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From conceptual model to simulation:
A participatory process for development of a GIS-based decision support system for environmental management

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Abstract

The Cooum River is an extremely polluted urban stream that flows through the heart of Chennai, India's fourth largest metropolis, into the Bay of Bengal. During the dry (non-monsoon) season, the upper reaches of the river are dry and flow in the river through the city may be attributed primarily to the production of sewage by the population. The river is essentially a foul-smelling open sewer.

The Cooum River Environmental Management Research Program is an on-going program of research in support of rehabilitation and management of the Cooum River and its surrounding area. The research program has drawn upon methods and techniques of Adaptive Environmental Management and Soft Systems Methodology to address the problem. In particular, this has involved a series of workshops which have brought together stakeholders in a participatory process oriented toward problem definition, system identification, determination of goals and objectives for rehabilitation and management of the system, the development of a conceptual model of the system, and generation of management alternatives. A central component of the program has been the development of the Cooum DSS -- a loosely-coupled GIS, environmental simulation model, and a decision support module based upon a framework provided by participants in the first workshop in the series.

This paper addresses the development of the Cooum DSS, and focusses particularly on the link between the conceptual understanding of the Cooum system, and (1) representation of the system in the GIS database and (2) the operationalization of critical processes of the system logically and algebraically, such that the representation of the system in the GIS/DSS modules can be used to parametize a water quality simulation model. In was found that the *process* of developing a conceptual model, and attempting to represent this in the Cooum DSS has made the a significant

contribution to understanding the Cooum system and provided a much needed forum for open debate and exchange of information, in addition to developing a potentially useful tool for planners, managers and researchers in Chennai.

Keywords
Urban environmental management, decision support system, geographic information system, adaptive management, soft systems methodology, participation, conceptual model, simulation.

Introduction

The Cooum River is one of several rivers in the Madras Basin in Southern India. It flows to the Coromandel Coast and into the Bay of Bengal from west to east through centre of the Chennai (formerly Madras) Metropolitan Area. Chennai, with a population of 3.9 million within the city limits and a metropolitan area population of 5.4 million persons in 1991, is the fourth largest city and third largest port in India. It is the dominant urban centre in the south of the country.

The Cooum River has been described as a "languid stream" which is almost stagnant and which carries little water except during the monsoon. It has also been noted that the Cooum "receives a sizeable quantity of sewage from its neighbourhood for disposal" (Government of Tamil Nadu, 1981). All along the river's course industries, institutions and households dispose of their waste. Although parts of the city are serviced by primary and secondary sewerage treatment, much raw sewage is diverted into the waterways and ocean (Srinivasan, 1991). The quality of water in the Cooum River is best demonstrated by values of the 5-day biochemical oxygen demand (BOD_5) which indicates the amount of organic content in the water by the amount of oxygen consumed by aerobic bacteria in decomposing it. These values have been reported as high as 315 mg^{-l} in the Cooum River (Gunaselvan, 1999). Compare this to the expected BOD_5 value of raw sewage in Chennai of 250 mg^{-l} (Ananthapadmanabhan, 1998).

Many government agencies have attempted to improve the situation. The list includes agencies such as the Tamil Nadu Public Works Department, the Chennai Metropolitan Development Authority, the Corporation of Chennai, the Chennai Metropolitan Water Supply and Sewerage Board, the Tamil Nadu Slum Clearance Board and others. However, over the decades, the problem continues to worsen. This is partly because previous attempts to address the problem have been piecemeal, using a reductionist engineering-oriented approach, and constrained by jurisdictional boundaries.

The situation of the Cooum River and surrounding area is an environmental problem situation characterized by both complexity and a high level of uncertainty. Complexity in the situation is due as much to population growth, poverty, uncontrolled urban development, jurisdictional conflicts, modes of behaviour of the citizenry, and institutional culture, as it is to physical and hydraulic characteristics of the system such as flat topography, monsoon flooding, tidal action, formation of sand bars and blockage of the river mouth. Uncertainty in the situation is both structural (What are the main processes occurring in the system? What is the nature of the primary relationships among the various actors and elements?), and parametric (scarcity of, restricted access to, and poor quality of data). Thus, the situation requires an approach which can deal with complexity and uncertainty.

