 m, except in the navigation channels where the depth is greater. Approximately 50% of its area has depth less than 6 m (SEMA 1997a). The bay holds in its eastern portion an
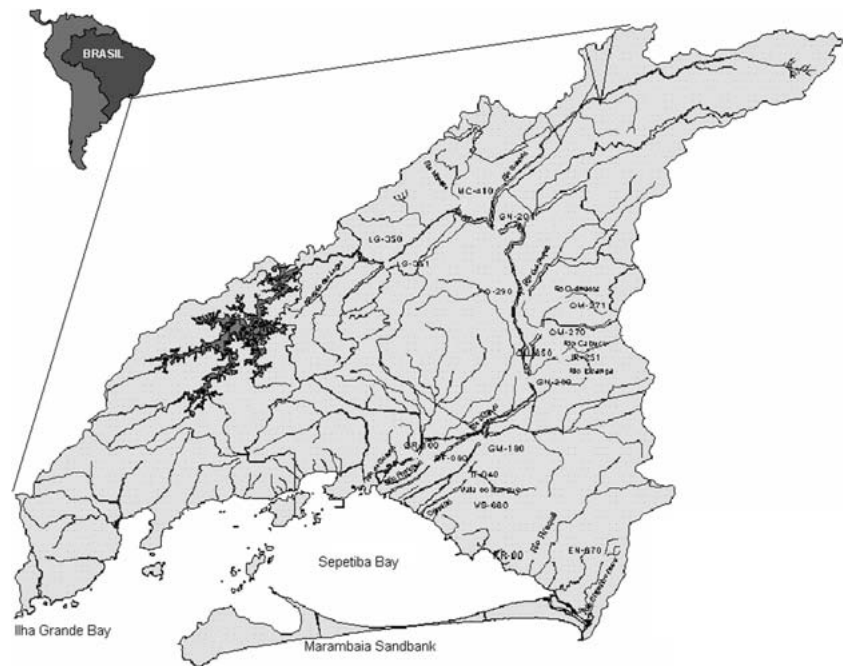
Fig. 1 Map of Sepetiba basin (adapted from SEMADS 2001)

archaeological and biological reserve, with an area of approximately 28 km^2, the majority of which is composed of flooded lands, margined with extensive mangroves (IBAM 1998).

Fishing is an important activity for the local community. It is mostly an artisanal activity and is directed toward the capture of shrimp, croaker, and mullet, among other species. Local tourists consume part of it and the rest is commercialized in the city of Rio de Janeiro's fish markets. In the mangroves, crabs and oysters are also captured for local consumption.

The proximity of Rio de Janeiro brings about a constant flow of recreational tourists in search of beaches and islands of the region, especially during weekends and holidays.

Since the 1970s, when industries were introduced, the Sepetiba region has had to cope with the highest rate of industry growth in all of the Rio de Janeiro Metropolitan Area. On top of that, the industrial activity that has come to the region has presented a high pollution profile. The consequence was a decline of the Sepetiba Bay water quality, demonstrated by a substantial decrease in dissolved oxygen, the beginning of a sharp upward movement in algae, and heavy metal concentrations that already exceed Brazilian standards (World Bank 1996).

The basins of rivers Guandu, Guandu-Mirim, Piraquê, Guarda, and Cação Vermelho hold 90% of the study area's 1.34 million inhabitants. In addition, these basins concentrate 91% of the potentially pollutant industries, either already installed or in the process of being installed. Because of that, they are responsible for more than 90% of the discharges reaching the Sepetiba Bay.

The State Government has declared as a strategic priority the development of the Sepetiba port and its related industries. Given the expected fast industrial development and population growth in the Sepetiba basin, there is an urgent need for a pollution management system in the region. The cost of preserving environmental quality varies strongly—and inversely—with the degree of cross-sector coordination of policies and regulation (World Bank 1996).

The question of how environmental issues should be managed in the context of such projected rapid increases in industry and population led to the idea of building a system dynamics model to support the overall planning process of environmental management of the bay's watershed. This model—the Sepetiba Bay Environmental Management model or SBEM—is presented in this paper, which is organized as follows: first, there is a description of the model together with the main hypotheses used in its development. Then, a selection of the results obtained is presented. Finally, there is a discussion about the lessons learned with the process of building the model as well as some indications for future developments.

Methods and Model Description

The major reason for choosing the system dynamics approach was its ability to represent complex interrelationships between human actions (economic

agents and government) and the socio-biological-physical environment (Costanza and Ruth 1998). It is a well-established method, which has been applied to the study of systems in several fields, such as management (Georgantzas 2003); policy analysis (Meadows and others 1992); economics (Radzicki and Sterman 1994); biology (Arquitt and Johnstone 2004); medicine (Dangerfield and others 2001); and climate change (Sterman and Sweeney 2002).

