The use of DPSIR framework to evaluate sustainability in coastal areas. Case study: Guanabara Bay basin, Rio de Janeiro, Brazil

E. D. Bidone · L. D. Lacerda

Abstract The Guanabara Bay basin, SE Brazil, is shown as an experimental site to evaluate development and sustainability in coastal areas. We developed a Driver–Pressure–State–Impact–Response (DPSIR) framework in a practical context to integrate natural and socio-economic indicators. Sustainability reflects public policies towards the utilization of natural resources. Cost-benefit analysis (CBA) included in DPSIR evaluates losses and benefits resulting from such policies. CBA has some limitations due to the difficulty of valuating environmental goods and services. Instead of valuating them we propose to combine sustainability indicators and defensive expenditures for the implementation of public policies. This approach agrees with the environmental conservation paradigm implicit in sustainable development. It allows an estimation of the physical natural capital depreciation (PNCD), by using it to correct the gross domestic product (GDP) of the study area, and demonstrating the present non-sustainable characteristics of the current policies applied to the area.

Keywords Guanabara Bay basin · Sustainability evaluation · DPSIR framework · Cost-benefit analysis (CBA) · Correction of conventional accounts (GDP)

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Introduction

This study was developed within the framework of the Land–Ocean Interactions in the Coastal Zone (LOICZ) Core Project of the International Geosphere Biosphere Project (IGBP). LOICZ focuses on the role of the world's coastal zones in the functioning of the Earth system: the way in which global changes will influence that role; the way in which such changes will affect the use of coastal space and resources by humanity; and the consequences of such changes for human welfare. LOICZ is a project designed to improve the scientific understanding of environmental change in coastal areas—driven by human use of environmental space and resources—and hence provides a sound scientific basis for their sustainable management/development. Details of the LOICZ-Basins core project which links catchment-based processes with coastal change issues, its objectives and goals can be found at http://w3 g.gkss.de/projects/loicz_basins/.

For any given coastal area (defined as encompassing the entire drainage network) there will exist a spatial distribution of socio-economic activities and related land uses—urban, industry mining, agriculture/forestry/aquaculture and fisheries, commerce and transportation. This spatial distribution of human activities reflects the final demand for a variety of goods and services within the defined area and from outside the area. Environmental pressure builds up via these socio-economic driving forces, causing changes in environmental systems states. These state environmental changes impact on human and non-human receptors, resulting in a number of perceived social welfare changes (benefits and costs). Such welfare changes provide the stimulus for management action which depends on the institutional structure, culture/value system and competing demands for scarce resources and for other goods and services in the coastal zone (Turner et al. 1998).

Land-based activities that impact on the coastal marine environment are not restricted to the "classical" coastal zone but are located throughout river catchments. Their impacts result from increased loads of nutrients and other biogeochemical materials, and alteration of river flow regimes and sediment discharges. 'Basins' is a core project within LOICZ [e.g., the South American Basins (SAmBas)] and is working inter alia to develop a global assessment of the importance of change in coastal seas by applying a

catchments scale. To generate a global picture, 'Basins' runs a set of standardized and thus at least basically comparable regional workshops and tries to scale up the information from single river catchment/coastal sea interacting systems to a larger sub-regional and finally full regional (i.e. sub-continental or continental) scale. In doing this, characteristic types or classes of coastal issues are identified and pressure-change scenarios are derived and compared in a qualitative or semi-quantitative way within and across regions (Lacerda et al. 2002).

In agreement with LOICZ's general goals, the aims of 'Basins' are: (1) to determine the biogeochemical fluxes —C, N, P, sediments, water and toxic contaminants—to the coastal zones (past, current and future); (2) to identify the main socio-economic drivers that have changed or will change the fluxes; and (3) to identify indicators for the impact of land-based sources on the coastal zone and to derive from them a critical load (Kremer et al. 2002). At a later stage these critical loads can be connected with the main socio-economic drivers on the continent, and subsequently a cost-benefit analysis can be carried out on those cases with negative impacts on the coastal zone, and the need for remediation of land-based point and diffuse sources can be determined.

To protect the coastal sea, abatement measures such as restricting the load of a harmful substance from a catchment may be imposed. The decision on how strict a load limit to impose requires an analysis of costs and benefits (CBA) to society. Following Kremer et al. (2002), there are three major challenges in such CBA: the time delay before the response to an abatement measure can be felt in the coastal sea; the complex sensitivity of the coastal sea environment to regulatory measures; and the multiplicity of interests and stakeholders affected by a regulatory measure. These challenges are interdependent.

To meet these objectives requires integration of natural, social and economic information into a broad analytical framework in which to set the more detailed analysis, and to provide the interdisciplinary working tool for a wide spectrum of users. The Driver–Pressure–State–Impact–Response (DPSIR) framework offers such a generalized context. The DPSIR analytical framework is not new but developed from the pioneering work by the Organization for Economic Cooperation and Development (OECD) in the 1980s, and was published in the early 1990s (Organization for Economic Cooperation and Development 1994). Our study was carried out under the SamBas LOICZ-Basin project, using Guanabara Bay, SE Brazil, as an experimental site (Fig. 1), aiming to develop the DPSIR framework into a practical working tool assisting the integration of natural and socio-economic indicators, and, in doing so, to evaluate development and sustainability in coastal areas.

The specific objectives correspond to the aims described above, i.e. to use the qualification and quantification of (1) the fluxes of biogeochemical materials carried by rivers into Guanabara Bay, (2) the main socio-economic drivers acting in the watershed tributaries of the bay, and (3) the impacts of land-based sources on the bay, as parameters that serve as major indicators of environmental function-
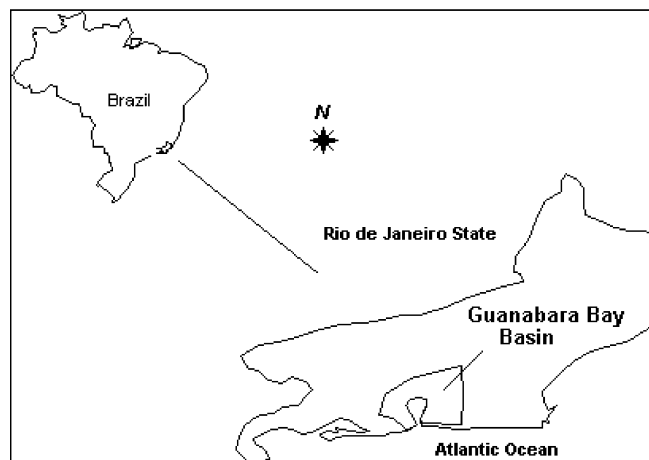

Fig. 1
Location of Guanabara Bay and the basin in southeastern Brazil

ing and sustainability of goods and services provision. Emphasis is given to develop practical approaches to 'link' natural and socio-economic indicators, in order to obtain an effective working tool. Also, a significant contribution of the present study is to give special attention to the use of CBA within the DPSIR framework. In view of the difficulty in valuating environmental goods and services in monetary terms, we propose to include natural environmental indicators (biogeochemicals) of the sustainability of fluvial water quality and therefore of the sustainability of the quality of Guanabara Bay waters. This allows reflection on the enforcement of control measurements (defensive expenditures) on the driving forces responsible for the pressures on the quality of these waters.

