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Ecosystem Stability in Integrated Catchment Management

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Abstract: Freshwater is vital for human civilization. Growing population and societal development demand for more water resources. Freshwater is not considered globally scarce, but its distribution across the planet is not even and many countries suffer from water shortage. Human activities constantly produce an impact upon natural waters causing their destruction, degradation and pollution. Freshwater is a multi-purpose resource and this circumstance dictates a need to coordinate the interests of various water users. Integrated catchment management is a framework with the explicit objective to improve natural resources management on a catchment basis. Water resources are an integral part of ecosystems and their sustainable management is only possible within an ecosystem-based approach. It is important to predict ecosystem stability properties in response to exogenous stress. The paper discusses ecosystem stability from mathematical and ecological perspectives and demonstrates invariant patterns in ecosystem stress reactions. Using the typology of the stress reactions, the tasks of integrated catchment management can be viewed as a prediction of a particular type of ecosystem behaviour in response to the expected effects of planned activities.

Keywords: Global warming; Anthropogenic pollution; Freshwater resources; Natural ecosystem; Stability.

1. INTRODUCTION

Water resources play a vital role for human survival, health and development. While being not scarce globally, in many countries, resources of freshwater are limited and insufficient. Freshwaters account for only three per cent of the total planetary water reserve, of which 87 per cent are not accessible. More than two billion people are affected by water shortages in over 40 countries. It is predicted [WCU, 2000] that by the year 2025, water abstractions will increase by 50 per cent from 2,600 to 3,800 km^3/year in developing countries and by 18 per cent from 1,200 to 1,400 km^3/year in developed countries. Human activities negatively affect both water quantity and quality causing destruction, degradation and pollution of natural waters. A compounded stress of population growth, global warming and deforestation results in such extreme events as flooding and drought. For example, human and livestock wastes and airborne pollutants have caused eutrophication and acidification of many water bodies worldwide and contaminated them with pesticides, mercury, other toxic chemicals and pathogens that greatly increase the cost of water treatment and health costs from waterborne illnesses. Two million tones per day of human waste are deposited in water courses. 90 per cent of natural disasters in the 1990s were water related.

According to UNEP data [Water, 1995], 90 per cent of all the world's lakes are suffering from eutrophication as a result of anthropogenic pollution. Southern Scandinavia, north-eastern United States/eastern Canada, and eastern China are declared as areas where acidification of natural waters is a major issue. Projected rapid economic growth and related increase in atmospheric pollutants emission are likely to create future problem areas in Nigeria, India, Venezuela, southern Brazil and south-east Asia. As predicted by Schindler [2000], acute water problems in the United States, Middle East and other parts of the world will even threaten the security of water-rich countries like Canada.

Recently, these problems are being coupled with and amplified by the cumulative effects of global warming and, in a broader sense, of climatic change. Simulations by 8 different climate models (i.e., CCSR/NIES, CCCma, CSIRO, HADCM3, GFDL, MPI-M, NCAR PCM, NCAR CSM) demonstrated that, under different scenarios of greenhouse gas emission, the average global temperature from 1990 to 2100 is expected to rise between 2.2-4.7°C. The lowest predicted warming is 0.55°C south of South America and the highest is 9.2°C in the Arctic Ocean (Figure 1).

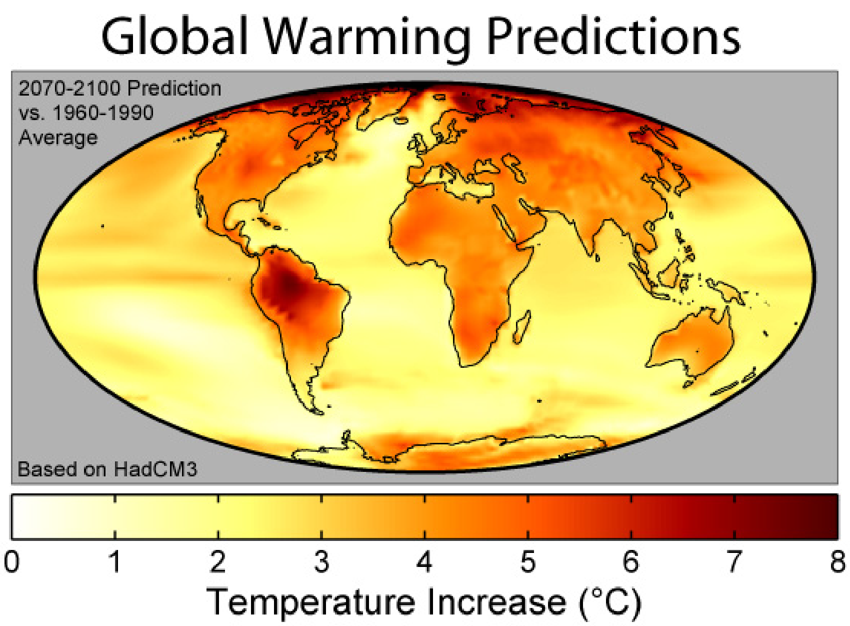

Figure 1. The predicted global warming over the 21st century according to the HADCM3 climate model [HCCPR, 1999].

