A System Dynamics Bioeconomic Model for Ecologically Sustainable Economic Development in Coastal Ecosystems

Georgia Mavrommati[a], Kostas Bithas[b] and Panayiotis Panayiotidis[c]

[a]Post-doctoral Research Associate, Center for Water Sciences, Michigan State University, US. Email:geomavro@msu.edu

[b]Associate Professor, Department of Economics and Regional Development, Panteion University of Social and Political Sciences, Greece. E-mail: kbithas@gmail.com

[c]Research Director, Hellenic Center for Marine Research, Greece. Email: ppanag@ath.hcmr.gr

Abstract:

The current paper proposes a System Dynamics Bioeconomic Model (SDBM) of coupling urban and coastal systems under the environmental objectives imposed by the Water Framework Directive. We developed a SDBM that connects the pollutant loads produced by urban systems' socioeconomic activities with biological quality elements reflecting the ecological condition of coastal ecosystems. This model enables quantitatively coupling of anthropogenic stressors (produced by the urban system) to the abundance of macrophytes (biological indicator of coastal system). Our case study focuses on the receiving waters of Athens Metropolitan area which is a typical example of a Mediterranean coastal city with high population density. This framework can inspire the development of other methodologies applicable to other types of ecosystems with different sources of pollution.

Key-words: Socioeconomic System, Pollutant Loads, Biological Quality Elements, Ecological Evaluation Index, Good Ecological Status, Socioeconomic activities, System Dynamics

1. Introduction

The scientific dialogue over the application of the concept of Sustainable Development (SD) has set the foundations for a new discipline, the so-called field of sustainability science. The sustainability science rejects the traditional separation of social and natural sciences and calls scientists to move beyond the methodological barriers of their discipline to better approach common research questions. On the one hand, social sciences and decision makers, based on the acknowledgement that crucial ecosystem functions and processes are in danger, are called to incorporate the knowledge of natural sciences into the decision making process (Clark and Dickson, 2003). The recognition that natural systems provide crucial functions and processes for socioeconomic activities and human well-being might change the way of adopting and implementing environmental policies. On the other hand, natural sciences are called to focus their research on the effects of anthropogenic activities on ecological processes in concrete terms as by this way the scientific knowledge can be attractive to decision- policy makers (Cash et al., 2003).

The Clean Water Act (CWA) and the Water Framework Directive (WFD) are two indicative examples of incorporation of ecological knowledge into the decision making process (USEPA, 1972). Both policies define environmental objectives for aquatic ecosystems in an integrative way by using several biological elements together with physicochemical and pollution elements (Borja et al., 2008; EC, 2000).

Coupling socioeconomic and natural systems for sustainability requires defining: (i) the operational content of the concept of sustainable development, which in this paper it is refereed as Ecologically Sustainable Economic Development (ESED); (ii) the interdependence between those systems; (iii) measures for the adjustment of socioeconomic systems within the boundaries that natural systems impose (Rockstrom et al., 2009).

The current paper proposes a SDBM for coupling urban and coastal systems under the environmental objectives set by the Water Framework Directive (WFD).We present a SDBM to identify the mechanisms linking urban patterns to ecosystem function with specific focus on the impacts of pollutant loads arising from a point source of pollution. The WFD is used as a policy guidance which provides the required environmental objectives based on the policy-makers political goals, the available scientific knowledge and public awareness (Steyaert and Ollivier, 2007).

The proposed System Dynamics Bioeconomic Model (SDBM) adopts the WFD ecological target that requires good status in all surface and groundwater bodies by 2015 (Article 4.1, WFD). The WFD defines ‘good status’ in terms of ecological and chemical parameters as well as water quantity (Article 1, WFD). For assessing the ecological status of coastal waters the “Ecological

Evaluation Index" (EEI) has been proposed (Orfanidis, 2001; Orfanidis et al., 2003; Panayotidis et al., 2004). Based on the EEI, the current study attempts to provide a SDBM for linking anthropogenic activities taking place in Athens Metropolitan Area with the ecological status of the Inner Saronic Gulf. The study focuses on the impacts of the pollutant loads form the wastewater discharges on the ecological status of waters. We assume that the achievement of GES, based on the approach of Biologically Crucial Levels, can be used as an operational condition for ESED.

2. The preservation of Biologically Crucial Levels approach

The concept of ESED has grown in popularity since the publication of the Brundtland report (WCED, 1987). The report defined the ESED as the "development that meets the needs of present generations without compromising the ability of the future generations to meet their own needs". Since then, they have been proposed several approaches for achieving ESED at operational level based on different assumptions concerning the needs and preferences of the future generations (Bithas, 2008; Bithas and Nikjamp, 2006; Costanza and Daly, 1992; Daly, 1996; Daly et al., 2007; Ekins et al., 2003a; Ekins et al., 2003b; Neumayer, 2010). Our study defines the concept of ESED based on the the Biologically Crucial Levels (BCLs) approach (Bithas, 2008; Bithas and Nikjamp, 2006) for two main reasons. First, the BCLs approach seems to reflect the rational of two current major environmental policies for aquatic ecosystems (Water Framework Directive and Clean Water Act) (Mavromati and Bithas, 2010). Secondly, the BCLs approach seems to more attractive to coastal experts according to a questionnaire survey in the context of coastal ecosystems (Mavrommati, 2011).

The BCLs approach is a relatively new approach, within the so-called bioeconomic framework, taking as its starting point the explicit equal consideration of the welfare of future generations, to those of current generation(Mavrommati, 2011; Mavrommati and Richardson, 2012). The BCLs approach considers that the socioeconomic system is a subsystem of the natural system. In this respect, the maintenance of the proper functioning of natural system constitutes a prerequisite for the existence and evolution of social and economic processes.

This approach defines two distinct operational conditions for sustainable development, classified hierarchically to reflect their relative importance. The “necessary” condition demands “the maintenance of the biologically and ecologically critical levels (BCLs) of environmental system’s assets and processes that ensures the ecological integrity of ecosystems. The concept of BCLs extends to the so-called pollutants that should be reduced below those crucial levels that may disturb the “healthy” functioning and evolution of ecosystems. As a result, the BCL approach adopts a biological constraint on the socioeconomic processes and development.

The prime criterion of sustainability is the biological and ecological integrity of ecosystems in the long run. In this context, the BCL approach seeks the preservation of at least the “minimum” critical biological levels of environmental assets and processes in order to ensure biological integrity and healthy evolution in nature. Irreversible deterioration of ecosystems is not a sustainable path. In this context, the BCL approach proposes the avoidance of any species extinction because it is an irreversible change.

The second condition refers to the provision of inputs to the productive sector of the economy in the form of sufficient natural energy and resources. This provision should have a long run perspective, taking systematically into account the potential needs of future generations. The use of natural resources as inputs to the production process should be covered by: avoidance of wasting non-renewable resources, limiting the use of renewable within their regeneration rate, gradual substitution of non- renewable resources with renewable ones.

Our study focuses on the first (necessary condition) of BCLs approach by defining the biological crucial elements according to the Water Framework Directive.

3. Study Area and problem articulation

The Inner Saronic Gulf is a coastal water body located in the vicinity of Athens, the capital of Greece shown in Figure 1. The population living in Athens Metropolitan Area (AMA) is the 35.45% percent of the total population of Greece which according to the last census is around 3800000 (ESYE, 2011).

