Working Paper

Models of the Water Systems in Mauritius

Ferenc L. Toth

WP-92-71
September 1992

IIASA

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ABSTRACT

Criteria for sustainable development in terms of managing a nation's water resources include the availability of water in required quantity and appropriate quality. This paper presents a set of water models developed for the IIASA/UNFPA Mauritius Project for use as an integral part of a system of models including demographic, economic, and land use models. The paper identifies the most important factors determining the available freshwater resources in Mauritius (climate, geology, hydrology), and presents a simple approach to modelling water supply. Based largely on Mauritian data sources, the most important components of freshwater use are also identified and a model with appropriate linkages to demographic and economic processes is presented. Next, a dynamic model of water quality in the lagoons is discussed. Finally, possibilities to test various water management strategies with the model and the related scenario development procedures are presented.

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Appendix. Technical Description of the Water Model

MODELS OF THE WATER SYSTEMS IN MAURITIUS

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The IIASA/UNFPA project on Population and Sustainable Development is intended to serve the needs of development planners and policy makers in developing countries who confront numerous trade-offs between the immediate needs to solve current problems and the long term needs to pursue sustainable development strategies, between development objectives and possible resource and environmental constraints, and between maximizing economic efficiency and improving social equity. In addition, they find that these problems are characterized by significant scientific uncertainties, low levels of social consensus, and enormous decision costs. The goal of this project was to develop an integrated system of computer models and data bases that will help strategic planners address these problems by analyzing long term interactions of population, socio-economic development, and the natural environment. The system should also be useful for educational purposes by providing user-friendly tools for in-depth analyses of the various system components (demography, economy, environment) and for synoptic analyses of the linkages and interactions among those components.

This paper is concerned with the water systems in Mauritius. Section 1 identifies water management and land use as the most important long term environmental issues in Mauritius. Section 2 provides a brief overview of various components of water systems within Mauritius. The conceptual framework and principles of operation of the surface freshwater model are described in Section 3, followed by the presentation of the lagoon model in Section 4. Technical descriptions and the data base for these models constitute the Appendix. Finally, Section 5 presents the user interfaces of the water models, through a discussion of the principles for scenario construction and the user-specified water policy variables.

1. INTRODUCTION

Mauritius has, so far, been able to avoid the disruptive environmental implications of hard-core poverty and fast economic development. Although there are signs of environmental degradation, up to now they have not been very severe. Environmental problems in the past were largely episodic, localized events. Flyash emission from burning bagasse at sugar factories, release of dust at stone crushing plants, and exhaust gas emissions of vehicles in congested urban areas are the most typical forms of air pollution (MEQOL 1991). Due to massive fertilization of sugar cane plantations, high values of nitrates (30 to 50 mg/l) have been measured at some groundwater extraction points, but they were short-lived (CWA 1991). There are also localized water quality degradation problems in estuaries near urbanized or industrial areas, and in closed segments of the lagoons in the vicinity of high density tourist locations. By and large, however, various components of the environment in Mauritius are still in a relatively good condition.

Mauritian society has successfully completed demographic transition. Fertility rate dropped to near-replacement level within in a few years in the late 1960s and early 1970s (Lutz and Wills 1991, Xenos 1991). The Mauritian economy is beyond the take-off phase of economic development; real annual GDP growth rates scored between 5 and 9 per cent in the mid 1980s, industry grew between 8 and 16 per cent annually, and industrial investments doubled (747 to 1480 Million Rupees) between 1984 and 1988 (CSO 1988). Unlike in most LDCs, especially in the African region, future pressure on the environment will not originate from fast growing numbers of additional people, but rather from the increasing wealth of the slowly growing population which is expected to stabilize at 120 to 140 per cent of the present population size (Prinz 1992).

Now beyond demographic transition and economic take-off, Mauritius has reached a critical phase of development. In less than a decade, the government has successfully solved the problems of the early 1980s: inflation, unemployment, balance of payment problems in the domestic economy and associated foreign exchange shortages, debt problems in the international economic relations. Now there is a possibility to look further into the future to assess the full range of available development options (see, for example, MIIT 1990). Current economic policies will shape the next cycle of investments and may lead to changes--desired or undesired--in the economy, society, and environment of the country.

At this threshold, there is now increasing concern about longer term prospects for economic development, and for the environmental quality to support it. An option that has gained some popularity in many developing countries is to speed-up economic development at the expense of the environment and restore the environment later when it is easily affordable. This is simply not viable for Mauritius for several reasons. First, due to the small area and high population density, relatively small degradations would be felt even in the short term, in the form of health effects for the population and natural resource constraints for the economy. Second, island ecosystems tend to be more fragile than their continental counterparts, making it possible that minor degradations may be irreversible. Third, the tangible finiteness of the resource base (soils, groundwater) makes any loss much more painful than at other locations where reserve areas are available.

The concerns expressed above support the proposition that the sooner Mauritius finds its way towards sustainable development, the better. This was recognized, in the late 1980s, by the Government of Mauritius and several international agencies. As a result of their joint effort, a National Environmental Action Plan was developed. This meant that Mauritius became the first country in Africa to implement an environmental strategy in accordance with the recommendations of the Brundtland report: economic growth and environmental protection are to be considered as mutually reinforcing (Rathnam and Opsal 1989). "The foundation of our national policy is: to protect and improve the environment as well as to foster harmony between the quality of life and sustainable development for the economic, social and cultural benefits of the present and future generations" (GOM 1991:1).

The geographical location of Mauritius reduces the usually long list of environmental concerns to problems related to water and land use. Although incidents of local visibility degradation and dust pollution are occasionally reported, their long term impacts are negligible. Air pollutants are swept out by the almost permanent medium speed (7-16 knots) winds and distributed over the ocean. (In the least windy month of April, there are less than 3 days of calm period altogether.) ****Deforestation was by and large completed by the 1930s leaving a meager one per cent covered by native vegetation.***

This leaves us with two major environmental and resource management issues. First, the issue of allocating land to its most suitable use among the many competing land use options (conservation, tourism, settlement, agriculture, industry), combined with a sustainable management of land use. These issues are addressed by Holm (1992). The second issue is a major concern for environmental management : water. This paper deals with the surface freshwater system and the lagoons of Mauritius.

The highly acclaimed Brundtland report has been severely criticized for its failure to adequately address the issue of the role of water in sustainable development (Falkenmark 1988). Mankind's interaction with the global water cycle has substantially intensified over the past few decades. Even more significant are the disruptions to, or degradation of, water resources at the regional and local scale in many parts of the world. The advantage that Mauritius has is that, being an island, inhabitants have complete control over their own water resource base.

Sustainable development in terms of water managements implies a long term availability of water in required quantity and appropriate quality. The aims implicit in any meaningful sustainability study means that we are primarily concerned with gross, highly aggregated figures and indicators which detect and analyze imbalances at this aggregated level. As a consequence, attention to regional and seasonal imbalances are omitted in our water quantity analyses, along with episodic high levels of pollutant discharges and the associated environmental damages.

The modeling approach for the water part of the Mauritius model system was selected to fit the purposes of a long term, sustainability study. Additional selection criteria included the special characteristics of the hydraulic system of the island, and the availability of data on both quantity and quality aspects of natural water systems and water use from Mauritian sources.

2. OVERVIEW

Mauritius' hydrological network follows the typical pattern of small volcanic islands. Rivers originate in the center and radiate towards the coast through a dense and heterogeneous river network. (A map of drainage areas and river basins is presented in Figure 1). Were the island a perfect circle, the average river length would be 24.3 km. Of the 93 rivers registered by the Central Water Authority, the shortest one is 130 meters long (des Galets), while the longest river is 38.4 km (Grand River South East). The average river length is 9.38 km.

