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A Spaital Model For Analysing Impact of Land Use Catchment Policies in Water Resources:
a case of study in South of Brazil

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Abstract

Although several models exist, the availability of information to run such models is usually very limited and few of those available are easy to use, can operate over a variety of conditions, and integrate the wide range of information that planners and managers need. In this context, the development of a regional modelling framework for assessment the impact of management activities on catchments is extremely challenging because of the expansive and heterogeneous land areas on which the activities occurs. The models must represent the resource diversity and the continuum of production practices that may be employed under alternative resource settings. In addition to a strong physical component, modelling framework must also include a component which simulates the decision making of water users procedures. This paper presents a spatial model that is capable of estimating the effects of scenarios on water resources. Several authors have noted the critical need for knowledge about why landscape changes occur and how environmental factors interact. Rivers and streams, for example, frequently are used as jurisdicional boundaries, bisecting catchments. Consequently, the units for which land management and planning are undertaken frequently little attention is given to the water resources and environmental system inside then and their connections and/or to their links to economic and social processes. In the light of the new Water Resources Policy in Brazil (since 1997), this paper attempts to make greater and more consistent use of economic instruments to water allocation as a complement or a substitute to other policy instruments such as regulations, taking into account physical-socio-economic conditions. With the use of this framework it is expected improvement in the allocation of water resources and efficient use of natural and environmental resources by means of economic instruments so as to better reflect the physical-social-economic costs of the use of these resources. To do that a better modelling and forecasting techniques was developed through the integration of remote sensing, geographical information systems and mathematical modelling to provide information on environmental consequences of alternative policies actions and their economic effects. The system was designed to be consistent with the availability of data in less developed countries and one of its major advantages is that the parameters involved are easily defined in terms of physical characteristics alone. The modelling capabilities of the system are tested on the Ibicuí catchment (38.000 km^2) in southern Brazil in the border between Uruguay and Argentina. The overall model is run in a recursive manner, with model coefficients updated to reflect the environmental dynamics occurring in previous time period. Based upon land characteristics (natural and human) comprising each hydrologic cell, estimates of total annual (or monthly) water withdrawals are made for each cell. These data are then employed to the water taxes system inducing users to choose efficient, cost-minimising, pattern of abatement in response to the water price. Analysis of the case study results indicate that the system is capable of generating reasonable trends in flow which reflect the impact of management activities. This paper also demonstrates how policies might be altered to accommodate instream flow protection within the context of water marketing, with the objective of improving the efficiency of water allocation among instream and consumptive uses.

Keywords

Water Resources, Geographic Information Systems (GIS), Integrated water management, Environmental Economics, Sustainable land use planning Ecological modeling.

Introduction

Even more than in developed countries, environmental quality programs and objectives in developing countries have only a secondary status in comparison with national and regional economics development and, in some cases, the obejective of meeting basic human needs. Following the post war time, the first thrust of developing nations was toward economic development in the classic Western form of industrialization, urbanization, agricultural development for export markets, and provision of major infrastrucuture. In this they followed the leadership of developed countries, multilateral aid agencies, and the United Nations. This approach revelead serious limitation, especially in dealing with endemic poverty. Until now, despite big efforts, most developing countries had placed little or no emphasis on the problems of natural resource deterioration and degradation of air, water and land quality. Although some advances have been made in the priority given to environmental quality problems, in places such Brazil the greatest weight is still placed on objectives for economic development and promotion of exports. In such a context, it is especially important that environmental quality and natural systems analysis and valuation stress the positive role they can play in long range sustainable economic development and natural resources management.