A CBA methodology also allows an estimate of the physical natural capital depreciation (PNCD), i.e., the environmental losses remaining non-restored by the defensive expenditures, used for the correction of the gross domestic product (GDP) of the studied area (Rio de Janeiro). Adjustments of the GDP appear to be necessary in the two areas noted above: (1) the so-called defensive expenditures to protect or restore the environment (i.e., the cost of abatement measures restricting the load of harmful substances from the watershed tributaries of Guanabara Bay); and (2) the depletion and degradation of natural resources (measured in terms of PNCD).

Materials and methods

The integrated modeling approach proposed for the Guanabara Bay basin is based on the generic DPSIR framework (Fig. 2). From top to bottom the diagram presents the specific system elements (socio-economic and natural) considered up to the present time in this case study:

1. Socio-economic drivers. Indicators: demographic growth and increase in land use/cover (principally residential land occupation); gross domestic product
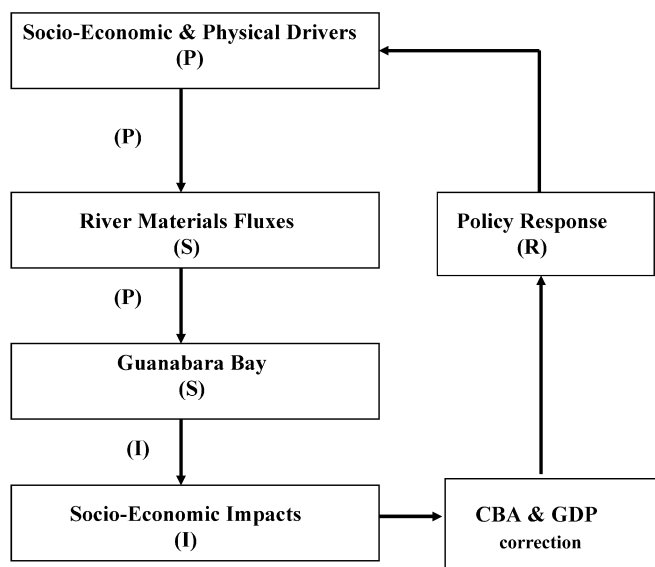
Fig. 2
Integrated model used in the Guanabara Bay case study, based on the Drivers–Pressure–State–Impact–Response framework. *P* Pressure indicators; *S* state indicators; *I* impact indicators; *R* response indicators

per capita (GDP/inhab); income distribution indicators; Human Development Index (HDI).

2. Physical drivers. Indicators: seasonal change in climate conditions (essentially rain intensity and distribution).

3. River material fluxes. Indicators: BOD, C, N, P, suspended solids and heavy metals.

4. Guanabara Bay. Indicators: DOC, heavy metals and chlorophyll-*a* concentrations in water; TOC, N, P and heavy metals in sediments, and heavy metals in fishes (particularly Hg).

5. Socio-economic impacts. Indicators: human activities—fisheries, recreation, etc. in Guanabara Bay.

6. Policy response: approach based, firstly, on the evaluation (CBA) of those public policies and management actions included in the 'Guanabara Bay Recuperation Program', conduced by Rio de Janeiro State Government, and, secondly, on the correcting account (GDP of Rio de Janeiro) for defensive expenditures and physical natural capital depreciation.

7. CBA: this study proposes the use of CBA, in which standards of sustainability (reflecting estimated critical loads of selected substances/indicators) are fixed and the analysis attempts to highlight the cost means of achieving them.

The practical solution of each sub-system (specific system elements) of the proposed DPSIR, and of the links between them (represented by arrows in Fig. 2), show different degrees of difficulty.

Sub-systems involving natural elements and potential indicators of pressure, state change and environmental impact—i.e., rain distribution (physical driver), river material fluxes, Guanabara Bay water and sediment composition, and fish contamination—need a standard, referenced scientific and technical approach. Essentially, the

methodological approach used was to collect and rework the available data set in a compatible manner. For example, to estimate river material fluxes and their links with rain distribution, several studies were carried out since the 1980s in the watersheds and tributaries of the Guanabara Bay basin, providing relevant data on the biogeochemistry of river waters.

For the sub-systems involving socio-economic parameters, statistics available at the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística—IBGE) were collected. These were used to construct the socio-economic indicators applied in this study. The costs of defensive expenditures were obtained in the reports of the 'Guanabara Bay Recuperation Programme', conduced by the Rio de Janeiro State Government.

Results and discussion

The Guanabara Bay basin: physical or primary environmental indicators

The study area, Guanabara Bay basin (Fig. 1), located in Rio de Janeiro state (22°40′–23°00′S and 43°00′–43°20′W), is the most prominent coastal bay in Brazil. The bay is located in the metropolitan region of Rio de Janeiro city and has a drainage basin of about 4,000 km^2. The Bay area is about 346 km^2, including 59 km^2 of islands, and has a perimeter of 130 km. Average water volume is 2.2×10^9 m^3, water depth ranges from 1–30 m with an average of 7.7 m, and renewal time of 50% of the bay water volume is about 11 days (Kjerfve and Dias 1997).

The Guanabara Bay basin is backed by a high (1,000- to 1,500-m) relief mountain range ("serras"). It is characterized by a large number of small catchments (more than 40), usually <100 km^2. The river profiles are characterized by a very strong slope changing—in a few tens of kilometers—to a relief of hills before reaching the coastal plain. The ratio between slope:hill:coastal plain areas is variable and follows a general empirical rule: the magnitude of the hill and coastal plain areas increases with the size (i.e., total area) of the watersheds.