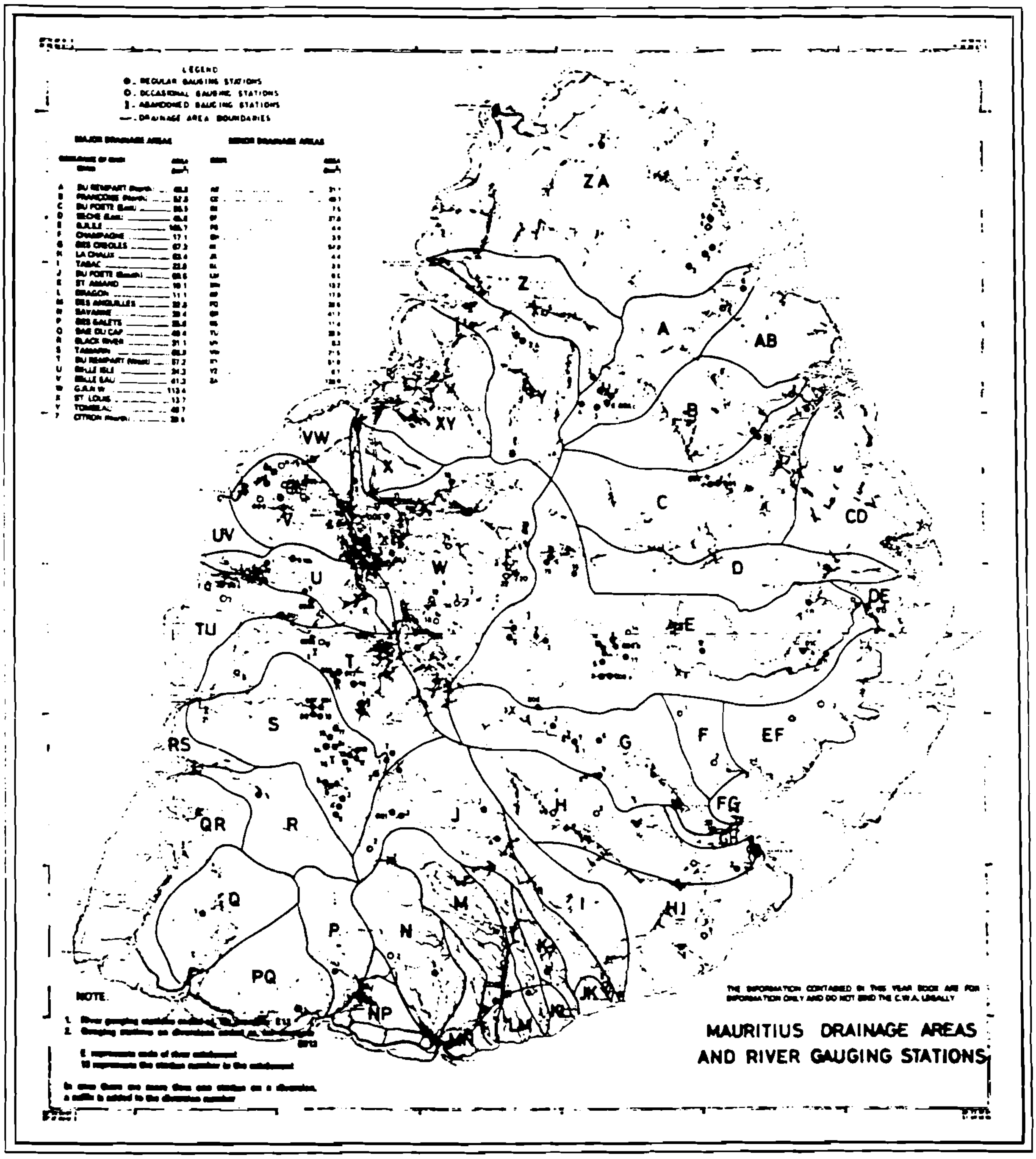


Figure 1. River basins in Mauritius. Source: CWA.

In most regions, the rivers interfere with the rich and versatile ground water systems of the island. A geological heritage of volcanic origin is present in the form of aquifers. These are permeable basaltic lava rocks that lie between two relatively impermeable strata. The aquifers receive their recharge in an area where they are exposed at the surface (mainly in the Central Plateau region). The infiltrating water percolates downward through openings in the rocks (spaces between the grains of sedimentary rocks, lava tubes, openings between lava flow layers) until it reaches an impermeable stratum at the bottom. At this point, water accumulates in the rock. Wherever the land surface intersects the water table, the water flows out as springs.

An example of the diverse relationships between surface and ground water systems is found in the Central-East region of Mauritius. River Françoise provides a significant amount of water to the underlying aquifer, while further downstream, the same aquifer feeds Deep River, especially during the dry season. In the north, several perennial rivers (River du Tombeau, River des Calebasses and others) are known to be connected to the aquifers of the region. In the south, flow values of River Tabac were observed to be connected to fluctuations of the water table in the region, indicating that there is a water transfer from the river to the aquifer (CWA 1991).

This geophysical network is operated by the annual climate cycle. The moderate tropical climate dominating in Mauritius is characterized by two seasons. Rainy and warm summers (November to April) often bring tropical cyclones--which are sometimes devastating, but they also provide large amounts of rainfall. In cyclone-free years, precipitation is normally not sufficient for surface reservoirs to completely refill and underground aquifers to fully recharge. Cooler and drier winters (May to October) sometimes bring droughts, especially between September and November. The amount and spatial distribution of long term average rainfall for four characteristic months are presented in Figure 2. Monthly average rainfall data for the whole island is summarized in Table 1, and demonstrate that the annual distribution of precipitation in Mauritius is uneven though not extreme.

Table 1. Monthly rainfall, Mauritius average. Source: Padya 1989.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
mm	295	280	309	216	161	140	133	124	83	74	101	206	2122
% of annual	13.9	12.2	14.5	10.2	7.6	6.6	6.3	5.7	3.9	3.5	4.7	9.7	100

The relatively high annual levels of rainfall do not guarantee that sufficient amount of water is always available. A major source of water loss in Mauritius is evaporation and evapotranspiration, both direct functions of the heat input which is in turn determined by the net global radiation. Data on sunshine hours (annual mean) and monthly mean temperatures (for February and August) are shown in Figure 3. The spatial distribution of the resulting mean annual evaporation rates is presented in Figure 4.

Since the early days, people in Mauritius have increasingly interfered with the island's surface and underground water systems. First, inhabitants of the island were fortress-minded and coast-bound. Their top priority was a well protected and easily defendable port--as they depended on external linkages for their food supplies--and the availability of fresh water. Over the centuries, with the growth of population and the spread of economic activity, the natural conditions of the island were modified. Land was cleared for new sugarcane plantations, thus modifying the rainfall-runoff conditions and evapo-

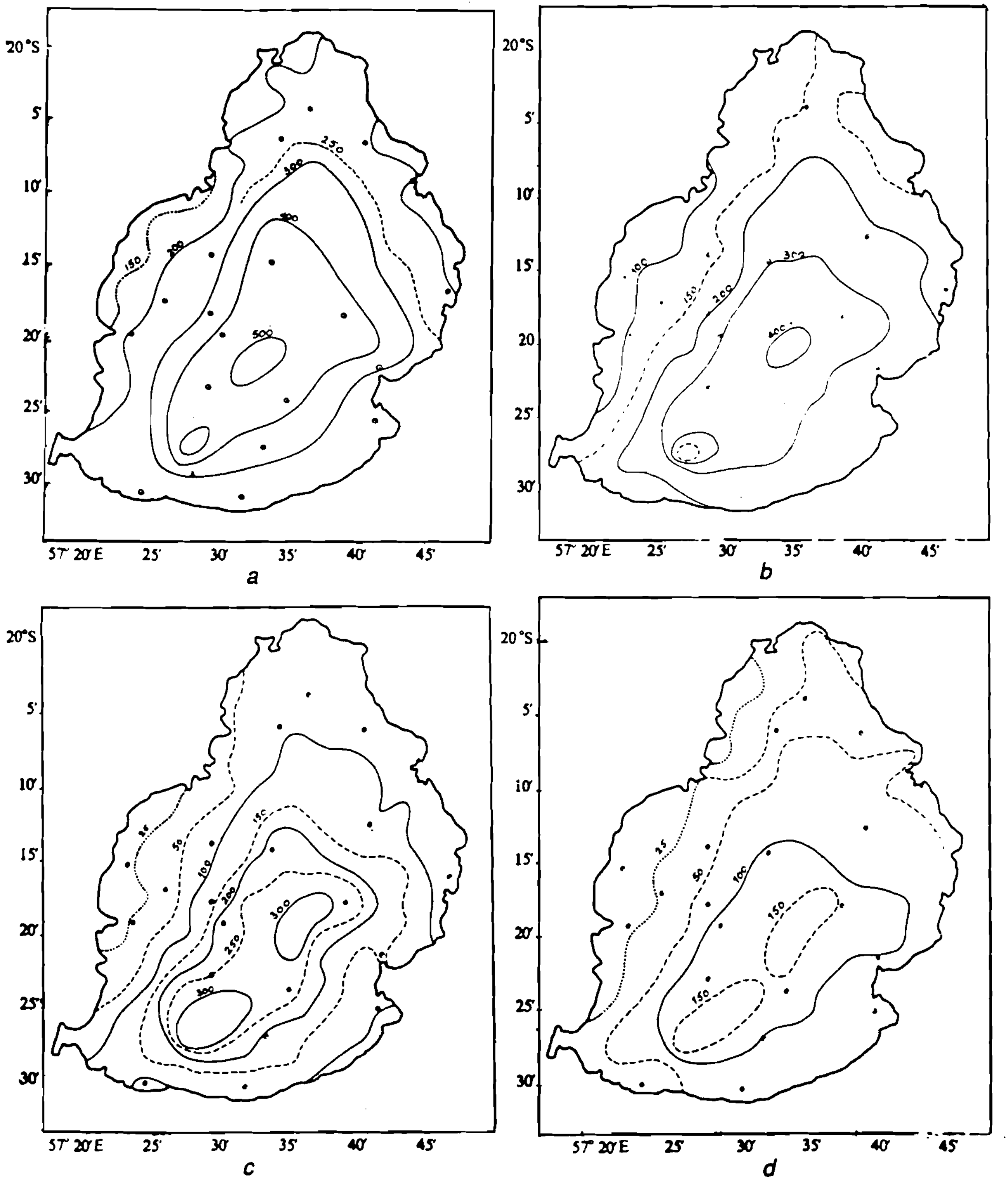
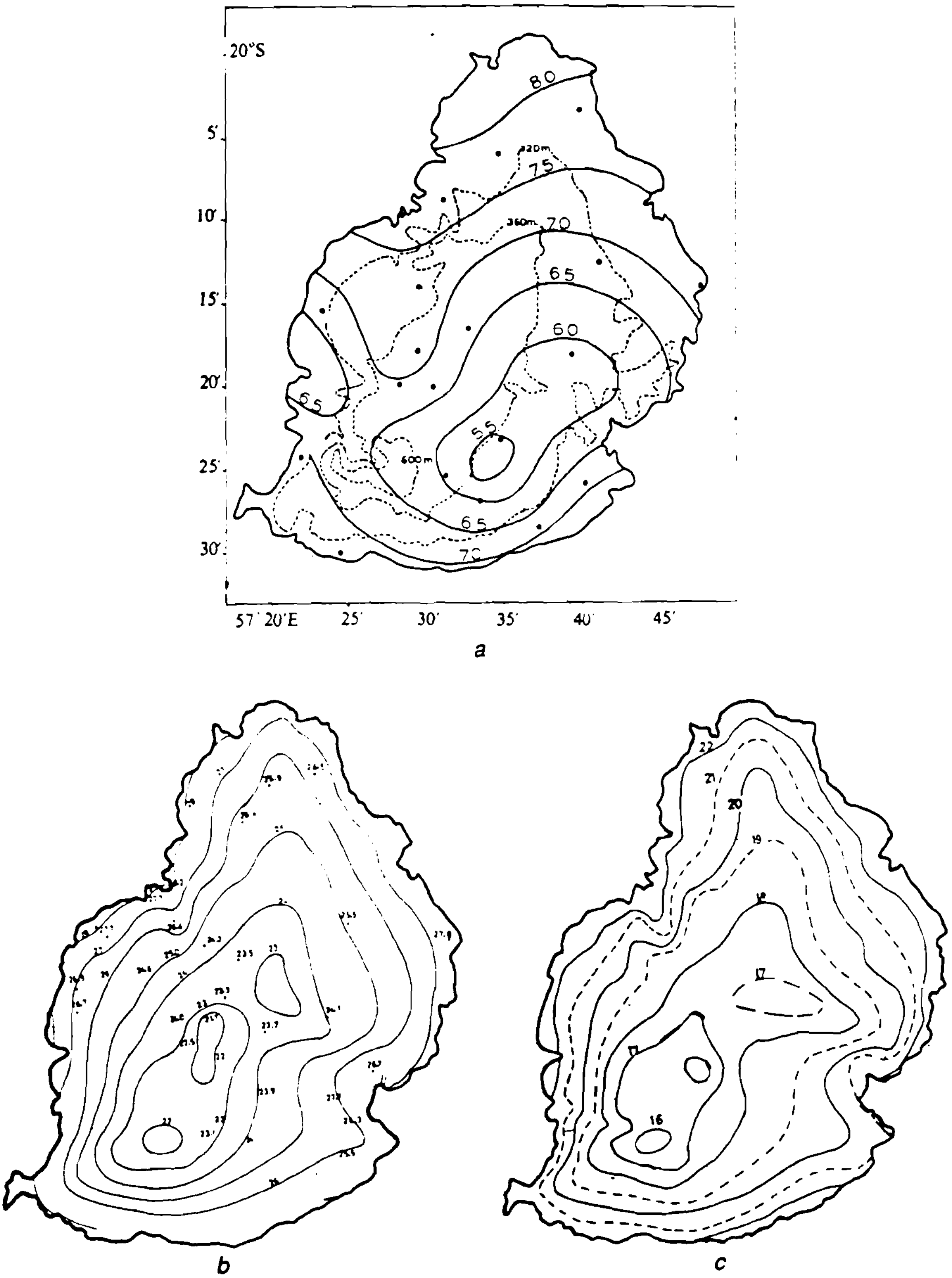


