Simulation Modelling in Quantifying Ecosystem Services and Sustainable Environmental Management

Khaiter, P. A.

SASIT, York University, Canada, E-Mail: **pkhaiter@yorku.ca**

Keywords: Ecosystem services; Sustainable management; Simulation modelling; Optimum control; Multi-objective optimization.

EXTENDED ABSTRACT

Sustainable management of environmental systems requires an adequate consideration of various ecological and socio-economic services provided by the ecosystems. It is well recognized that ecological systems generate a spectrum of diverse benefits that are vital to humankind. Valuing of these benefits is a crucial component of sustainable management.

The problem, however, is that many of the ecological and social amenities are not currently incorporated into the decision-making process. From the perspective of economic theory, they reveal themselves as positive externalities and as such have no direct market price. Another fundamental issue is getting at the quantitative characteristics of the ecosystem services. Traditionally, publications on this matter note that simulation models of the phenomena in question have to be used for this purpose. In fact, a whole family of simulation models is required. Such models should represent the main components of an ecosystem, their interrelationships and linkages to the system's environment at the appropriate time and space scales. They should also model physical, chemical and biological processes pertaining to the ecosystem studied. It has to be taken into account that any planned activity will substantially affect the ecosystem's components and their ability to generate goods and services. It is therefore necessary to understand qualitatively and to measure quantitatively the changes, sometimes irreversible ones, which may occur in the ecosystems and their services under various management interventions and compare expected benefits with possible losses. This knowledge should be incorporated into the process of decision-making.

This paper describes a modelling framework for the sustainable management of environmental systems (MFSM). As shown in Figure 1, the architecture of the MFSM is built on three main components: 1) simulation modelling block, 2) economic assessment block, and 3) management block. The modelling block includes models of natural dynamics (ND-models), anthropogenic dynamics (AD-models) of the environmental system being studied, and a module designed to estimate the quantitative characteristics of the ecosystem services (QS-models). The economic assessment block provides a valuation of ecosystem benefits (VS-module). The management block implements the tasks of optimal control (OC-module) and multi-objective optimization (MOO-module). The MFSM is a tool in support of sustainable environmental management.

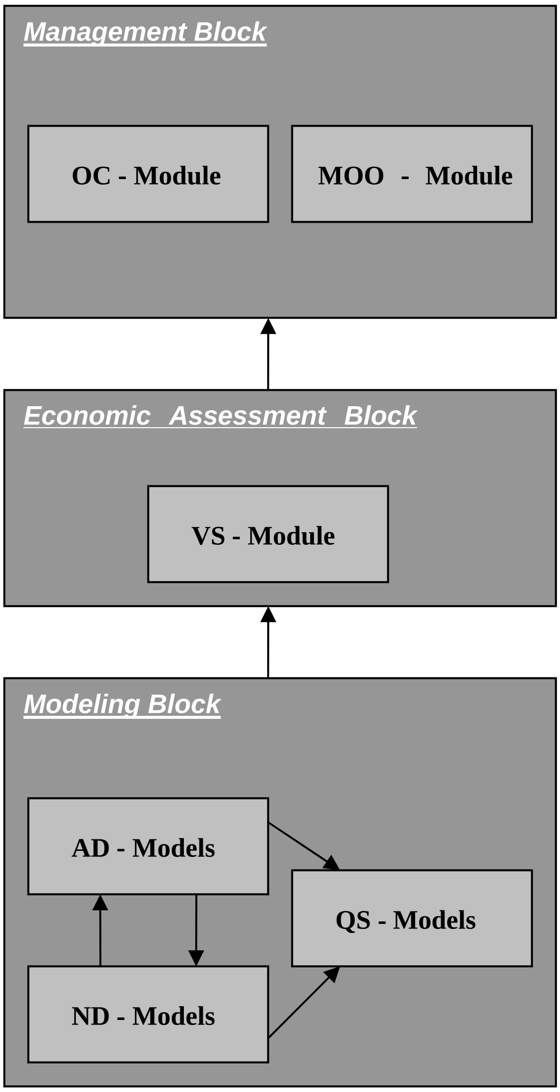

Figure 1. The architecture of the MFSM.