Problem statement

Over the past decades, water resources have been altered by human activities. Quality and quantity have usually deteriorated gradually over time until degradation has become apparent and measurable. Taking water pollution as an example, awareness has therefore often taken considerable time, and application of the necessary control measures has taken even longer [1]. The appearance of pre-industrial and industrial (types of) water pollution, which occurred over 100 years ago or more in Europe, has occurred within one generation in developing countries with fast growing populations such as Brazil, China, India, Indonesia, Mexico and Nigeria, where pollution sources and demands upon water resources are expanding. Only 10 out of the 60 countries in this category have established effective laws, regulations, and an enforcement infrastructure to cope with pollution problems [1]. In Brazil, which is a huge country (8,547,403 km^2) with diverse regions, abundant natural resources, large-scale industry, and strong links with the global economy, there is an increasing growth of urbanisation. In 1990 twelve metropolitan areas had a population of more than one million; moreover, both Rio de Janeiro and São Paulo are now megacities with populations of more than ten million. Brazil, having one of the largest percentage of world river flow needs to enable monitoring and prediction of the potential impacts of human activities on the environment. Accurate and timely information about the quantity and quality of its water resources is needed, so that it can make scientifically-based decisions and policies at all governmental levels. During the past two decades Federal, State, and Local governments have made significant commitments to the protection and enhancement of water resources (in 1997 the National Water Resources Policy was approved by the Federal Goverment). In spite of these investments, information is not available to answer some rather fundamental questions to the satisfaction of the scientific, regulatory, and management communities, and the public. River systems are a major source of water for agricultural and urban water needs. Water resources assessments of river systems are becoming critical throughout Brazil and there is a concern about the sustainable supply of quality water and the health of the water bodies. River systems should be continuously monitored to assess the effects of different land management practices on water resources, but, few of any river system are continuously monitored at present due to high costs. Therefore, there is a need for an alternative tool such as a basin-scale hydrologic/water quality model that is capable of predicting the effects of land management. Also, nationally consistent and comparable information is needed to make valid regional and national statements about current water-resources conditions and changes in these conditions. Existing programs designed to report on the status of Brazil's water resources have not always proved meaningful. In many instances, there are consist problems because field and laboratory procedures and methods are not uniform and comparable among Federal, State, and Local agencies and often change through time; sites are selected to investigate a specific water-resource problem that is not representative of the surrounding area; long-term monitoring is lacking and trends are difficult to detect; data are lacking on potentially toxic constituents such as trace elements, pesticides, and other organic constituents of concern; most studies have not been of an interdisciplinary nature involving comprehensive use of physical, chemical, and biological data, nor have these studies been integrated to assess the interaction of the various resources on observed or predicted water quality conditions. Because of the wide range of different government and economic conditions around the world, it is difficult to provide general guidelines regarding the role of government in environmental protection that cover all possible situations. In spite of efforts by Brazilian government, at many levels, to control the causes of environmental problems, water resources have continued to deteriorate in many streams, lakes, reservoirs and coastal areas in Brazil, produced by a great diversity of demand, pollution types, climatic factors, river flow and pollutant transport capacity. Thus, solutions to such problems in industrialised countries are often not directly applicable to developing countries. Many different surface and subsurface hydrological process may contribute to streamflow generation and quality in catchments, and the relative importance of the processes may vary in space and time. Knowledge of the relative importance of the different processes is central to the understanding of many of the features of the catchment. This paper aims to develop a model, appropriate for Brazilian conditions, capable of predicting water resources policies at the basin scale. The key to this approach is the development of information on physical, chemical, and biological conditions, and responses of individual catchments to both natural and human-induced changes. It is important that catchment information be comprehensive, it should have a full description of the hydrologic cycle including the interaction of the quantity and quality of ground water, surface water, and atmospheric inputs. In most catchments in Brazil, comprehensive and integrated information of this type is lacking. Where information is available, it has seldom been compiled or analysed with the objective of understanding the interaction of all components of the hydrologic system and using this information to support the development, implementation, and evaluation of water-resource management actions.