The basic source of pollution at the Inner Saronic Gulf is from the disposal of the AMA wastewater. The greater part of AMA has from most part a separate sewer system with the exception that the center of Athens has a combined sewage system (wastewater is mixed with urban runoff). Until 1995, the wastewater of AMA was discharged untreated in the shallow waters of Keratsini Bay through the Central Sewage Outfall and the Saronic Gulf was considered to be one of the most polluted areas in the eastern Mediterranean. During 1995, the operation of the wastewater treatment plant (WWTP) of Athens in Psitalia Island has started with primary level of treatment. The WWTP is designed with a maximum capacity of 1.000.000 m3d^{-1} and since 2004 uses secondary treatment technology.

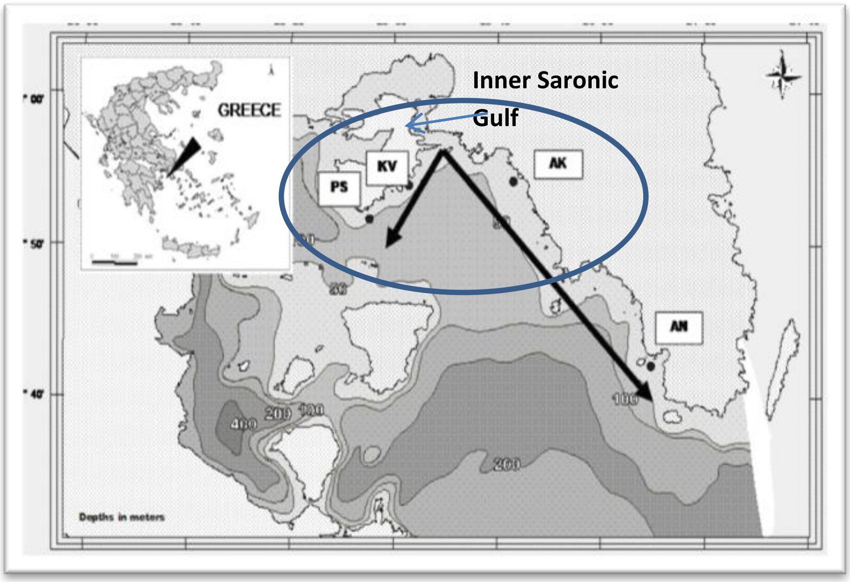

Figure 1: Sampling sites for Saronikos Gulf macroalgae: PS=Peristeria, KV=Kaki Vigla, AK=Agios Kosmas, AN=Sounio

The basic purpose of SDBM is: (i) to identify the interactions between the socioeconomic and coastal system and (ii) to define under which conditions the socioeconomic and coastal system sustainably coexist.

Based on the EEI, the current study attempts to propose a SDBM for linking anthropogenic activities taking place in Athens Metropolitan Area with the ecological status of Inner Saronic Gulf. The study focuses on the impacts of the pollutant loads from the wastewater discharges on the ecological status of waters.

4. Structure of the SDBM

The Systems Dynamic Bioeconomic Model (SDBM) is comprised of two sectors: the socioeconomic sector and the bio-ecological sector. Figures 2 and 3 illustrate the elements (stock, flow, converters and exogenous converters) of each sector and their relationships. The stocks represent the accumulations in the system, which can be changed only through flows that are the rates of change of the system (Ford, 1999). Converters can play many roles in the system but the most important is to define the flows. It should be noted that very often flows can be represented with converters depending on their role in the system.

The model is designed to run 43 years with a ΔT equal to 0.25 years. This model is written in the STELLA software simulation language (version 9.1.4).

The elements used in the SDBM defined through a systematic process including interviews with experts from the Ministry of Environment, Energy and Climate Change (YPEKA), the Athens Water Supply and Sewerage Company (EYDAP SA) and the Hellenic Center of Marine Research (HCMR). The sources of the statistical data used for describing the external variables and validating the model are described in Table 1.

Element	**Note**	**Period**	**Source**
Net Migration Rate, Crude Birth Rate and Crude Death Rate	The demographic dynamics in Athens are inextricably linked to historical fact irrelevant from our model purpose	1987-2008	Eurostat and Hellenic Statistical Authority
Gross Domestic Product Per Capita (GDP)	There is no clear relationship between population and GDP.	1987-2008	Eurostat and Hellenic Statistical Authority
Water Price	The process of price changes is irrelevant from our model purpose. Water price is the mean weighted average price	1987-2008	EYDAP SA.
Impact of Drought	Takes the value of 0 or 1. It is estimated from	1987-2008	Hellenic National Meteorological Service

	rainfall data.		(EMY)
Policy	Takes the value of 0 or 1. The dynamics of policy change is the next step of our model.		Policies are defined through the national and European legislative frameworks.
Rainfall		1987-2008	Hellenic National Meteorological Service (EMY)
Phytoplankton 1, 2 and 3	Expert knowledge		Hellenic National Meteorological Service (EMY)
Total	100. By this parameter is defined the total space.		HCMR
BCL	0.6. It is defined through theory and policy		HCMR
Months	It is defined through the counter function		

Table 1: Exogenous Parameters of the SDBM

4.1 Socio-economic Sector

The socioeconomic sector presents how urban population affects, through the wastewater disposal, the ecological condition of the Inner Saronic Gulf. Urban coastal systems are contaminated by pollutants loads via many ways (e.g. point sources of pollution, non-point sources of pollution, overflows). In our case study, the main source of pollution is the wastewater disposal of urban population. Due to this reason our focus is on the factors that generate the volume and the pollutant loads of wastewater.

The pollutant loads from wastewater disposal in AMA depends on residential and industrial wastewater. The impact of pollutant loads on the ecological condition of Saronic Gulf has been studied several times since now (Andreadakis and Christoulas, 1992; Dassenakis et al., 2003; Lekkas et al., 2008; Scoullos et al., 2007). In our model, we adopt the assumption that the volume of wastewater disposal depends mainly on residential water consumption (76%) and secondly on industrial water consumption (24%). This assumption is based on the data from EYDAP SA from 1987 until 2010 for each category of water consumption. Moreover, we assume that the precipitation affects the volume of wastewater and the relevant pollutant loads as during periods of heavy rainfall, the combined wastewater can exceed the capacity of wastewater treatment plant. This parameter is named ‘Inflow due to rain’ and describes the inflow of stormwater to the sewerage system, during rainfall. The estimation of this parameter is based on a relevant methodology and assumptions developed for Greek cities (Zalachori et al., 2008)

The volume of wastewater is crucial for deciding the carrying capacity of wastewater treatment plants and the associated investment and operational costs. Considering that part of the sewerage system in AMA is combined, the carrying capacity of wastewater treatment plant is very important for predicting and managing overflows.

The pollutant loads of residential wastewater disposal depend on the volume of wastewater disposal, lifestyle and the level of treatment (Kato, 2005). Two categories of pollutant loads used in our analysis: Biological Oxygen Demand (BOD_5) and Total Suspended Solids (TSS).