1. INTRODUCTION

In application to environmental issues, *sustainability* is understood as maintaining natural capital and resources (Goodland, 1995). A sustainable management, therefore, is the one that is in compliance with and is able to provide a sustainable type of societal development. The concept of sustainable development is at the centre of public attention since late 1980s. Various definitions have been proposed, most of which are variations of the theme. The report of the World Commission on Environment and Development *Our Common Future* (1987) defines sustainable management as “development that meets the needs of present generations without compromising the ability of future generations to meet their needs.” The breadth and vagueness of the definition, however, makes it of little use in practice. Barett and Odum (2000) have suggested that sustainable development may be dealt with in terms of the concept of the optimum carrying capacity in the same way as it is used in ecology to determine the upper limits for basic structures and functions of a given ecosystem that can be sustained by the available incoming energy over long periods in the face of environmental uncertainties. From the perspective of environmental economics, sustainable development can be considered as a certain harmonization of economic capital and natural capital.

It is reasonable to claim that under either approach, sustainable management of natural resources and environmental systems requires an adequate consideration of various ecological and socio-economic services provided by ecosystems. A practical implementation of an idea of sustainable environmental management is only possible if all the goods and services generated by an ecosystem are properly quantified, evaluated, and incorporated into the decision-making process at its early stages. Such an interpretation of sustainability requires a framework which incorporates simulation modelling, economic assessment, and methods of optimization within a single theoretical approach.

2. SUSTAINABLE MANAGEMENT: A MODELLING FRAMEWORK

This paper presents a modelling framework for the sustainable management of environmental systems (MFSM). As shown in Figure 1, the architecture of the MFSM is built on three main components: 1) simulation modelling block, 2) economic assessment block, and 3) management block. The modelling block includes models of natural dynamics (ND-models), anthropogenic dynamics (AD-models) of the environmental system being studied, and a module designed to estimate the quantitative characteristics of the ecosystem services (QS-models). The economic assessment block provides a valuation of ecosystem benefits (VS-module). The management block implements the tasks of optimal control (OC-module) and multi-objective optimization (MOO-module).

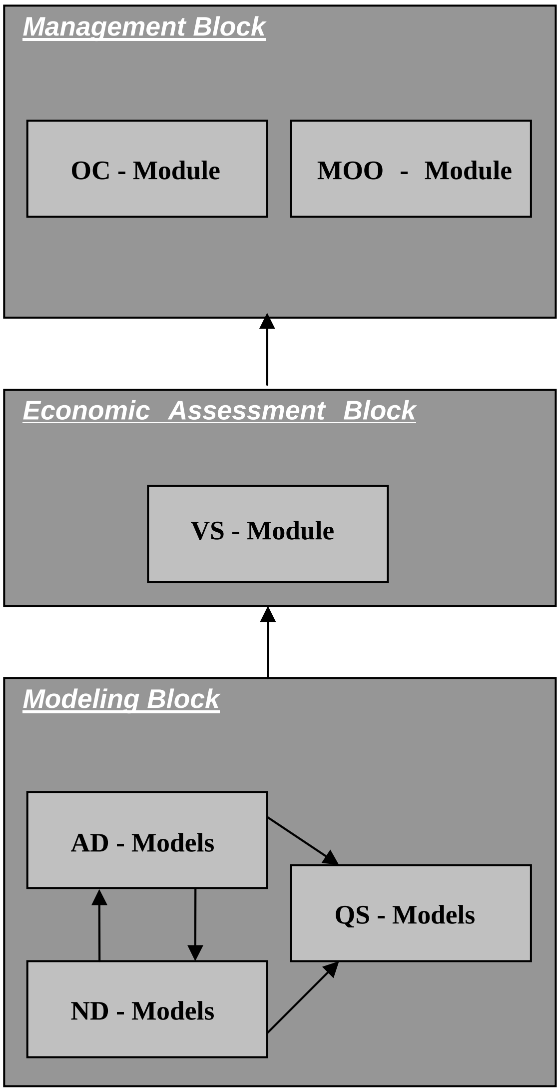

Figure 1. The architecture of the MFSM.