The predominant rock types are pre-Cambrian migmatites and gneisses with associated intrusive granites and diabase dykes. The material of the hills was apparently originated from the weathering of the rocks at the base of the slopes. Alluvial Quaternary and recent sediments compose the coastal plains. On the higher slopes, the predominant materials are essentially colluviums. Towards the lowlands the soils are thicker and generally of the latosol type. Hydromorphic soil types predominate in the lowlands. The climate of the study area is tropical humid. Temperature and atmospheric precipitation are very variable, from >24 °C and <1,000 mm $year^{-1}$ in the lowlands to <18 °C and >2,500 mm $year^{-1}$ on the high slopes. The mean annual river discharges are small and vary from 10^{-2} to 10^{-1} m^3 $s^{-1.}$ In densely populated areas, the river discharge increases due to wastewater inputs *in natura*, i.e., without previous treatment. Because of their small areas, the watersheds have low hydraulic retention times.

Consequently, during large rainfalls or storms (~ 80 mm or more), the effects upon river discharge are almost instantaneous, reaching several cubic meters per second. In urban areas these storm surges may have catastrophic effects.

Bidone et al. (1999), in accordance with land use criteria, classified the watersheds of the Guanabara Bay region into three types: (1) the pristine type, without anthropogenic activities, which generally belongs to legal environmental protection areas, with Mata Atlântica (i.e., a mountainous tropical rainforest type) and/or similar abundant vegetation on the slopes and natural coastal vegetation in the lowlands (grasses, savannas, "restingas"); (2) the weakly impacted type with well-preserved Mata Atlântica and/or other remnant vegetation on the slopes, and lowland sectors with human activities (small-scale farming, tourist-urban activities); and (3) the highly impacted watersheds, densely populated and/or industrialized.

Socio-economic drivers and indicators

The Guanabara Bay basin occupation began four centuries ago and became more intense in the early 1970s when large industrial development took place. Nowadays, there are 12 municipal districts, 7.8 million inhabitants and around 12,500 industries distributed unevenly over the drainage basin area (4,000 km^2). As a result of this occupation currently heavy metals, PAHs, phenols, cyanides, etc. but also 350 t BOD and 18 t oil are discharged into the bay on a daily basis. This explains the poor quality of water and sediments observed mainly in the western part of the bay. To recognize and characterize socio-economic activities is not complicated since the Guanabara Bay basin is a relatively well-documented region. Taking into consideration its cultural and historic importance to Brazil, the large numbers of urbanization and development programs and the many scientific studies by local universities and state agencies, it was possible to identify the major activities affected by eutrophication and pollution of Guanabara Bay—fisheries and tourism-recreation activities. Along river catchments, major activities affected are the use of water by the population and industry, needing a relatively unpolluted water supply. In general, surface water use is substituted by the use of groundwater, or water supplied by the state, obtained by diversion from other basins, such as the Paraíba do Sul River (Molisani et al. 2003).

The principal socio-economic drivers are urbanization and industrialization. Urbanization and industrialization processes generate, respectively, diffuse and point sources of wastewaters and toxic effluents for the rivers, and from them to Guanabara Bay. Thus, these materials are the principal pressure elements causing state changes in water quality (eutrophication and contamination), and so impacting the economic activities dependent on water quality (fisheries and recreation—including tourism activities).

Indicators of the socio-economic driver 'industrialization' are emission factors of pollutants from existing point sources, which are largely used by government agencies for control and monitoring of pollution sources. These indicators are discussed elsewhere (Bidone et al. 2002).

The present paper will concentrate on the discussion of the socio-economic indicators linked to the driver 'urbanization', the major responsible for the increased fluxes of materials and for the extensive contamination of Guanabara Bay (Japan International Cooperation Agency 1994). The principal socio-economic indicator related to urbanization is the demographic growth and increase in land occupation for residential purpose. This shows a significant positive linear relation with biogeochemical substances fluxes, used as natural indicators in this study. On the other hand, pressures on ecosystems generated by urbanization of watersheds are directly related to the socio-economic profile of the population. In the case of Guanabara Bay and other similar areas in developing countries, income level of the population relates directly with the lack of proper sanitary conditions and is directly responsible for the poor environmental quality conditions in which this population lives.

A very often utilized socio-economic indicator for the characterization of the economic activity (wealth) of a population is its GDP per capita (GDP/inhab). In the study area the GDP/inhab is about US$ 3,500. However, in this case this indicator fails, since it does not take into consideration the concentration of income and wealth distribution within the population. The higher the income concentration the higher the number of poor population and the worse the quality of life of the population, including sanitary conditions.

Frequently used income distribution indicators are the Gini Coefficient and the Theil Index. These indicators take into consideration the average familiar income per capita of a given region. Index of coefficient 1.0 represents the largest uneven distribution of income among the population. In Brazil, the average index is 0.74, one of the highest in the world. In Rio de Janeiro city between 1981 and 1985 this value was 0.57, and between 1995 and 1999 it was 0.60, suggesting a deterioration of social conditions. Today, the 50% poorer element of the population have only 13.1% of the city's income, whereas the 1% richer have 11.8%.

In our study we have also investigated the applicability of the Human Development Index (HDI) on the Guanabara Bay basin. This index allows the comparison of life quality, taking into consideration information on income, health and education level of the inhabitants. The HDI ranges from 0 to 1.0, the higher the value the better development achieved by a give population (HDI >0.8=high, HDI between 0.5 and 0.8=medium, and HDI <0.5=low). Our results show that high (>0.8) development is associated with better sanitary conditions.

Complementary socio-economic indicators based on sustainable development issues

In a wide sense, LOICZ-Basins projects deal with sustainable coastal development, which can be described as 'the proper use and care of the coastal environment borrowed from future generations' (Turner et al. 1998). Sustainable development was defined by the 'Brundtland Report' or 'Our Common Future' (World Commission on Environment and Development 1987) as that which 'meets the needs of the present without compromising the ability

of future generations to meet their own needs', and it was suggested that economic development and environmental well-being are not mutually exclusive goals. In order to achieve critical sustainable development objectives for coastal environments and coastal development policies, it is important to have strategies such as: conserving and enhancing the coastal environment, managing risk and coastal vulnerability, and merging coastal environmental considerations with economics in decision making. However, to be socially sustainable, the total capital of a given economy requires the inclusion of those considerations related to the biophysical environment.

