Management of water resources and quality in tropical river catchments

Y. R. Fares
Fluids Research Centre, School of Engineering, University of Surrey, England, UK.

Abstract

The main hydrological and environmental problems in tropical catchments are reported, 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 the 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 within Citarum catchment on the degree of availability and quality 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 level and quality in form of quantitative strategies are also given. Finally, an overview is given on the management strategies for water resources, which can be used to improve the present deterioration of water resources and to cope with the predicted increasing future demands.

1 Introduction

Tropical regions are of special interest to scientists and engineers because of the various environmental problems associated with these regions which include social, cultural and economic dimensions. Whilst research into hydrological processes has continued fast in semi-arid regions, humid tropical regions have received relatively little attention in the past thirty years ([1], [2]). 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 ([1], [3], [4]). It is widely accepted that, in many tropical regions, the core of environmental problems is essentially of 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 effect of land use change on global climate.
- Changes in catchments yield runoff and regimes by land use change.
- 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 continents, between the Tropic of Cancer (23.5° N) and Tropic of Capricorn (23.5° S). One of the most complex tropical catchments exists in Java and Borneo in the Indonesian Islands. Tropical regions are characterised by high temperature and rainfall rates. Tropical rainforests have average daily temperature about 25°C and annual rainfall rate ranges between 1500 mm and as much as 10000 mm in rainforests during the monsoon season ([3]).

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 analysed. These characteristics include, water resources, water quality, from which management strategies are suggested for the protection and preservation of natural environment, and for future improvement.

2 Characteristics of tropical catchments

One of the main problems in tropical catchments is the accurate definition of their boundaries. Personal knowledge of a catchment and use of advanced surveillance techniques are therefore essential. Almost half of all tropical land surfaces can be classified as humid, with rates of annual rainfall matching or exceeding those of evapotranspiration. The major anomalies in the global circulation pattern at low latitudes (tropics) are the monsoon pattern, which are driven by thermal gradients between land and large water bodies. Consequently monsoons are best developed over the margins of Asian large landmass. The extreme low-pressure zone develops over Asia during summer precipitates inflows of moist causing instability of air over southern Asia, constituting the rainy summer monsoon. Latent energy is then transferred inland through airflow and released during conventional activity. In contrast, cooling and high-pressure zone develops over Asia in winter, resulting in an outflow of cool and stable air over southern Asia, forming the dry winter monsoon. The Asian monsoon, coupled with smaller monsoon in northern Australia, brings a wet monsoon season to the area. Conversely, high-pressure zone develops over Australia during the Asian summer monsoon and south-easterly offshore airflow from that continent pass over Indonesia and contributes to the Asian summer monsoon.

Assessment of the catchment hydrology is therefore crucial to ensure that future developments will not cause unacceptable harm to the environment. So calculation of the water budget in the catchment should include ([2], [5]):
- Estimation of effective rainfall intensities, evaporation and natural runoffs.
- 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% of all tropical rainstorms exceed 25 mm/hr, a rate that causes the rainfall to be erosive ([2], [3]). In contrast, temperate areas are estimated to receive only 5% of their rainfall in such intense storms. During May-October months, 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.

3 Characteristics of Citarum catchment

One of the complex tropical catchments is the Citarum catchment, West Java, Indonesia. Fresh water availability in recent years has proven to be scarce, and therefore with a distinct economic value. Increase in population density, growing economy and threatened natural environment all depend on reliable supply of good quality water. 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\textsuperscript{3}. The Java Island contains about 60% of the country’s population of 200 million ([6], [7]). The average annual runoff per capita in Java is much lower reaching about 1750 m\textsuperscript{3} and is widely distributed across the catchment. This causes many problems such as drought in dry periods and floods in wet periods. The Government of Indonesia has recognised the importance of good planning and management system for realising sustainable water practice. As such, local and regional management units have been developed to tackle the problems with water practice in the Citarum catchment.