In complex systems, interactions among processes presenting positive and negative feedback loops of varying strength are present. System dynamic models explicitly represent these feedback loops and their—usually nonlinear—relationships. As a result, it is possible to model the dynamics of complex systems behavior in a natural way (Hannon and Ruth 1994). In addition, by introducing the possibility of dealing with qualitative aspects present in long-time-scale contexts, system dynamics models can represent phenomena in ways that go beyond what traditional time series models are able to do.

In the specific instance of the Sepetiba watershed, the need for a methodology that would be able to deal with the inherent natural complexity associated with the management of ecosystems is even more striking. Indeed, the 12 counties that comprise the study area show marked socioeconomic differences, with many diverse problems and demands.

The system dynamics model developed sought to represent the most relevant interrelationships among the several agents involved in the region, in such a way as to obtain a general view of the time-changing behavior of the environmental variables and their response to different policies.

One way to view a watershed is as a space and ecological entity that concentrate and enhance the pollution effects and the sediment contribution from its several watercourses to the reception body. In addition, as a socioeconomic and political unit it can be utilized for management planning, conservation strategies, and implementation purposes (Clark and others 2005). This is the reason why many studies on the environmental problems—and possible solutions as well—of the Sepetiba Bay area defined the bay's watershed as their primary focus.

The SBEM followed these lines for two reasons: first, because it employed many of the available studies formerly made for the bay's watershed; and second, because it was conceived as a decision support tool to assess possible courses of action for the management of bay's watershed. Specifically, its objective was to provide the Rio de Janeiro State Environment Secretary—SEMA—with a mechanism to assess and develop integrated actions on the watershed, considering several branches of environmental knowledge, in a multidisciplinary approach. Additionally, it should assist SEMA in the coordination of actions taken by different agencies institutionally responsible for the administration of the watershed area, by supplying the Secretary with a "hub model" for further environmental modeling. Along these lines, SBEM's initial goal was to achieve a conceptual model capable of identifying the most relevant problems in the watershed system.

Most of the model's database was obtained from extensive studies that analyzed many aspects of the watershed, such as demography and population growth, industrialization, land use, water resources, and sanitation (SEMA 1997a, 1997b, 1997c, 1997d, 1998). In addition, information on key planning elements such as those related to effluents and water quality were gathered through interactions with stakeholders familiar with the watershed system. Actually, continuous consultation with those stakeholders (public officials, members of grass root organizations, inhabitants of the area, and so on) allowed for the identification of the complex relations, which spring from social and economic factors. The consultation process worked through the presentation of reports on the model's stage of development in meetings with stakeholders and the SEMA team. The information sharing with those people involved with the main issues about the watershed generated feedback that helped to identify the model's functional relations and contributed to its acceptance by the stakeholders.

The SBEM was built around eight distinct sectors. These sectors were defined in such a way as to facilitate a separate view of each component of the Sepetiba Bay watershed system, while maintaining the systems approach comprehensive view. The chosen sectors were the following: population dynamics; industry; commerce, services and tourism; agriculture and cattle breeding; infrastructure; land use; public finance; and effluent, residues, and solid waste (Fig. 2).

By dividing the model into sectors, it was possible to investigate a set of causal relationships within a particular context more thoroughly, leaving the task of finding interconnections between sectors to a later stage. Moreover, the sector partition facilitated the work division among the different levels of expertise that composed the interdisciplinary team in charge of the model's construction, thus maximizing the potential of each one's contribution.

The model attempted to represent the main factors responsible for the environmental degradation of the watershed and the water pollution of the Sepetiba Bay

Fig. 2 Interrelationships among the Sepetiba Bay Environmental Management Model–SBEM sectors
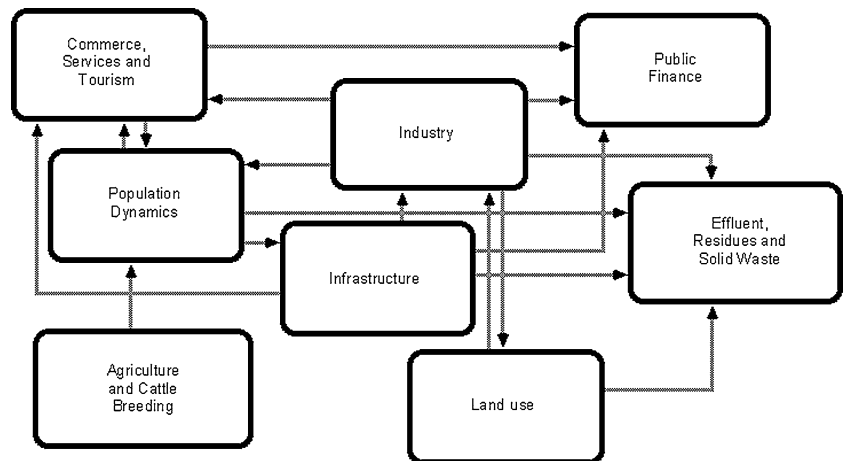
by depicting the structure of the system that produces and maintains that degradation. The purpose was to provide a reference framework for seeking answers to the following (decision) questions: (1) which command and control actions—or economic mechanisms—should be used for environmental pollution control; and (2) which should be the investment priorities to interventions for the area's environmental preservation and recovery.