This paper reports part of a process which (1) approaches the Cooum problem situation in a more holistic manner than previous attempts, and (2) is rooted in systems thinking. The research on which it is based employs an ecosystem approach operated by tools and techniques borrowed from adaptive environmental management and Soft Systems Methodology. In particular, this paper discusses the development, within this approach, of a decision support system based on a loosely-coupled GIS and environmental model. The process of developing the DSS, and the GIS database it employs, has made an important contribution to the understanding of the problem. The DSS and GIS database itself may be seen as an expression of a common conception of the system to which a wide variety of stakeholders in the situation may lay claim.

The Approach in General

The primary framework for this research is provided by an ecosystem approach (see Kay et al., 1999) which is operated by methods and techniques derived from adaptive management (specifically Adaptive Environmental Assessment and Management or AEAM) and Soft Systems Methodology (SSM), both of which are rooted in systems thinking. Adaptive management is oriented toward managing environmental change in uncertain and complex situations. It emphasizes communication and participation, experimentation, learning from the experience of managing ecosystems, and flexibility of management programs in the face of new knowledge and changing goals. The approach intentionally operates a learning cycle. Main operational components of AEAM are (1) a series of workshops that bring together scientific experts, planners, policy makers and representatives of the public to make use of best-available knowledge and to design interventions in the system to generate knowledge and facilitate learning, and (2) the development and use of a simulation model as an aid in system understanding and the exploration of possible management scenarios. This particular research makes use of Geographic Information System technology in support of the system modelling component of adaptive management.

This research is also heavily influenced by Soft Systems Methodology (SSM). SSM is a methodology intended to deal with "messy" or complex, unstructured "problematic situations" having to do with human activity. It involves the perception and interpretation of a real world problem situation and provides tools for expressing it. Expression of the problem situation leads to the identification of key themes which may be modelled as relevant systems of purposeful human activity. These conceptualizations are compared to each other and to the expression of the problem situation. This is intended to stimulate thinking about desirable and feasible change. That is, expression, conceptualization and comparison leads to debate about action to improve the situation. Action in the real world changes the situation, which then requires new expression, conceptualization, debate, etc.. Thus, as with Adaptive Management, Soft Systems Methodology formally operates the learning cycle, employing learning from the experience of applying the methodology to further inform purposeful action in real world situations (Checkland and Scholes, 1990).

Operating the Approach

Problem Definition and System Identification

This program of research has involved several workshops, the development of a system model in the form of a loosely-coupled GIS and water quality simulation model, and the use of this decision support system (the Cooum DSS) by workshop participants to develop management scenarios and undertake exploratory scenario analysis. The first workshop in March 1998, brought together stakeholders in the situation (government managers and scientists, academics, NGOs and other public representatives) to define and scope the problem situation, generate objectives for rehabilitation and management of the system and to discuss potential interventions to achieve those objectives. The ultimate aim of this first workshop was to encourage a more pertinent, (less jurisdictional and disciplinary), conceptualization of the system which would inform the development of a framework for a decision support system and simulation model. The workshop also served to develop an understanding of the cultural climate of the situation, including values and norms which influence participants' vision of desirable future system configurations.

Expression of the problem situation involved exercises for identification, definition and measurement of various actors, elements, interactions and relationships within the system. A key technique use here was the collaborative development of a ‘Rich Picture' of the problem situation. This diagrammatic technique (adapted from SSM) provided a forum for participants to express the complexity and scale of the problem without necessarily organizing their observations of it as a system. (Figure 1 is part of this Rich Picture).