Figure 2. Normal monthly rainfall 1951-1980 (mm) for January (a), April (b), July (c), and October (d). Source: Padya 1989.



a

b

c

Figure 3. Radiation and temperatures. (a) Annual mean duration of bright sunshine in hours per day. (b) and (c): Mean monthly temperatures (°C) in February (b) and August (c). Source: Padya 1989.

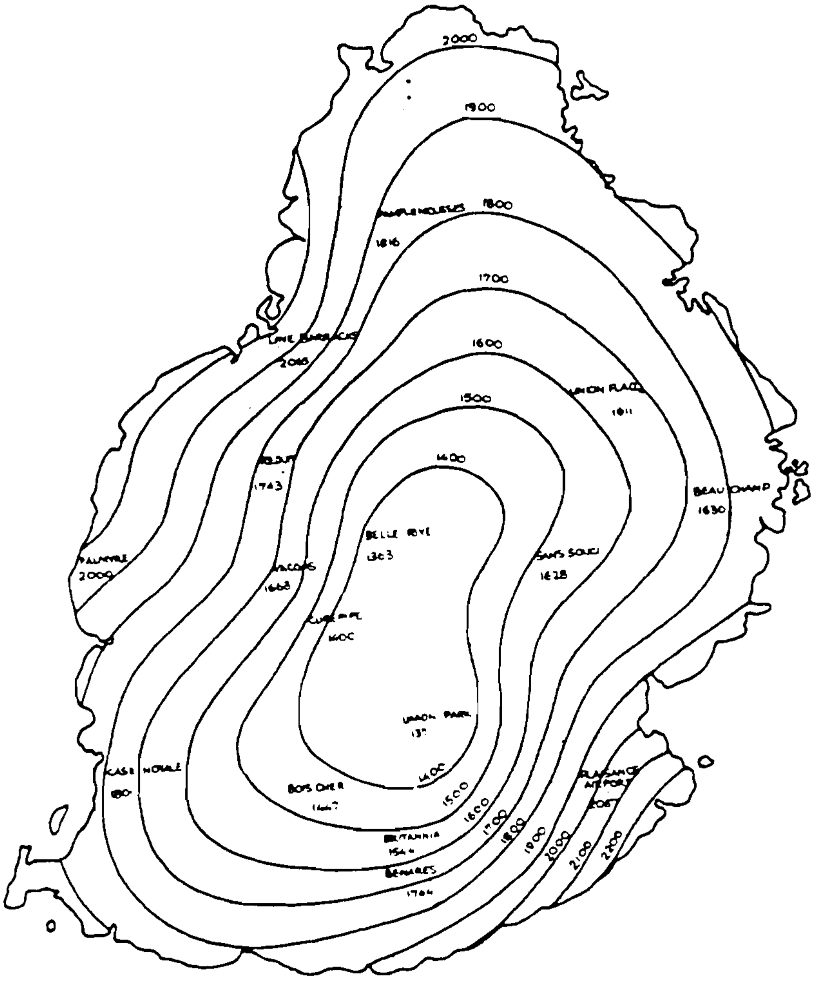


Figure 4. Mean annual evaporation (mm). Source: Padya 1989.

transpiration ratios. Water diversions were created to transfer water to areas where it was not available but was badly needed. Boreholes were drilled and pumping stations installed in order to utilize ground water resources.

The present freshwater network includes 93 rivers in 47 river basins with more than hundred diversions on rivers, 5 man made lakes, 2 natural lakes and 9 storage reservoirs on the surface. The underground system includes four main aquifers exploited through 239 boreholes and small wells at the rate of 80 to 100 thousand m^3/day. Major flows in the water system are presented in Figure 5.

This system has to support a water-intensive economy. An estimated one-fifth of the agricultural area is irrigated--approximately 15,000 hectares which is largely covered by sugar cane plantations. The most important industrial sector is also a heavy water user: in 1987 2.83 million m^3 water was consumed by the textile industry, the bulk being used for dying textiles in the dye-houses. The water demand of the most successful sector of the 1980s in services--the tourism industry--has also increased drastically. In itself, the high population density of the island suggests a high density of water use by the domestic sector. The demand for the supply of clean freshwater is projected to increase over the coming decades in each sector (CWA 1989).