A critical situation with water resources dictated a necessity to overcome a conventional top-down and sectoral approach that failed to produce desired results and often led to further environmental degradation [WCU, 2000]. Integrated catchment management is viewed as an alternative aimed at getting to sustainable water use.

2. INTEGRATED CATCHMENT MANAGEMENT

Objectively, there are different users of water resources: industry, agriculture, municipal water supply and sanitation, energy generation, recreation, forestry, fishery, shipping, *etc*. Natural waters also play an important environmental role in maintaining the functioning of terrestrial and aquatic ecosystems. A multi-purpose role of water resources and interdependency of their various users necessitate a coordinated approach to all water-related issues including decisions regarding water conservation, restoration, allocation, withdrawal, redistribution, monitoring and management. Such an approach should be able to take into account social, economic, and environmental goals and lead to the achieving of sustainable development.

Over the past two decades, the term *integrated catchment management* has evolved into an umbrella concept for a multi-objective approach to environmental problems with the explicit objective to improve natural resources management on a catchment basis. The interdependency of water cycle elements and processes of water use requires to consider a basic hydrological unit (i.e., a catchment) as a subject of management efforts.

Geographically, a catchment can be defined as an area of land and water drained by a watercourse and its tributaries to a single defined point. It can range in size from the slope of a hill side through to the runoff area of a major river system. For example, Canada has four major watersheds: Hudson Basin, Pacific, St. Lawrence, and the Arctic. Physically, a catchment is made up of soil, water, air and vegetation; it provides habitat and supports biodiversity. Together these components support life and make up an ecosystem in which a whole range of biophysical processes operates. Carbon based materials (the 'energy' materials), nutrients and water cycle within the catchment area. Each component is linked so that changes made to one will ultimately affect one or more others. Water resources are an integral part of ecosystems and their sustainable management is only possible within an ecosystem-based approach.

Integrated catchment management is a framework to coordinate development and management of water, land and related resources to enhance economic and social welfare without jeopardizing the sustainability of the ecosystems (Figure 2).

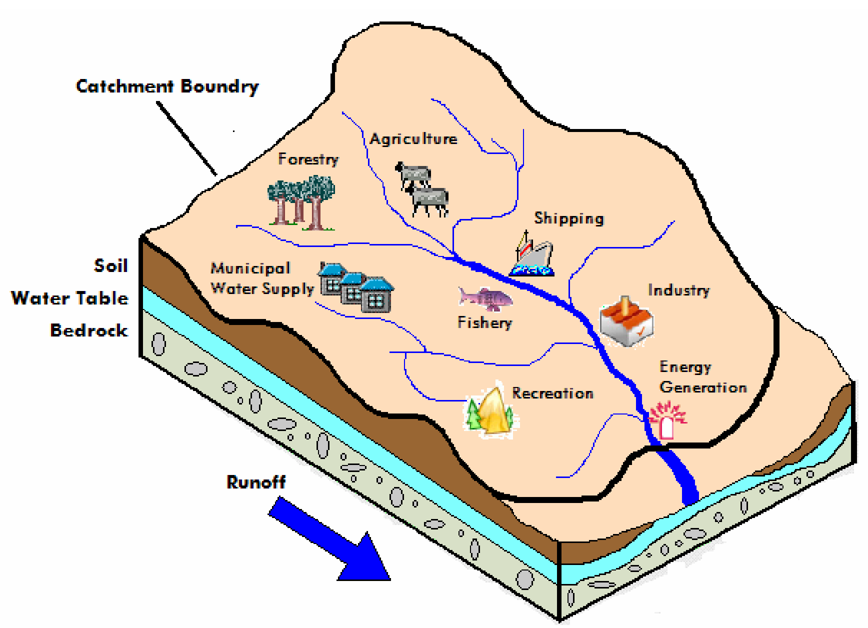

Figure 2. Integrated catchment management.

For practical implementation of the framework, it is important to understand the possible effects of human activities onto the ecosystems and predict ecosystem behaviour under the conditions of anthropogenic stress. The topic of ecosystem dynamics under exogenous disturbances has received considerable attention in the literature mostly within the studies on ecosystem stability.