Sustainability from an economic perspective requires a non-declining capital stock over time to be consistent with the criterion of intergenerational equity. Sustainability therefore requires a development process that allows for an increase in the well- being of the current generation, with particular emphasis on the welfare of the poorest members of society, while simultaneously avoiding uncompensated and significant costs to future generations. Policy would be based on a long-term perspective, incorporating equity as well as an efficiency criterion, and would also emphasise the need to maintain a healthy global ecological system (Turner et al. 1998).

The total capital of an economy may be described as the sum of man-made capital, natural capital, human capital and social/moral capital. Thus, beyond the need of maintaining the natural capital at a constant or rising over time, social sustainable development requires an improvement in the human capital and social/moral capital.

Socio-economic indicators of human capital and social/moral capital could be considered as 'complementary socio-economic indicators'. The practical aim of their utilization within the DPSIR framework would be to support the social evaluations and considerations obtained from the use of the proposed 'socio-economic driver indicators'. They are expected to be value adding also for reinforcing: (1) the basin typology characterization and its comparability for scaling purposes; (2) the characterization of the socio-economic profile of the population living in the basins (in terms of its 'quality of life' characterization); and (3) the evaluation of the results of public policies.

At Guanabara Bay basin up to now no study has included an evaluation of complementary socio-economic indicators of human and social/moral capitals such as infantile mortality, poverty, education, health and public safety in the face of their links with biophysical indicators of environmental change.

For example, 'infantile mortality' is an index measuring the number of children who died before completing their first year of life (number of deaths/1,000 births). This index for the Guanabara Bay region varies from about 5 in basin areas occupied by high HDI (>0.800) to about 45 in basin parts with populations with medium or low HDI (>0.500–<0.800).

The 'poverty index' considers (in percent of inhabitants) the number of the poorest members of the population of a given area. A 'poor member' is defined as someone with monthly revenue of about US$ 40 or less. The preliminary Guanabara Bay results show that areas with a high HDI value have a 'poverty index' of about 4% or less, while areas with low HDI values show a 'poverty index' higher than 20%. The 'education index' (average number of years spent in school of the adult population) varies from 11 years in areas with higher HDI values to about 7 years in areas with lower HDI values. The 'public safety index' used in this case study is the number of violent crimes per year. This varies from about 200 in higher HDI areas to 4,000 in lower HDI areas.

Natural indicators

The specific material fluxes of polluted and highly polluted rivers are one to two orders of magnitude higher than those estimated for unpolluted or weakly polluted rivers. Also it has been shown that the highly variable hydrology of the studied rivers directly controls the natural and anthropogenic concentration levels of biogeochemical materials in river water and their runoff loads. In "pristine" rivers during high rainfalls (80 mm or more), the increase in material fluxes was about one order of magnitude. In highly polluted watersheds measured on rainy days (25 mm day^{-1} rainfalls) the material fluxes were two times greater than those measured on non-rainy days (when the preceding period of non-rainy days was 5 days or more). Detailed approach, results and discussion can be found in Bidone et al. (1999).

Transfer of materials through the aquatic continuum—including the river system, estuaries, and wetlands to the bay—involves the passage through ecosystems, which can act as very effective and selective material "filters". The effectiveness and selectivity of the processes of transformation, elimination or immobilization of materials during their transfer through the aquatic continuum depends on their biogeochemical behavior and are also strongly influenced by hydrology and land use (Billen 1993).

These are relevant aspects in all basic biogeochemical studies, as well as for surveys of river water quality control and the establishment of watershed management policies. However, to evaluate the effectiveness and selectivity of controlling processes of the biogeochemical behavior of materials in river waters is often a difficult endeavor. In this study, using a mass balance approach between continued river segments, it was possible to identify portions of the Guanabara Bay basin with active transformation processes, including the elimination or immobilization of materials during their transfer through the aquatic continuum.

The P-PO$_4$ and N-NH$_4$ concentrations increase exponentially with pollution level, by about three orders of magnitude from unpolluted rivers (or river stations placed on the uncontaminated slope portions) to highly polluted rivers by domestic wastewater. The N-NO$_3$ natural concentrations are apparently little affected by industrial pollution. On the contrary, they increase by about one order of magnitude when the river waters are polluted by domestic wastewater. However, a decreasing trend appears when river waters are highly polluted. A similar fate can be observed in dissolved oxygen (DO) concentrations when pollution levels increase considerably (Fig. 3). Billen
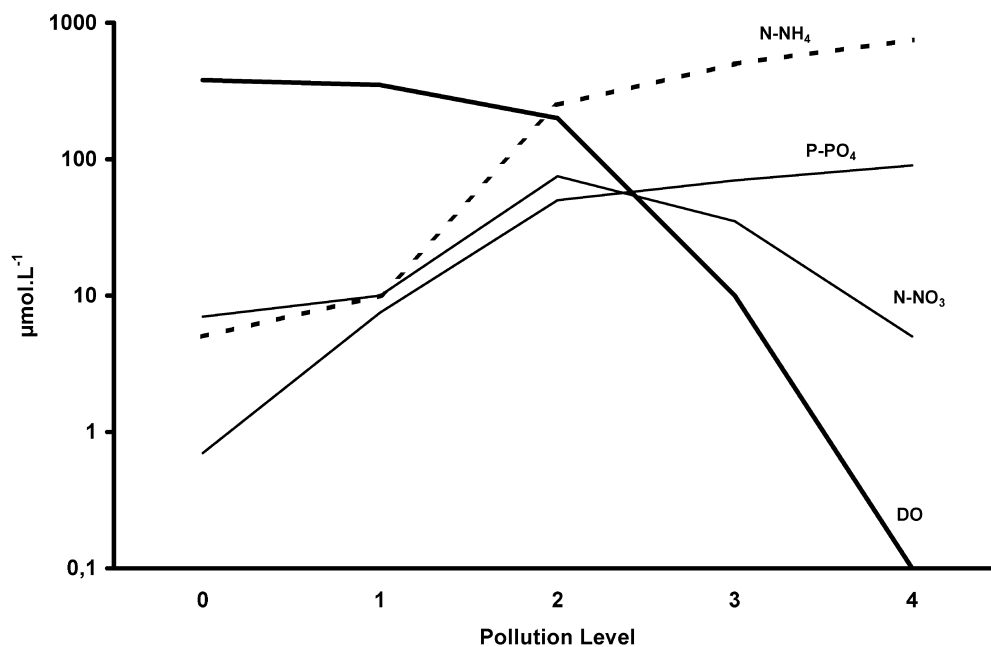
Fig. 3
Concentration levels of N and P dissolved inorganic species, and dissolved oxygen (*DO*), related to increasing pollution levels in small rivers flowing into Guanabara Bay. Pollution levels 0–4 are arbitrary: *0* unpolluted rivers; *1* weakly polluted rivers by domestic effluents and farming; *2* polluted rivers by industrial and domestic wastewater; *3* polluted rivers by domestic wastewater; *4* highly polluted rivers by domestic wastewater. [From Bidone et al. (1999)]