Influence of landscape strucuture on environmental resources

Several authors have noted the critical need for knowledge about why landscape changes occur and how environmental factors interact (e.g., [2], [3]). Rivers and streams, for example, frequently are used as jurisdicional boundaries, bisecting catchments. In this context, the units for which land management and planning are undertaken frequently little attention is given to the water resources and environmental system inside then and their connections and/or to their links to economic and social processes. In the light of the new Water Resources Policy in Brazil (since 1997), this paper attempts to make greater and more consistent use of economic instruments to water allocation as a complement or a substitute to other policy instruments such as regulations, taking into account physical-socio-economic conditions. With the use of this framework it is expected improvement in the allocation of water resources and efficient use of natural and environmental resources by means of economic instruments so as to better reflect the physical-social-economic costs of the use of these resources. To do that a better modelling and forecasting techniques was developed through the integration of remote sensing, geographical information systems and mathematical modelling to provide information on environmental consequences of alternative policies actions and their economic effects. It was found [4] in some regions of the world that the likelihood of forest cover being disturbed was a function of (a) the type of owner; (b) environmental attributes such as slope, aspect, and elevation, and (c) locational variables, such as distance to roads or market centers, which are related to the economics of forest harvest and residential development. In Rondonia, Brazil, [5] it was demonstrated that the land use and land cover changes were a function of individual parcel sizes and shapes, attributes of individual land owners, site characteristics such as soils and agricultural suitability, and the distances to the road network. Analysis of human responses to landscape structure is complicated both by the role humans play in structuring their environments to suit their needs and by the fact that their habitant requirements are defined by their culture [6]. Moreover, humans are capable to satisfy their material needs by exchanging goods and services on a global scale rather than just locally. In this context, the challenge for environmental managers is to find how the goods and services needed by society can be produced while also maintaining the landscape structure that will ensure perpetuation of essential environmental process ([7] and [8]). For example, individual small and localized land use decisions occurring over several years appear insignificant at the landscape level. However, consideration of the environmental impact caused by these aggregated decisions could prevent landscape structure from crossing a threshold that would cause permanent and undesirable change.

Methodology to achieve socio-economic and environmental sustainability

The present state of the catchment (our piece of landscape) is a function of previous land use decisions. Also the social-economic factors impinging on land use decisions are, in part, a function of the existing state of the land use. These feedback loops are used to explain landscape sustainability based on the quantity and quality of river flow (the main indicator in this approach) through economic instruments. The methodology used is mentioned below. Hornberger et al., (1985) [9] trying to define the modelling processes using available field data found that *'hydrological quantities measured in the field tend to be either integral variables* (that is, river discharge, which reflects an integrated catchment response) *or point estimates of variables* (such as precipitation, soil hydraulic conductivity, etc.)'. It was further noted that success in hydrologic modelling '*has proved elusive because of the complexity of the processes, the difficulty of performing controlled experiments, and the spatial and temporal variability of catchment characteristics.*' They conclude that *'even the most physically based models cannot reflect the true complexity and heterogeneity of the processes occurring in the field'*. This paper presents a spatial model that is capable of estimating the effects of scenarios on water resources, based on the assumption that river discharge reflects an integrated catchment response in terms of quantity and quality as indicated in figures 1 and 2. The system is designed to be consistent with the availability of data in less developed countries and one of its major advantages is that the parameters involved are easily defined in terms of physical characteristics alone. The methodology presented has been designed to support the determination of water resources changes resulting from decisions in a large river basin with diverse land uses, taking into account both the intensity and spatial distribution of the water resources. This methodology is capable of implementation on land surfaces having heterogeneous water resources effects. This system is based on a cellular configuration where physical and climate information is manipulated using models and geographical information systems (GIS). Using this cellular structure, runoff from the individual cell (figure 3) is routed through the catchment using a physically-based model. The modelling capabilities of the system are tested on the Ibicuí catchment (38.000 km^2) in southern Brazil in the border with Uruguay and Argentina. Analysis of the case study results indicate that the system is capable of generating reasonable trends in flow which reflect the impact of management activities. This paper also demonstrates how policies might be altered to accommodate instream flow protection within the context of water marketing, with the objective of improving the efficiency of water allocation among instream and consumptive uses.