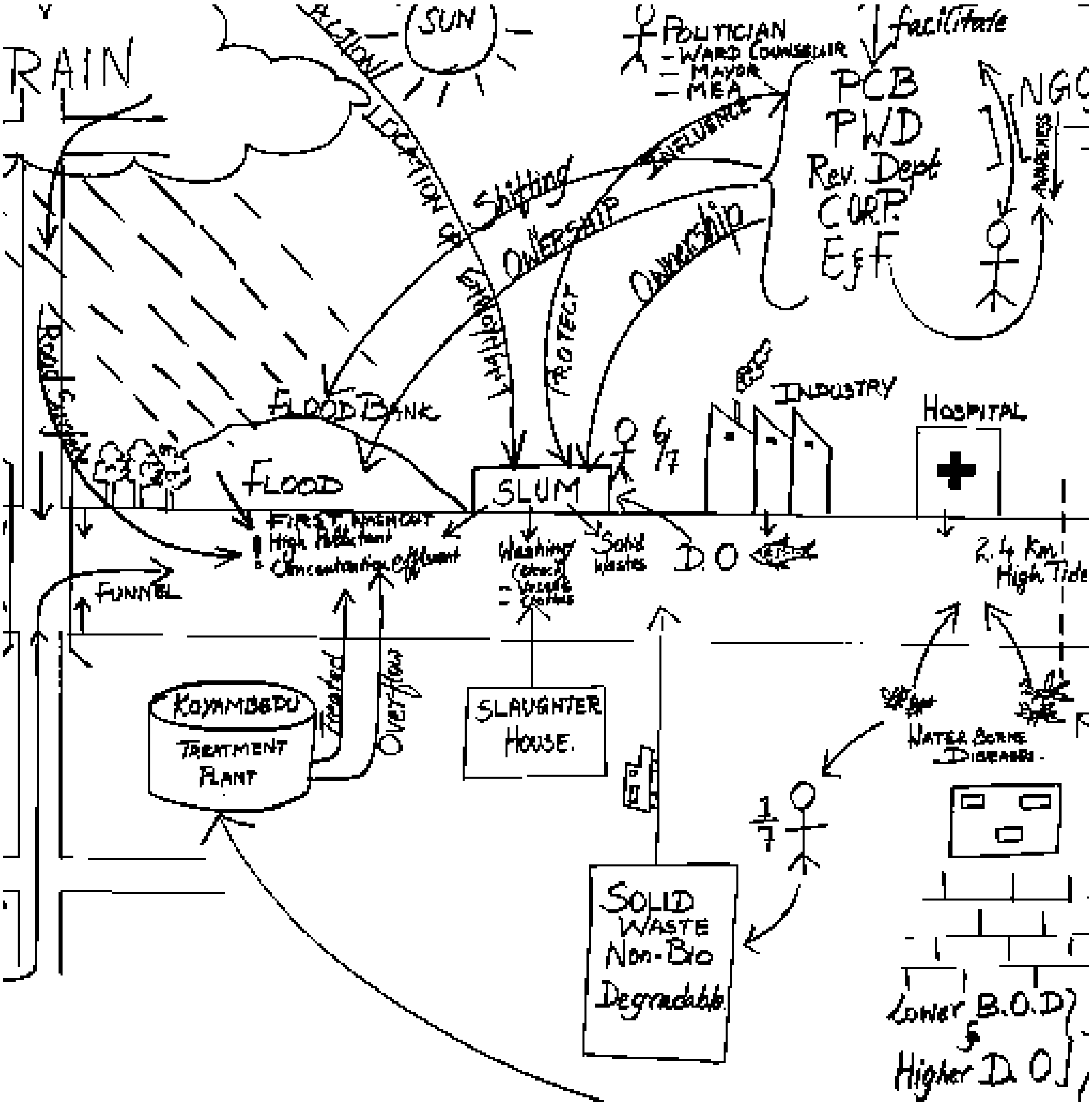


Figure 1: Part of a Rich Picture of the Cooum problem situation developed by participants in the Cooum River Environmental Management Research Program.

System Conceptualization

While the Rich Picture is useful to express the situation and to aid problem definition, not all of the actors and elements represented are critically important to describe the core nature of the system. Various systems may be conceptualized in such a complex problem situation. The nature of these depends on the perspectives taken to draw elements, actors and relationships to the foreground out of the complexity of the real world situation. One technique for drawing out and conceptualizing key characteristics of a problem, is the development of root definitions of human activity systems which reflect the aspects of the mnemonic "CATWOE" (Checkland, 1979):

C	Customer	Who would be victims or beneficiaries of this system?
A	Actor	Who would perform the activities?
T	Transformation	What input is transformed into what output?
W	Weltanschauung	What view of the world makes this system meaningful?
O	Owner	Who could abolish this system?
E	Environmental Constraints	What in its environment does this system take as given?