Two additional points of the SBEM architecture are worth mentioning. The first one is the interaction with specific models built for the watershed, as, for example, the Model for Simulation of Dissolved Oxygen—SIMOX (SEMA 1998), developed by the Pan American Centre for Sanitary Engineering and Environmental Sciences—CEPIS, Lima, Peru. Thus, rather than building yet another model, the SBEM's modeling of the Biochemical Oxygen Demand (BOD) parameter used SIMOX results. The second point is the model's account of the three levels of government intervention in the watershed: county, state, and federal.

The software used in the SBEM implementation was the Stella graphical interface (High Performance Systems 2002). The subsections below present a brief description of the sectors that compose the model.

Agriculture and Cattle Breeding

Agriculture and cattle breeding is not an expressive sector in any of the region's counties, be it in terms of the amount of land used or production's value. For that reason, the model did not consider the use of agrotoxins and effects of these activities on soil degradation. However, this sector has some impact on the population dynamics caused by the migration to different counties according to the availability of new jobs. Thus, the model represents the agriculture

and cattle breeding sector dynamics through its contribution to the creation of new employment opportunities, which is assumed to be a function of the annual variation of the value of the production. The number of new jobs is estimated mathematically as the product of the total value of the production and the average worker's productivity, which corresponds to the inverse of the mean income each worker brings to the sector.

Industry

The Sepetiba watershed is the major area for industry expansion in the Rio de Janeiro Metropolitan Area. Actually, within its boundaries a considerable proportion of the State's industrial plants is installed already. In SBEM, the modelling of the industrial sector considered 10 different activities: metallurgy, beverage, rubber, editing and printing, chemistry, textile, mechanics, plastic products, clothing, and "other." These activities are linked to each of the 12 counties that compose the watershed and are represented through the array tool provided by Stella, which allows for the duplication of systems with similar characteristics.

The industrial production dynamics considered three scenarios for the region: "Business as usual," "Industry concentration in Itaguaí" (the county where the port of Sepetiba is located), and "Intense secondary industrialization in the watershed" (SEMA 1997b).

The first scenario presupposes a movement towards the usual spatial concentration of the industrialization process, which is characterized by a polarization around labor force markets, infrastructure, and available services. This means that the present process of industry location is expected to continue, that is, it will cluster in those sites that already have been perceived as preferential options for industrial investment

decisions. The second scenario depicts a cumulative development in Itaguaí County, which has its input/output links associated with the import/export activities of the Sepetiba port. The third scenario contemplates a situation of a diversified industrial development with an internal integration made possible by predominantly regional input/output links, which usually are present in durable goods production hubs.

The main variable represented in this sector is the annual level of industrial production for the various activities and counties, measured in constant 1995 prices. This is a stock variable, whose dynamics are given by the rate of industrial growth. This rate is a flow variable that conditions the increase or decrease of production levels. The magnitude of the flow depends on the scenario under analysis, but it is always limited by the availability of land allotted to industry. In order to consider the effects of regional infrastructure investments in the rate of industrial growth, an ''industry attractiveness'' function was implemented. A function of the growth rate of each industry sector that takes into consideration both the current and the previous years defines the dynamics of the number of industry jobs. This function is designed in such a way as to slow down any sharp change in the industrial production.

Infrastructure

The model represents the infrastructure sector by dividing it into three modules: the Sepetiba port, the sewage treatment plants (STP), and the solid waste management. In the Sepetiba port module, the growth of cargo movements—arising both from the existing pier (coal, carbon coke, and alumina) and from piers to be implemented at the new terminals (container, iron ore, and bulk cargo)—is calculated.

The sewage treatment plant (STP) module quantifies the investment needed to implement the chosen option for intervention, according to the Regional Sewage Master Plan (SEMA 1997d), which proposes a total of 29 STP subsystems. The model allows for a choice between two stages of STP implementation. In the first stage, which refers to the time period between years 2000 and 2009, 50% of the area's population will be assisted. In the second stage, corresponding to the 2010/2020 time period, there would be an upgrading of some STPs, as well as the construction of new ones, which brings out an increase of sewage services to 80% of the area's population. The SBEM assumed that STPs would provide reductions of biochemical oxygen demand of 40% and 90%, during the first (2000–2009) and the second (2010–2020) time periods, respectively.