The MFSM is a tool consolidating methods of simulation modelling, environmental economics, and optimization within a common approach to sustainable management of natural resources. It allows the task of sustainable management of environmental systems to be formulated as an optimum control or multi-objective optimization problem using the system of simulation models as constraints. Subsequent sections of this paper describe components of the MFSM and demonstrate applications of the framework for the practical sustainability. Forest resources are used as a case study ecosystem.

3. THE CONCEPT OF AN FEES-SYSTEM

Forests fulfil a variety of diverse functions that positively influence many aspects of human life and the environment. They provide timber and firewood resources, overall ecosystem health and sustainability, protect water and air quality, support biodiversity and wildlife habitats, supply recreation and aesthetic enjoyment, etc. In order to accommodate the multifunctional role of a forest within a single theoretical approach, the concept of a *forest ecological-economic-social* (FEES) system has been proposed (Khaiter, 1991, 1996, 2005; Gorstko and Khaiter, 1991). According to this concept, the set of possible forest-related benefits can be classified into three main categories: (1) *ecological* amenities that combine protective and conservational influences on the environment; (2) *economic* amenities related to the generation of food, fodder, and industrial raw materials that are used or that can be potentially used by an economy; and (3) *social* amenities that include the creation of comfortable conditions for humans from sanitary, cultural, aesthetical, recreational, and environmental points-of-view.

The state of an FEES-system at a given moment in time, t, can be described by a phase vector $\mathbf{x}(t) = (x_1(t),\ldots, x_n(t))$. The coordinates of vector $\mathbf{x}$ represent quantitatively the components (sub-systems) of the FEES-system, such as timber stand (species, age, area, biomass), grass and shrub belt, forest food (mean harvest of fruits, berries, mushrooms, etc), litter, detritus and other edaphic factors, animal species, microorganisms, local topography, moisture stock, etc. The system is influenced by three sets of inputs: 1) stochastic disturbances, vector $\mathbf{d}$ (e.g., catastrophic events like forest fire, hurricane or flood)**,** 2) registered disturbances, vector $\mathbf{r}$ (e.g., meteorological conditions), and 3) controlled disturbances, vector $\mathbf{u}$ (e.g., management activities). In the general case, the coordinates of vector $\mathbf{x}$ will depend on the inputs $\mathbf{d}$, $\mathbf{r}$, and $\mathbf{u}$ and all other coordinates:

$$\dot{\mathbf{x}} = \mathbf{f}(t,\mathbf{x},\mathbf{d},\mathbf{r},\mathbf{u}). \tag{1}$$

The outputs of the FEES-system are the quantitative values of the three categories of benefits that were introduced in the preceding section. Vector $\mathbf{p}^\mathbf{E}$ will denote economic amenities, vector $\mathbf{p}^\mathbf{L}$ ecological amenities, and vector $\mathbf{p}^\mathbf{S}$ social amenities. Each of the vectors $\mathbf{p}^j$ (j = E, L, S) will be determined by the phase vector and the three system's inputs, i.e.

$$\dot{\mathbf{p}}^j = \mathbf{g}^j(t,\mathbf{x},\mathbf{d},\mathbf{r},\mathbf{u}), \quad j=\text{E, L, S}. \tag{2}$$