At the first workshop in 1998, this technique was used to draw key themes (which workshop participants believed to be important in the problem system) out of the Rich Picture. Themes modelled in this way were; slum dwellers as squatters, provision of sewerage services, provision of water supply, the population of Chennai as polluters, animal husbandry, the stormwater drainage system as flood protection, the use of the stormwater drainage system for sewage disposal, political protection of slums, and agency intervention and control of activities. In addition, the hydraulic operation of the river and tidal action were important physical themes that were discussed in terms of elements and physical processes.

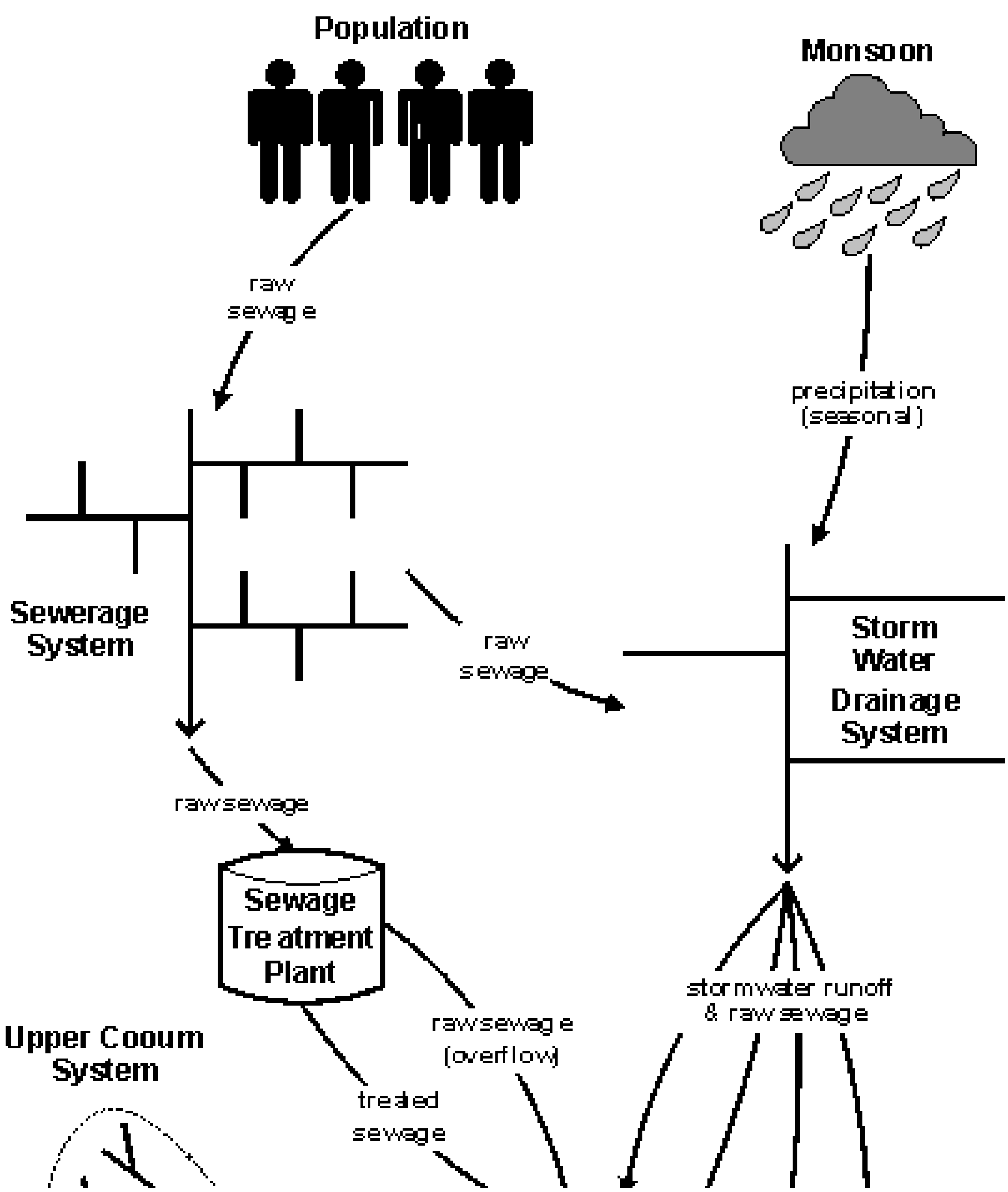
For example, facilitated discussion to draw out important systems identified the polluting activity of Chennai residents as a primary human activity system that was relevant to the Cooum problem. The CATWOE description of the system may be expressed as:

C	citizens of Chennai
A	citizens of Chennai
T	waste in need of disposal --> waste disposed of
W	waste should be disposed of in the most convenient and least costly manner to the household
O	Chennai Metropolitan Water Supply and Sewerage Board, Chennai Metropolitan Development Authority, Corporation of Chennai
E	inefficient sewerage system (with connection charges), storm water drainage accessible in many areas

These basic system definitions were expanded in further discussion, debate, paper presentations, and working sessions (which were oriented toward scoping the system in time and space, the development of management objectives and indicators, and discussion of data required to model the system). Overall, this participatory process of problem definition and system identification lead to a shared understanding and conceptual model of the system (as well as objectives for management and potential interventions) that were substantially different from those employed in the past. Significant characteristics of this conceptual model include the prominence of human behaviour, the identification of the urban and waste carrying aspects of the system, and the separation of the lower (urban) and upper (rural) catchments as distinct subsystems characterized by different actors, elements, activities and processes.

A Framework for a System Model

The development of a conceptual model of the Cooum system emphasizing human activity instead of merely biological and physical processes represented a dramatic rethinking of the problem situation for most of the workshop participants. Previous attempts to deal with the problem understood it to be a primarily physical one and targeted hydraulic characteristics of the system for intervention (such as clearance of the coastal sand bar, flushing, dredging of sludge, and removal of blockages to the flow along the course of the river). This new understanding of the system was reflected in a basic framework for a computer simulation model derived from workshop participants. This is summarized in Figure 2 which presents the structure of the system.



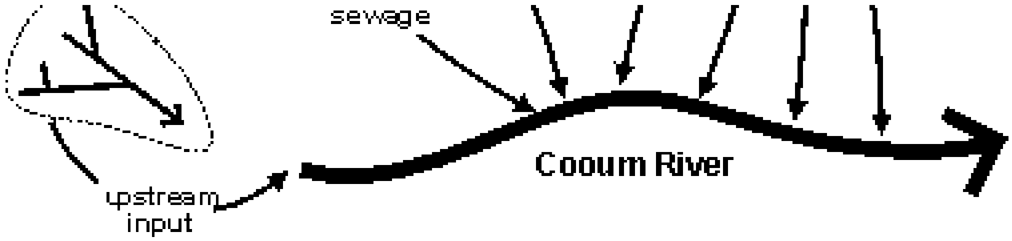


Figure 2: Core structure of the Cooum system as it emerged from the first workshop of the Cooum River Environmental Management Research Program. This provided a framework for the construction of a computer simulation model of the system.

This framework is based on a set of themes (above) which may be modelled as systems. The most important of these themes have been operationalized in a prototype system simulation model. These key themes include (1) the production of sewage by the population of Chennai, (2) the routing and treatment of sewage by the sewerage system, (3) the routing of runoff (and sewerage overflow and diversions) via the storm water drainage system, and (4) the transport of stormwater runoff and sewerage effluent by way of the Cooum River. Another theme, slums, was also indicated as important. The slum theme has to do with the production and disposal of sewage and solid waste in locations not serviced by the sewerage system. Although this theme may not be absolutely crucial for the basic functioning of the system, because of its persistence in discussion and debate among workshop participants it was deemed important enough to try to incorporate into the model. (In Figure 2, slums are subsumed in the population component).

Operating the Framework

The prototype Cooum DSS, which operationalizes the conceptual model of the Cooum system, simulates hydraulics and water quality in the Cooum River with a water quality simulation module. The rest of the system is modelled in a GIS and a GIS-based decision support module which are used to parametize the water quality model. Development of the GIS database and decision support modules of the Cooum DSS was a valuable exercise in explicitly expressing and formalizing the relationships described by workshop participants.