The solid waste management adopts a simple structure in the model. It just follows the Solid Waste Management Master Plan, concerning the amount of investment made in each county, distributed along medium-term (2000–2010) and long-term (2010–2020) time periods. The information generated in this module passes on to two other sectors: industry (which computes investments in industrial infrastructure) and public finance (which calculates the total investment per county).

Land Use

Similarly to the infrastructure sector, land use is divided into modules: industrial areas and sand extraction. The industrial areas module makes an assessment of the land-use needs for industrial purposes in each county. The modeling methodology used in this case was to compute an average area for each industrial activity present in the database of 105 industries established in the Sepetiba watershed furnished by the Rio de Janeiro State Industrial Development Company (CODIN). This average multiplied by the number of production units defines the total amount of land needed (demand) in the industry sector. The comparison between industrial demand and supply of land—the latter being a function of each county's characteristics—provides an upper bound to the rate of industrial growth, thus controlling the flow of industrial development, and indicating the need for investment in infrastructure as well.

The mineral extraction in the region centers on sand exploitation and is an important source of the Sepetiba Bay pollution. The sand extraction is mainly done along the banks of one of the largest rivers in the region, the Guandu River, in Itaguaí County, which is a major supplier of sand for the construction industry in the Rio de Janeiro metropolitan area. The sand extraction causes not only the environmental problems arising from the throwing of suspended material into the river waters but also produces the loss of the river's original banks.

The main variable used in this module is the ''area of the extraction site.'' This area is a function of the volume extracted and of the depth of the sand mine, which could reach 30 m. The variation of the volume extracted depends on the annual growth of the construction industry demand. Additionally, the sand extraction module calculates the amount of suspended material thrown into the river waters as a (fixed) percentage of the volume extracted. This calculation is then taken to the Effluent, Residues, and Solid Waste sector, for further computations of its impact.
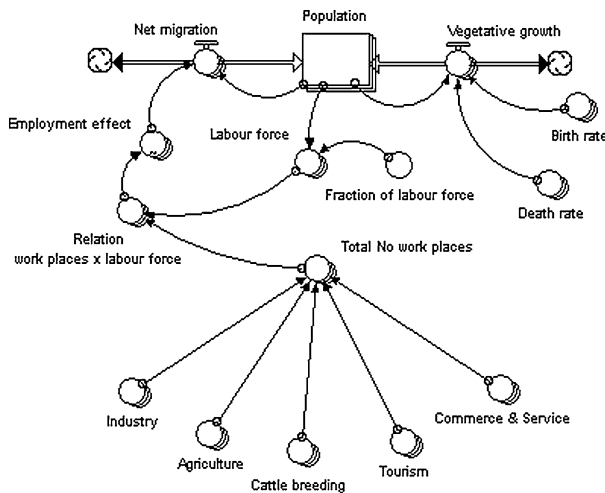
Fig. 3 Dynamic model for the Population sector

Population Dynamics

Because of the lack of sewage collecting systems in the Sepetiba Bay region, the number of inhabitants in a county directly influences the bay's pollution. Actually, house sewage is usually disposed of, without any kind of treatment, into streams and rivers that flow into the bay, thus affecting their water quality. Therefore, it is especially important to model population growth in order to analyze its effects on the environment.

The population growth was modeled under the assumption that the number of inhabitants in each county varies as a function of net birth rates (birth rate minus death rate) and net migration (immigration minus emigration). The net migration is influenced by the "attraction factor" of each county—which is a function of the system's economic components—translated into the number of jobs available in the county (employment effect variable). The employment effect estimates empirically the fluctuations in population growth over the vegetative growth rate. It is defined as the ratio between the number of work places—a variable that varies according to inputs generated from the model's further sectors (Fig. 3)—and the county's estimated labor force. Therefore, the model's population dynamics strongly interacts with other sectors.

Public Finance

This module represents the most relevant interactions between tax-generated revenues and development needs of the Sepetiba Bay region, so that comparisons between investment needs and financing resources can be performed.

The model allows for the simulation of changes in average tax rates over total value of production, dis-

criminating different levels of government (federal, state, and county). In addition, it is possible to simulate the percentage of tax revenue (direct or indirect) that is available locally.

Effluent, Residues, and Solid Waste

The model has taken into account the following pollutants: organic load, measured by the BOD; toxic substances, assessed by the "Chemiotox index" (SEMA 1998); suspended material; and oil/grease. All of these pollutants were considered as arising from anthropogenic actions, basically represented by the dynamics of industrial production and population growth. The Chemiotox index provides a quantitative assessment of the toxicity of industrial effluents as a function of the intrinsic toxicity of contaminants present in a particular production process.