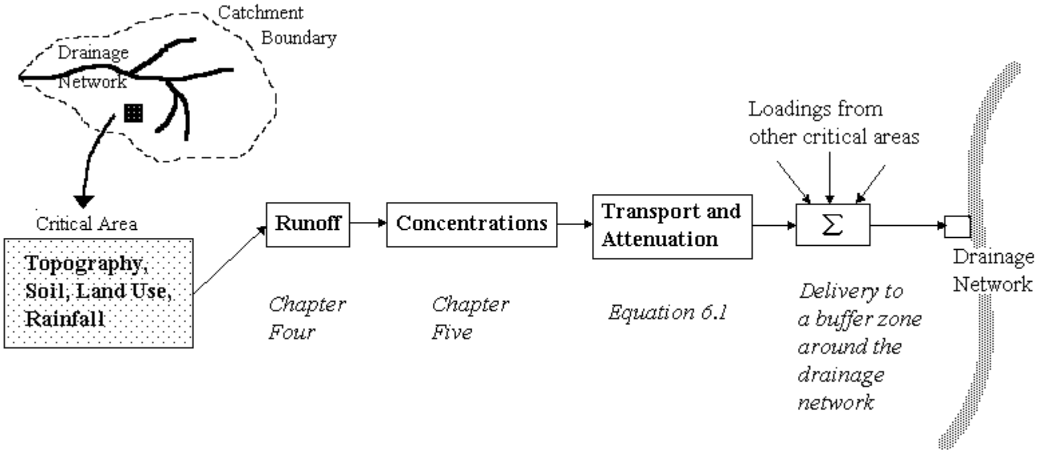

Figure 1 - Loading functions for estimation mass transportation (water, sediments and pollutant) entering a drainage network.

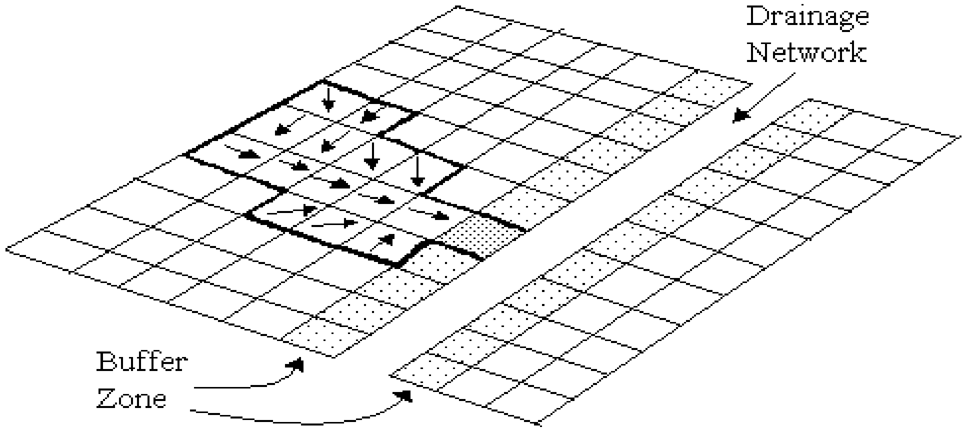

Figure 2 : Buffer zones around drainage network.