(1993) suggests that the development of phytoplankton might be an important factor in the oxygen balance of river systems. Phytoplankton respiration and decay of its biomass result in the establishment of heterotrophic conditions. Moreover, in the case of urbanized systems, these naturally heterotrophic sectors of the watershed are where most of the population is concentrated. They thus receive additional organic inputs from domestic or industrial sewage, eventually resulting in anoxic conditions. Under such circumstances, denitrification occurs at elevated rates in the water column and in sediments. In denitrification, bacteria use the oxygen in the nitrate ion to oxidize organic carbon to CO_2 in a complex series of reactions. This can lead to the elimination of an important fraction of the $N-NO_3$ load.

From those results it was possible to establish the transport rates of the biogeochemical materials along the watersheds and towards their destination, resulting in an estimation of the material loads carried by rivers into the Guanabara Bay. For example, the estimated loads of BOD, TN and TP into Guanabara Bay were 350, 122 and 20 t, respectively, on a daily basis.

The principal impacts of biogeochemical loads into the bay are eutrophication, pollution, excess sedimentation and trophic state change from its original trophic characteristics to eutrophy and to hypereutrophy (chlorophyll-*a* concentrations >100 µg l^{-1}). This results in a reduction in fishery production and high biodiversity loss (for which real numbers can be estimated), interdiction of beaches to recreation and high levels of heavy metal pollution in sediments. We estimate that over the past 20 years there has been a decline of about 90% of the Bay's fisheries. Mangrove area of the bay, an important ecological factor for maintaining abundant fisheries, was reduced by nearly 50%. On the other hand, poor water quality hampers aquaculture, and all 53 beaches of the Bay are improper for recreation.

To assess the ecological and human health risks resulting from heavy metals and other contaminants (particularly PAHs, PCBs, DDT, etc.), we have adapted the Potential Ecological Risk Index (PERI) originally proposed by Håkanson (1980, 1988) as a contamination control for lakes and coastal systems of Scandinavia. In order to achieve a satisfactory performance, we have introduced a few adaptations to PERI's constituent elements. Among them, the most important adaptation is concerning the estimate of the trophic state system by using the bioproduction number (BPN). The N:organic matter ratio in sediments, originally used for the calculation of BPN, was substituted by the evaluation of chlorophyll-*a* levels in the water column. Due to the high trophic state observed in Guanabara Bay, the PERI obtained was low (PERI=36). Among heavy metals, Hg was identified as being the main contaminant:

Hg=25.4>Cd=5.7>Cu=2.8>Pb=1.2>Cr=0.3>Zn=0.2.

Details of this approach can be found in Campos and Bidone (2000). Assessment of the risk due to microorganic contaminants is still needed.

To make the link (transfer) between contaminants and biota (fishes in this case study), we have used an approach developed by Castilhos et al. (2003) firstly to Hg contamination. It suggests a parameter allowing us to normalize for Hg concentration in fish based on the time of exposure, which is needed to reach some percentage of their maximum length, in this case 50%, a graphical method to estimate Hg daily uptake rates by these fish, an estimate of the time of exposure necessary to achieve 0.5 µg g^{-1}, the United States Food and Drug Administration (FDA) advisories' level for concentration of mercury in fish, and, to establish the dose-response relationship for Hg accumulation. The results showed that the fish of Guanabara Bay, notwithstanding their general contamination by pathogenic microorganisms, presented relatively low concentrations of heavy metals, probably due to the

immobilization of heavy metals with organic matter and sulfides. However, the associated risk from heavy metal exposure through fish contamination tends to increase as the abatement of organic pollution increases. The change of the present hypereutrophic, anoxic environment to a less eutrophic, oxic environment will result in the remobilization and increasing bioavailability of the heavy metals immobilized in bottom sediments under the present environmental conditions (Carvalho and Lacerda 1992).

The results of the existing studies suggest that it is possible to integrate the results obtained in the different sub-systems involving the natural elements of the proposed model z(river material fluxes, internal bay system, etc.) in order to identify potential indicators of pressure, state change and impact. The current major requirement is to integrate the natural and the socio-economic elements included in the proposed system model for the Guanabara Bay basin.

Integration between socio-economic and natural indicators

Primarily, indicators of the socio-economic drivers must be directly linked to demography and land occupation indicators (in this case, for residential purpose), to provide an understanding of the external forcing effects of socio-economic changes such as, for example, population growth, on fluxes of biogeochemical materials. Population growth (i.e., human occupation) of watersheds draining into Guanabara Bay is linear and without treatment of domestic sewage. In critical areas surrounding the Bay (particularly along its NW coast), less than 60% of the population has access to adequate sewage treatment, only about 10% of the total sewage is treated before being released into the Bay, the rest being released untreated into the Bay's tributaries.

Concentrations and fluxes of materials change linearly with the population density (Japan International Cooperation Agency 1994; Bidone 2000). For example, dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) increase by about three orders of magnitude from unpolluted rivers to highly polluted rivers. N:P ratios clearly define the different intensities of basin occupation and reflect the levels of fluvial water contamination. These ratios show a decreasing trend inversely proportional to the degree of contamination of fluvial waters (Table 1).

Table 1
DIN:DIP ratios for different intensities of watershed occupation in the Guanabara Bay basin. [Source: Bidone (2000)]

Population density (inhab km^{-2})	DIN:DIP (mole:mole)	Level (state) of fluvial water contamination
10^{-1}	100 or more	Pristine
10	10–100	Unpolluted
10^{2}	1–10	Weakly polluted
10^{3}	0.1–1	Polluted
10^{4}	0.01–0.1	Highly polluted

From fluvial material fluxes it is possible to derive loads of substances from domestic sewage. Thus fluxes to Guanabara Bay of BOD, TN and TP were estimated as 0.03 kg BOD inhab^{-1} day^{-1}, 0.01 kg TN inhab^{-1} day^{-1} and 0.002 kg TP inhab^{-1} day^{-1} (Bidone 2000). Fluxes of suspended solids, heavy metals, PAHs and other hydrogeochemical materials follow the same pattern, according to reports from the Rio de Janeiro State Environmental Agency.