3.1 Hydrological characteristics

The total surface area of the Citarum catchment is about 11 510 km\textsuperscript{2}. The population of one of the heavily populated cities in the catchment, Bandung City, is more than 10 millions. 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 long into the Java sea, close to and north-east 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 flows northwards to 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\textsuperscript{3}. Further downstream follows the Cirata Reservoir, which was built in 1988 and has a capacity of 2 billion m\textsuperscript{3}. Last in series lies the Jatiluhur Reservoir, built in 1963, with a capacity of 3 billion m\textsuperscript{3}. The Saguling and Cirata Reservoirs are mainly used for hydropower generation and fresh fish farming.
While the Jatiluhur Reservoir serves more purposes, such as, 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%), low wind speed (<2m/s) and evaporation. The average annual rainfall over the Citarum catchment is about 2500 mm ([6], [7]). However, in the upper catchment, upstream of the Saguling Reservoir, the annual rainfall is about 4000 mm. In the coastal plain near Java Sea, however, the 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 found to be less than 1500 mm, much drier than that of 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. The seasonal variations in rainfall and surface runoff rates over the catchment are found to be strongly correlated. Low rainfall intensities occur between the June-October period. In wet season (November-May), about 66% of the runoff water are spilled into the Java Sea, largely as excessive water flow.

The estimation of potential and actual evapotranspiration rates is also crucial in calculating the water budget in the catchment. From the past records of collected data from the meteorological stations cited over the catchment, average monthly values of the potential evapotranspiration was estimated for both lowland and upland areas ([3]). From this, it was found that the actual evapotranspiration rates are generally about 70% to 85% of that of the potential evapotranspiration, which was also found to be have higher values in upland regions that those in lowland regions throughout the year.

3.2 Land use changes

In the Citarum catchment, the municipal, domestic and industrial water demands is about 5% of the total runoff, however only 0.5% of the total runoff is withdrawn. While the irrigation demand is 5% of the total runoff volume, from which only 3.5% are effectively withdrawn from the system. Furthermore, about 6% of the Citarum water budget are withdrawn from the surrounding areas ([3], [8]). As such, most of the runoff is not utilised in an appropriate manner, and hence the need for a sustainable and efficient water management. The current land use in the Citarum catchment is given in Table 1. As can be seen, 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 most populated areas are located in the middle and upper parts of the catchment.

3.3 Groundwater subsidence

In general, but particularly in the middle and upper Citarum sub-catchments, groundwater is abstracted as source of domestic and drinking water. In Bandung area, groundwater is heavily used for industrial water supply as well. That excessive groundwater abstraction has resulted in decline of groundwater depths and pollution of the groundwater ([4], [5], [9]). The hydro-geological profile of the Bandung Plain has changed in recent years as a result of the industrial
Table 1: Land use in the Citarum catchment

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Surface Area (ha)</th>
<th>% of total land use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigated areas</td>
<td>334 000</td>
<td>29%</td>
</tr>
<tr>
<td>Non-surface irrigated agricultural areas</td>
<td>364 000</td>
<td>32%</td>
</tr>
<tr>
<td>Forest</td>
<td>213 000</td>
<td>18.5%</td>
</tr>
<tr>
<td>Human settlements (urban/industrial/rural)</td>
<td>86 000</td>
<td>7.5%</td>
</tr>
<tr>
<td>Swamps and fish ponds</td>
<td>46 000</td>
<td>4%</td>
</tr>
<tr>
<td>Infrastructure, surface water, uncultivated areas</td>
<td>108 000</td>
<td>9%</td>
</tr>
<tr>
<td><strong>Total SWS Citarum</strong></td>
<td><strong>1 151 000</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Figure 1: Pollution sources and cycle within the catchment
development of the area. Before industrial development, water levels were above the groundwater table, resulting in artesian conditions. In recent years, however, this has changed dramatically, resulting in groundwater being abstracted from shallow aquifers downward to the semi-confined aquifers.

Recent deforestation and change in land use in the catchment have also caused excessive soil erosion. About 60% of soil erosion occur in slopes greater than 40%, while higher erosion rate of 90% occur on slopes in excess of 15%. The eroded soil causes increase in sediment budget in rivers and the reservoirs downstream, hence decreasing the soil productivity and reservoir capacities. As a result, peak run-off and flood risks increase, which result in turn in less infiltration rates to the groundwater ([10]). One obvious solution to the erosion problem would be reforestation of land steeper than 40% slopes. This, however, could pose a problem due to agriculture use by local populations in these areas. On the other hand, deforestation of regions with smaller slopes can reduce erosion rates by 40% to 70%. Most of eroded sediments are trapped in the Saguling reservoir causing reduction in its capacity as well as in its life expectancy.