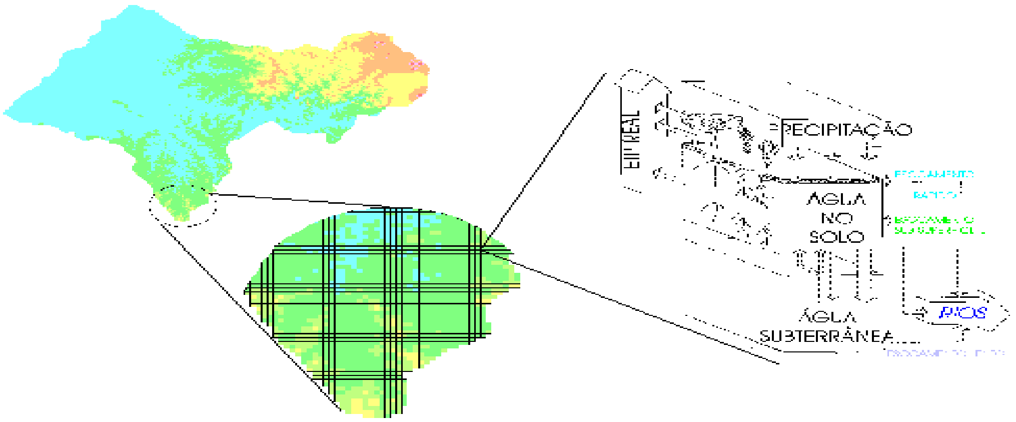

Figure 3 : Hydrological modelling approach integrated to GIS framework.

Application of the model

The regional water resources policy modelling consists of four components: (a) a regional hydrologic mathematical model, (b) a regional groundwater model, (c) a combined crop simulation/quantity of irrigation demand model and (d) land-use change model. The relationship between agricultural practices, weather events and physical characteristics of the catchment is capable of simulating simultaneously the effects of different agricultural management practices associated with runoff, sediment, and percolation. Estimates of the quantity of irrigation water pumped monthly are predicted. This general approach integrates the water permit to four principal sets of activities: (a) production activities, (b) irrigation volumes, (c) environmental preservation (wetlands, groundwater recharge zones) and (d) land-use conservation. The user that requires some volume of water will pay "more" or "less" taxes according to their environmental behaviour and position in the landscape sensitivity. These ideas are very similar to the studies of "pay-per-bag" for domestic refuse collection. The form of the charge is related to the amount of refused collected in a relatively rough-and-ready way, rather then through precise measurement. Thus, many unit-based pricing programmes require households to pay for the number of bags or bins of refuse collected; the relationship to waste volumes or weight arises either because they require households to use containers of a standard size or format, or because limits are placed on the amount of waste which each may contain [10]. The charge may be levied through billing for a chosen number of bags or bins per week, through the sale of bags, or through the sale of stickers which households are required to place on each bag of waste put out for the collection. A more restricted variant on this arrangement is when households continue to face a fixed monthly fee or pay for solid waste disposal through their annual property tax but face a surcharge on "excess" quantities. Under this approach, households face a marginal cost of zero for waste up until the trigger volume for the surcharge is reached [11]. Very similar to the "pay-per-bag" approach is the water resources policy where the volumes and quality within drainage network are related to the human behaviour on the landscape. Based on this conception the water allocation permits and taxes are linked to the best land-use management practices associated with environmental sustainability. It is proposed that the water allocation taxes contemplates the optimisation of water resources quantity and quality ensuring environmental local conditions that in aggregated manner prevent landscape structure as a whole, from crossing a threshold that would cause permanent and undesirable change. The formulation is presented as follow:

Water allocation taxes (US\$/month) = Volume (m^3/month) x Unit costs (US\$/m^3)

The unit cost per volume (m^3) is associated with water resources use. For example, the value to be paid by the irrigation users are different to the human supply. Thus, this value will increase or decrease according to the various criteria presented below.

Unit costs (US\$/m^3) for irrigation = BC x [(CRU/ACC) x (1-R) x Tec

Where: BC - Basic cost (US\$/m^3), defined by the catchment committee independently of the water use; CRU - Consuption Requested by the User; ACC - Average Catchment Consumption; R - Rating of the water production (capacity of the environment suply water in a sustainable condition). Tec - Level of technology applied to the agricultural system.