For practical applications, it is necessary to distinguish between the natural dynamics of the FEES-system and the anthropogenic dynamics (i.e., caused by human activities). Taking into account that vector $\mathbf{u}(t)$ represents management strategies, it is possible to conclude that by excluding $\mathbf{u}(t)$ from all equations in (1), the latter will describe the dynamics of the FEES-system under natural conditions. In such a case, the anthropogenic trajectories of the FEES-system can be found as:

$$\mathbf{x}^\mathrm{A} = \mathbf{h}(\mathbf{x}^\mathrm{N}, \mathbf{u}), \tag{3}$$

where $\mathbf{x}^\mathrm{N}$ **,** $\mathbf{x}^\mathrm{A}$ are values of the state vector $\mathbf{x}$ before (i.e., the natural, untouched state) and after an anthropogenic impact, respectively. Recent studies (e.g., Dale et al., 2000; McNulty and Aber, 2001) have suggested that climate change affects forest ecosystems and demonstrated a complicated interplay between natural dynamics, human influence, forest disturbances and climate change. The later phenomenon, therefore, should be reflected in general ecosystem models like (1). Climate variations reveal themselves through increasing/decreasing air temperature and precipitations (in which case they will be caught by vector $\mathbf{r}$) as well as in catastrophic events such as fire, drought, hurricanes, windstorms and ice storms (what will be represented by vector $\mathbf{d}$). This allows the separation of stresses induced by climate change from those caused by human interventions. In such a case, each h_k in vector-function $\mathbf{h}$ from (3) represents a transition of the FEES-system from the natural conditions to the anthropogenically impacted state caused by the corresponding management activity u_k, that is

$$h_k : \mathbf{x}^N \xrightarrow{u_k} \mathbf{x}^A, \quad u_k \in \mathbf{U}, \tag{4}$$

where $\mathbf{U}$ is the set of permissible management activities. Building the functions h_k is a substantial and non-trivial task which requires extensive observation data on the dynamics of the components in the FEES-system as it responds to each kind of management strategy. This is an area in which the application of genetic algorithms and heuristic procedures may be suitable. A sample study on building the functions h_k can be found in Khaiter (1991). Following the classical papers by Holling (1973) and Odum (1983), a typology of the ecosystem stress dynamics has been suggested (Khaiter, 2005).

Models $\mathbf{x}^\mathrm{N}$ form the module of ND-models in the framework while equations $\mathbf{x}^\mathrm{A}$ represent the module of AD-models.

4. QUANTIFYING ECOSYSTEM SERVICES

Measuring the benefits generated by an ecosystem is a non-trivial task. It should be noted that there is no analytic expression for the individual functions in the vector-functions **f**, $\mathbf{g}^j$, and **h** from (1) – (3). In most cases, the values on their right hand sides can only be found by building simulation models of the phenomena in question. As Costanza and Folke (1997) put it, “one way to get at these values would be to employ systems-simulation models that incorporate the major linkages in the system at the appropriate time and space scales.”

For example, the regulation of water flows (i.e., the hydrological role) is one of the most prominent ecological services supplied by a forest. In order to quantify it, it is necessary to compare the components of the water balance in an experimental watershed with and without forest cover. It is obvious that the availability of such “paired” watersheds is extremely limited since the watershed without timber stand could be obtained only after the trees in the forested watershed are cut down. Using two physically different watersheds would limit the comparability of the results due to the uniqueness of each watershed in terms of local topology, geology, and vegetation. Subsequently, the results registered in an experimental watershed are not always applicable to other watersheds, even if they are within the same geographical area and of approximately the same size.

To overcome these methodological difficulties, an approach has been proposed (Khaiter, 1993) that is based on a simulation modelling of the processes of moisture transformation in a forested watershed. A simulation model “Forest hydrology” (SMFH) takes as its inputs a limited set of parameters and initial values such as forest type and age, percent forested area, meteorological data, soil type and physical properties, and projected management activity. Based on this input information, the SMFH simulates the processes of forest hydrology, and it calculates crown interception, evaporation from snow and water, snowmelt, water release from snow, freezing and thawing of soil-grounds, infiltration, formation of all kinds of runoff, and transpiration. The model produces as outputs the values of the water balance components, and it provides a quantitative assessment of the hydrological role of the forest.