3.4 Water quality

Due to rapid industrial development and growing population in the upper Citarum catchment, particularly in the City of Bandung, deterioration of quality water remains the main threat in present as well as for future developments ([6], [7]). 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 noticeably increased. In the Citarum River, the average BOD concentrations in 1993 recorded was 10 mg/l, and in the region upstream of the Saguling reservoir was over 20 mg/l, well above the standard BOD concentration which should be 6 mg/l. In 1994, these concentrations were 18 mg/l and 40 mg/l respectively. However, downstream of the Saguling reservoir, the recorded BOD concentrations were found to be within the permissible standards. As such, the Saguling reservoir is acting, in effect, as a treatment plant for the incoming water and protecting the downstream part of the Citarum River from high pollution levels caused by the heavily presence of domestic and industrial waste, including heavy metals and Ammonia ([11], [12]).

Pollutant substances entering into the water system are due to the degradation of disposed solid wastes or by wastewater discharges ([13]). The total pollutant loads are generally divided into two main types. These are gross and net pollutant loads, as can be seen in Figure 1.

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 Saguling Reservoir. This situation causes water quality in the Saguling reservoir to fall much below the standard limits, particularly during dry periods. Downstream reservoirs, i.e. Cirata and Jatiluhur, however, have much better water quality standards.

As stated earlier and 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 Saguling reservoir; Middle Citarum - between
the Saguling and Jatiluhur reservoirs; and Lower Citarum – downstream of Jatiluhur reservoir up to the Java Sea. Table 2 gives the total amount of organic waste load generated 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 ([6], [7], [11]). As can be seen in Table 2, domestic wastewater is considered 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% of the catchment population are located, waste discharges are disposed of directly to local rivers by 60% of the population, while the remaining 40% use septic tanks, latrines, ponds or fields. In the middle Citarum, again around 59% of the population use direct disposal methods and the remaining 41% use indirect methods. Finally, in the lower Citarum 53% of the population use direct methods and 47% practice indirect disposal methods respectively. Organic pollution from agricultural land causes also considerable pollution by fertilisers and pesticides, which usually include nitrogen (N), phosphorus (P) and potassium (K).

Table 3 shows the estimated future pollution load in the Citarum catchment from various sectors and activities, presented by BOD/day values ([8]). As can be seen, the domestic waste load has the biggest contribution factor to pollution follows by industrial waste. While agricultural waste, though significant, has the lowest contribution.

4 Problems with water demand

Domestic and municipal Sectors in larger cities consume much 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% for Bandung area, 20% for nearby sizeable urban areas and only 10% 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 less extent with surface water, such as the West Tarum Canal for the greater Jakarta City. The efficiency of the PWS system is further deteriorated by major problems in the network itself through leakage.

The largest consumer of water in Citarum 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 is within the Citarum catchment ([8], [11]). This again stress on 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 it during dry times. Finally, the estimated total annual irrigation water demand in 1995 within the boundaries of the catchment has been estimated to be about 5771 m$^3$. 

Table 2: Estimation of organic waste in the Citarum catchment (1991-1995)

<table>
<thead>
<tr>
<th>Pollution Sources (BOD)</th>
<th>Upper Citarum (x 10^3/day)</th>
<th>Middle Citarum (x 10^3/day)</th>
<th>Lower Citarum (x 10^3/day)</th>
<th>Total BOD (x 10^3/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>56.16</td>
<td>12.08</td>
<td>24.07</td>
<td>92.3</td>
</tr>
<tr>
<td>Industry</td>
<td>43.67</td>
<td>1.64</td>
<td>12.06</td>
<td>57.37</td>
</tr>
<tr>
<td>Agriculture</td>
<td>1.85</td>
<td>1.96</td>
<td>5.99</td>
<td>9.8</td>
</tr>
<tr>
<td>Livestock</td>
<td>11.30</td>
<td>5.87</td>
<td>5.87</td>
<td>23.04</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>118.83</strong></td>
<td><strong>21.55</strong></td>
<td><strong>47.99</strong></td>
<td><strong>188.37</strong></td>
</tr>
</tbody>
</table>

