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WATER RESOURCES MANAGEMENT IN TROPICAL RIVER CATCHMENTS

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The main hydrological and environmental problems in tropical catchments are discussed, with particular emphasis on the complex issues of the Citarum River catchment, West Java, Indonesia. The concept of basin planning is introduced, from which decision-support systems are suggested within water resources management strategies. The relationship between available water resources and various water demand sectors (such as domestic, municipal, industrial) is given. The effect of land use and various industrial activities on the degree of availability and quality of water is also included in the study. The various degrees of contamination in groundwater are presented in detail. Practical measures on how to remedy the continuous decline of groundwater levels and quality in the form of quantitative strategies are also given. Finally, an overview is given of the management strategies for water resources, which can be used to improve the present deterioration of water resources and to cope with increasing future demands.

INTRODUCTION

Tropical regions are of special interest to scientists and engineers because of the various environmental problems, which include social, cultural and economic dimensions. Whilst research into hydrological processes has continued rapidly in semi-arid regions, humid tropical regions have received relatively little attention in the past thirty years (World Resources Institute, 1985; Goldsmith, 1998). However, growing concern over the environmental sustainability of tropical eco-systems, and an increasing awareness of the global climatic impact on these regions, have stimulated considerable interest in the environmental problems and associated hydrological processes (Duke, 1996; Pereira, 1973; World Resources Institute, 1985). It is widely accepted that in many tropical regions the core of environmental problems is essentially of a socio-economic nature coupled with increased pressure on use of natural resources by rapidly expanding populations. Hydrological research has therefore tended to focus on the effects of land use management; particularly on the following issues:

- land-atmosphere interactions and effects of land use change on global climate,
- changes in catchments yield runoff and regimes by land use change, and
- hydrological regime changes impact on soil and aquatic biology.

Tropical areas or tropical rainforests around the world are situated along the equator, mainly in Latin America, Africa, and Asia, between the Tropic of Cancer (23.5^{o} N) and Tropic of Capricorn (23.5^{o} S). Tropical regions are characterised by high temperature and rainfall rates. Tropical rainforests have average daily temperature of about 25^{o}C, and annual rainfall rate ranges between 1500 mm and as much as 10000 mm in rainforests during the monsoon season (Pereira, 1973).

In this study, the characteristics of river catchments in tropical regions are presented, with particular emphasis placed on the Citarum catchment, West Java, Indonesia, as a case study. The main characteristics affecting the catchment will be analyzed. These characteristics include water resources and water quality, from which management strategies are suggested for the protection and preservation of the natural environment, and for future improvement.

CHARACTERISTICS OF TROPICAL CATCHMENTS

The major anomalies in the global circulation pattern at low latitudes (tropics) are the monsoon patterns, which are driven by thermal gradients between land and large water bodies. Monsoons are best developed over the margins of the Asian large landmass. The extreme low-pressure zone that develops over Asia during the summer causes inflows of moist air, instability over southern Asia, and the summer monsoon. Latent energy is transferred inland through airflow and released during convectional activity. In contrast, cooling and high pressure develops over Asia in the winter, causing an outflow of cool and stable air over southern Asia, and the dry winter monsoon. The Asian monsoon, coupled with a smaller monsoon in northern Australia, brings a wet monsoon season to the area. Conversely, a high-pressure zone develops over Australia during the Asian summer monsoon and a south-easterly offshore airflow from theAsian continent passes over Indonesia and contributes to the Asian summer monsoon.

Assessment of catchment hydrology is crucial to ensure that future developments will not cause unacceptable harm to the environment. Calculation of the water budget in the catchment should include (Goldsmith, 1998; Holt, 2000):

- estimation of effective rainfall intensities, evaporation and natural runoffs, and
- percolation to groundwater including outflow through water boundaries, abstractions from wells, boreholes and changes in underground water storage.