The SMFH represents the distribution of precipitation using the following water balance equation:

$$PR = EVC + EVF + EVS + Q_{SUR} + Q_{SUB} + TR + \Delta SM + Q_{GR} \qquad (5)$$

where PR is atmospheric precipitation; EVC, EVF, and EVS are evaporation from canopy, floor and soil, respectively; Q_{SUR}, Q_{SUB} are surface and subsurface runoffs, respectively; TR is transpiration; ΔSM is the variation of soil moisture content; and Q_{GR} is inflow to the groundwater table. The modelling of moisture transformation takes place at three levels (or *hydrological niches* as proposed by Voronkov, 1988): (1) tree crown, (2) forest floor, and (3) soil layer of a given thickness. The balance condition should obviously be satisfied for each of the hydrological niches:

$$\frac{dM^j}{dt} = \sum_i INC_i^j - \sum_k OUT_k^j \qquad (6)$$

where j denotes a hydrologic niche ($j = 1, 2, 3$); M^j is the moisture content in the jth hydrological niche; INC_i^j, OUT_k^j are the ith income and kth outcome water balance item, respectively, for the jth hydrological niche.

In order to quantitatively assess the hydrological value of a forest, it must be formally defined. Thus, according to Molchanov (1963), it could be expressed through the positive influence of forest vegetation on both the richness of streamflows and the soil moisture content. Given that traditionally in hydrology all items from the water balance are considered as positive (or useful) ones, except for losses to evapotranspiration and surface runoff, a formalization of the notion of the *hydrological function of a forest* and its estimation $\Delta QUSE$ was proposed (Khaiter, 1991, 1993) in the form of the following expression:

$$\Delta QUSE = \sum_{t=1}^{T} \Big\{ \big[\Delta SM^f(t) + Q_{SUB}^f(t) + Q_{GR}^f(t) \big] - \big[\Delta SM^o(t) + Q_{SUB}^o(t) + Q_{GR}^o(t) \big] \Big\} \qquad (7)$$

where the superscripts f and o denote forested and open (forestless) watersheds, respectively; t is the time variable; T is duration of a specified time interval.

The computer experiments with the SMFH have been carried out for a watershed in Northeastern Europe (Karelia, Russia). The modelled watershed represented a boreal forest with a 40-50 year-old spruce tree stand, sandy and sandy loam soils, and a plant density equal to 0.9. The computed estimate of the hydrological function in this simulation was 2720 cubic meters per hectare per year.

Similar simulation models are obviously needed to quantify all other ecosystem services and goods as specified in section 3. They form the module of QS-models in the framework.

5. VALUING THE ECOSYSTEM BENEFITS

Any decision related to natural resources or environmental systems will necessary involve valuation issues. This imperative is caused by the need to choose from a set of possible alternatives and to determine which of them is more preferable than others. This choice cannot be made reasonably without attributing some monetary value to a whole spectrum of ecosystem benefits. As Goulder and Kennedy (1997) state, it is always required "to indicate which alternative is deemed to be worth more."

The problem, however, is that many of the ecological and social amenities currently have no direct market price. From the perspective of economic theory, they reveal themselves as positive externalities. Nevertheless, valuation of these benefits is a crucial component of a sustainable management. The existing approaches to valuation of ecosystem benefits include the following techniques.

1. *Direct valuations* based on market prices can be applied to the ecosystem goods or services that have a direct consumptive use as food or raw material. This method is used to valuate the economic amenities of the FEES-system.

2. *Willingness to pay* is based on a utilitarian basis that is determined through the amount that people would be willing to pay or sacrifice in order to enjoy ecosystem services. This method is suitable for social and ecological amenities supplied by the FEES-system.