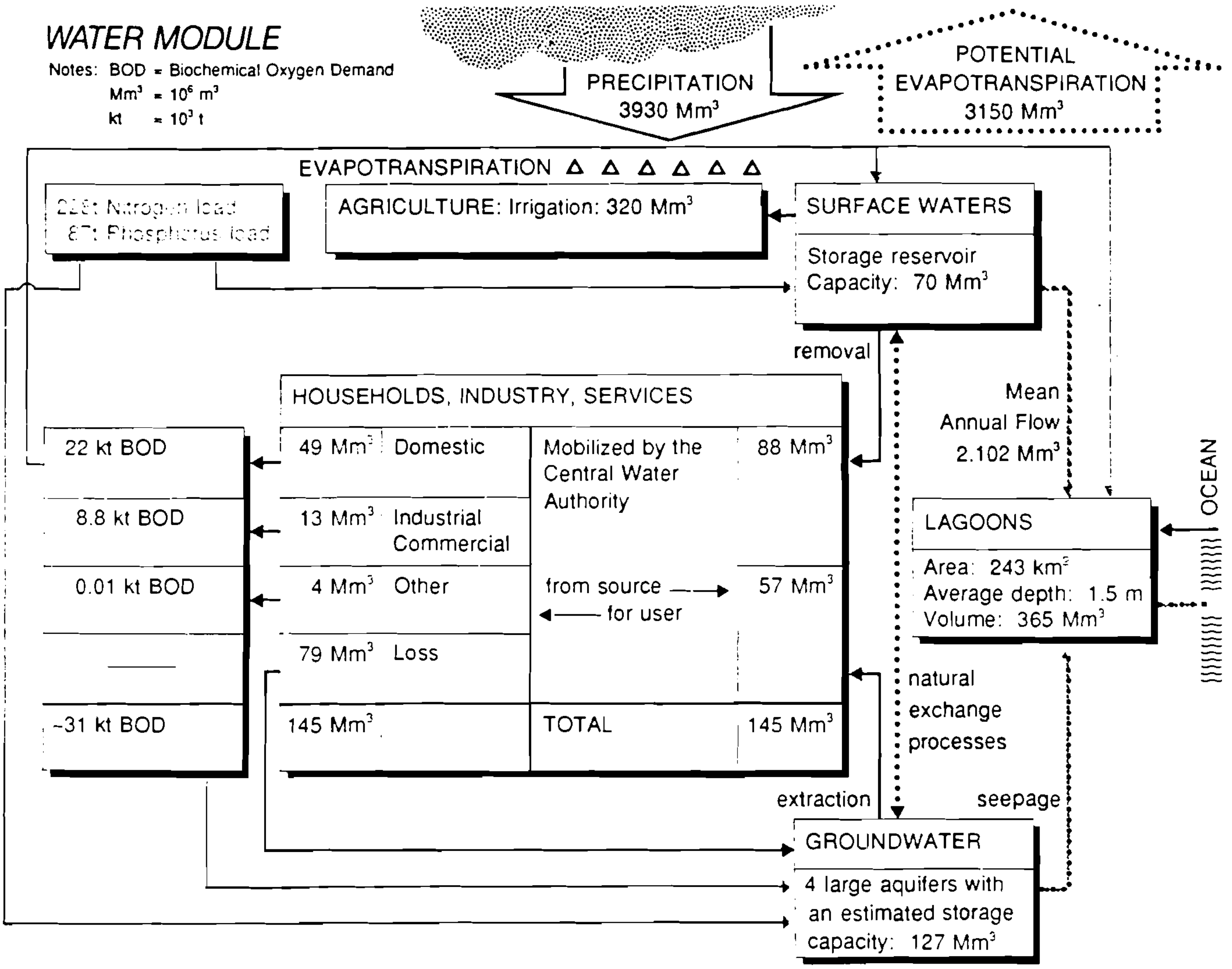


Figure 5. Major water stocks and flows.

In the past, the utilization of water resources successfully contributed to economic growth. However, evidence that indicates that this contribution has not been without a price is accumulating. The high Nitrogen levels (45-50 mg/l) which are occasionally measured in boreholes, especially in the Northern and Eastern regions during the sugar cane plantation period, are due to high levels of fertilizer use in the cane fields. Although there has been no apparent sign of an increasing tendency of Nitrogen levels, these values may indicate that the buffering capacity of the soils is becoming depleted. Very little is known about the fate of industrial pollutants discharged with the waste water. Dye-house effluents contain such pollutants as Ammonia, Chloride, Nitrate, Phosphate and Sulphate. Many dyes contain chromium and other heavy metals. Industrial effluents are discharged largely untreated. As the most typical waste disposal method is soak pits, most of these pollutants seep into the ground. There are no signs of any impact on the ground water system yet, but if this practice continues the Mauritians may well be building an underground chemical time bomb for themselves.

Because rivers in the island are short and relatively fast-flowing, there is little chance for pollutants to undergo biochemical degradation. However, this also implies that the possibility for deposition of pollutants in river beds and sediments is also very limited. The ultimate result is that most pollutants are transported by rivers to the lagoons, which are formed by a barrier reef around most of the island's coastline. They are shallow, partly open and partly semi-closed bodies of water that are regularly "renewed" by a relatively large volume of tidal exchange. Despite this, signs of local degradations of both water and sediment quality have been detected in several segments of the lagoon. It is therefore important to trace the fate of pollutants in the lagoons by examining the potential accumulation processes and the long term changes in concentrations of pollutants in the water and in the sediment.

Freshwater comprises a substantial part of the very limited natural resource base of Mauritius. Being a vital resource, there is a definite need to study the water constraints when we look at long term development options and want to ensure the sustainability of development. Studies and models must include both quantity and quality aspects. This involves modeling both the resource and the waste management implications of alternative development paths. The lack of appropriate data, together with the uncertainties associated with such long time horizons as the present project is examining, inhibit the building of very detailed models. On the other hand, there is no real for them. The level of aggregation in the water model corresponds to that of the economic model. Despite this, the approach chosen makes it possible to analyze long term trends and constraints, and to find a sustainable development strategy in terms of a long term balance between water supply and water requirements.

3. THE SURFACE FRESHWATER MODEL

The surface freshwater part of the water module is an integrated economic-ecological model covering both the quantity and quality aspects of water management. The primary objective of the model is to calculate the balance of water requirements (demand) and water availability (supply) for any given scenario of demographic and economic development according to the water policy specified by the user.

Some of the basic ideas used in this model originate from a study prepared by the Resources for the Future (see Wollman and Bonem 1971) in the 1960s. The RfF model in turn draws on the work done by the Senate Select Committee on National Water Resources (Wollman 1960). The water supply section of the Committee report was considerably improved by a study conducted by Löf and Hardison (1966).

The present model considers Mauritius as a single region. There are several arguments for and against this treatment. One could argue that the inhomogeneous hydrological network, along with the uneven distribution of population and economic activities would call for a regionally disaggregated approach. This would not be practical for several reasons. Firstly, the population and economic modules track demographic and development processes at the level of national aggregates. An attempt to decompose these processes for smaller regions would increase the complexity of the model to such an extent that--considering the area of the island--would simply not be justifiable. (The total area of Mauritius is far below the typical unit size in regional development and environment models.)

The second reason for the aggregated approach also follows from the small geographical size. It is relatively inexpensive to divert water from regions (watersheds) of abundance to those of shortage, or to allocate water intensive activities in regions where the resource is available. Similar arguments are valid on the water pollution side. One strategy would be to locate new polluting activities in regions where present discharge levels are low, thereby "spreading out" pollution around an average level (the model is doing just that). Alternatively, one could concentrate these economic sectors in specific areas,which would make the provision of treatment facilities economically more efficient and reduce pollutant discharge altogether (this option is also available in the model).

Supply of and demand for water are specified in terms of physical quantities in the water model. (An overview of the water model is presented in Figure 6.) For each time step, the size of population and the level and structure of economic activities are considered in order to calculate the demand for water. Demand is also affected by two water policy variables, which in turn determine the dilution flow component of water demand (see below). Firstly, the user's target for water quality, which is specified in terms of required water quality standards for rivers. Secondly, the user's decision about investments in waste water treatment.

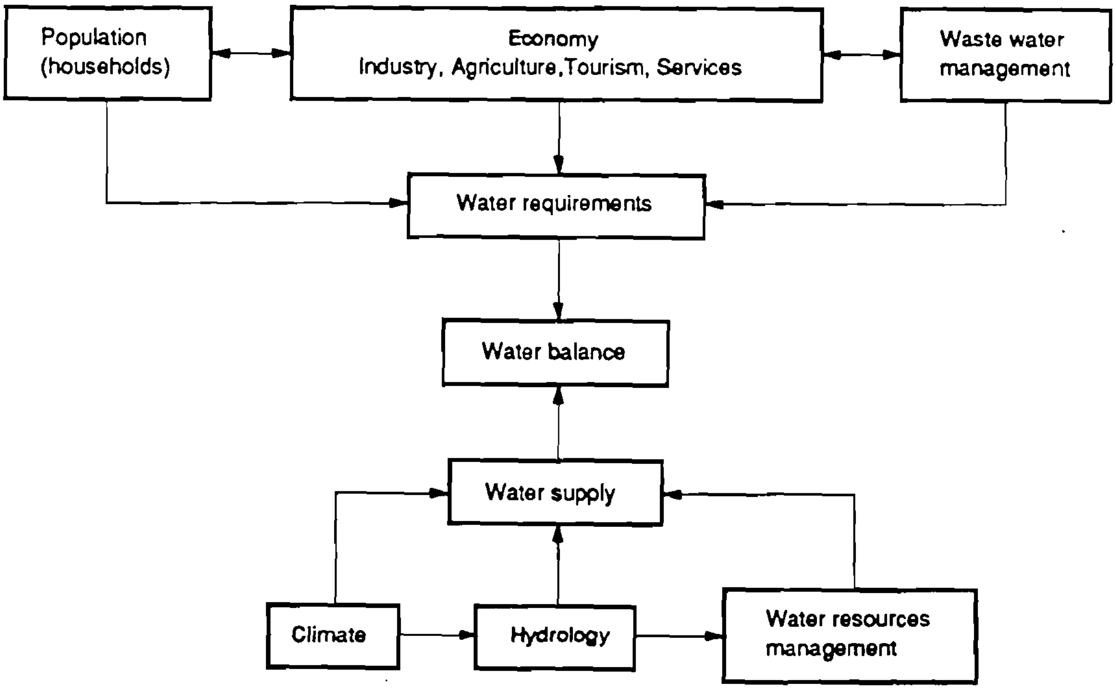


Figure 6. Overview of the surface fresh-water model.

Water supply is calculated on the basis of historical flow data. The policy instrument available to the user to increase the supply of water is to invest in storage facilities--that is, to construct new reservoirs.

Finally, the water balance is calculated in each time step through a comparison of supply and demand. As irrigation is the single biggest component of water demand, and the bulk of the irrigation water goes to sugar cane, it follows that the water available for sugar cane irrigation is the only feedback from the water balance to the other two models. The amount of irrigation water is automatically reduced to the level of water availability. This would, of course, affect sugar cane productivity. Nevertheless, the model gives a warning to the user that a water deficit is detected in the current scenario run. It is then left to the user to experiment with the water policy variables in order to establish whether water supply and demand can be balanced for the given scenario by implementing other water policies than restricting irrigation. If this is not possible, the intended development path is clearly not sustainable due to natural resource constraints.