The basic equations for estimating the volume of wastewater and pollutants are the following:

WWflow =Residential__Flow+Non__Residential_Flow+Inflow_due_to_rain (3.1)

Residential__Flow = 0.8*Population_Attiki*Water_Demand__per_capita (3.2)

Non__Residential_Flow = 0.35*Population_Attiki*Water_Demand__per_capita

Inflow due to rain = $\mathcal{F}(precipitation)$, $\mathcal{F}(0)$=0 (3.3)

SSOUT = SSIN*(1-TRTSSIN) (3.4)

BODOUT = BODIN*(1-TRBODIN)(3.5)

N = 0.180*BODIN*(1-TRN)

Where:

SSOUT: The outflow of TSS

BODOUT: The outflow of BOD_5

SSIN: The inflow of TSS

BODIN: The inflow of BODIN

TRTSSIN = Level of treatment, $0 \leq TRTSSIN \leq 1$

TRBODIN = Level of treatment, $0 \leq TRTSSIN \leq 1$

Water_Demand__per_capita=

(EXP(-6.226-0.1*LOGN(Water_Price)+0.44*LOGN(GDP))+(Impact_of_Drought))*Demand_Coefficient (3.6)

$R2=0.798$

Std. Error of the Estimate=0,082

The water demand per capita function was estimated based on actual data from EYDAP SA from 1987 until 2010.

The level of wastewater treatment in AMA seems to be induced by environmental policies imposed by the EU. Apart from the WFD, one more policy related to our case study is the Directive 91/271/EEC concerning urban wastewater treatment. The Directive 91/271/EEC sets certain criteria for wastewater pollutant loads discharged to surface and coastal waters, depending on the size of the wastewater treatment plant and the sensitivity of the receiving water. In particular, the minimum required reduction in relation to the load of the influent for BOD_5 and TSS are 70-90% and 90% respectively ((E.C, 1991). In the case that discharges are generated from urban wastewater treatment plants located in sensitive areas then additional reductions of total phosphorus and total nitrogen around 70-80% are required ((E.C, 1991)

In our SDBM three periods of wastewater infrastructure are defined:

- 1987-1995: Wastewater pretreatment. The pretreatment of influent wastewater takes place at Akrokeramos and involves debris removal, screening, grit removal and odor control units.

- 1995-2004: Primary treatment. In 1995 has started the operation of the Primary Wastewater Treatment Plant of Athens in Psitalia. Approximately 35% of the incoming BOD_5 and 60% of the TSS are removed during the primary treatment.
- 2004-present: Secondary treatment. The secondary treatment TSS removes 90% of the BOD and TSS presented in inflow of wastewater.

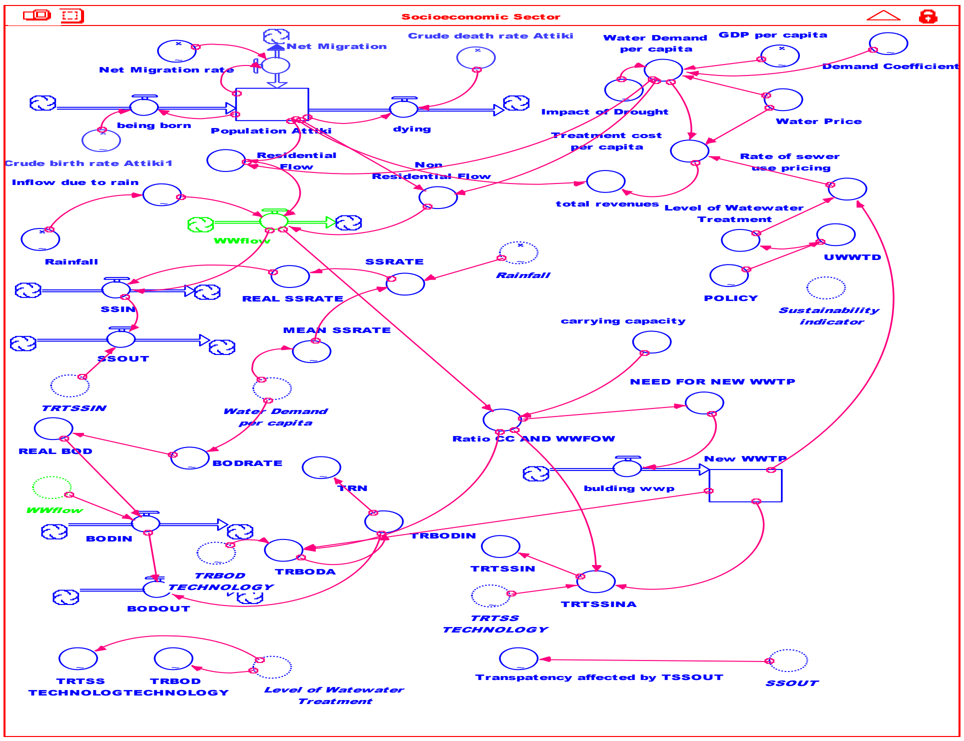

Figure 2: Stock-Flow Diagram of the Socioeconomic Sector

4.2 Bio-Ecological Sector

The bio-ecological sector describes the biological crucial levels of the species affecting the ecological condition of the Inner Saronic Gulf. This description is based on the first condition of the BCL approach which requires the maintenance of the minimum biological integrity of ecosystems (the condition of biological sustainability). In our study, we equalize the concept of biological sustainability with the objective Good Ecological Status (GES) of the WFD. The definition of GES (Annex V, WFD) explicitly spells out the key role that biological quality elements play in the structure and function and provides the appropriate legislative framework for protection of ecosystem services contributing to human well-being (Mavromati and Bithas, 2010).

Among other biological quality elements, the WFD includes marine benthic macrophytes as a biological quality element for the classification of marine coastal waters. Based on marine benthic macrophytes the EEI has been developed (Orfanidis, 2001; Orfanidis et al., 2003; Panayotidis et al., 2004). The EEI is an indicator that reflects the impact of anthropogenic stress on biological quality elements. According to EEI, marine benthic macrophytes are classified into two groups, the Ecological Status Group I (ESG I) and Ecological Status Group II (ESG II). 'ESG I includes seaweed species with a thick or calcareous thallus, low growth rates and long life cycles (late successionals), whereas the ESG II includes sheet-like and filamentous seaweed species with high growth rates and short life cycles (opportunistic)'(Orfanidis et al., 2003).

The average abundance (%) of ESG I and ESG II determine the ecological status of coastal water (Figure 3). The EEI takes a numeric value ranging from 0.2 (bad ecological status) to 1 (high ecological status). In order to maintain the function of ecosystems, the numeric value of EEI should be at least equal to 0.6 that corresponds to GES. Human systems should modify their activities within the boundaries imposed by the EEI (Figure 3). The conceptual framework for defining elements of the bio-ecological sector is described in Figure 4.