The most important feature of rainfall in the tropics is rainstorms with short duration and high intensity. It is estimated that 40 percent of all tropical rainstorms exceed 25mm/hr, a rate that causes the rainfall to be erosive(Goldsmith, 1998; Pereira, 1973). In contrast, temperate areas are estimated to receive only 5 percent of their rainfall in such intense storms. During May to October, intense rainfall rates have been recorded in many tropical areas around the world causing river flows to have seasonal variations in rainfall inputs. With minor exceptions, tropical soil profiles and underlying layers are generally deep and contain fine sediments (e.g. clay) that have high storage capacity of moisture. In areas with little rainfall changes, the entire soil profile remains at close to field capacity throughout the year.

CHARACTERISTICS OF THE CITARUM CATCHMENT

The Citarum catchment, West Java, Indonesia, shown in Figure 1, is an example of a complex tropical catchment. Increase in population density, a growing economy and threatened natural environment all depend on reliable supplies of good quality water. Fresh water availability in recent years has proven to be scarce, and therefore it has a distinct economic value. Meanwhile, fresh water resources, apart from being irregular or limited over the catchment, are also polluted. In Indonesia, the average annual runoff per capita is about 17 000 m^3. The island of Java contains about 60 percent of the country's population of 200 million (Setiono, 2001a, 2001b). The average annual runoff per capita in Java is much lower, about 1750 m^3 and is widely distributed across the catchment. The Government of Indonesia has recognized the importance of good planning and management systems

Figure 1. Citarum catchment.

for sustainable water resources. Local and regional management units have been developed to tackle the problems with water use in the Citarum catchment.

Hydrological characteristics

The total surface area of the Citarum catchment is about 11 510 km^2. The population of one of the heavily populated cities in the catchment, Bandung City, is more than 10 million. In the heart of the Citarum catchment lies the Citarum River, which originates at Mount Wayang, in the area of Bandung. The Citarum River flows northward through the Western parts of Java along a stretch of 269 km into the Java sea, northeast of Jakarta. The Citarum River is the one of the most important sources of water in the catchment. The Citarum catchment covers most of the Citarum river as well as small rivers that flow northwards to the Java Sea. The catchment is dominated by three large reservoirs, the uppermost is the Saguling Reservoir which was built in 1986 with a capacity of 900 million m^3. Further downstream is the Cirata Reservoir, which was built in 1988 and has a capacity of 2 billion m^3. Last in series is the Jatiluhur Reservoir, built in 1963, with a capacity of 3 billion m^3. The Saguling and Cirata Reservoirs are mainly used for hydropower generation and fresh fish farming. While the Jatiluhur Reservoir serves more purposes, including domestic and public water supply, flood control and irrigation.

The most characteristic feature of the tropical climate of Citarum catchment is its uniformity with respect to temperature, humidity (>80 percent), low wind speed (< 2m/s) and evaporation. The average annual rainfall over the Citarum catchment is about 2500 mm (Setiono, 2001a, 2001b). However, in the upper catchment, upstream of the Saguling Reservoir, the annual rainfall is about 4000 mm. In the coastal plain near the Java Sea, annual rainfall can be less than 1500 mm. Records confirmed that in the Bandung area, which is situated in the upper catchment, the annual rainfall is less than 1500 mm, much drier than the rest of upper catchment. This is not unexpected since the Bandung area is surrounded by mountain ranges that tend to reduce the rainfall dramatically. Strong correlation is found between the seasonal variations in rainfall and surface runoff rates over the catchment. Low rainfall intensities occur in the June-October period. In the wet season (November-May), about 66 percent of the runoff goes into the Java Sea.

The estimation of potential and actual evapotranspiration rates is also crucial in calculating the water budget for the catchment. From past records of meteorological stations, average monthly values of the potential evapotranspiration was estimated for both lowland and upland areas (Duke, 1996). They show that the actual evapotranspiration rates are generally about 70 to 85 percent of the potential evapotranspiration, which also had higher values in upland regions that those in lowland regions throughout the year.

Land use changes

In the Citarum catchment, the municipal, domestic and industrial water demands are about 5 percent of the total runoff, however only 0.5 percent of the total runoff is withdrawn. The irrigation demand is 5 percent of the total runoff volume, from which only 3.5 percent is effectively withdrawn from the system. About 6 percent of the Citarum water budget is withdrawn from the surrounding areas (Ministry of Public Works, 1998; Pereira, 1973).Most of the runoff is not utilized in an appropriate manner, hence the need for a sustainable and efficient water management. Current land use in the Citarum catchment is given in Table 1. A considerable proportion of the land is used for agriculture, especially in the northern parts of the catchment. The coastal zones include limited areas with swamps and fishponds, while urban and highly populated areas are located in the middle and upper parts of the catchment.