3.1. Water Supply

In this model, the supply of water is measured in terms of aggregated minimum flow. This definition has the following three implications:

Firstly, water supply is measured by streamflow--the amount of water passing a gauging station or measuring device at any given time. Water supply is the frequency distribution of these measurements over time. The frequency distribution under natural (unregulated) conditions depends on the physical geography of the watershed. The amount of precipitation and its variation over time determine the "natural supply" of water; geology and topography influence the ratios for infiltration and runoff, and biogeography (vegetation cover) is the primary factor in evaporation losses (evapotranspiration). As presented in Section 2, the seasonal distribution of precipitation is uneven, though not extreme, in Mauritius. Correspondingly, flood flows are very high and low flows are relatively low, but most rivers are perennial. (Typical flow duration curves for rivers with large, medium, and small discharges are presented in Figure 7.)

The streamflow approach to water supply implies that the model does not allow either water imports from outside Mauritius or the desalination of sea water. None of these options are affordable under present conditions, and are likely to remain economically inefficient over the long term (e.g. the use of desalinized sea water for irrigation). The model also assumes that aquifers discharge into a surface water course, hence automatically including their contribution in the measures of surface flow. The diverse linkages between surface flows and the ground water system were presented in Section 2. These linkages demonstrate the important role of groundwater in measures of historical surface flows. There are no slowly recharging "stock-type" underground aquifers in Mauritius (like the Ogallala aquifer in North-America or the huge aquifer under the desert in Libya), therefore groundwater abstraction and recharge processes can be considered as additions and subtractions from the same resource of surface flows. A minor source of error can arise from the fact that past and present utilization of groundwater resources has not yet reached the maximum sustainable level. The historically observed minimum flow value should be revised upwards, to the extent additional groundwater mobilization can increase the minimum dependable flow (the bottleneck in the low-flow period), but this error is estimated to be below 3 per cent. As long as groundwater abstraction and recharge are kept in balance, the model provides a reasonably accurate representation of the water resources.

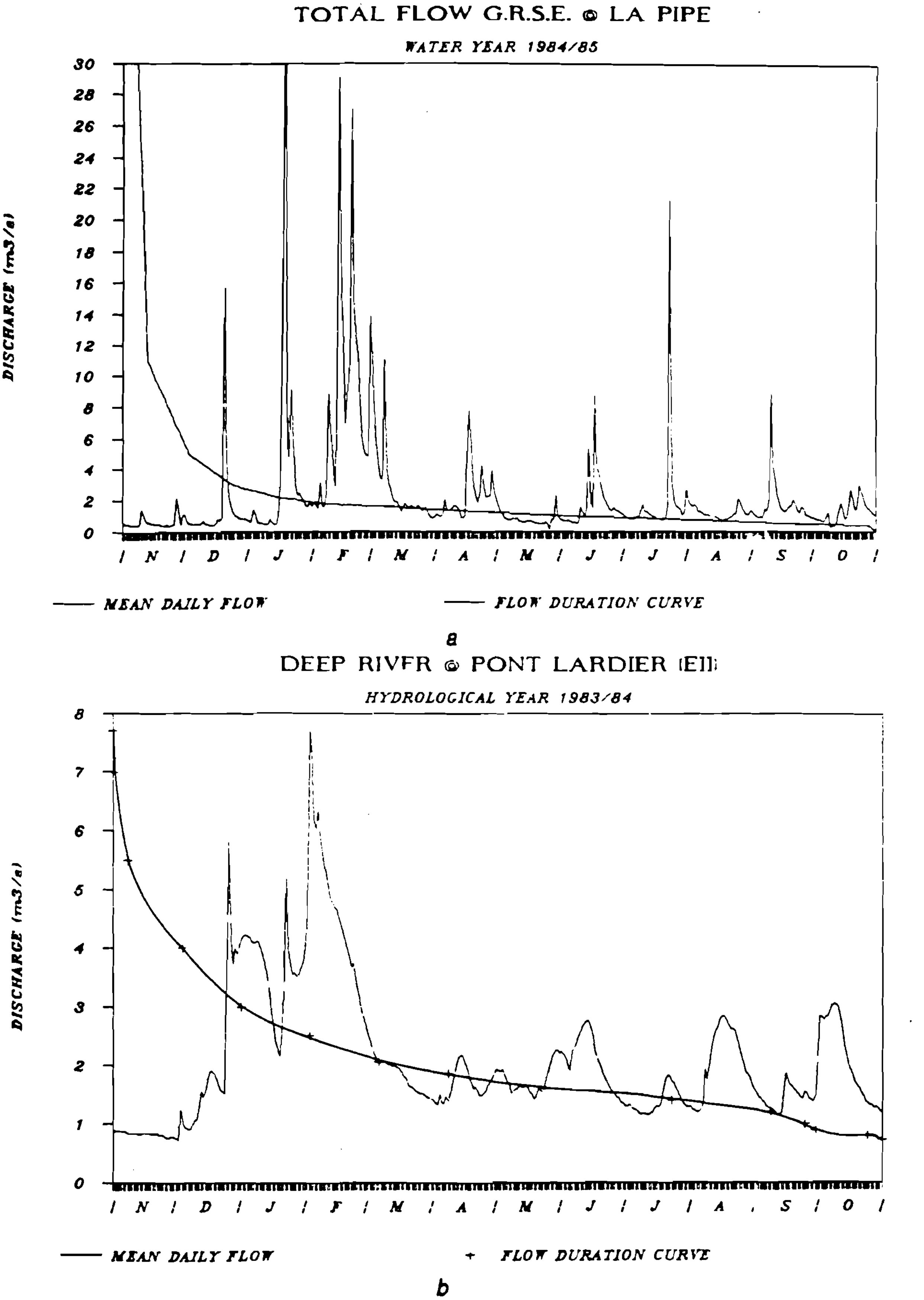


Figure 7. Typical flow duration curves for high (a), medium (b), and low (c) capacity rivers. Source: CWA 1988.

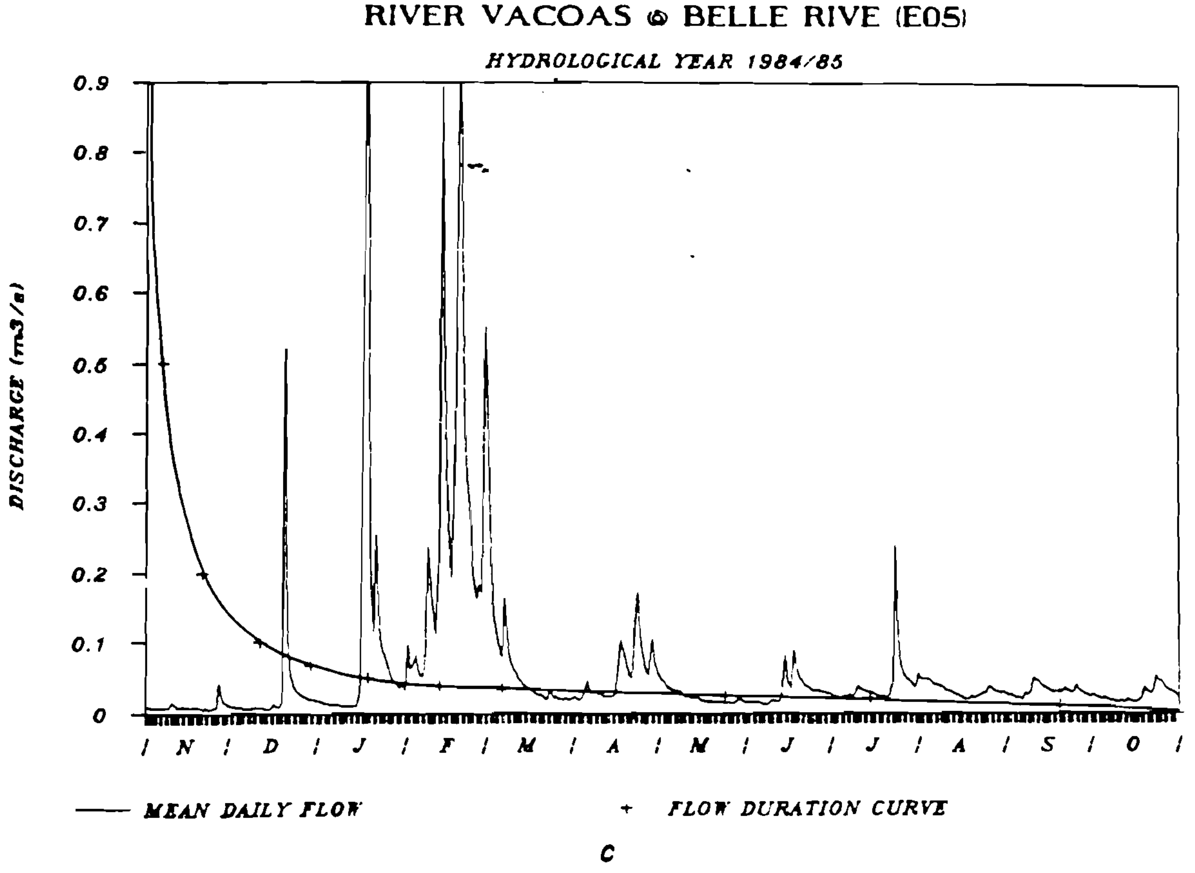


Figure 7. Continued.