Organic Load

Because the major source for BOD increase is the population itself, rather than the industry, the model considered only the BOD associated with the number of inhabitants. The BOD (mg/L) evaluations in the watershed were made only for spots closest to the mouth of the rivers.

The following equation is an example of how the model represents the effect of a source of pollution on the environment. The purpose was to maintain the model's complexity at a reasonable level. The equation attempts to model situations at different stages of the sewage treatment plants implementation along several time periods:

$$\text{BOD}(t) = \text{BODc} \times \text{TR} \times \text{POPa}(t) + \text{BODc} \times (P(t) - \text{POPa}(t))$$

where
$\text{BOD}(t)$ = Total BOD at time t
BODc = BOD per capita (mg/L/inhabitant)
TR = treatment reduction (according to the technology employed in the STP)
$P(t)$ = Population of the subwatershed at time t
$\text{POPa}(t)$ = population assisted at time t

This equation is implemented in the model as follows:

a) For the period without treatment: TR = POPa = 0; and BODc is taken as the observed 1996 BOD per capita;

b) For the period 2000–2009, after the first-stage implementation of a STP: BODc = BOD per capita foreseen for the year 2005; TR = 0.4 (corresponding to the primary treatment of sewage);

POPa(t) = 50% of the subwatershed estimated population; and

c) For the period 2010–2020, after the second-stage implementation of a STP: BODc = BOD per capita foreseen for the year 2015; TR = 0.9 (corresponding to the secondary treatment of sewage); POPa(t) = 80% of the subwatershed estimated population.

Toxic Substances

Metallurgy is the industry responsible for more than 90% of the toxic substances produced in the region (SEMA 1998). For this reason, only the contribution of this activity was modeled. The model used a technical coefficient based on the Chemiotox index and the value of the metallurgy industry production. A graphical input was used so as to consider variations among different time periods.

Suspended Material

The main sources for suspended material generation are the following: sand extraction; population activities; and industrial production. The model allows the simulation of reductions—based on the treatment of industrial effluents—in the amount of suspended material discharged.

Oils and Greases

Oil and grease pollution is generated by industrial activities and by gas station operations, associated with rainfall runoff. The model, in the current version, takes into account only the impact of industrial activity, because of its importance as compared to other sources.

Solid Waste

In considering the variable "solid waste," the model employs two categories: dangerous waste, subdivided into organic and inorganic, and nondangerous waste, also subdivided into organic and inorganic. The only source for dangerous waste considered was the industrial activity. The amount of waste produced by the population was calculated by taking an average per inhabitant and multiplying it by the number of inhabitants at a particular time, for each county.

The model features keys, which can be used to simulate the implementation of solid waste treatment systems in different counties, based on guidelines for short, medium, and long terms, as well as the time period in which the guidelines should to be effective.
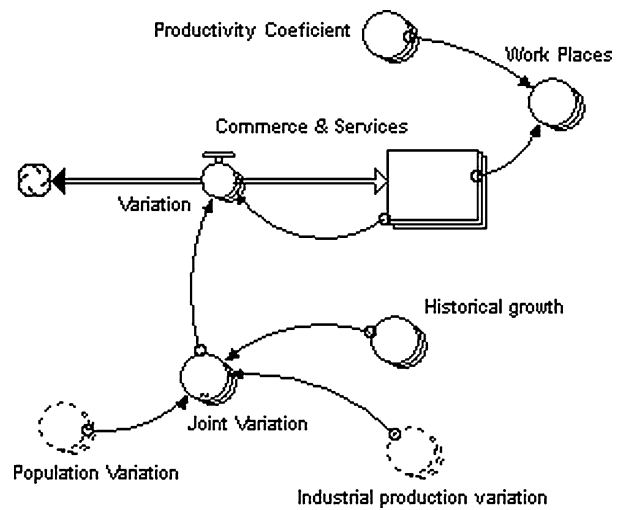
Fig. 4 Dynamic model for the Commerce and Services sector

The cost of implementing solid waste treatment and management systems is reflected in the Public Finance sector, in terms of investment needs.

Commerce, Service, and Tourism

In the Sepetiba watershed, the industrial activity and the number of inhabitants strongly influence the Commerce and Service sector of each county. Because of that, the dynamics of the model (Fig. 4) assumes that the level of commerce and service activities (measured in monetary terms) varies according to a rate that depends on three variables: change in the value of annual industrial production; annual population change; and historical growth of trade and service activities. The ratio of the level of these activities and the estimated productivity coefficient for each worker furnishes the number of workplaces generated by those activities.