Table 3: Estimation of total pollution load in the Citarum catchment for year 2025

<table>
<thead>
<tr>
<th>Source of waste load</th>
<th>Upper Citarum</th>
<th>Middle Citarum</th>
<th>Lower Citarum</th>
<th>Total Waste load for Citarum catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic waste load</td>
<td>167.6</td>
<td>39.9</td>
<td>76.4</td>
<td>283.9</td>
</tr>
<tr>
<td>Industrial waste load</td>
<td>85.16</td>
<td>5.85</td>
<td>20.69</td>
<td>111.7</td>
</tr>
<tr>
<td>Agricultural waste load</td>
<td>1.85</td>
<td>1.96</td>
<td>5.99</td>
<td>9.80</td>
</tr>
<tr>
<td>Livestock waste load</td>
<td>11.30</td>
<td>-</td>
<td>11.75</td>
<td>23.05</td>
</tr>
<tr>
<td><strong>Total waste load</strong></td>
<td><strong>265.91</strong></td>
<td><strong>47.71</strong></td>
<td><strong>114.83</strong></td>
<td><strong>428.45</strong></td>
</tr>
</tbody>
</table>

**Population**  
9,133,000  
1,933,000  
4,077,000  
15,142,000
In the Bandung area, about 90% of water usage in industry are obtained from groundwater sources. The remaining 10% of water demand are derived from the Citarum River and its tributaries. In Bandung area, almost 100% of the industries fulfil their water demands by using groundwater, from which about 40% of industries abstract water from unlicensed sources. In addition, about 105 million m³/year of water withdrawn by the industrial sector are from the Citarum water resources, of which about 80% 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% 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. While because of the increasing demand for water resources, the Jatiluhur reservoir is inclusively used for supplying water only for domestic, municipal, industrial sectors ([8]).

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In industrial zones, shallow groundwater levels were subsided by 0.1m/year to 9m/year, in the intermediate depths by 1.5m/year, and 12m/year in the 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/year. This situation has caused a change to the groundwater flow patterns. More notably, subsidence 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 problem is found in the Bandung area yet, it may become one in the near future.

At the present time, 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 ([8], [11]). Various laboratory analyses were carried out on chemical, physical and bacteriological characteristics of water sources (shallow water and deep wells for samples taken from in rural, urban and industrial areas. The results of research have confirmed the presence of heavy metals, such as nickel (Ni), mercury (Hg) and the detergent contents, 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.

In order to manage the groundwater resources in the catchment, many measures could be used, such as introducing licensing scheme 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.
- Limiting industrial expansion to availability of surface water.
5 Planning concept

In order to realise a consistent management style for water resources; a concept for catchment planning has to be developed where the water resources system can be accurately identified ([14], [15]). In general, the water resources system consists of:

- Natural resources system, which includes surface and groundwater resources, water infrastructure, and the natural ecosystems.
- Socio-economic system, which includes agricultural, industrial, and municipal sectors. The system demands are related to the natural resources system, by water quantity and quality requirements.
- 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 ([16]). Water resources planning should include analyses of the natural resources the socio-economic systems. The proposed concept of catchment analysis is given in Figure 2. The different scenarios presented on Figure 2 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 (such as dams, diversions, etc.) or non-structural (legal measures 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.

6 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 to 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 sources demands. One very essential step is the reduction of pollutant loads by taking all necessary.
CURRENT SITUATION

Natural Resources System
Climate, (geo)hydrology
Infrastructure, Environment

Socio-economic System
Land use, Population
Rural, Urban, industry

Administrative System
Law, Regulations, Institutional

Formation of Major Development Issues

FUTURE PROJECTIONS

Population Projections
Spatial, Economic planning

Scenarios, Water demand, Pollution loads

Decision Support System

Measures
Structural
Non-structural

Evaluation

Strategies
Water Supply
Water quality
Groundwater management
Environment, etc.

Catchment Water Resources

Figure 2: Planning concept for the Citarum catchment
measures, particularly in densely populated areas. Such measures may include effective full-scale waste treatment facilities and urban drainage system.

Land use patterns influence the requirements of future water availability and also determines the anticipated distribution of waste loads. Therefore, the need for preparing an integrated land use planning and regulation programme 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 are provided.

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References