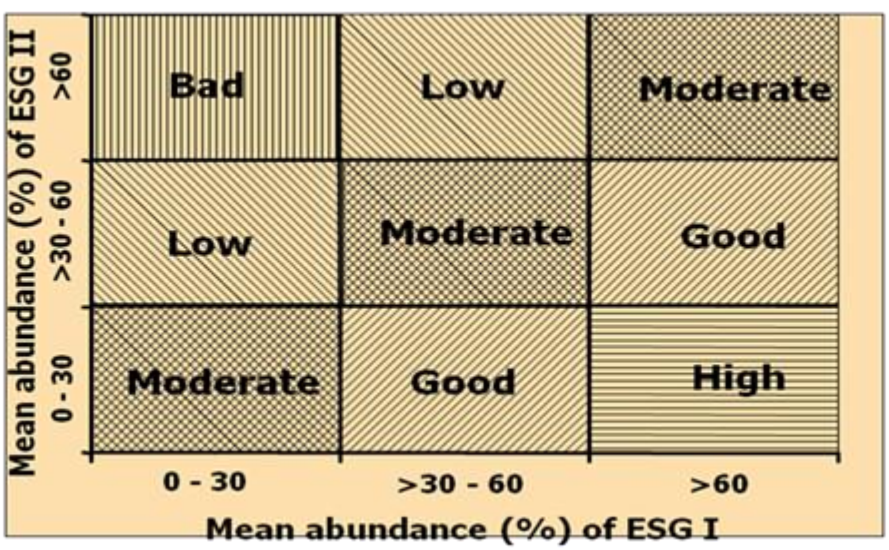

Figure 3: A matrix based on the mean abundance (%) of ESGs to determine the ecological status

of transitional and coastal waters

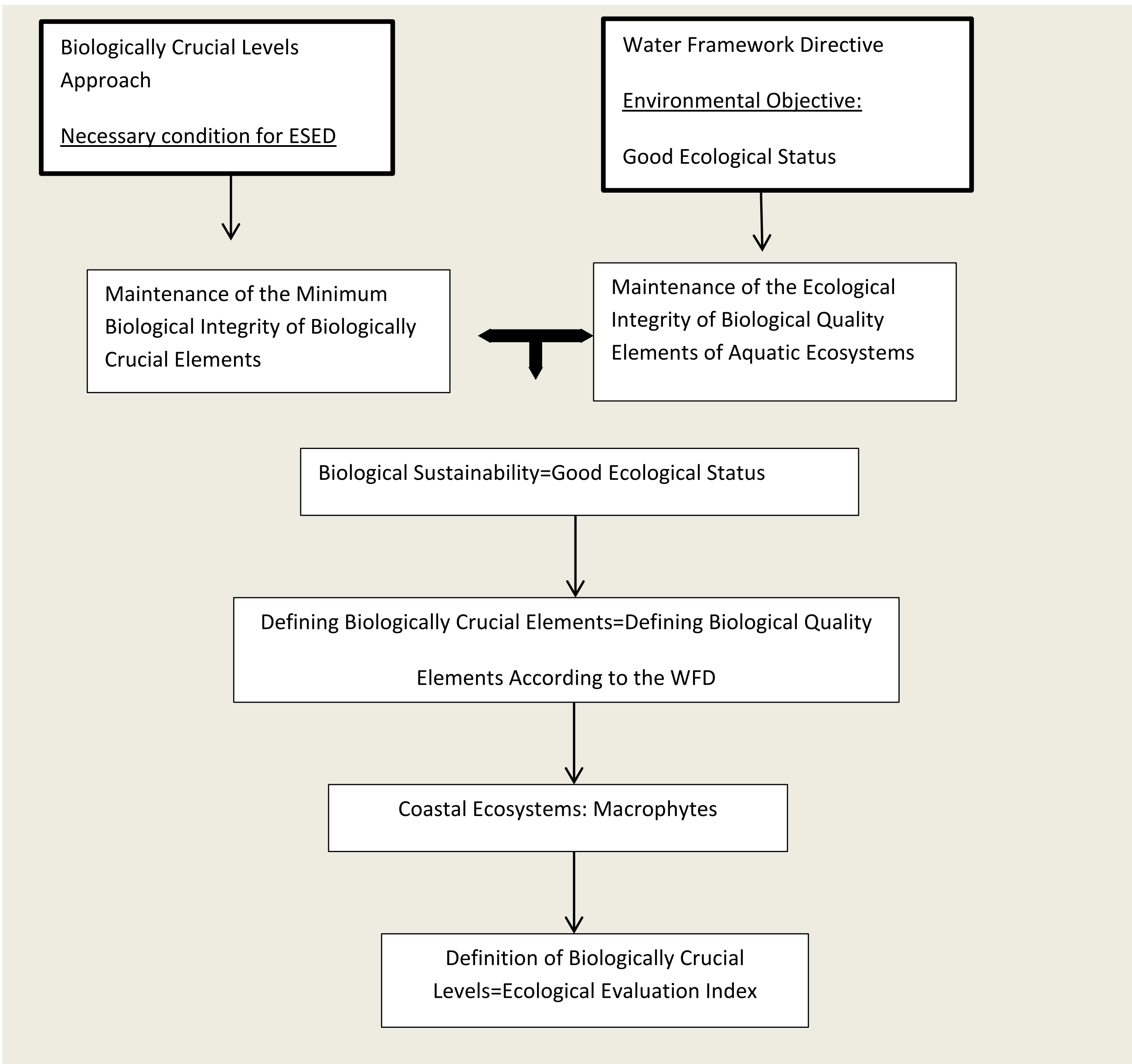

Figure 4: Conceptual Framework for defining the elements of the Bio-ecological Sector

The main objective of the bio-ecological sector is to describe the ecological condition of the coastal ecosystem in accordance with the EEI. The main assumption of the bioecological sector is that the ESG I and ESG II compete for the same space and are affected from the Nutrients and Transparency. Figure 5 shows the competition of ESG I and ESG II for open space at the bottom of coastal waters. The model is based on a two species colonization model (Chang et al., 2008; Hannon and Ruth, 1997). There are five stock variables (OPEN, ABUNDANCE II, ABUNDANCE I, Transparency and Nutrients) and three flow rates (NET GROWTH ESG I, NET GROWTH ESGII, ESG I DISPLACING II,). The growth rates of both species are defined through the concentration of Nutrients and Transparency (Secchi Disc) both of which are inputs from the socioeconomic system and defined through BODOUT and SSOUT.

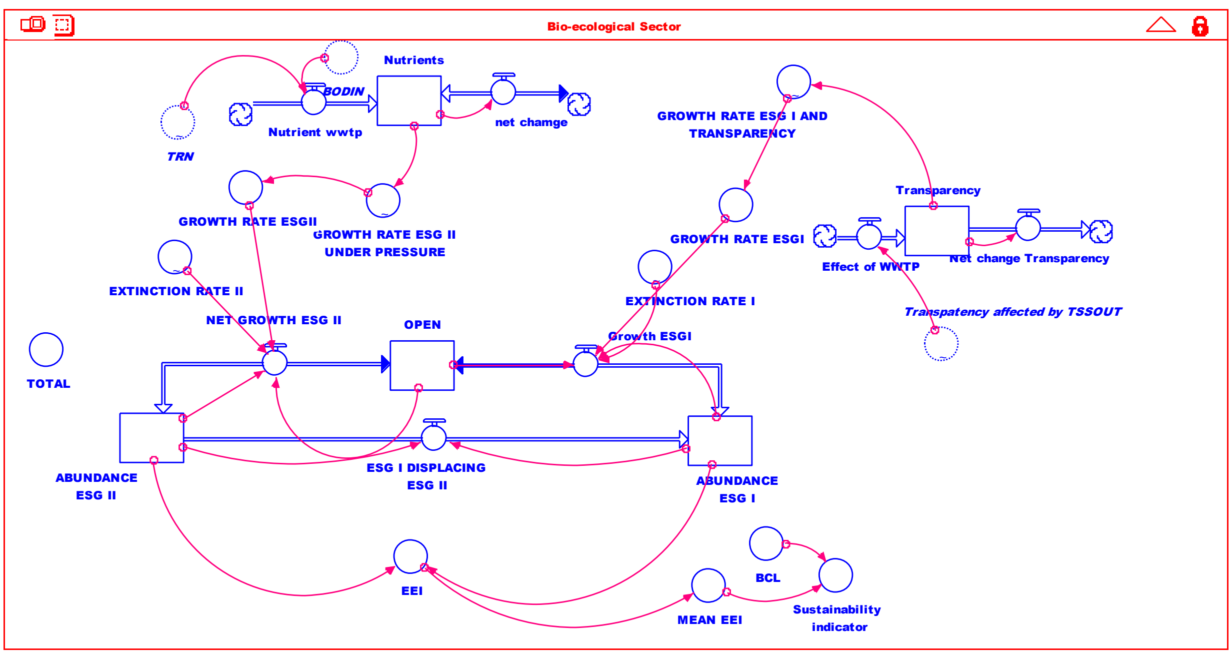

Figure 5: Stock-Flow diagram of the Bio-ecological Sector

The main equations of bio-ecological sector are:

ABUNDANCE__ESG_I(t) = ABUNDANCE__ESG_I(t - dt) + (ESG_I_DISPLACING__ESG_II + Growth_ESGI) * dt

ABUNDANCE_ESG_II(t) = ABUNDANCE_ESG_II(t - dt) + (NET_GROWTH_ESG_II - ESG_I_DISPLACING__ESG_II) * dt

OPEN(t) = OPEN(t - dt) + (- Growth_ESGI - NET_GROWTH_ESG_II) * dt

The relevant abundance of ESG I and ESG II determine the value of the EEI (Figure 2). The comparison of EEI and BCL define a sustainability indicator. The next step of our research is to analyze how the proposed sustainability indicator can inform decision making.

Verification of SDBM: Behavior Reproduction Tests

In order to test the ability of SDBM to reproduce the behavior of key parameters the metrics described in Table 2 were used. Those metrics are common statistics for assessing model fit to data (Sterman, 2000).

Metric / Parameter	Data	R^2	MAE	RMSE	Theils Inequality Statistics (U_M+U_S+U_C=1)	
Population Attiki	**1987-2008**	**0,99**	**277,6**	**9100**	U^M	**0,097094482**
					U^S	**0,0023694**
					U^C	**0,9**
Water Demand per capita	**1987-2010**	**0,95**	**0,02**	**0,026**	U^M	**0**
					U^S	**0,999558863**
					U^C	**0,000441137**
WWflow	**2003-2007**	**0,6**	**32618,62**	**45367**	U^M	**0**
					U^S	**0,12945501**

					U^C	**0,87048719**
BODOUT	**2003-2007**	**0,904**	**26,445**	**102,058**	**U^M**	**0,0000931**
					U^S	**0,0254861**
					U^C	**0,9744208**
SSOUT	**2003-2007**	**0,962**	**18,2**	**65,148**	**U^M**	**0,051**
					U^S	**0,064**
					U^C	**0,885**
EEI	**1997-2007 (for some year we do not have data)**	**0,974**	**0,024**	**0,0006**	**U^M**	**0,0132**
					U^S	**0,0133**
					U^C	**0,9735**

Table 2: Behavior Reproduction Tests

Results and Discussion

The model includes the period 1987 until 2030 as we want to test the effect of WWTP operation on the ecological quality of Inner Saronic Gulf. Four graphs are presented for each scenario. The first graph depicts the population and water demand per capita. The second graph describes the pollutants loads (BODOUT, SSOUT) and volume of wastewater (WWflow). The third and fourth graph present the ecological condition of the coastal ecosystem based on the abundance of macrophytes (ESG I and ESG II) and the ecological evaluation index (EEI) in relation to the sustainability indicator (BCL=0.6). It should be highlighted that the scope of our model is to show reasonable long-term trends and not to predict precisely the evolution of systems' elements under different conditions. Table 3 summarizes the scenarios presented below.

Scenario 1: Business as Usual Scenario

The baseline scenario assumes that the external variables of the model continue to have the past behavior resulting in the increase of population and water demand per capita. Figures 6 to 9 are very useful for understanding the significant role that the wastewater infrastructure plays for combating the impact of pollutant loads on coastal ecosystems. Apparently the pollutant loads decreased considerably after the operation of the wastewater treatment plant of Psitallia and especially the secondary treatment after 2004 (Figure 7). Subsequently, the relevant abundance of ESG II decreases gradually after 1995 and accordingly the abundance of ESG I increases. As a result the average EEI is above the biological crucial level of 0.6 after 2007 reflecting the good ecological status of coastal waters. Under the current conditions, the achievement of the environmental objective of GES seems achievable. Water demand per capita fluctuates during the year reflecting the seasonal variation of this variable. The abundance of ESG I and ESG II have a yearly cycle and for this reason both have a minimum and maximum value during the year.