Secondly, water supply is the minimum amount of water that is available at a specified level of reliability over time. It is also called the minimum dependable flow. In this model, the flow that is equal to or exceeded 95 percent of the time under present regulatory (storage) conditions is considered to be the present minimum flow. The minimum flow approach fits the overall objective of our model system: to find water management strategies that satisfy the water demand of population and economy over the long term, without extended periods of water deficiency when water-related activities would need to be reduced or temporarily suspended. Minimum dependable flow at 90 percent of reliability implies a 10 percent chance of deficiency. This corresponds to a deficiency period of more than one month every year when irrigation and water-intensive industrial activities (textile dying), the two most important foreign exchange earners, would need to be reduced. The economic implications of regularly returning periods of extended water shortage would probably be severe (reduced yields, lower industrial output). This supports the proposition that environmentally unsustainable development is also not affordable economically.

Thirdly, flow data from all watersheds are combined to provide the total amount of water available. Aggregated flow data indicate the sum of flow measurements from those gauging stations located closest to the discharge point in each watershed. Due to the special circumstances in Mauritius (irrigation is by far the biggest water user), and because the relatively short 20-30 year flow records do not account for the amount of water lost up-stream via irrigation, the minimum flow data have had to be modified in order to keep the model consistent. This was achieved by increasing the level of minimum flow by the amount of water lost (evaporated and evapotranspirated) due to irrigation upstream in the period when minimum flow values were measured.

Virgin or unregulated flow conditions can be modified by adding storage capacities to the hydrologic system. The purpose of additional storage capacity is to "smooth" the flood frequency curve by retaining water from flood flows and using it to increase the level of minimum dependable flow in periods of low flow. The theoretical maximum flow that could be achieved by maximum regulation is the mean annual flow. This is the level of water supply when the surplus flow gained from additional storage is equal to the evaporation losses resulting from the newly added storage facility.

Flood control storage requires special treatment in this formulation of a flow-storage relationship. Due to specific operating considerations, storage capacities created explicitly for flood control purposes are only partially useful for minimum flow regulation. As the river basin approaches maximum regulation, the need for separate flood control storage capacity decreases. The model takes care of this assumption by including only that fraction of existing flood control storage corresponding to the ratio of present (actual) flow to maximum attainable flow.[1]

The data base of the model includes inventories of past and possible future storage facilities. Data in the past reservoir inventory (PRI) include the most important parameters of all reservoirs completed before the base year of the model, such as purpose (irrigation, flood control, hydroelectric, recreation or mixed), capacity and depth. Similarly, data in the new reservoir inventory (NRI) cover all possible sites where future reservoir constructions are either planned or considered by the Central Water Authority. Again, the parameters include purpose (as above), location, capacity, depth, surface area, evaporation rate, total cost and cost per unit of storage capacity (Rps/m^3).

The user's water policy, related to water supply, is entered in the model via the NRI table. The most relevant data in the table are displayed under the appropriate submenu in the scenario setting phase. The user can decide which reservoirs should be constructed and when, by entering the year in which construction should be started. The total costs are automatically accounted for, in the economic model, under the government expenditures category. Completion is assumed to take five years with the newly built storage becoming available at the beginning of the next period.

The supply section of the model (see Section A1 in the Appendix for the technical description) begins by calculating the initial flood control storage. That is, the total amount of storage capacities that were built primarily for flood control purposes prior to

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[1] It turns out that none of the reservoirs in Mauritius are explicitly operated as flood control storage facilities. Regardless of this, the procedure to handle flood control storage was implemented anyway,in order to keep the model general and easy to implement for other countries.

the initial year of the model. This capacity would gradually be included in the available total gross storage at the rate at which total capacity is approaching full regulation.

For each time step (every five year period), the model calculates the present minimum flow--that is, the level of water supply. The procedure is started by determining the present total gross storage through adding the newly completed storage capacities (depending on the user-specified investment decisions) to the already existing storage capacity. Due to the special treatment of the initial flood control storage capacity, some adjustment is necessary. The present total available storage is computed by adding a fraction of the initial flood control storage (according to the ratio of the present net flow in the previous time stop to the mean annual flow) to the present total gross storage.

The flow-storage function describes the relationship between the total storage capacity available for flow regulation and the level of minimum sustained flow. The next step in the model makes use of the flow-storage function to determine the present gross flow from the present total available storage. The resulting value, however, needs to be adjusted for the evaporation losses from the newly completed reservoirs.

Evaporation losses from existing storage (from those completed before the base year) are already captured by the historical flow data. The evaporation loss rate is derived by subtracting the basic evapotranspiration rate of the vegetation cover before the reservoir was constructed from the reservoir evaporation rate. Total evaporation loss is then the product of evaporation loss rates and the area of reservoirs.

Finally, present net flow is calculated by reducing the amount of gross flow according to the total evaporation losses. This, then, will be the level of water supply on which the population and the economy is Mauritius can count on with 95 percent reliability. Results from the demand section of the model will determine whether it is sufficient for the given socio-economic development scenario.

Depending on the user's decision, the above procedure can be used in the model to test water availability with a reliability of 98 per cent. In this case, a modified flow-storage function is used to determine the actual flow values. In addition, the model makes it possible for the user to study the impacts of unusually long drought periods. For these experiments, the level of present net flow is reduced according to a user-specified shortage ratio.

3.2. Water Demand

Similarly to water supply, the demand for water in this model is also expressed in terms of physical quantities. Water demand represents the total amount of water required for various uses. Hydrologists and water managers distinguish three categories of water use: withdrawal uses, when water is physically removed from the natural watercourse (households, industry, agriculture, services); on-site uses, for which the amount of water available in the watercourse as a stock is critical (navigation, water required to keep the ecological balance of swamps, wetlands, or for controlling soil erosion); and flow uses, when the rate of water availability is the key factor (hydroelectric power generation, waste dilution, estuary maintenance). Some uses do not affect water quality, while others severely downgrade the quality of water which they return to the natural water course. Some uses return practically the same amount of water as was diverted, while such other uses as irrigation imply high rates of water loss.

Due to the size, geographical characteristics and hydrological conditions of Mauritius, and partly due to data limitations, two components of water demand are considered in this model: losses from withdrawal uses and the dilution flow required to keep water quality in streams and rivers above the specified standard values. Through these components, water quantity and quality considerations are linked in the model. Total water demand is expressed in terms of stream flow (e.g. m^3/sec) and is directly comparable to water supply. (Formal description of the demand model is presented in Section A2 of the Appendix.)

Withdrawal losses

There are two components of losses associated with water withdrawals for use in households and the economic sectors. The first component is net water consumption, which is the amount of water not returned to the natural watercourse because it was evaporated, transpirated by plants, incorporated into products, or other reasons. The second component follows from a special feature of waste water management in Mauritius: a considerable fraction of residential and industrial sewage is directly discharged into the lagoons. (There are also plans to extend sewage outfalls beyond the reef and discharge sewage into the ocean.) This water is lost as a freshwater resource, thus the direct discharge part of water loss includes the total amount of waste water which was discharged into receiving media other than rivers and ground.

Net water consumption is derived from the population module for households and from the input-output model for the economy. Specific gross intake figures (m^3/person-year and m^3/MRs of output) were calculated from the 1987 input-output table, irrigation data, and water statistics of the Central Water Authority. Total gross water intake, in each time step, is computed by the model using actual population size and actual levels of economic activity in each sector. For each present (and possible future) sector of the economy, rates of loss were also estimated indicating what fraction of the water intake is "used up" (evaporated, incorporated into products, etc.) by the given sector. Net water consumption is then calculated from gross intake values and rates of loss.

Direct discharge, the second component of withdrawal losses, accounts for the amount of water which is not returned to the freshwater course (streams, lakes, rivers), but rather discharged into salty waters--in the case of Mauritius, the lagoons. Direct discharge is calculated in this model by reducing the amount of return flow (gross intake minus net consumption) according to the ratios of waste water discharge into lagoons (and, when appropriate, ocean).

Dilution flow

Required dilution flow is calculated according to the user-specified water quality standards from the amount of pollutants discharged into streams and rivers after various levels of waste water treatment. Three types of pollutants are considered in this model: organic wastes expressed in terms of Biochemical Oxygen Demand (BOD), Nitrogen (N) and Phosphorous (P). Required dilution flow is calculated for each pollutant and the largest of the three values is taken as the ruling dilution flow.

Specific gross BOD discharge rates (kg BOD/person-year and kg BOD/MRs of output) were derived from the 1987 input-output table and various studies conducted by the Central Water Authority. These specific values are combined in the water model with actual population figures from the demographic model, along with structure and levels of economic activities in the input-output model, in order to provide gross BOD production values for each of the 16 sectors (15 economic sectors and the domestic sector).

Although the current level of waste water treatment in Mauritius is very low, the model provides the necessary tools to analyze the environmental impacts of alternative development strategies both in terms of waste production and waste management, as well as to keep track of costs and necessary investments to prevent environmental degradation. Four levels of treatment are considered in the model: no treatment (raw discharge), primary, secondary and tertiary treatment. Fractions of waste water, from all sectors subject to one of the three "real" treatment levels, depend on the amount of sewage generated and the available treatment capacities.

For each period in a given scenario run, the user can allocate money to construct new treatment capacities for each treatment level. Specific treatment costs include annualized construction and operating costs per m^3 of waste water treated. Newly added treatment capacities are derived from a combination of the investment decisions specified by the user and the specific treatment costs stored in the model's data base. Thus, new treatment facilities can become available with a one period delay. Given the updated inventory of treatment capacities, the model calculates what fraction of waste water from the different sectors is going through each of the four levels of treatment.