Table 1. Land Use in the Citarum Catchment

Land Use	Surface Area (ha)	Percent of Total Land Use
Irrigated areas	334 000	29
Non-surface irrigated agricultural areas	364 000	32
Forest	213 000	18.5
Human settlements (urban/industrial/rural)	86 000	7.5
Swamps and fish ponds	46 000	4
Infrastructure, surface water, uncultivated areas	108 000	9
Total SWS Citarum	1 151 000	100

Groundwater depletion

In general, but particularly in the middle and upper Citarum sub-catchments, groundwater is abstracted as source of domestic and drinking water. In the Bandung area, groundwater is heavily used for industrial water supply as well. Excessive groundwater abstraction has resulted in a decline of groundwater levels and pollution (Duke, 1996; Holt, 2000; Legret et al., 1999). Before industrial development, water levels were high, resulting in artesian conditions. In recent years, however, this has changed dramatically as groundwater has been abstracted from shallow and deeper aquifers.

Recent deforestation and change in land use in the catchment have also caused excessive soil erosion. About 60 percent of soil erosion occur in slopes greater than 40 percent, while higher erosion rate of 90 percent occur on slopes in excess of 15 percent. The eroded soil causes an increase in sediment in rivers and the reservoirs downstream, hence decreasing the soil productivity and reservoir capacities. Peak runoff and flood risks increase, which result in less infiltration to groundwater (Komuscu, 1999). One obvious solution to the erosion problem would be reforestation of land steeper than 40 percent. However, this could pose a problem to agriculture use by local populations in these areas. On the other hand, deforestation of regions with smaller slopes can reduce erosion rates significantly. Most eroded sediments are trapped in the Saguling reservoir, causing a reduction in its capacity as well as in its life expectancy.

Water quality

Due to rapid industrial development and growing population, particularly in the city of Bandung, deterioration of quality water remains the main threat today as well as in the future (Setiono et al., 2001). Waste loads on the water systems have increased significantly in the past few years. The biological oxygen demands (BOD) of river waters and shallow ground water has increased noticeably. In the Citarum River, the average BOD concentration in 1993 was 10 mg/l, and in the region upstream of the Saguling reservoir, it was over 20 mg/l, well above an acceptable BODconcentration of 6 mg/l. In 1994, these concentrations were 18 mg/l and 40 mg/l respectively. However, downstream of the Saguling reservoir, the BOD concentrations were found to be within the permissible limits. As such, the Saguling reservoir is acting, in effect, as a treatment plant for the incoming water and protecting the downstream part of he Citarum River from high pollution levels caused by the presence of domestic and industrial waste, including heavy metals and ammonia (Foster, 1995; Sriwana et al., 1998).

Pollutants entering into the water system are from to the degradation of disposed solid wastes or wastewater discharges (Sukhodolov et al., 1997). The total pollutant loads are generally divided into two main types. These are gross and net pollutant loads, as shown in Figure 2.

The deterioration of water quality is particularly evident in the Saguling Reservoir. These problems are caused primarily by waste discharges from industrial and domestic areas upstream of the reservoir. Water quality in the Saguling reservoir falls much below the standard limits, particularly during dry periods. Downstream reservoirs, i.e. Cirata and Jatiluhur, however, have much better water quality.