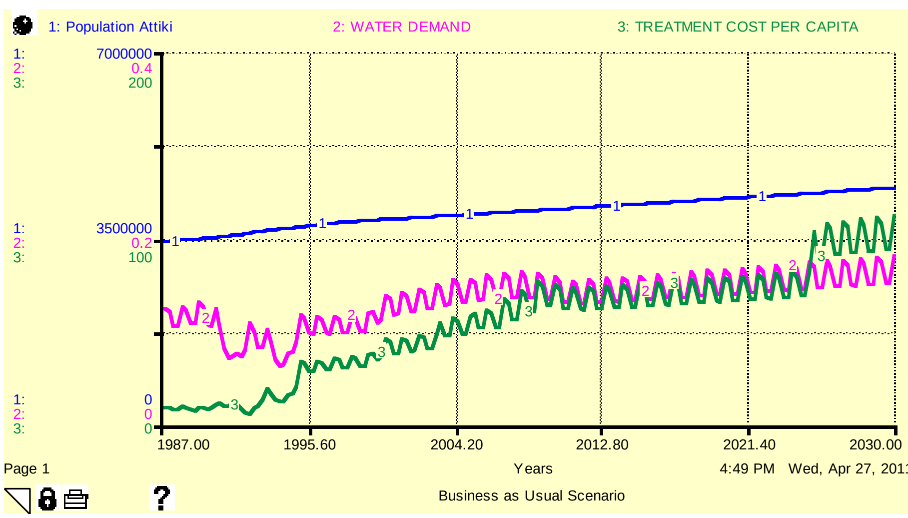

Figure 6: Population and water demand per capita_Scenario 1

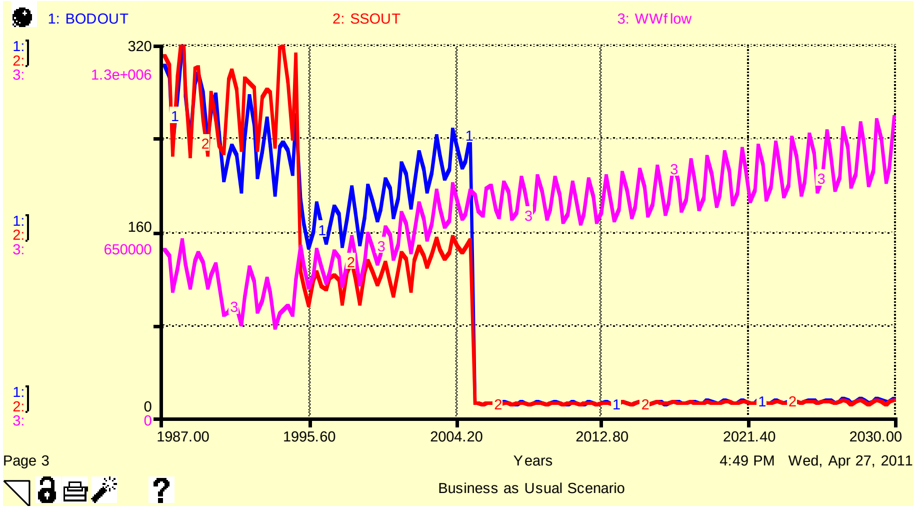

Figure 7: Pollutant loads outflow and the volume of wastewater_Scenario 1

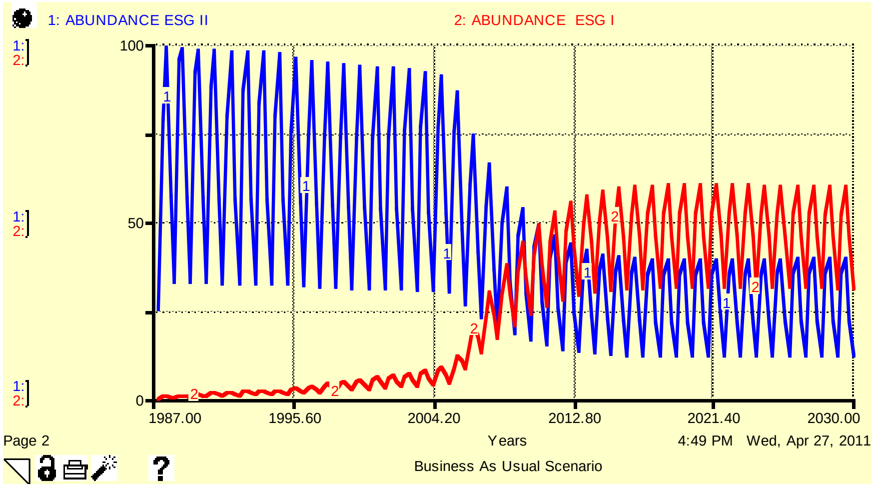

Figure 8: Percentage of space occupied by ESG I and ESG II_Scenario 1

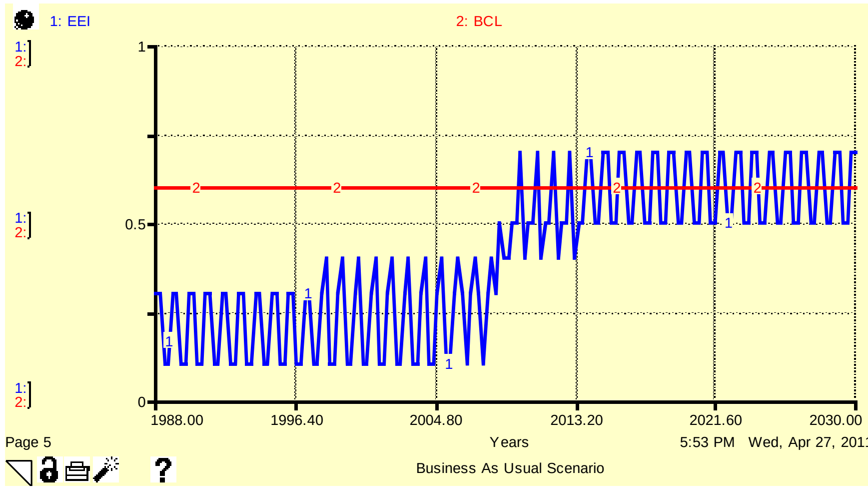

Figure 9: Ecological Evaluation Index (EEI) and Biologically Crucial Level (BCL)_Scenario 1

Scenario 2: Increase of Storm-water Flow

This scenario adopts the same assumptions of scenario 1 with the difference that the volume of storm-water flow considerably increases for the years of 2013 and 2014. We assume that the carrying capacity of the WWTP of Psitallia is exceeded due to the increase of stormwater system as part of Athens sewerage system is combined. In this case, the combined sewer system discharges the excess wastewater directly to the coastal water of the Inner Saronic Gulf and the pollutant loads outflow considerably increase. The result of this scenario is very revealing as it shows that the achievement of desirable environmental objectives is subject to unexpected situations. The construction and operation of a WWTP does not secure the achievement of GES even if the population and the structure of socioeconomic activities remain the same. Climatological parameters (increase of rainfall intensity due to climate change) or unexpected events (oil spill) can provoke deviation of GES. Especially, in the Mediterranean countries, it is expected the increase of rainfall intensity due to climate change. Figures 10 to 13 show that for the years 2013 and 2014 the pollutant loads considerably increase and the coastal systems' ecological status is below the biologically crucial level (EEI<0.6).