Tourism in the Sepetiba Bay mainly takes place in the coastal zones. It is characterized by a floating population from Rio de Janeiro's middle class families and is structured around second residences. Landscape attractiveness strongly influences tourism, thus making sewage treatment an important factor for the flow of tourists. Accordingly, tourism dynamics in each county takes into account, for the computation of tourist flow per year, the historical rate of investments in sewage treatment. The product of annual tourist flow per year and an estimated average expense per tourist infers the income generated by tourism. Finally, the model uses an estimate of the number of necessary workers per tourist to calculate the number of workplaces generated by this activity.

Results

The different sectors of the model simulate possible outcomes in the context of the three base scenarios that represent the possibilities of industrial growth in the area. Besides intrasector interactions, there are intersector feedback loops, which are the basis for capturing the simultaneity of actions and reactions in time, thus providing useful information for the implementation of comprehensive actions.

Population pressure is an important driving factor within the model. The outcomes that emerge from the structure adopted for the population dynamics are not simply linear extrapolations of trends, but complex patterns, ensuing from many interacting processes. Demographic parameters acting jointly with economic and policy variables influence, in different ways, the population change in different counties. For instance, in Itaguaí—the county most affected by the simulations of the industrialization process under diverse scenarios—the time trajectories of the variable "total number of workplaces" imply a variation of the county's population in the range of 5%, by the end of the study period (from 224,000 to 236,000).

The module dealing with land-use dynamics helps to identify, through scenario analysis, which locations could be congested in the near future. It does not, however, indicate explicitly a constraint to the amount of area available for industrial development. Of course, this could occur because of the several changes taking place in the region. Nevertheless, the watershed is heterogeneous and gathers very distinct regions, from densely urbanized spaces and strictly industrial zones to areas with few or no economic activities. It was thought then that it is up to each county to decide upon its own vocation, which in turn will play a critical role in the definition of the feasible policies to be implemented by the agencies responsible for the watershed development.

Another point brought out by the model was that pollution abatement policies in Sepetiba Bay should concentrate initially in the decrease of pollutant loads, such as organic matter, nutrients, and toxic substances. A representative example of such a result is the quantitative dependence between the implementation of control measures and pollution decline. This is shown by the simulation of BOD decrease as a function of the strategy for STPs distribution over the watershed, together with the chosen treatment technology. In addition, it is possible to compare different strategies for STPs "year of operation beginning" in terms of how a particular configuration performs vis-a-vis the BOD level. Figure 5 shows the BOD variation
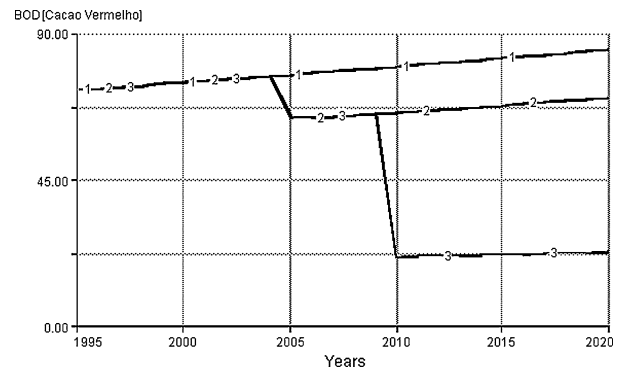

Fig. 5 Biochemical oxygen demand (BOD) at Cação Vermelho River mouth. (1) Without sewage treatment plants (STPs) implementation; (2) implementation of primary STP in 2005; (3) implementation of a primary treatment STP in 2005 and secondary treatment STP in 2010; biochemical oxygen demand (BOD) in mg/L

in time at the mouth of Cação Vermelho River, for a given configuration of interventions under the assumption of the "business as usual" scenario. The Cação Vermelho River drains a basin with the smallest discharge in the region and crosses, in its high and medium courses, a large and densely inhabited urban area. Because of this, the combination of domestic and industrial effluents produces a discharge that is larger than the river's natural flow, thus configuring a very difficult situation for water treatment.

Through the linkage between the Effluent, Residues, and Solid Waste, and the Public Finance sectors, the model allows for an evaluation of the implications in the sanitation system of either anticipating or postponing investments. In the Cação Vermelho watershed, for instance, the implementation of STPs with primary treatment would require investments in the order of US$ 30 million and would cause a BOD reduction by year 2020 to 70.33 mg/L, which corresponds to a cost of about US$ 2 million per unit of BOD. By adopting the secondary sewage treatment, the cost–benefit relationship would be more favorable, because it would reduce BOD to 22.56 mg/L, at a cost of about US$ 450 thousand per unit of BOD. Figure 6 illustrates the necessary investments to implement the 29 STPs delineated in the Regional Sewage Master Plan, at an estimated total of US$ 150 million. In order to give an idea of the financial capability of the region's different counties, Figure 6 also shows the total taxes generated in each county.