3. *Travel-cost* method is a kind of willingness to pay approach. It is used to ascertain some of the values provided by parks, lakes, and rivers. In this method, the overall travel cost is a sum of the transportation cost, the entry fee (if any), and the time cost expended to visit a particular site, and this is a measure of the marginal "willingness to pay" for the social amenities.

4. *Contingent valuation* method is another variation of the willingness to pay technique. It relies on surveys to determine how much value people place on non-consumptive uses. A random survey samples people's willingness to prevent ecological harm of a certain sort, or alternatively, their willingness to accept compensation for that injury to the natural ecosystem. This approach is most applicable for valuation of the ecological amenities provided by the FEES-system.

5. *Avoided cost* is evaluated through the cost or expenditures that society or businesses would have to pay if there is no ecosystem providing the services (e.g., pest control, flood control, soil fertilization, and water filtration). This approach could be used to value ecological amenities generated by the FEES-system.

6. *Replacement value* method is based on calculating the cost of replacing the ecosystem services by industrial, agricultural or other methods in the case that they are lost as a result of some human activity. Provided that the ecological system can be restored, this approach could be used for valuation of social and ecological amenities generated by the FEES-system.

The full value of an FEES-system has to include the monetary equivalents of all of the goods and services that it generates and supplies to society. An idea of an integral valuation of the ecosystems has been expressed in a number of publications since mid-1970. Most of them simply sum up the monetary values received for various market and non-market benefits. It is, however, important to take into consideration a competitive or even conflicting nature of the benefits. For example, using the social amenities of a forest park for recreation purposes will negatively affect and reduce its ecological services and make it practically impossible to utilize most of the economic goods. Therefore, at every moment of time and for each planned scenario of exploitation, $u_k(t)$, it is necessary to determine from all of the potential benefits $\mathbf{P}$ ($\mathbf{P} = \mathbf{p}^{\mathbf{E}} \cup \mathbf{p}^{\mathbf{L}} \cup \mathbf{p}^{\mathbf{S}}$) the subset of mutually compatible benefits, $\mathbf{P}^u \subset \mathbf{P}$. The only way to find $\mathbf{P}^u$ is to rely on expert knowledge on the behaviour of a particular ecosystem that is being converted into the formal heuristic rules. In all further considerations, it is assumed that the FEES-system benefits $p_i \in \mathbf{P}^u$.

Another important issue is the long time span required to grow a forest and its subsequent existence as a mature tree stand. Some forests may become commercially significant only after the age of eighty or older. This requires that any consideration of an FEES-system be conducted on a time scale of many decades or longer. An FEES-system is considered over an interval of T years from the moment of its planting.

For methodological reasons, an integral value of the FEES-system benefits, V_O, will be calculated as a sum of two items: the monetary equivalent of timber, V_T, and that of non-timber goods and services, V_W:

$$V_O = V_T + V_W. \tag{8}$$

V_T is the sum of the annual net present values of the timber biomass annual increment, $\Delta BI(t)$, and operating costs, $OC(t)$, over the specified period T:

$$V_T = \sum_{t=0}^{T} \left[c_B(t) \cdot \Delta BI(t) - OC(t) \right] \cdot DF(t), \tag{9}$$

where $c_B(t)$ is a market price of a biomass unit, $DF(t)$ is a discount factor. V_W is determined from:

$$V_W = \sum_{t=o}^{T} \sum_{p_i \in \mathbf{P}^u} cp_i(t) \cdot p_i(t) \cdot DF(t), \tag{10}$$

where cp_i is a monetary value of the i-th service or good generated by the FEES-system estimated by one of the above-mentioned methods. Computations of equations (8)-(10) form the VS-module in the framework.