For the purpose of evaluating the pollution loads, the catchment is divided into three regions, or sub-catchments. These are: upper Citarum – up to the beginning of the Saguling reservoir; middle Citarum - between the Saguling and Jatiluhur reservoirs; and lower Citarum – downstream of the Jatiluhur reservoir up to the Java Sea. Table 2 gives the total amount of organic waste load generated

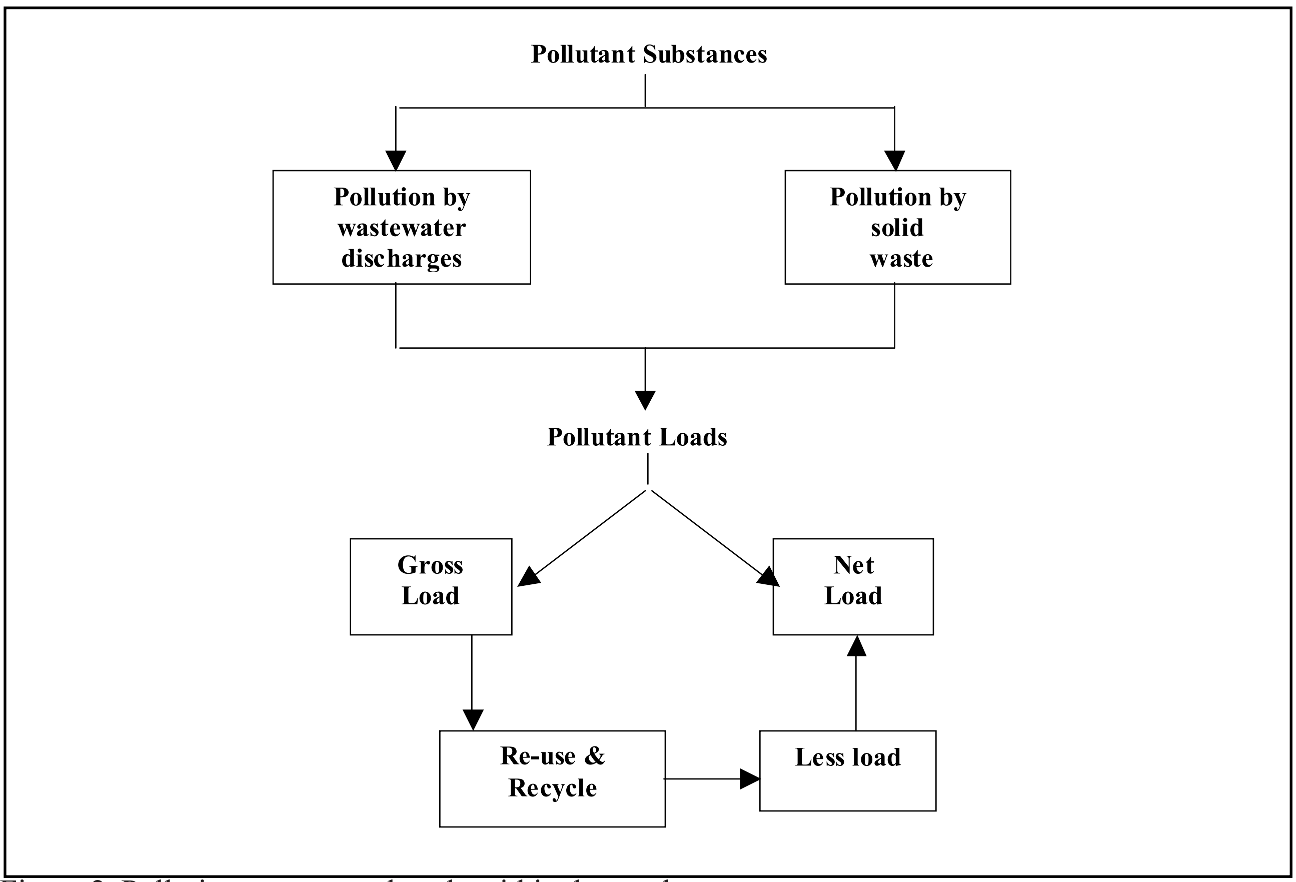

Figure 2. Pollution sources and cycle within the catchment.

by various sectors in the upper, middle and lower sub-catchments of the Citarum basin, presented in terms of biochemical oxygen demand (BOD/day) values (Setiono et al., 2001; Sriwana et al., 1998). Table 2 shows domestic wastewater to be the major source of pollution in the catchment. Most urban areas do not have centralised domestic wastewater treatment. In the upper Citarum, where almost 70 percent of the catchment population are located, waste discharges are disposed of directly to local rivers by 60 percent of the population, while the remaining 40 percent use septic tanks, latrines, ponds or fields. In the middle Citarum, again around 59 percent of the population use direct disposal methods and the remaining 41 percent use indirect methods. Finally, in the lower Citarum, 53 percent of the population use direct methods and 47 percent practice indirect disposal methods respectively. Agricultural lands contribute considerable pollution as fertilisers and pesticides.