The implementation of the STPs outlined in the Master Plan would reduce BOD to acceptable levels, as the following numbers show: Guandu watershed: 0.69 mg/L (the region's lowest value because of its largest discharge); Guarda: 12.37 mg/L; and Piraquê: 15.91 mg/L. In the basins of the Cação Vermelho and
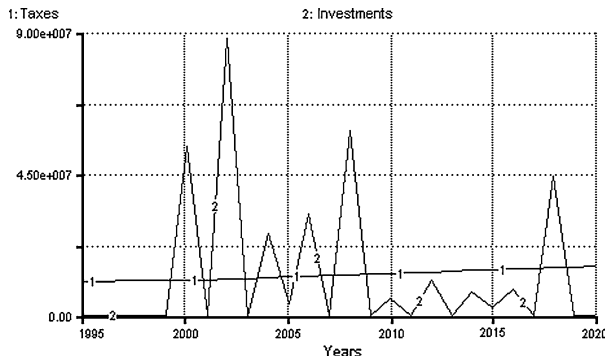
Fig. 6 Investment values in sewage treatment plants and tax generation in the counties of the Sepetiba Bay

Guandu Mirim Rivers, because of their extreme pollution condition, the BOD reduction would be less sensitive, reaching levels of 22.56 mg/L and 27.09 mg/L, respectively, which suggests that in those cases more investments, aiming at the implementation of secondary sewage treatment systems, is necessary.

With the Master Plan implementation, an environmental improvement is expected. This improvement should have a direct impact on counties where tourism-related proceeds have a representative contribution to revenue. For instance, in the case of Mangaratiba, a coastal county, the model indicates that with STPs implementation there would be a 9.5% increase in tourist flow, with a consequent increase in revenues.

Conclusions

The complex problems inherent to an area such as the Sepetiba Bay watershed demand new and more comprehensive approaches to environmental management. The system dynamics approach makes it possible to build a model that is capable of representing the interactions among the several stakeholders involved in the Bay's environmental system, as described in this paper, thus increasing the quality of the analysis of possible interventions.

In the case of the SBEM, the idea was to build a model that would motivate users with reduced or no programming familiarity to operate and to participate in the model's construction as well. The target was thus to make a model as easy to understand and simple to operate as possible.

In order to tackle multifaceted and interrelated issues such as those that are present in the Sepetiba Bay watershed, rather than to go deeply into details, it is necessary to abstract from them and focus on a larger picture. For this reason, the model developed for the watershed environmental management took into consideration only the most relevant subjects related to economic, social, and geographical issues, along with their major interactions.

It is worth noting that the SBEM model was built with a modular concept in mind, in such a way as to facilitate communication with specific models developed for the analysis of particular sectors, as, for instance, those focused on land-use change dynamics (Verburg and others 2002) or population growth (Krutilla and Reuveny 2006). Thus, the SBEM model can be viewed as a high-level interface between different models, providing outputs to multiple social and ecological systems and receiving inputs from them.

Statistical data were scarce for many of the variables depicted in the model, a fact that hindered attempts to establish quantitative links, connections, or dependency relations between them. The fisheries sector is an example of such a difficulty. Despite its importance to the local economy—especially the trawling activity to catch shrimp and related species—it was not possible to model adequately the relation between pollution, silting up, and fisheries production. Another example is the unfortunate lack of information concerning the overall reduction or degradation of mangrove areas, making it impossible to relate them to population growth and the increasing pressure for land use.

However, even with the liabilities imposed by the limited availability of quantitative data, the dynamic system modeling approach and the stakeholders' effective participation made possible the building of credible future scenarios for the watershed. This participation came forward with the qualitative data obtained through their knowledge of the region and in their validation of the generic assumptions of the model.

Nonetheless, it is important to point out that the results acquired with the help of the model are essentially indicative of how the different phenomena represented by the variables modeled, such as those in the industrial and public finance sectors, affect and modify the watershed's environment. The same holds true for the potential of pollution generated by human activities, *i.e.,* the model provides just a reference ground for the assessment of environmental management strategies.

An environmental target can be reached through different resource allocation strategies, which are distinct spatially and temporally. The SBEM flexibility can help in the definition of where, when, and which investment efforts should be prioritized in respect to which control actions should be put into effect in order to reduce pollutant loads.

Because of its suitability to scenario analyses of a system with the complex characteristics of the Sepetiba Bay's watershed, once the SBEM's basic principles and interrelations are well understood, it could satisfactorily answer technical questions related to the environmental management of the watershed. If used as a decision support tool for diverse agencies, the model could provide sound analyses of the consequences of different public policies. Moreover, the dissemination of information of these consequences to a larger public could contribute to a greater transparency of government actions.