In Guanabara Bay basin the observed linearity is due to the high rates of population growth and to unplanned occupation of watersheds, without the proper infrastructure to cope with their effluents. This can be related to the life quality of these populations. High HDI (>0.8) can be associated with better sanitary conditions. Thus material fluxes through rivers are smaller as well as the impacts on the coastal zone. Sub-basins with high HDI also presented low population densities, whereas low HDIs occur in areas of high population density. Thus considering two sub-basins of similar 'physical typology' (i.e., sub-basins with similar primary environmental indicators), but with different values for the HDI, that with the lowest value will show the highest biogeochemical fluxes, and therefore pressure on fluvial waters and impacts on the coastal zone. At the moment we are ranking the sub-basins and relating HDI values with estimated biogeochemical fluxes. Independent of the result, these indexes prove fundamental as a 'socio-economic driver' indicator essential to any desired typology definition, and even spatial and temporal upscaling procedures to other regions.

In this case, the question is whether the fluxes of materials would still reflect the indicators of demographic change if all basins, independent of their population density, had their sewage effluents treated. The more realistic answer to this question is, probably, yes! Theoretically, a reduction of the forcing of anthropogenic activities upon the study areas would be achieved by introducing environmental protection rules for these activities. However, technical measures frequently do not solve the problem but only decrease its velocity, since the growth of a given activity in general surpasses the effect of the measure due to delayed effects of the contamination. Even considering the long term, the ideal environmental control of such typology as that of Guanabara Bay is probably a utopia.

Mitigation measures are being implemented under the 'Guanabara Bay Recuperation Program', conducted by Rio de Janeiro State Government. 'Mitigation' is not rhetoric; there is no possibility of returning to an original, natural state with the increasing occupation pressure, mostly due to the prohibitive costs, the impossibility of implementing ideal control measurements, e.g., lack of areas to construct tertiary treatment systems, the low human development of the local society and the inadequacy of public policies.

Impact-response indicators: merged socio-economic and natural indicators—CBA

The DPSIR framework captures the assessment of the human welfare impacts of flux changes due to changes in processes and functions in coastal resource systems. Such assessments of the social costs and benefits involved will

provide essential coastal management intelligence based on social science and possible resource and value trade-offs. In the section headed 'Natural indicators', we have already discussed the main impacts resulting from the input of biogeochemical materials carried into the bay by rivers.

Conducting an analysis of the impacts of resource management decisions requires a clear distinction and delineation of the limits of appraisal. Such appraisal often has economic dimensions. Where all factors, both economic and non-economic, are brought into an economic framework, this is known as extended CBA, a standard economic tool (Turner et al. 1998).

CBA has its strengths and limitations. Originally, CBA employs a set of economic techniques that produce information intended to improve the quality of public policies. In this context, 'quality' refers to a measure of the social well-being that the policy conveys to society. Policies that reduce well-being are a priori inferior to those that improve well-being. Conceptually, CBA could than be used, among others, (1) to evaluate the results of an environmental public policy and/or a resource management action; (2) to rank policies and/or resource management options; and, even, (3) to evaluate the consequences of the absence of a necessary environmental public policy and/or the absence of resource management action. These evaluations and ranks are conceived to be realized based on improvements or reductions in socio-economic well-being.

Because policy decisions are required relating to a range of spatial and temporal scales and different socio-economic and political levels, several broad assessment categories need to be distinguished (Barbier 1993). LOICZ proposes three assessment categories: (1) the impact analysis: in this category, a specific environmental impact is assessed via the valuation of the environmental state changes in the coastal resource(s) connected to the impact; (2) the partial valuation analysis, encompassing situations that require the evaluation of alternative resource allocations or project options; and (3) the total valuation analysis; this third assessment category covers the evaluation of protected areas schemes involving restricted or controlled resource use (Turner et al. 1998).

All these assessment categories require estimates of the environmental benefits and costs. For example, in an impact analysis, the total cost of the environmental impact in social welfare terms is the foregone net of environmental benefits. This and other strategies of CBA are apparently simple, but to practically valuate in monetary terms natural resources, environmental goods and services, environmental benefits and associated costs to the environmental degradation, etc. is a very difficult task. This is mostly due to the non-quantifiable nature of the environment and/or the non-marketable character of its goods and services in the existing economic framework. However, there are various methods and approaches to the economic valuation of environmental state changes: hedonic property method, travel cost, cost of illness, contingent valuation, etc. It is not our objective here to review these methods. Ample bibliography is available in Turner

et al. (1998), as well as on the conceptual, theoretical and empirical problems encountered in quantifying economic value for the environment (e.g., Pearce and Turner 1990; Costanza 1991).

As stated, CBA is a technique intended to improve the quality of public-policy decisions, which quality is defined according to the change in social well-being that they bring about. CBA forces us to use a measurement of social well-being, which we refer to as social welfare. The measure of social welfare in CBA and how it is affected by a policy depend on how the welfare of individuals is affected by the policy and how individuals' welfare levels are aggregated. Individual welfare is assumed to depend on the satisfaction of preferences and on the theoretical construct of economic value derived from the axioms of preference satisfaction (Kopp et al. 1997).

Many of the critiques of CBA encountered in everyday policy debates are echoes of the more conceptual issues. They include the following: (1) the environment is a public good that is not exchanged in markets and therefore defies economic valuation. Thus, the use of CBA to evaluate environmental policies is inappropriate; (2) environmental protection is often desirable for reasons that cannot be quantified (social, spiritual, and psychological values that defy valuation in simple economic terms); and (3) CBA does not take the "rights" of future generations into account. Beyond these and other conceptual issues, criticisms of CBA focus on several overlapping points: the notion that preference satisfaction gives rise to individual well-being, the elements of the social-welfare index, the notion that economic value is a measure of preference satisfaction, the empirical and philosophic problems encountered in quantifying economic value, the presumption that the well-being of society can be defined as some aggregation of the well-being of individual members of that society, and the methods by which the aggregation is performed (Kopp et al. 1997).

An alternative approach to CBA, for which the valuation of goods and services is not necessary is presented below for the present case study.