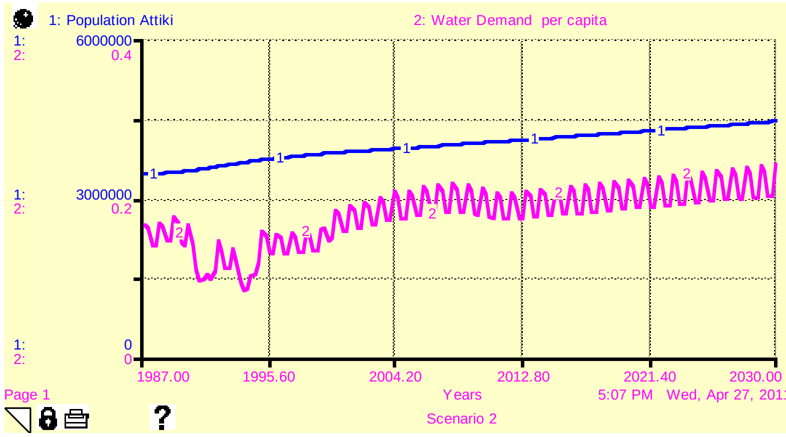

Figure 10: Population and water demand per capita_Scenario 2

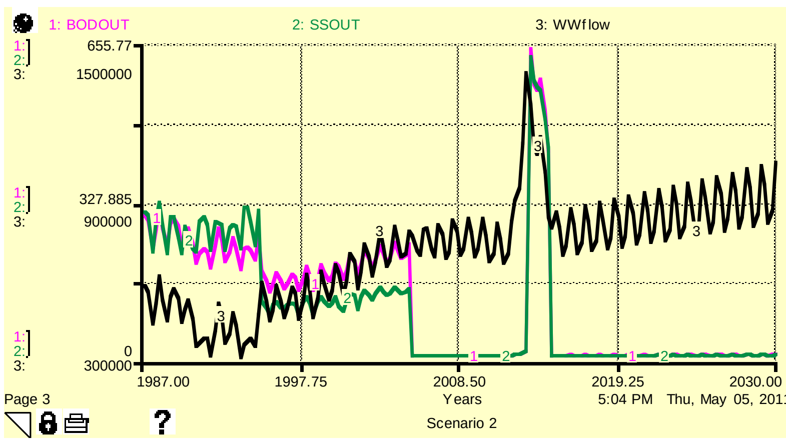

Figure 11: Pollutant loads outflow and the volume of wastewater_Scenario 2

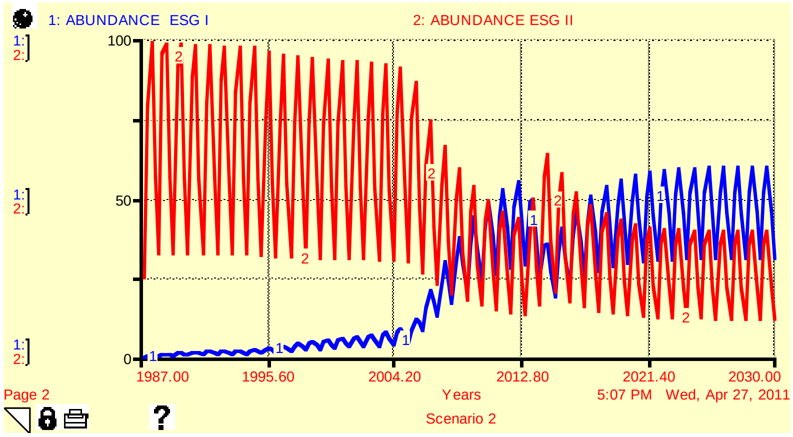

Figure 12: Percentage of space occupied by ESG I and ESG II_Scenario 2

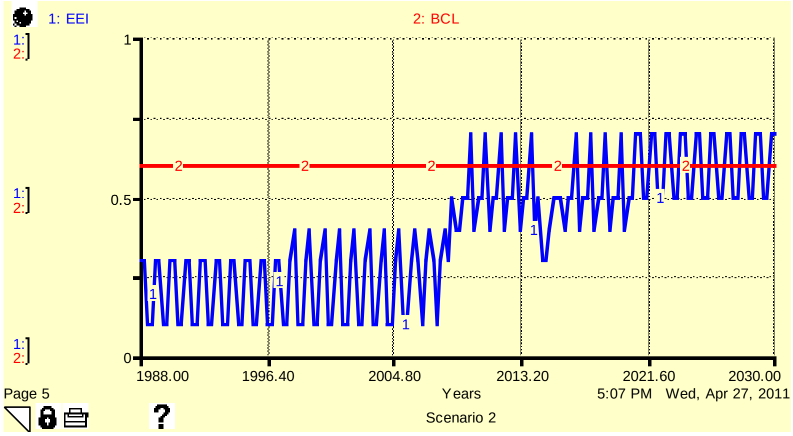

Figure 13:Ecological Evaluation Index (EEI) and Biologically Crucial Level (BCL)_Scenario 2

Scenario 3: Increase of Water demand per capita, GDP per capita and Pollutant loads rate of industrial activities

This scenario assumes that there is an increase of water demand per capita, Gross Domestic per capita and at the same time increase of industrial pollutant loads. The increase of water demand per capita can be generated from many reasons such as change in lifestyle, climatological conditions, income increase etc. In this study we assume an increase of water demand per capita due to a change of income elasticity from 0.44 to 0.5 (equation 3.6). The increase of income elasticity along with the increase of GDP per capita increases the water demand per capita. At the same time, the change of non-residential pollutant loads rate changes the contribution of industrial sector to pollution. Although we assume a small increase of BODrate and SSrate, this change marginally creates changes to those physicochemical parameters associated with eutrophication in coastal ecosystems.

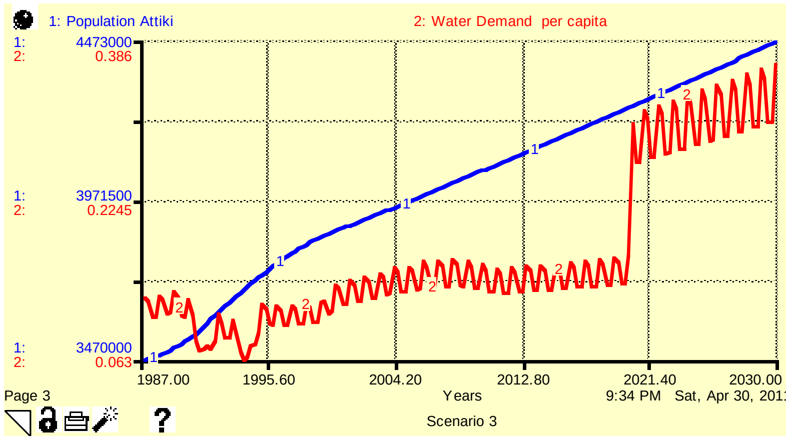

Figure 14: Population and water demand per capita_Scenario 3

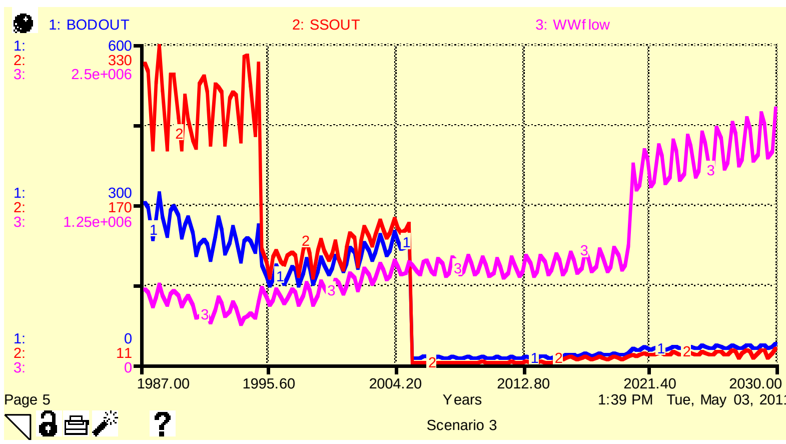

Figure 15: Pollutant loads outflow and the volume of wastewater_Scenario 3

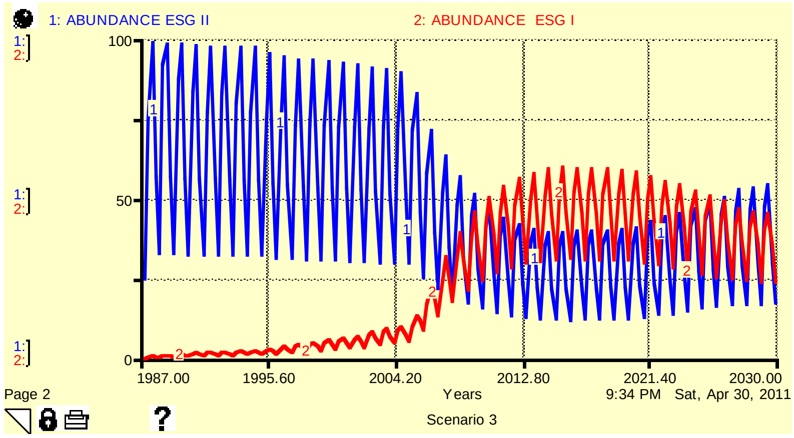

Figure 16: Percentage of space occupied by ESG I and ESG II_Scenario 3

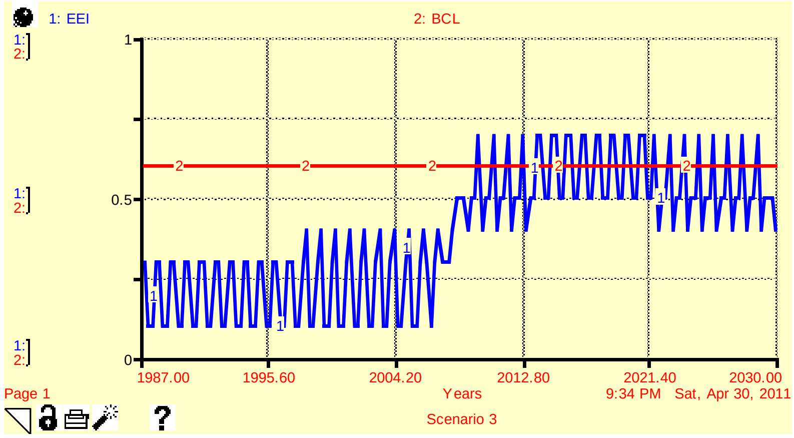

Figure 17: Ecological Evaluation Index (EEI) and Biologically Crucial Level (BCL)_Scenario 3

Our analysis since now indicates that under the current conditions the objective good ecological status is achievable. This means that the secondary level of wastewater treatment constitutes a sufficient tool for protecting the ecological condition of coastal ecosystems. However there are certain conditions that the degradation of coastal system seems questionable. Those conditions can be either produced from the socioeconomic or the bio-ecological sector.