3. ECOSYSTEM STABILITY CONCEPT

As Odenbaugh [2001] noted, stability has many different meanings and hence ecological theories are imprecise and inapplicable to environmental policy. Moreover, if stability has many different meanings, then theories that employ stability concepts will lead to different conservation strategies. Intuitively, ecosystem stability is understood as an ability to persist in the course of a sufficiently long time in spite of perturbations coming from the environment. Many researchers noted that, though intuitively clear, the notion of ecosystem stability can scarcely be defined in a formal and unambiguous way. A formalization of ecosystem stability is sought in a well-developed mathematical theory of stability, first of all, in a sense of Lyapunov stability.

3.1 Lyapunov Stability

In general case, an ecological system can be represented at any given moment in time t by a non-negative vector $\mathbf{x}(t) = (x_1(t),...,x_n(t))$ in an abstract *n*-dimensional state space E. The coordinates of vector $\mathbf{x}(t)$ designate quantitatively the components (or sub-systems) of the ecosystem and their properties, such as species numbers and composition, concentrations of organic and inorganic matters and polluting substances, biomass, primary production, dissolved oxygen, nutrients, *etc*.

Due to the complexity of real-world ecosystems, a direct prediction of the system trajectory $\mathbf{x}(t)$ is seldom possible. For this purpose, a mathematical model of an ecosystem is constructed and the question of ecosystem stability or instability, thus, becomes an exercise in mathematical (extreme) properties of a model solution $\overline{\mathbf{x}}(t)$, first of all, in a sense of Lyapunov stability.

Following a unified notation proposed by Ide *et al.* [1997], a model for the natural evolution of the system is governed by an equation:

$$M[t, \overline{\mathbf{x}}(t), \mathbf{p}] = 0 \tag{1}$$

with the initial conditions $\overline{\mathbf{x}}(0) = \overline{\mathbf{x}}_{\mathbf{0}}$. Here M is the model dynamics operator and $\mathbf{p}$ is the vector of model parameters. Depending on the aim of research, a particular ecosystem being modelled and observation data available, the operator M may be in a form of an algebraic expression, differential or integral operator. Often in ecological applications, M characterizes ecosystem dynamics in terms of ordinary differential equations and then formula (1) can be rewritten as:

$$\frac{d\overline{\mathbf{x}}}{dt} = \mathbf{F}(\overline{\mathbf{x}}(t), \mathbf{p}), \tag{2}$$

where vector-function $\mathbf{F}$ represents the magnitude and change of direction it induces on model trajectory $\overline{\mathbf{x}}(t)$. Points in E for which $\mathbf{F} = 0$ are called equilibrium points and the corresponding solution $\overline{\mathbf{x}}^*$ nullifying the right-hand side of (2) are equilibrium solutions. Lyapunov stability is a property of system behaviour in neighbourhoods of equilibria.

Definition. An equilibrium solution $\overline{\mathbf{x}}^*$ ($\overline{\mathbf{x}}^* \in E_x \subseteq E$) is said to be *Lyapunov stable* if

$$(\forall \varepsilon > 0)(\exists \delta > 0)(\left|\overline{\mathbf{x}}_0 - \overline{\mathbf{x}}^*\right| < \delta \Rightarrow (\forall t \geq t_0)(\left|\overline{\mathbf{x}}(t, \overline{\mathbf{x}}_{\mathbf{0}}) - \overline{\mathbf{x}}^*\right| < \varepsilon)), \tag{3}$$

where ε and δ are real values, $\overline{\mathbf{x}}(t, \overline{\mathbf{x}}_{\mathbf{0}})$ designates the solution corresponding to the initial state $\overline{\mathbf{x}}_{\mathbf{0}}$, and '$|\cdot|$' designates a Euclidian distance metric on E. If, in addition to (3),

$$\lim_{t \to \infty} \overline{\mathbf{x}}(t) = \overline{\mathbf{x}}^*, \tag{4}$$

it is said that $\overline{\mathbf{x}}^*$ is *asymptotically Lyapunov stable* in E_x. The subspace E_x of E within which the system is (asymptotically) Lyapunov stable is called the (*attraction*) *stability domain* of $\overline{\mathbf{x}}^*$. If the (attraction) stability domain is all of E, $\overline{\mathbf{x}}^*$ is said to be (asymptotically and) globally Lyapunov stable.

3.2 Ecological Stability

Lyapunov defined the concept of stability to describe equilibrium behaviour of the solar system. But his definition is used outside its original context, particularly, to analyse mathematical models of biological communities [Svirezhev and Logofet, 1978] or relationships between stability and complexity of such models [May, 1974].