Practical example of CBA in the DPSIR framework of the Guanabara Bay case study

In this case study, the 'policy responses' and their practical 'management options' are those included in the 'Guanabara Bay Recuperation Program', conduced by the Rio de Janeiro State Government. The program is a water pollution control plan intended to reduce the inflow of wastewaters into Guanabara Bay. It includes the construction of several treatment plants, stabilization ponds, ocean outfalls with primary treatment, and other actions and facilities aim at the recuperation of the best conditions for the bay. The program was initiated in 1995 with a projected cost of about US$ 793 million, aiming to reduce the load of present pollutants to the bay by 80%.

Based on the conceptual and theoretical issues described, and the practical difficulties in valuation of environmental goods and services for a proper CBA of 'policy responses' and 'management options' of the 'Guanabara Bay Recuperation Program', we utilized a strategy that does not

require the valuation of the environment in monetary terms (Bidone et al. 2002). Conceptually, this strategy is in agreement with the necessary environmental conservation paradigm implicit in sustainable development. Even with the best possible data and scientific understanding, the sense in which economists can value nature's services is limited. Valuing these services is much less important than providing incentives for their conservation, and valuation and providing incentives for conservation are quite different. Valuation is neither necessary nor sufficient for conservation, whereas providing the right incentives is (Heal 2000).

The theoretical and practical basis of the proposed strategy is partially based on Hueting (1991) with suggestions and modifications more suitable to the present situation. The essential question concerns the necessity to assign monetary values to the external benefits and costs to the environment which arise from the project, policy, etc., so that these may be incorporated in the CBA, together with market values of other project attributes. This is not a straightforward task, owing to the intangibility in monetary terms of most environmental goods and services. Hueting (1991) proposed the following procedure: (1) define physical standards for environmental functions, based on their sustainable use; (2) formulate the measures necessary to meet these standards; and, finally, (3) estimate the amount of money involved in putting the measures into practice.

Presently we have focused on the economic–environmental evaluation of the results on fluvial water quality and the defensive expenditures adopted by the Guanabara Bay Recuperation Program. Table 2 shows a synthesis of a practical example of the proposed CBA to the economic–environmental evaluation of the results obtained by sanitary measures on fluvial water quality. The example was performed by grouping the available data from the watersheds of the NW sector of Guanabara Bay, the most critical in socio-economic and environmental terms. This procedure could be applied for each watershed draining into Guanabara Bay. Thus, general considerations and total values to the elements listed in Table 2 could be obtained for the entire Guanabara Bay basin from the individual value for each sub-basin.

In spite of considering an example based on only the watersheds draining into the NW sector of the Guanabara Bay, it becomes immediately evident how enormous the financial investments would be that are necessary to implement sanitary measures in the study area (see, in Table 2, the costs of the planned sanitation measures, cost per capita, and ratio 'cost per capita:family revenue per capita').

However, even with this high financial investment in defensive expenditures one would still be unable to eliminate the environmental pressures on river water quality, and, therefore, over Guanabara Bay waters according to the quality standards. Table 2 shows a one order of magnitude difference between the 'forecast of state change' (i.e., reduction of 80% of current pollutant discharge to fluvial waters) and the 'standard concentrations of sustainability'. Recent data, however, on the concentrations of biogeochemical materials present in rivers draining into Guanabara Bay NW sector (Monitoramento das Águas da Região NW da Baía de Guanabara, CENPES-UFF, 2002, unpublished report) show the same values reported for the period 1990–1995, published by the Rio de Janeiro State Environmental Authority. These results shows that after 8 years and over US$ 600 million, the Guanabara Bay Recuperation Program shows no significant changes in water quality of the Bay. The report on human development of Rio de Janeiro, published by the Rio de Janeiro Municipality with support from the United Nations Development Program (UNDP), indicates that the Guanabara Bay Recuperation Program has been inefficiently enforced and that the expected positive impacts on

Table 2
Practical example of the proposed CBA. Data from watersheds draining into the critical NW sector of the Guanabara Bay

Population and population density	300×10^3 inhab and 10^3 inhab km^{-2}
Human Development Index (HDI)	HDI <0.500 (low)
Biogeochemical concentrations and fluxes in river waters (1995 to start of the Guanabara Bay Recuperation Program)	Concentrations (mg L^{-1}): BOD=26, TN=12, TP=1.3 Fluxes: 40 t BOD, 5.8 t TN, 1.2 t TP (on a daily basis)
Pollution level of rivers	High
Planned sanitation and flood control measures (to reduce approximately 80% of the effluent inputs)	Construction of: collecting system for wastewater and effluents, primary and secondary treatment plant, construction of stabilization pond and capacity-up of existing treatment plants, retardation pond, dredging and other canal works
Costs of the planned sanitation measures	US$ 280×10^6
Cost per capita	920 US$/inhab
Ratio cost per capita: family revenue per capita	9
Forecast of state change (approach considering linear 80% load reductions)	Concentrations (mg L^{-1}): BOD=10, TN=2.5, TP=0.4 Fluxes: 8 t BOD, 1.2 t TN, 0.2 t TP (on a daily basis)
Standard of sustainability (concentrations from non-polluted to weakly polluted rivers of the Guanabara Bay basin)	Concentrations (mg L^{-1}): BOD=3, TN=0.2, TP=0.08
Natural background level (concentrations from pristine-forest rivers)	Concentrations (mg L^{-1}): BOD=1, TN=0.07, TP= 0.006
Physical natural capital depreciation (PNCD)—estimated from technical measures for tertiary treatment	US$ 62×10^6 or 207 US$/inhab
Pressures on other resources	Drainage and occupation of wetlands
Benefits	Improved human health and urban life conditions. Increase in productivity of economic activities

the environment have not occurred. The original chronogram was never implanted and the state showed weak capacity for its management. Government authorities present a simple explanation: "there is a lack of sewage treatment plants". Although many were constructed, they are inactive or working below capacity due to widespread absence of infrastructure such as pipelines connecting the households in the catchment.

These facts point to the sustainability of the program proper and thus of the studied coastal area itself. The definition of sustainability involves diverse dimensions apart from the environmental, such as social, political, economic, moral, cultural and institutional dimensions, among others. For example, the economic dimension implies an efficient management of resources in general and is characterized by a regularity of public and private investment; thus the efficiency has to be evaluated in view of macro social processes.

Moreover, even if the defensive expenditures of the Guanabara Bay Recuperation Program are applied *in total*, an important environmental passive is left in terms of water quality for future generations—this may be approached by physical natural capital depreciation (PNDC) estimates.