Table 2. Estimation of Organic Waste in the Citarum Catchment (1991-1995)

Pollution Sources (BOD)	**Upper Citarum** (x 10^3/day)	**Middle Citarum** (x 10^3/day)	**Lower Citarum** (x 10^3/day)	**Total BOD** (x 10^3/day)
Domestic	56.16	12.08	24.07	**92.3**
Industry	43.67	1.64	12.06	**57.37**
Agriculture	1.85	1.96	5.99	**9.8**
Livestock	11.30	5.87	5.87	**23.04**
Total	**118.83**	**21.55**	**47.99**	**188.37**

Table 3 shows the estimated future pollution load in the Citarum catchment from various sectors and activities, presented by BOD/day values (Ministry of Public Works, 1998). The domestic waste load is the biggest contributer to pollution, followed by industrial waste. Agricultural wastes, though significant, show the lowest contribution.

Table 3. Estimation of Total Pollution Load in the Citarum Catchment for Year 2025

Source of waste load	**Upper Citarum**	**Middle Citarum**	**Lower Citarum**	**Total Waste load for Citarum catchment**
Domestic waste load	167.6	39.9	76.4	283.9
Industrial waste load	85.16	5.85	20.69	111.7
Agricultural waste load	1.85	1.96	5.99	9.80
Livestock waste load	11.3	-	11.75	23.05
Total waste load (x 10^3 BOD/day)	265.91	47.71	114.83	428.45
Population	9,133,000	1,933,000	4,077,000	15,142,000

PROBLEMS WITH WATER DEMAND

Domestic and municipal sectors in larger cities consume more water than the smaller urban areas, due to greater economic and industrial infrastructure. In 1994, the Jabotabek Water Resources Management Study (JWRMS) programme concluded that the percentage of population satisfied by water demand from the Public Water Supply system (PWS) in the catchment was 22 percent for the Bandung area, 20 percent for nearby sizeable urban areas, and only 10 percent for rural areas. These figures confirm the need for a new improved and well-managed public water supply system for the Citarum catchment. It should be mentioned, however, that the existing PWS system operates mainly with groundwater sources and to a much lesser extent with surface water, such as the West Tarum Canal for the greater Jakarta City. The efficiency of the PWS system is further reduced by major problems in the network itself through leakage.

The largest consumer of water in the catchment is agriculture and this situation does not seem to change in the near future. The statistical records for irrigation published by the Directorate General of Water Resources Development DGWRD in 1996 revealed that West Java Province has about 867, 228 hectares of irrigated areas, half of which are within the Citarum catchment (Ministry of Public Works, 1998; Sriwana et al., 1997). This stresses the fact that a well structured, managed, and controlled plan for water supply in irrigated areas is imperative. Large reservoirs could be a solution for storing water during wet periods and supply during dry times. Finally, the estimated total annual irrigation water demand in 1995 within the boundaries of the catchment is about 5771 m^3.

In the Bandung area, about 90 percent of water usage in industry is obtained from groundwater sources. The remaining 10 percent of water demand comes from the Citarum River and its tributaries. In the Bandung area, almost all of the industries fulfil their water demands by using groundwater, and about 40 percent of industries abstract water from unlicensed sources. In addition, about 105 million m^3/year of water withdrawn by the industrial sector is from the Citarum water resources, of which about 80 percent return back to the system as polluted water.

Hydropower demands are also considerable in the catchment. The northern part of West Java is the major part of the power demand and generation in the island, with Jakarta and Bandung as large load demand centres. The total energy production in West Java in 1994 was about 17 000 GW/hr, which represents some 33 percent of the country's total production. The major power generation is produced by the largest three reservoirs in the catchment (Saguling, Cirata and Jatiluhur). The first two reservoirs (Saguling, Cirata) are entirely used for power generation, due to high pollution levels. Because of the increasing demand for water resources, the Jatiluhur reservoir is also used for domestic, municipal and industrial purposes.