Finally, it is necessary to report an unfortunate setback in the SBEM's implementation. Despite the intense stakeholders' interest, the recommendations of the model were never put forward. As a new government of the Rio de Janeiro State came into power, there was reluctance to comply with them and as a result, the model could not be validated entirely. Even so, it remains a valid tool for policymakers who are committed to basing their decisions on firmer ground.

References

Arquitt A., R. Johnstone. 2004. A scoping and consensus building model of a toxic blue-green algae bloom. System Dynamics Rev 20:179–198

Clark B. T., N. Burkardt, M. D. King. 2005. Watershed management and organizational dynamics: Nationwide findings and regional variation. Environ Manage 36:297–310

Costanza R., M. Ruth. 1998. Using dynamic modeling to scope environmental problems and build consensus. Environ Manage 22:183–195

Dangerfield B. C., Y. Fang, C. A. Roberts. 2001. Model-based scenarios for the epidemiology of HIV/AIDS: the consequences of highly active antiretroviral therapy. System Dynamics Rev 17:119–150

Georgantzas N. C. 2003. Tourism dynamics: Cyprus' hotel value chain and profitability. System Dynamics Rev 19:175–212

Hannon B., M. Ruth. 1994. Dynamic modeling. Springer-Verlag, New York, 248 pp

High Performance Systems. 2002. Stella technical documentation. High Performance Systems Inc., Hanover, New Hampshire

IBAM. 1998. Guia das Unidades de Conservação Ambiental do Rio de Janeiro. IBAM/DUMA/PCRJ/SMAC, 208 pp

Krutilla K., R. Reuveny. 2006. The systems dynamics of endogenous population growth in a renewable resource-based growth model. Ecol Economics 56:256–267

Meadows D. H., D. L. Meadows, J. Randers. 1992. Beyond the limits: confronting global collapse, envisioning a sustainable future. Chelsea Green Publishing Co., Post Mills, Vermont, 320 pp

Radzicki M. J., J. D. Sterman. 1994. Evolutionary economics and system dynamics. In R. W. England (ed) Evolutionary concepts in contemporary economics. University of Michigan Press, Ann Arbor, 272 pp

SEMA—Secretaria de Estado do Meio Ambiente do Estado do Rio de Janeiro. 1997. Relatório R5-consolidação das bases para planejamento, tomo I, volume III–caracterização e diagnóstico das comunidades bióticas marinhas da baía de Sepetiba. In Macroplano de gestão e saneamento ambiental da bacia da Baía de Sepetiba. Rio de Janeiro, 167 pp

SEMA–Secretaria de estado de meio ambiente do estado do Rio de Janeiro. 1997b. Relatório R5-consolidação das bases para planejamento, tomo III-uso do solo urbano e análise do zoneamento industrial. In Macroplano de gestão e saneamento ambiental da bacia da Baía de Sepetiba. Rio de Janeiro, 129 pp

SEMA–Secretaria de estado de meio ambiente do Estado do Rio de Janeiro. 1997c. Relatório R3—estudos sócio-econômicos e projeções demográficas. In Macroplano de gestão e saneamento ambiental da bacia da Baía de Sepetiba. Rio de Janeiro, 252 pp

SEMA–Secretaria de estado de meio ambiente do estado do Rio de Janeiro. 1997d. Relatório R8-plano diretor de recursos hídricos e de saneamento, tomo IV—plano diretor de esgoto sanitário. In Macroplano de gestão e saneamento ambiental da bacia da Baía de Sepetiba. Rio de Janeiro, 50 pp

SEMA–Secretaria de estado de meio ambiente do estado do Rio de Janeiro. 1998. Relatório R8-plano diretor de recursos hídricos e de saneamento, tomo II-I—instrumentos de apoio à decisão—modelo SIMOX. In Macroplano de gestão e saneamento ambiental da bacia da Baía de Sepetiba, Rio de Janeiro

SEMADS–Secretaria de estado de meio ambiente e desenvolvimento sustentável. 2001. Avaliação da qualidade da água da bacia da baía de Sepetiba, outubro/1995–julho/1998. Rio de Janeiro, 178 pp

Sterman J. D., L. B. Sweeney. 2002. Cloudy skies: assessing public understanding of global warming. System Dynamics Rev 18:207–240

Verburg P. H., W. Soepboer, A. Veldkamp, R. Limpiada, V. Espaldon. 2002. Modeling the spatial dynamics of regional land use: The CLUE-S model. Environ Manage 30:391–405

World Bank. 1996. Brazil: managing environmental pollution in the state of Rio de Janeiro. Volume I—policy report. August 22, 1996 (available at http://www.worldbank.org)