In a practical application of the approach to the valuation of the ecosystem benefits, two alternative strategies of exploitation of a forestland have been considered: u_1 – harvest of timber annual increment (selective felling) and u_2 – recreation use. The annual values per one hectare include \$134 for ecological amenities (carbon and dust sequestration, oxygen generation, watershed functions, etc.), \$106 for timber, \$51 for minor forest products, and \$67 for social amenities (recreation). As a result, the integral value of an FEES-system under the strategy u_1 is estimated as $V_O(u_1)$ = \$291 while using the strategy u_2 gives $V_O(u_2)$ = \$358.

6. MANAGING AN FEES-SYSTEM

From the above, it follows that the integral value of the FEES-system benefits depends on a chosen strategy of exploitation, i.e., $V_O = V_O(u_k)$. It is realistic to assume that the strategy is not constant over the whole period (t_0, T) but it may be determined for shorter time intervals, e.g., every 5-10 years. This will split the whole period of consideration into n intervals (t_0, t_1), (t_1, t_2),…, (t_{n-1}, T). The choice of a management strategy, $u_k(t_j)$, occurs in the moments t_j, at the beginning of each interval (t_j, t_{j+1}) $(j = 0, .., T\text{-}1)$ and the integral monetary value $v_0(u_k)$ of the benefits is computed for each time interval separately as specified in (5)-(7). Then, the problem of sustainable management of an FEES-system can be viewed as the maximization of the overall integral value $V_O(u_k)$, i.e., finding the vector of optimal controls $\mathbf{u}^* = (u^*(t_0), u^*(t_1), \ldots, u^*(T - 1))$ from the condition

$$\mathbf{u}^* = Arg \max_{u_k \in \mathbf{U}} \sum_{j=0}^{T-1} v_0(u_k(t_j)) \tag{11}$$

The framework proposed also allows various practical problems of sustainable development to be solved. Thus, it is important to determine the optimum percentage of the forested area or, in other words, a reasonable in terms of "cost-benefit" fraction of a given watershed covered by forest vegetation. It is an obvious trade-off between the generation of ecosystem services on the one hand, and the necessity to produce timber and other raw materials on the other hand. This problem can be solved as a multi-objective optimization

It is possible to consider V_T and V_W from (8) as functions of percent forested area, $F\%$, i.e., $V_T = V_T\ (F\%)$ and $V_W = V_W\ (F\%)$. In such a case, an obvious goal is to maximize a monetary cost of forest services, V_W, and to minimize maintenance and protection-related expenses, V_T, i.e.,

$$\begin{aligned} &\max_{F\%} V_W(F\%) \\ &\min_{F\%} V_T(F\%) \end{aligned} \tag{12}$$

Using a Pareto-optimum approach, a compromise set (P) and the corresponding values of F% can be found. In the experiments, we used a step of simulation $\Delta F\%$ equal to 5%. Among the Pareto-optimal solutions (set P) we further determined a subset of efficient solutions R ($R \subset P$), where, for each point $V\ (V_T, V_W)$, an inequality is satisfied:

$$D(V_P) < D(V_R) \tag{13}$$

Here metric D is calculated from:

$$D(V) = \frac{V_W(F\% + \Delta F\%) - V_W(F\%)}{V_T(F\% + \Delta F\%) - V_T(F\%)} \tag{14}$$

As a result, the R-area was estimated: $R = \{V \mid 65\% < F\% < 80\%\}$.

Problems of optimum control of environmental objects using a system of simulation models as constraints in the form of (11) is implemented by the OC-module while specific problems of sustainable management in the form of multi-objective optimization similar to (12)-(14) constitute the MOO-module of the framework.