In industrial zones, shallow groundwater levels were dropped by 0.1m/yr to 9m/yr, and 12m/yr at deeper depths. The uncontrolled use of groundwater, particularly around the Bandung area, causes the groundwater table to subside by an average rate of about 4m/yr. This situation has caused a change to the groundwater flow patterns. More notably, lowering of groundwater table levels can cause severe land subsidence. This, in turn, can result in an increase of flood risks, as has been clearly observed in the Jakarta area. While no evidence of such a problem is found in the Bandung area yet, it may become one in the near future.

Research on water quality in the Citarum catchment is carried out by the Research Institute for Water Resources (RIWR), Ministry of Public Works, as part of a national water quality monitoring programme. In 1992, RIWR conducted a study on the contamination of groundwater in the Bandung catchment (Ministry of Public Works, 1998; Sriwana et al., 1997). Various laboratory analyses were carried out on chemical, physical and bacteriological characteristics of water sources from shallow and deep wells in rural, urban, and industrial areas. The results have confirmed the presence of heavy metals, such as Nickel (Ni), Mercury (Hg) and detergents in shallow wells in industrial areas. Since most industrial activities in the Bandung area produce textiles, it is likely that industrial wastewater effluents were responsible for contamination of wells.

To manage the groundwater resources in the catchment, many measures need to be used, such as introducing licensing schemes, and establishing groundwater protection zones. The latter measure can limit further abstraction in areas that have serious groundwater problems and encourage the development of new industries that can resist this impact. Detailed measures to protect and manage groundwater in the catchment may include one or more of the following:

- registration of all deep wells and monitoring of groundwater use,
- introducing water-saving and water re-use measures to industrial sector,
- improving operational efficiencies of existing piped water supply, and
- limiting industrial expansion to availability of surface water.

PLANNING CONCEPT

In order to realize a consistent management aproach for water resources, a concept for catchment planning has to be developed where the water resources system can be accurately identified (Clarke, 1994; Gardiner, 1994). In general, the water resources system consists of:

- a natural resources system, which includes surface and groundwater resources, water infrastructure, and the natural ecosystems,
- a socio-economic system which includes agricultural, industrial and municipal sectors where demands are related to the natural resources system, by water quantity and quality requirements, and
- an administrative and institutional system, which includes legal frameworks for management, responsibilities and all monitoring systems and regulations.

The relationship between the above three systems can be described as follows: the natural resources system provides the water, the socio-economic system uses and changes it, and the administrative system manages both (Harper, 1999). Water resources planning should include analyses of the natural resources and the socio-economic systems. The proposed concept of catchment analysis is given in Figure 3.