There is a direct link between the expression of the problem situation, identification of important themes in that situation, conceptualization of systems relevant to the problem, and their representation in the GIS database and simulation model. Consider the example above, in which the population of Chennai and their activity was identified as a relevant system. In this case, working sessions aimed at expressing the problem situation, identifying relevant systems and describing them, resulted in the recognition of sewage generating and disposal activities of the Chennai population as central to the Cooum problem. (In the past, the jurisdictional situation of agencies in Chennai had prevented this rather obvious connection from being expressed in models for management of the situation). Discussion, debate and workshop exercises furthered understanding about this sewage generation system. Properties of the system such as the impact of income on the quantity and water quality characteristics of sewage generated and the relationship between this system and other components in the situation (such as the storm water drainage and sewerage systems) were expressed.

To represent these key activities in the decision support system, a population ‘calculator' was developed which generates figures representing the amount of sewage produced by a city ward's population. (Other calculators addressed improvement and clearance of slums, allocation of sewage to spatial units for routing, routing of sewage to treatment plants or to the river, and the final transport of data into the water quality model). The working of the population calculator is based on a conceptual model of a human activity system which generates waste for disposal. It derives from the theme of the population of Chennai which was drawn out of the Rich Picture using CATWOE analysis and further conceptualized throughout the first workshop. Since sewage generation is related to water consumption, and water consumption in Chennai is a function of income, this involves an expression of the relationship between level of income (broken into three categories, high, middle and low), water consumption, and proportion of water consumed that is transformed into sewage. The conceptualization of this human activity system supports the development of the GIS/DSS database by indicating data sets required (population, population growth rates, income distribution, water consumption) and the use of this information to simulate the system (by describing the transformation which is to be modelled). The relationship can be expressed algebraically for both incorporation into the model and communication back to workshop participants.

Algebraic expression of the relationship also facilitates the explicit statement of assumptions. E. g., this relationship assumes that sewage generation factors and water consumption figures for each income group will not vary spatially across the city. That is, spatial variation in the amount of sewage produced by a given population is determined by income distribution alone. This process of explicit statement of relationship and assumptions, based on a participant-derived conceptual model of the system together with the capability to visualize data in the GIS module, effectively illuminates the black box of simulation models for the user. In this research the process was found to facilitate learning about the system. For example, several assumptions that were presented to participants in a second workshop (in 1999) were questioned, leading to revisions in the conceptual model of the system. This illustrates an iteration of a learning cycle in which the process of problem definition, system identification, conceptualization, and simulation modelling has stimulated new insight into the problem situation.

Conclusions

The process of problem definition, system identification and exploratory scenario analysis in workshops of the Cooum River Environmental Management Research Program resulted in the development of a shared understanding of the problem situation which was unlikely to have arisen in the normal course of management by the Indian institutions. This understanding of the

Cooum system as characterized by human activity, urban processes and waste disposal, influenced objectives for management of the system (e.g., targeting recreation and tourism) and the choice of interventions in the system to achieve them (e.g., targeting human behaviour). The evolution of the conception of the system from a primarily physical river system to an urban system, resulted in a system model which expresses and simulates not merely elements and processes, but actors and activities in the Cooum system.

This work has also led to an understanding that the original concern of participants of the program of research -- that of water quality in the Cooum River -- is really an indicator of the health of a larger socio-ecological system. In modelling the system, human actors and activities must be represented. The standard engineering approach to this problem that has dominated in Chennai (based on a reductionist understanding and physical intervention) has resulted in solutions such the lining of banks and dredging of the river. In contrast, it is conceivable that, based on the understanding of the system generated in this research, one could manage the system to improve water quality by intervening to affect such things as the distribution of income in the city.

The development of the Cooum DSS has provided a tool to explore such alternatives and stimulate continued learning about the system. In fact, exploratory scenario analysis with the Cooum DSS has already produced some interesting and unexpected results. Simulations of simple management scenarios indicate a severe under-capacity of the sewage treatment plant, for example, and there is evidence that improving slums (providing them with sewerage service) may actually worsen the condition of the Cooum River.

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