Based on the treated amount and the efficiency of treatment, we get the total amount of pollutant discharge. As mentioned before, only part of the total waste water discharge goes into rivers. Therefore, only the fraction discharged into streams and rivers is considered when we calculate the required dilution flow. For BOD, a simple biodegradation model is used to calculate the level of flow necessary to meet the specified water quality standard. The biodegradation model calculates the waste assimilation capacity of the fresh water system. It is based on the amount of water available for the reoxygenation process in the rivers, and the specific reaction coefficients characterizing decomposition and reaeration processes under Mauritian conditions.

The procedures to calculate required dilution flows for Nitrogen (N) and Phosphorous (P) are quite similar. Amounts of discharge are linked to amounts of BOD discharges through sector specific ratios. Sectors 1 and 2 (sugar cane production and other agriculture) are notable exceptions; no BOD is produced in the sugar cane sector, but the amount of N and P leaching into the groundwater and rivers are significant due to high ratios of fertilizer use. There is some BOD discharge from the "other agriculture" sector because it includes animal husbandry, but it is impossible to keep track of its share from the total output value in the input-output model. Waste water discharge from the animal husbandry sector goes to the ground anyway, so it does not affect the quality of inland surface waters and the quality of water in the lagoon. Therefore, only the N and P loads to rivers from "other agriculture" is taken into account.

Parts of the N and P discharges will be consumed in biodegradation processes. Actual amounts will depend on BOD availability and on the ratio at which N and P, and BOD will enter these processes. Any remaining amounts of N and P will need to be diluted according to the user-specified water quality standards.

The above procedures provide three values of minimum flows which are necessary to dilute the amounts of BOD, N, and P reaching the surface freshwater system in Mauritius. The ruling dilution flow will be the highest of these three required flows.

Water balance

The sum of the required dilution flow and withdrawal losses is taken as total water demand. It is expressed in terms of flow (m^3/sec) in order to make it comparable to the level of water availability, which is also calculated in terms of stream flow. The resulting water balance is reported to the user, together with other results of the model.

The only implication of a negative water balance on the demographic processes or economic development is the reduced availability of water for irrigation. Unless there is a real danger of absolute water shortage when the physical quantity of water is insufficient or it is so polluted that it cannot be used even for the least demanding industrial purposes--which is not the case in Mauritius--this approach is realistic. Poor water quality does not necessarily inhibit economic growth. Witness the Chao Phraya river which has been practically dead for years, yet Thailand's economic growth--headquartered in Bangkok--still continues at double digit rates.

In particular, there is no feedback to the population module in the form of increasing mortality or morbidity rates. Despite increasing evidence that various forms of environmental pollution affect the health status of the population, these relationships are difficult to quantify. Therefore, any attempt to include this linkage in a simple aggregated model like the one built for Mauritius would have resulted in obscure relationships. The model does not include economic feedbacks either. There is no penalty for increasing costs of providing potable water due to higher treatment requirements from river abstraction points when water quality in rivers declines. These are clear deficiencies of the model, but they cannot be avoided if we want to keep the model defendable. The information provided by the Surface Freshwater Model is nonetheless useful and important for the user. In Section 5, its uses for formulating water policies will be discussed.

4. THE LAGOON MODEL[2]

The coral reef surrounding the island of Mauritius encloses a shallow body of water. The reef extends over 70-80 per cent of the coastline at a distance from one hundred meters to several hundred meters. (The location of the reef around the island is presented in Figure 8.) There are both positive and negative consequences of this formation. On the positive side, the barrier reef breaks the high energy waves of the ocean far off the coast, thus significantly reducing coastline erosion and beach erosion. On the negative side, however, the reef traps part of the pollutants reaching the lagoon from inland. This leads to considerable degradation of water and sediment quality, especially in the closed parts of the lagoon.

Figure 8. The lagoons of Mauritius.

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[2] The author is indebted to László Somlyódy for his guidance in developing and formulating the lagoon model. Special thanks are due to Günther Fischer for his help in providing a numerical solution to the model.

The coral reef itself is in danger. Coral and coral sand are extracted at rates far above natural replenishment (Manrakhan 1991). Shells and fish are selectively removed both by spearfishing and aquarium collecting (GOM/World Bank 1988), thus disturbing food chains and the ecological balance. Raw sewage being pumped into the lagoons is also killing the living coral. In addition, still existing illegal fishing methods using explosives, and the use of chemicals (poison) by aquarium fish catchers (World Bank 1989) are the major coral killers. An estimated one-third of the corals is already dead.

The economic value of the lagoons is significant. The Ministry of Economic Planning and Development (1988) estimated the economic value of various activities related to the lagoons at 2.8 billion Rupees per year. Direct employment in these activities involves over 10,500 people. 98 per cent of the economic value and 73 per cent of employment is associated with the tourism industry.

It follows from the above that the reef and the lagoons play an important role both in maintaining the environmental quality and economic prosperity of the island. Therefore, the future of the lagoons must be addressed by any sustainability study concerned with the management of the island's limited natural resources.

The lagoon model of the water module is a simple two-box model which keeps track of the fate of pollutants reaching the lagoons. (An overview of the model is presented in Figure 9. See Section A3 in the Appendix for a technical description.) The first box represents water quality--that is, the concentration of pollutants in the lagoon water, while the second box represents the quality of the sediment. The two boxes are linked by a series of exchange processes, and their dynamic behavior is modeled by a pair of inhomogeneous differential equations.

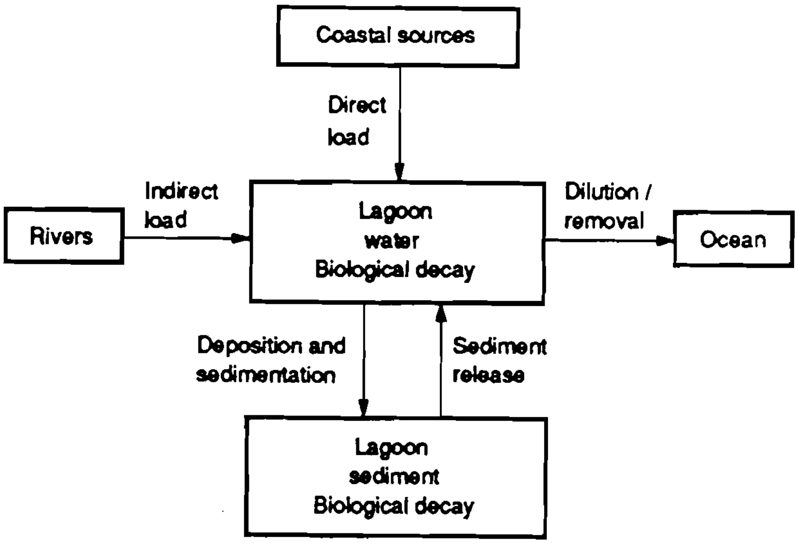

Figure 9. Pollutant flows in the Lagoon Model.

The Surface Freshwater Model, presented in Section 3, keeps track of three pollutants (BOD, Nitrogen, Phosphorous) as they are generated, treated and discharged. There are two sources of pollution load to the lagoons. The first source is direct discharge, and includes the amount of pollutants discharged to the lagoon directly from their sources located near the coast or via one of the four sewage outlets. The second source of lagoon pollution is the rivers system. The amount of pollutants discharged to rivers is reduced according to a simple biodegradation model, the remainder being added as pollutant load to the lagoon.

In the model, six processes affect the concentration of pollutants in the lagoon. The quality of water is decreased by the incoming flow of pollutants (direct discharge and via rivers). Pollutant concentration is decreased by a biological decay process. The amount of water delivered to the lagoon by rivers causes the same amount of outflow from the lagoon, thus removing the corresponding amount of pollutants from the lagoon. Tidal water brings significant amounts of water to the lagoon in a regular cycle. This water dilutes pollutants in the lagoon water and removes part of them with the low tide. The rate of dilution depends on turbidity and the rate of exchange--that is, the ratio of the volume of water coming in with the tidal waters to the volume of water in the lagoon at low tide. The current version of the model assumes perfect mixing, taking the whole lagoon volume as effective volume.

The process of sedimentation also reduces the concentration of pollutants in the water by depositing and accumulating pollutants in the bottom sediment. Depending on the relative concentration of pollutants in the water and in the sediment, this process can also go in the opposite direction. In this case, the sediment is releasing pollutants back to the water. The rate of sedimentation is a function of turbidity and pollutant concentration.

The accumulation of pollutants in the sediment is primarily driven by the concentration of pollutants in the water. Deteriorating water quality (higher pollutant concentration) leads to more intensive sedimentation and results in increasing accumulation of pollutants in the sediment. Depending on the oxygen balance of the sediment and the availability of oxygen in the system, part of the deposited pollutants will undergo biological decay in the sediment. In turn, high pollutant concentration in the sediment will increase the internal load of pollutants as a result of a higher level of sediment release. The process also works in the opposite direction: if external pollutant load is reduced and water quality thus improved, internal load will decrease as well with a certain time lag.

While in the case of the surface freshwater system the aggregated approach is appropriate for purposes of the present model system, it is much less defendable for the lagoon model. Extended parts of the coastline, especially in the South, are completely open and the coral fringe is missing altogether. Pollutants discharged or delivered to the ocean in this region are immediately diluted and washed away by the ocean. At the opposite extreme, closed segments of the lagoons in the vicinity of outflows of polluted rivers, dense industrial and tourist areas show signs of severe degradation. These parts of the lagoons receive much more pollutant per unit of water volume, while processes of pollutant removal (outflow, biological decay) are limited. Averaging out these regional differences is a serious source of error in the current version of the model. Despite intensive efforts, however, it was impossible to get access to the appropriate data that would have made regionalization of the lagoon model possible. Yet, the possibility is there. The same model could be used for one or more selected segments of the lagoon by replacing current aggregated values by appropriate parameters (volume, area, pollution load, rates of deposition, decay, etc.) characterizing the lagoon segment at hand.