Physical natural capital depreciation (PNCD) and gross domestic product (GDP) correction

The capital of an economy is its stock of actual goods with the potential to produce in the future more goods and services. As such, the capital of an economy should include the natural resources of a given region, once they have the potential to generate more goods and services in the future, both as a source of raw materials and as receptors of effluents and wastes generated by human activities. Therefore the impoverishment of natural resources must be viewed as un-investment and should be discounted from the incomes generated by production as a "depreciation of the natural capital" (El Serafy 1991).

One reason that depreciation exists is because of a reduction over time in the physical ability of capital to generate consumable services. This loss in physical ability—physical depreciation—may also lead to a loss in the value of the capital stock—value depreciation. In other words, value depreciation may be caused by physical depreciation. However, value depreciation can also arise from other reasons. For example, the value of capital can fall due to a change in tastes for those consumption items produced by the capital or simply because of a change in interest rates. Thus, the value of total depreciation (Peskin 1989) could be considered as:

$$\text{Value depreciation} = \text{physical depreciation} - \text{capital gain (or + capital loss)}$$

We will only consider the physical depreciation (PNCD). Capital (in financial terms) gains and/or losses are already included in conventional accounts (GDP). In this study we propose to estimate PNCD through the estimation of the environmental costs associated with the remaining biogeochemical loads in the river waters (i.e., the environmental losses that are not restored or compensated). This is done by estimating the costs of the necessary measures to reach the natural background concentrations of local fluvial waters, i.e., to attain the original state of the river water quality. In the example shown in Table 2, an estimate of US$ 62 million for the PNCD was obtained considering the inclusion of a tertiary treatment of domestic wastes, the best technical approach to reach the natural background level for river waters in the study area. This value corresponds to approximately 10% of the global inversion of the Guanabara Bay Recuperation Program. The estimated values of PNCD for all watersheds draining into Guanabara Bay, not only for those of the NW sector used as an example in Table 2, shall be included in the "satellite accounts" to correct the GDP of Rio de Janeiro, together with the costs of defensive expenditures (sanitation measures) included in the Guanabara Bay Recuperation Program:

'Satellite Accounts'
$$= \text{GDP} - \Sigma \text{ Costs of defensive expenditures} - \Sigma \text{ PNCD}$$

Beyond the PNCD, the expression above shows that a correction is necessary for expenditure on compensatory, restoration and preventive measures, which only re-establishes or maintains environmental functions that would remain available without the negative impact of human activities on the environment. Generally, this expenditure enters as value added in the conventional GDP calculation. This leads to an overestimation of the increase in domestic income and conceals what is going on in the environment: loss is not written off; restoration is written up (Hueting 1991).

Complementary remarks on CBA performed in this case study and discussion

The priority in this study is to determine the pressures on the fluvial water quality, considered to be a key issue in order to ameliorate the water use of Guanabara Bay. However, also pressures on other environmental resources could be considered: for example, the strong reduction of the area of existing wetland ecosystems, which would require the establishment of reserves in other areas to partially minimize their reduction in the Guanabara Bay region and serve as genetic pools and biodiversity hot spots for future generations. The costs of such conservation projects would cover at least part of the value of these ecosystems. Beyond the enormous human pressures, the losses of wetlands are mostly due to the implementation of flooding control measures along the lower parts of river basins (ponds, dredging, canals, etc.). In general, theses measures are planned to positively interact with water treatment systems. However, neither is there any specific policy in place in the area to protect and/or manage the wetlands, nor is any consideration given to the impact of external forcing, e.g., sea level change and other on-going projects to do with development and management. These additional pressures reflect conditions, transport and exchange across the various other boundaries, such as direct

substance discharge, residual fluxes from atmospheric sources, as well as inputs and/or dilution across the ocean boundary. The quantification of these pressures is under way, but, up to now, in Table 2, only a qualitative approach is considered for the watersheds under study.

In the Guanabara Bay basin, as with many other densely populated coastal areas, better fluvial water quality means more and better water for human consumption. However, at present this use as well as its potential for other uses, e.g., tourism and aquaculture, is not properly recognized and many areas are already showing signs of potable water shortage. The costs of conservation projects concerning the vegetation cover of rivers draining into Guanabara Bay would cover at least part of the value of these ecosystems. In relation to the treatment of benefits, it is a basic principle of CBA that all benefit types should be accounted for somehow, whether they are quantifiable or not. Rather, the key issue is how to treat non-quantifiable elements. There are several options. One that has found favor among economists is a value-of-information approach. This involves estimating the net benefits for the quantifiable elements and asking how large the non-quantifiable elements would have to be to reverse the conclusion of the analysis. If the non-quantifiable elements were all on the benefits side and the net benefits were positive, information on the non-quantifiable benefits would have no value for the decision. If the net benefits were negative, the non-quantifiable elements would have to be at least as large to reverse the outcome of the analysis. The analyst or decision-maker could make a judgment about whether the non-quantifiable elements were likely to be greater than this amount (an easier judgment than one about the possible size of the non-quantifiable benefits) (Kopp et al. 1997). For instance, with respect to health benefits of the Guanabara Bay sanitation program, the effects of water and soil contamination with bacteria, viruses, etc. on human health are well known. Statistical data show that the population's health is improved after the implementation of sanitation measures. That is, the costs of illness treated are reduced over time, although it remains unclear by how much. To answer this question it is necessary to have available good statistical data on these costs, which are not readily available. For this reason, to estimate the approximate rates of illness reduction, observed over time in areas with sanitation controls, may be a sufficient approach of the benefits of sanitation programs.

Within the proposed methodology benefits are supposed to be directly included in the conventional calculation, on an annual basis, of the GDP of the area considered. These benefits result from the increasing productivity of economic activities (tourism, fisheries, aquaculture, etc.), reduction of costs in public health, maintenance of the urban infrastructure and of littoral protection, and other diverse benefits resulting from improving sanitary and environmental conditions.

Another relevant aspect refers to the quantification of the opportunity costs. According to World Bank estimates of the costs of prevention and recuperation of degraded ecosystems, changes of economic and political priorities should avoid both present and future risks of financial losses. For example, the cost to rehabilitate degraded ecosystems has been estimated as 10–50 times higher than the respective prevention costs (World Bank 1992). Thus, the high rate 'cost per capita:family revenue per capita', in Table 2, would be much smaller if instead of a delayed, expensive and insufficient recuperation program, effective public policies directed at degradation prevention, and coastal ecosystem conservation were in practice. The larger fraction of the ecosystems' recuperation costs could be directly applied to enhance the quality of life of the population.

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