Unit costs (US\$/m^3) for human suply = BC x 0.9 x LI

Where: BC - Basic cost (US\$/m^3), defined by the catchment committee independently of the water use; LI - Losses index for the distribution water systems.

Unit costs (US\$/m^3) for industry = BC x 1.1

Where: BC - Basic cost (US\$/m^3), defined by the catchment committee independently of the water use.

Unit costs (US$/m^3) for animals = BC

Where: BC - Basic cost (US$/m^3), defined by the catchment committee independently of the water use.

Summary and conclusions

Development of a regional modelling framework for assessment the impact of management activities on catchments is extremely challenging because of the expansive and heterogeneous land areas on which the activities occurs. The models must represent the resource diversity and the continuum of production practices that may be employed under alternative resource settings. In addition to a strong physical component, modelling framework must also include a component which simulates the decision making of water users procedures. The overall model is run in a recursive manner, with model coefficients updated to reflect the environmental dynamics occurring in previous time period. Based upon land characteristics (natural and human) comprising each hydrologic cell, estimates of total annual water withdrawals are made for each cell. These data are then employed to the water taxes system inducing users to choose efficient, cost-minimising, pattern of abatement in response to the water price. For example, the water tax, that is imposed on each region of the catchment, will mean that users with low agricultural technologic level (it means higher demand of water, pollution sediments, etc) will be more likely to choose to abate, and to make larger improvements in farm land, than pay a higher water tax. Despite the connection with water resources, many of the principles for evaluation set out in this paper would also be applicable to wider evaluations of environmental policies. In this context, it would be desirable to look much more closely and systematically than has been the practice up to now of regulatory policies. How far do such policies achieve the objectives they pursue, both in terms of environmental impact, and in terms of economic side-effects and administrative and compliance costs ? In this paper we tried to link the environmental performance in practice of economic instruments.

Bibliographical References

[1] Helmer, R., "Socio-economic development levels and adequate regulatory policy for water quality management" , Water Science Technology, vol. 19:257-272, 1987.

[2] Turner, M.G., editor, Landscape heterogeneity and disturbance., Springer-Verlag, New York, 1987.

[3] Baker, W.L., "A review of models of landscape change", Landscape Ecology, vol. 2:111-133, 1989.

[4] Wear, D.N., and Flamm, R.O., "Public and private disturbance regimes in the Southern Appalachians", Natural Resources Modeling, vol. 7:379-397, 1993.

[5] Dale, V.H.; O'Neill, R.V.; Pedlowski, M.; and Southworth, F., "Cause and effects of land-use change in central Rondonia, Brazil.", Photogrammetric Engineering and Remote Sensing, vol. 59:997-1005, 1993.

[6] Berger, P.; and Luckmann, T. ; The social construction of reality, Doubleday, New York, 1966.

[7] Franklin, J.F., and Forman, R.T.T., "Creating landscape patterns by forest cutting: ecological consequences and principles"., Landscape Ecology, vol. 1:5-18. 1987.

[8] Lee, R.G., "Institutional stability: a requisite for sustainable forestry". In 1990-1991 Starker Lectures. College of forestry, Oregon State University, Oregon, 1991.

[9] Hornberger, G.H.; Beven, K.J.; Cosby, B.J., and Sappington, D.E., "Shenandoah watershed study: calibration of a topography-based, variable contributing area hydrological model to a small forested catchment", Water Resources Research, vol. 21:1841-1850, 1985.

[10] Fullerton, D. and Kinnaman, T.C. "Household demand for garbage and recycling collection with the start of a price per bag", National Bureau of Economic Research - NBER Working paper No. 4670. Cambridge, Mass. 1994.

[11] Anderson, R.C.; Hofmann, L.A.; and Rusin, M., "The use of economic incentive mechanisms in environmental management", American Petroleum Institute - API Research Paper No. 051, Washington, 1990.

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