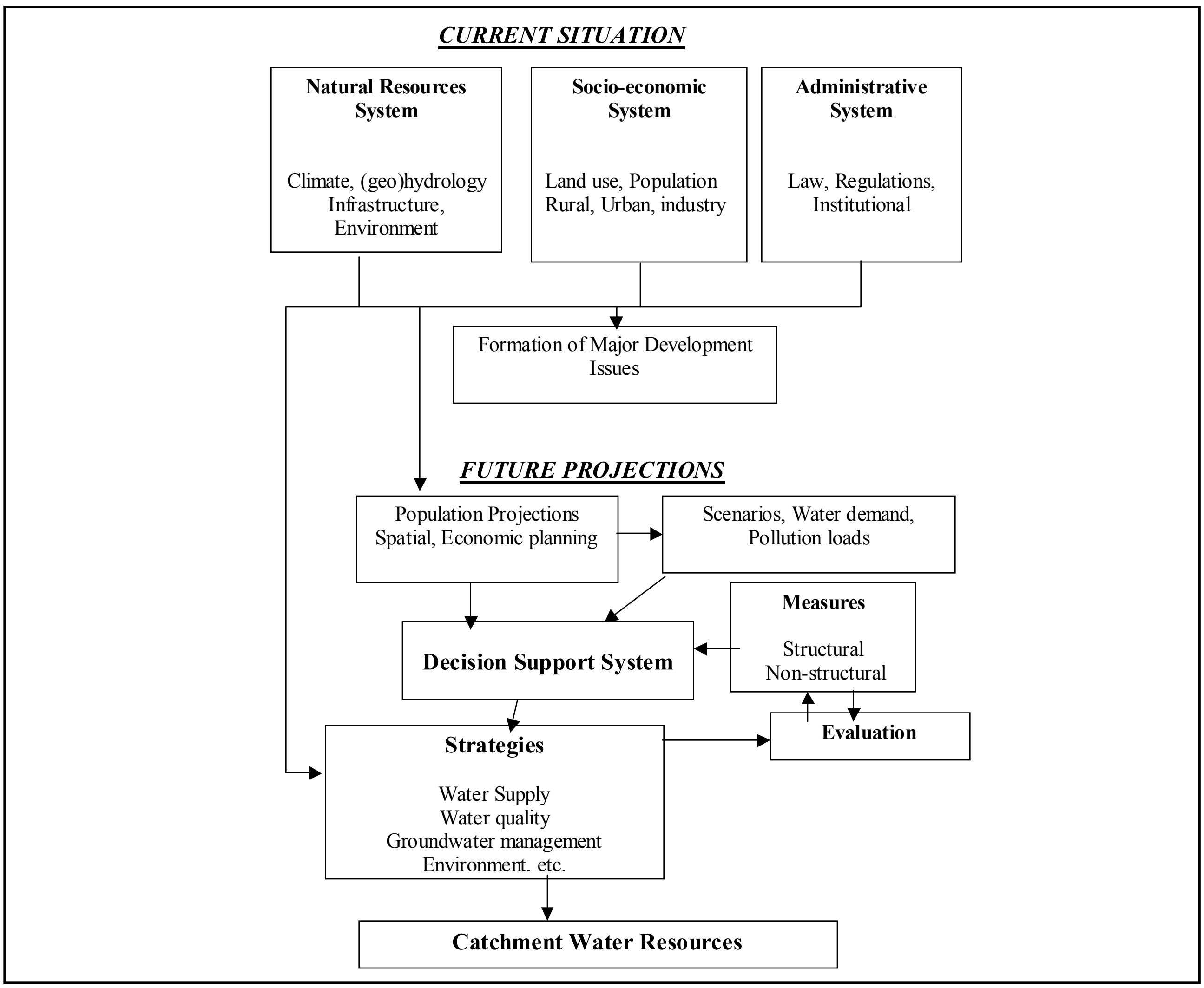

Figure 3. Planning concept for the Citarum catchment.

The different scenarios take into account important factors, such as population growth, economic growth, future land use, etc. The socio-economic demands within the presented scenarios become inputs in the core of planning, or to the decision-support system. Present water availability, quality and infrastructure are also inputs to the decision-support system. Based on the evaluation of present and expected water resources, strategies are generated as output of the system. These strategies are the results of the measures taken after the initial evaluation of the systems. In general, these strategies or measures could be structural (dams, diversions, etc.) or non-structural (legal or institutional). The decision-support system is used to evaluate the inputs of the water resources system and to adjust and optimise the strategies accordingly.

CONCLUSIONS

Within the Citarum catchment, effective conventional treatment processes of water and waste are challenging and costly due to high and fluctuating seasonal loads of organic pollutants and heavy metals. However, less costly solutions could be realised by better understanding of the water cycle in the catchment. Such understanding implies development of less polluted water sources, taking advantage of the self-purification capabilities of the reservoirs and protection of transport routes, within a careful integrated planning and management of the supply schemes.

With the predicted increase of population in the catchment, together with the rapid economic growth, water demands will continue to increase rapidly. Both groundwater and surface water sources should meet water resource demands. One very essential step is the reduction of pollutant loads by taking all necessary measures, particularly in densely populated areas. Such measures may include effective full-scale waste treatment facilities and urban drainage systems.

Land use patterns influence the requirements of future water availability and also determine the anticipated distribution of waste loads. Therefore, the need to prepare an integrated land use planning and regulation program is essential, where special protection zones such as watershed areas are defined, development of agricultural activities are monitored, and a framework for all other land uses related to socio-economic developments is provided.

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