7. CONCLUSIONS

The multiple goods and services supplied by ecosystems must be taken into account as an immanent part of sustainable management of natural resources and environmental objects. In order to accommodate the full spectrum of diverse ecosystem benefits within a single theoretical approach, a modelling framework for the sustainable management of environmental systems (MFSM) is proposed in this paper. Such a framework has to adequately address the issues of simulation modelling of both natural and anthropogenic dynamics of the studied environmental objects; underlying physical, chemical, and biological processes; quantification, economic assessment and valuation of natural resources and the benefits they generate and supply to the society; and provide a tool to analyse various planned scenarios of development from which the most appropriate control strategy from the perspective of sustainability can be selected. The MFSM is a tool that consolidates knowledge from all of these areas as it builds a theoretical and practical basis for environmental sustainable management. It is also aimed at the support of decision-making at different levels of environmental management.

It is demonstrated in this paper that the task of sustainable development can be handled as a problem of optimum control or multi-objective optimization where simulation models are used as a set of constraints. Using forest resources as a case study ecosystem, the architecture of the MFSM is described and applications of the framework to the sustainable environmental management are shown.

8. ACKNOWLEDGMENTS

I am thankful to two anonymous reviewers for constructive suggestions and comments on the manuscript. Part of this work was supported by the Atkinson Faculty Council through the 2004-2005 Grant “Quantification and Valuation of Ecosystem Services”. Helpful comments were provided by Stephen Chen.

9. REFERENCES

Barett, G.W., and E.P. Odum (2000), The twenty-first century. The world at carrying capacity, *BioScience*, 50, 363-368.

Costanza, R., and C. Folke (1997), Valuing ecosystem services with efficiency, fairness, and sustainability as goals, *Nature’s Services: Societal Dependence on Natural Ecosystems (G.C. Daily – Ed.)*, Island Press, pp. 49-68, Washington DC.

Dale, V.H., L.A. Joyce, S. McNulty, and R.P. Neilson (2000), The interplay between climate change, forests, and disturbances, *Science of the Total Environment*, 262: 201-204.

Goodland, R. (1995), The concept of environmental sustainability, *Annual Review of Ecology and Systematics,* 26, 1-24.

Gorstko, A.B., and P.A Khaiter (1991), On the question of the economic assessment of forest resources. *Economics and Mathematical Methods,* 27(3): 522-526.

Goulder, L. H., and D. Kennedy (1997), Valuing ecosystem services: Philosophical bases and empirical methods. *Nature’s Services: Societal Dependence on Natural Ecosystems (G.C. Daily – Ed.)*, Island Press, pp. 23-47, Washington DC.

Holling, C.S. (1973), Resilience and stability of ecological systems, *Annual Review of Ecology and Systematics*, 4, 1-23.

Khaiter, P.A. (1991), *Modelling of the anthropogenic dynamics of forest biogeocenoses*, Znaniye, 24 pp., Kiev.

Khaiter, P.A. (1993), Mathematical modelling in the study of the hydrological regime in 'Forest-Watershed' system, Int. Conference on *Computational Methods in Water Resources,* Boulder, Colorado, 1993, pp. 789-794.

Khaiter, P.A. (1996), Optimal control on the basis of a simulation system for environmental applications, *Numerical methods in engineering simulation*, 3rd Int. Cong. on Numerical methods in engineering and applied sciences, Mérido, Venezuela, February 1996, pp. 297-302.

Khaiter, P.A. (2005), Valuing the ecological and socio-economic services in management of headwater ecosystems, *Hydrology, ecology and water resources in headwaters*, 6th Int. Conf. on headwater control, Bergen, Norway, June 2005, pp. 1-10.

McNulty, S.G., and J.D. Aber (2001), US national climate change assessment on forest ecosystems: an introduction, *BioScience*, 51, 720-722.

Molchanov, A.A. (1963), *The hydrological role of forests*, US Dept. Commerce, 487 pp., Washington, D.C.

Odum, E.P. (1983), *Basic ecology*, Saunders College Pub., 613 pp., Philadelphia.

Our Common Future / World Commission on Environment and Development (1987), Oxford University Press, 383 pp., Oxford.

Voronkov, N.A. (1988), *The role of forests in the conservation of water*, Gidrometeoizdat, 286 pp., Leningrad.