Justus [2006] noted clear advantages of the definition of Lyapunov stability as it integrates ecological stability into a thoroughly studied mathematical theory and supplies analytical techniques to assess stability properties of community models. He, however, argued that ecological stability should not be defined as Lyapunov stability. Justus [2006] considered four types of Lyapunov stability: (1) local Lyapunov stability; (2) non-asymptotic stability within a non-local domain; (3) asymptotic stability within a non-local domain; and (4) global asymptotic stability and concluded that none of them captures perturbed behaviour of ecological systems because the latter are not completely analogous to physical systems for which Lyapunov's methods are so successfully applied.

It should also be taken into account that a mathematical model of biological communities does not represent an ecosystem as a single whole. From this perspective, a conclusion of an ecosystem stability or instability derived from an analysis of the extreme properties of a mathematical model is a mathematical artefact rather than a real characteristic of ecosystem behaviour and, thus, is a matter of mathematical convenience rather than ecological usefulness [Straškraba, 1995].

Therefore, it is much more important for integrated catchment management to predict the behaviour of the ecosystem state vector $\mathbf{x}(t)$ rather than trajectory of model's solution $\overline{\mathbf{x}}(t)$.

4. ECOSYSTEM STRESS DYNAMICS

Let $\mathbf{x}^A(t)$ be ecosystem state vector under stress conditions. If u denotes management activity that perturbate the ecosystem, its anthropogenic trajectories can be found as:

$$\mathbf{x}^A(t) = \mathbf{F}^A(\mathbf{x}(t), u) \tag{4}$$

It has been demonstrated [Khaiter and Erechtchoukova, 2007] that there are certain common patterns in the behaviour of ecosystems as they respond to anthropogenically caused perturbations and, following classical papers by Holling [1973] and Odum [1983], five scenarios in ecosystem behaviour can be determined.

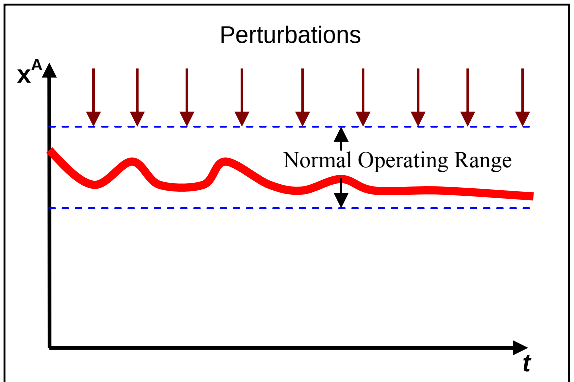

Figure 3. Resistance stability (RT-type of dynamics).

1. *Resistance* (RT-type). RT-type of dynamics occurs when the capacity of a system to sustain perturbations allows it – due to the built-in buffering mechanisms – to maintain its structure and functions within a certain "normal" operating range, and fluctuations of $\mathbf{x}^A(t)$ remain within a bounded domain at any time (Figure 3).

2. *Deformation* (DF-type). DF-type of dynamics represents the situation where external disturbances are applied to the system, which initially resists the perturbation demonstrating, thus, RT-type of dynamics. However, starting from some critical point in time, t_1, the system with DF-type of dynamics will leave its "normal" operating range (Figures 4*a*, *b*).

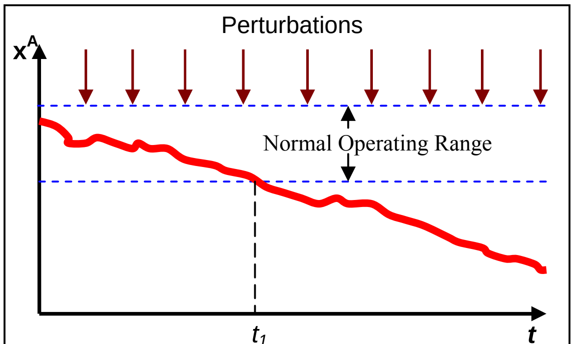

Figure 4*a*. Deformation (DF*a*-type of dynamics).

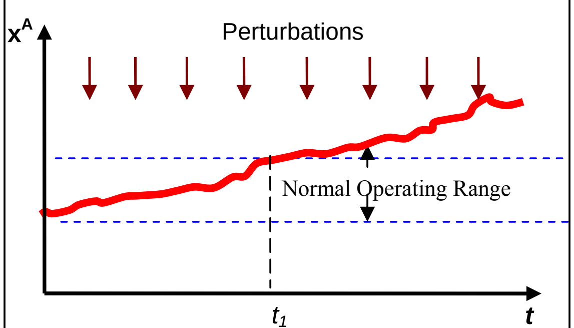

Figure 4*b*. Deformation (DF*b*-type of dynamics).