Scenario	Changing Parameters	Achievement of sustainability conditions (GES)	Source of the problem
1	None (baseline scenario)	YES	none
2	Increase of Storm-water Flow	NO	Exogenous- climate change
3	Increase of Water demand per capita, GDP per capita and Pollutant loads rate of industrial activities	Probably	Endogenous-urban dynamics

Table 3: Behavior under alternative scenarios

Conclusions

The proposed SDBM describes the interactions between the socioeconomic system of Athens Metropolitan Area and the ecological condition of Inner Saronic Gulf. This model is based on system dynamics methodology and provides the capability to integrate the scientific knowledge from various disciplines even if the available data are not sufficient for statistical analysis. The innovative element of our SDBM is that it connects the pollutant loads of a WWTP with biologically crucial elements that define the ecological status of Inner Saronic Gulf. The study of those biological elements is important for two reasons. First, the WFD proposes biological elements as ecological indicators for monitoring the ecological quality of ecosystems. Second, the BCL approach suggests crucial biological elements as indicators for sustainability.

Making policy making recommendations requires further analysis of our model in order to define more precisely the determinants affecting the urban dynamics, the water demand per capita and the industrial growth. In this context, our next step is to improve and enlarge our model by the inclusion of parameters that determine the urban population dynamics and are related with the use of natural resources in the socioeconomic process (second condition of BCL approach).

Acknowledgements: This work is supported in part by the National Science Foundation under award no. EAR-1039122

References

Andreadakis, A. D., and D. D. Christoulas. 1992. Treatment and disposal scheme of the sewage of Athens. Journal of IWEM 6: 20-26.

Bithas, K. 2008. Tracing operational conditions for the ecologically sustainable economic development: the Pareto optimality and the preservation of the biological crucial levels. Environment, Development and Sustainability 10: 373-390.

Bithas, K., and P. Nikjamp. 2006. Operationalising ecologically sustainable development at the microlevel: Pareto optimality and the preservation of biologically crucial levels. Int. J. Environment and sustainable development 5: 126-146.

Borja, A. et al. 2008. Overview of integrative tools and methods in assessing ecological integrity in estuarine and coastal systems worldwide. Marine Pollution Bulletin 56: 1519-1537.

Cash, D. W. et al. 2003. Knowledge systems for sustainable development. Proceedings of the National Academy of Sciences 100: 8086-8091.

Chang, Y. C., F. W. Hong, and M. T. Lee. 2008. A system dynamic based DSS for sustainable coral reef management in Kenting coastal zone, Taiwan. Ecological Modelling 211: 153-168.

Clark, W. C., and N. M. Dickson. 2003. Sustainability science: The emerging research program. Proceedings of the National Academy of Sciences 100: 8059-8061.

Costanza, R., and H. E. Daly. 1992. Natural capital and sustainable development. Conservation Biology 6: 37-46.

Daly, H. 1996. Beyond growth: The economics of sustainable development. Beacon Press, Boston.

Daly, H. E. et al. 2007. Are We Consuming Too Much—for What? Conservation Biology 21: 1359-1362.

Dassenakis, M. et al. 2003. The distribution of copper in Saronicos gulf after the operation of the wastewater treatment plant of Psitalia. Global NEST: The International Journal 5: 135-145.

E.C. 1991. Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC)

EC. 2000. Directive 2000/60/EC establishing a framework for the Community action in the field of water policy. . In: O. J. o. t. E. Communities (ed.). p 72.

Ekins, P., C. Folke, and R. De Groot. 2003a. Identifying critical natural capital. Ecological Economics 44: 159-163.

Ekins, P., S. Simon, L. Deutsch, C. Folke, and R. De Groot. 2003b. A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecological Economics 44: 165-185.

Ford, A. 1999. Modeling the Environment. An Introduction to System Dynamics Modeling of Environmental Sytems. Island Press, Washington, D.C.

Hannon, B., and M. Ruth. 1997. Modeling dynamic biological systems. Springer-Verlag, New York.

Kato, T. 2005. Simulation of water quality with the application of system dynamics model for population and land-use changes. Paddy and Water Environment 3: 103-109.

Lekkas, D. F., E. Manoli, and D. Assimacopoulos. 2008. Integrated urban water modelling using the aquacycle model. Global NEST: The International Journal 5 10: 310-319.

Mavromati, G., and K. Bithas. 2010. Ecologically sustainable economic development in aquatic ecosystems: from theory to environmental policy. Sustainable Development 10.1002/sd.504: n/a-n/a.

Mavrommati, G. 2011. Ecologically Sustainable Economic Development in Coastal Ecosystems: A Bio-economic Approach. Phd, Panteion University, Athens.

Mavrommati, G., and C. Richardson. 2012. Experts' Evaluation of Concepts of Ecologically Sustainable Development Applied to Coastal Ecosystems. Ocean & Coastal Management 10.1016/j.ocecoaman.2012.07.016.

Neumayer, E. 2010. Weak versus strong sustainability. Edward Elgar, Cheltenham, UK.

Orfanidis, S., P. Panayotidis, and N. Stamatis. 2003. An insight to the ecological evaluation index (EEI). Ecological Indicators 3: 27-33.

Orfanidis, S., Panayotidis, P., Stamatis, N. 2001. Ecological evaluation of transitional and coastal waters: A marine benthic macrophytes-based model. Mediterranean Marine Science 2: 45-65.

Panayotidis, P., B. Montesanto, and S. Orfanidis. 2004. Use of low-budget monitoring of macroalgae to implement the European Water Framework Directive. Journal of Applied Phycology 16: 49-59.

Rockstrom, J. et al. 2009. A safe operating space for humanity. Nature 461: 472-475.

Scoullos, M. J., A. Sakellari, K. Giannopoulou, V. Paraskevopoulou, and M. Dassenakis. 2007. Dissolved and particulate trace metal levels in the Saronikos Gulf, Greece, in 2004. The impact of the primary Wastewater Treatment Plant of Psittalia. . Desalination 210: 98-109.

Sterman, J. D. 2000. Business Dynamics. Systems Thinking and Modeling for a Complex World. Irwim McGrw-Hill, United States of America.

Steyaert, P., and G. Ollivier. 2007. The European Water Framework Directive: How Ecological Assumptions Frame Technical and Social Change. Ecology and Society 12: 16.

USEPA. 1972. Clean Water Act of 1972 (as amended) 33 U.S.C. §§ 1251 et seq.

WCED, W. C. o. E. a. D. 1987. Our Common Future. Oxford University Press, Oxford.

Zalachori, I., D. Koutsoyiannis, and A. Andreadakis. 2008. A Infiltration and inflow in sewer systems: Identification and quantification in Greece. Technica Chronica 28: 43-51.