3. *Resilience* (restoration) RL-type. RL-type of dynamics represents the situation where external disturbances are applied to the system, which initially resists the perturbation exhibiting thus RT-type of dynamics. Starting from some point in time t_1 the

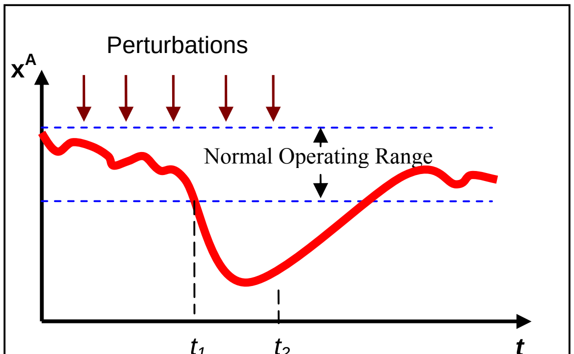

Figure 5. Resilience stability (RL-type of dynamics).

system leaves its normal operating range as in the case of DF-type of dynamics. However, in the subsequent time $t > t_2$, after the stress is terminated, the system is able to recover and return to its "normal" operating range (Figure 5).

4. *Degradation* (DR-type). DR-type of dynamics occurs under the conditions of the previous case (i.e., RL-type of dynamics), except the system stress-compensating capabilities are unable to cope with the stress, recover the damages and return the system to its "normal" operating range even after an external perturbation is discontinued, that is for $t > t_2$ (Figure 6).

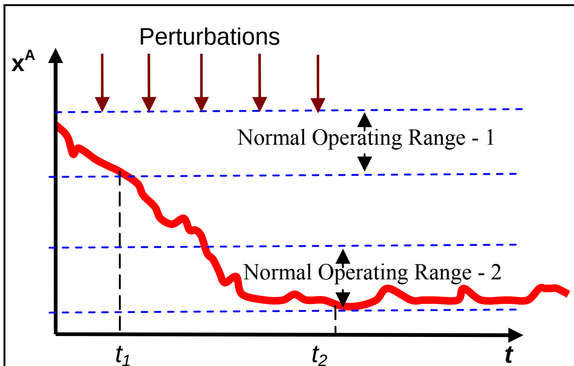

Figure 6. Degradation (DR-type of dynamics).

5. *Shift* (SS-type). SS-type of dynamics represents the situation where the magnitude and/or duration of the stress exceeds the ecosystem ability to sustain perturbations in terms of both RT- or RL-types of dynamics, eventually leading to the destruction of the initial ecosystem S1 and to its replacement by a new ecosystem S2. In most cases, a series of DR-type of changes will take place in the ecosystem S1 preceding the actual transformation S1 → S2 (Figure 7).

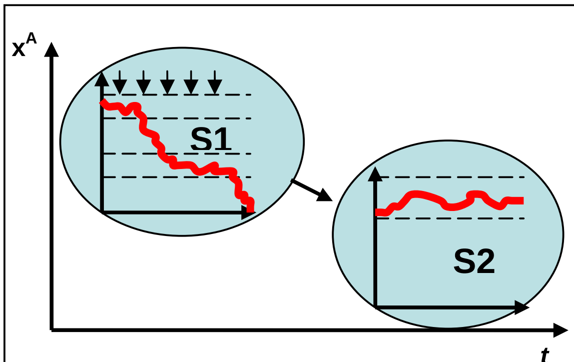

Figure 7. Shift (SS-type of dynamics).

5. CONCLUSIONS

Understanding the ecosystem dynamics and stability properties in response to exogenous perturbations is a crucial part of integrated catchment management. The patterns in the ecosystem behaviour allow for prediction of the under-the- and post-the-stress dynamics of ecological systems in study. They make also possible to assess the maximum allowable levels of anthropogenic impact the system would sustain without drastic, sometimes irreversible, alterations of its structure and functions as well as to judge on what will happen to the system if a critical level of stress is exceeded.

One of the main tasks of integrated catchment management is a restriction of anthropogenic impact onto the ecosystems so that their rehabilitation abilities were not exceeded, thus, preventing them from deterioration and destruction. A sustainable way of human development and maximum allowable level of anthropogenic load it produces should not, therefore, lead natural objects in question to either DR-type or SS-type of dynamics. In the practice of integrated catchment management, it is necessary to determine the threshold values of disturbances that trigger an ecosystem to DR- or SS-types of dynamics and select strategies generating lesser harm to the ecosystem.

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