Also due to lack of data, the only pollutant considered in the current version of the lagoon model is BOD. With the appropriate data on Nitrogen and Phosphorous available, the model could easily be supplemented with a simple eutrophication model. Yet again, this extension would only make sense for a regionally disaggregated version of the lagoon model.

Results of the lagoon model are reported to the user together with results of the surface freshwater model. The two most important output variables are the pollutant concentration figures for the water and for the sediment.

There is no feedback from the lagoon water quality to any other part of the system. This means that deterioration of the lagoon can reach arbitrarily high levels without any implication on the population or the economy. This is, of course, unrealistic. It is obvious from the economic data presented at the beginning of this section that the major loser due to polluted lagoons would be the tourism industry. Yet, it would take heroic assumptions to quantify the decrease in tourism demand as a function of pollutant concentration in the lagoon. Considering the Mauritian aspiration to discourage cheap, package-tour tourists and attract the "up-market clientele" of the "high-spending segment of the long-haul affluent markets" (MEQOL 1991:224), a decline of the tourism sector would be rather steep as a result of declining water quality in the lagoon.

If the user is not satisfied with the long term trend of water quality in the lagoon as it was reported from a given scenario run, the most useful option available is to increase sewage treatment. By investing in additional waste water treatment facilities, pollutant content of the direct discharge and the amount of pollutants delivered by rivers can be reduced. The fate of pollutants, once they get to the lagoon, is largely governed by natural processes, so there is not much a manager could do. In situ, rehabilitation techniques like sediment dredging or sludge removal are not permitted by the current version of the model, although they could be considered for a disaggregated version.

5. SCENARIOS AND WATER POLICIES

The basic difference between the water module and all the other modules in our model system is that it is not possible to predefine exact scenarios at the beginning of a 60 year time horizon. Water requirements and water quality will depend on the user's economic and social policy, along with what happens in the population and economic model as a result. Models in the water module measure the environmental implications of the given population and economic development scenario in terms of water balance in the inland surface water system, and in terms of water quality in the lagoons. The only resource constraint defined in the form of a direct feedback relationship is between the surface water and the economic model. When water shortage is detected by the model, the amount of water available for irrigation will be automatically reduced to restore the water balance. Reduced irrigation leads to lower yields and lower sugar cane production. This implies that the user should apply a trial and error approach by resetting the water policy variables for the same demographic and economic scenario, should it be found that the results are not satisfactory in terms of water availability and/or water quality.

5.1. Water Policy Variables

There are three groups of variables in the water module that reflect the user's preferences or intentions in terms of water management. These are:

- required water quality standards
- investments in treatment
- investments in storage.

Since the model combines quality and quantity aspects, water balance requirements for any given scenario of population and economic development can be met by a large set of combinations of the above three policy variables. The principal difference between the quality standards and the other two variables is that the formes reflects the user's preference for environmental quality, while the treatment and storage variables are the basic instruments to achieve the given environmental quality.

Thus, the scenarios can be classified in terms of target environmental quality as follows:

- moderate	RWQS is 4 mg/l for dissolved oxygen (DO), 10 mg/l for N and 0.1 mg/l for P; these are the current environmental standards in Mauritius and also the default values that appear in the scenario setting menu;
- high	RWQS for DO could be pushed as high as 6 mg/l, while they can be reduced to 5 mg/l for N and to 0.05 mg/l for P;
- low	RWQS for DO can be reduced to 1 mg/l, while permitted N and P concentrations can be allowed to increase up to 30 mg/l and 0.3 mg/l, respectively.

Due to the non-linearities characterizing the system both on the input side (pollutant discharge vs. treatment) and on the impact side (eutrophication, biochemical degradation, and other processes), small changes in the RWQS parameters tend to generate major shifts both in the water balance (calculated and reported by the system) and in the induced environmental impacts (not represented in the system).

Water management strategies are specified by allocating investments in waste water treatment and water storage facilities. Again, there are major differences associated with each of the two options. Investments in treatment reduce the overall load on the water system by abating pollutants before the waste water is returned to the natural watercourse. They also reduce the required dilution flow necessary to maintain the specified RWQS. In contrast, investments in storage will increase the minimum sustained flow, thus the amount of flow available to dilute pollution discharge in order to meet the specified RWQS will be higher. In the short rivers of Mauritius, however, biochemical degradation is limited. Therefore, the use of increased dilution flow as a strategy to maintain water quality in the rivers implies a pushing out of the problems to the lagoons, which will thus receive much higher pollutant loads than they would under a treatment-oriented strategy. Additional flaws of the storage-oriented strategy include the land area lost due to inundation to construct dams and reservoirs, along with other environmental impacts of dam construction and operation. Nonetheless, both the treatment and storage options are available in the model.

The attempt to define sensible scenarios for investments in either treatment or storage should be based on preliminary knowledge of the economic development scenario. Some directions in economic development imply heavy increases in the "production" of water pollutants included in our model, others may imply discharge of pollutants not included, still others may not affect the water system at all. An expansion of leather tanning as an EPZ sector would fall in the first category, some branches of the electronics industry with their heavy metal problems are examples for the second, while some service industries such as information technology (software development) or financial services (off-shore banking) have no water-related effects. Yet, an attempt to define extreme water strategies might involve the following:

A) Treatment

- no investment in water treatment
- "low investment" scenario; e.g. 1% of the current government investments allocated for waste water treatment
- "high investment" scenario; e.g. 10% of the current government investments allocated for waste water treatment

B) Storage

- no investment in water storage
- "low investment" scenario; e.g. one-quarter of the potential dams constructed between 1990 and 2050 in ascending order of the cost per unit of storage;
- "high investment" scenario; e.g. all potential dams constructed between 1990 and 2050 in ascending order of the cost per unit of storage.

It will take some experimentation with the model for any user to determine the sensible range of default scenarios and water policies in terms of their cost effectiveness. The author's recommendation for a default scenario is the following: unless the specified economic policy is expected to generate drastic increases in the discharge of BOD, N and P from industrial and agricultural sources, the best use of resources implies a combination of moderate investments in treatment (somewhere between the "low" and "high" treatment scenarios) and no investment in storage. This scenario might also help to keep water quality in the lagoon at an acceptable level.

A combination of the recommended default scenarios for RWQS and for water management should keep a positive water balance in terms of river flows. This may still imply unacceptable deterioration of water quality in the lagoons. Due to lack of data, it was not possible to build a large number of meaningful and defendable feedback relationships into the model. Therefore, for the default run and for any subsequent scenario runs, the user should always check and evaluate environmental implications of population and economic scenarios, both in terms of inland surface water and lagoon water quality.

5.2. Other Water Management Parameters

There are four environmental media receiving waste water discharge in the current version of the model: ground, rivers, lagoon and the ocean beyond the reef. Direct discharges to the rivers and the lagoon, and pollutant transport by the rivers to the lagoon is properly handled by the model. The missing link in the present version of the model is the pollutant transport from groundwater to rivers and the pollutant absorption capacity of the ground water system.

Lacking any data on groundwater movement and quality, it was impossible to construct a meaningful model of these processes. It is evident, however, that the absorption capacity of the groundwater system is limited. Therefore, direct discharge of untreated sewage from domestic and industrial sources to absorption pits must be eventually phased out. The user can model this transition by modifying the disposal matrix that indicates what fraction of the waste water from different sectors is discharged to which receiving media. Even if this redirected discharge is treated, it will pose an additional load to the surface flow or the lagoon model.

When and how fast this transition takes place depends on when and how fast the signs of contaminating groundwater will make it necessary. Three basic scenarios can be proposed as default:

- transition soon and fast: phasing out groundwater discharge starts in 1995 and will be completed by 2015;
- transition soon and gradual: phasing out starts in 1995 and completed by 2040;
- transition later and gradual: phasing out starts in 2020 and groundwater discharge is reduced to 30 per cent of its original value by 2050.

The geographical location of Mauritius would clearly permit the discharge of untreated sewage in the ocean beyond the reef. If the pipes go sufficiently beyond the reef, wastes are diluted by the ocean and are not expected to pose any significant repercussions on either the corals or the lagoon. Yet, this solution does not appear to be environmentally friendly. Moreover, the costs of building and operating these kinds of "disposal facilities" might well be close to what it would take to build and operate treatment plants. Currently none of the sewage outlets go beyond the reef. We have no data about the construction and operation costs of such facilities. If this option will be seriously considered in the future, the model can be easily modified to accommodate it.

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APPENDIX. TECHNICAL DESCRIPTION OF THE WATER MODEL

A1. Water Supply Model

Water supply is calculated in terms of streamflow that can be depended on 95 per cent of the time. The amount of dependable flow can be increased by regulation, that is by constructing water storage facilities to smooth seasonal variations in precipitation and run-off. Quality aspects of water supply are also considered and the flow must satisfy the user-specified quality criteria (see Section A2).

The initial task in the water supply model is to determine the amount of initial flood control storage (IFCS) that is the amount of storage in the base year of the model which was primarily built and operated for flood control purposes. This is required to determine the present total gross storage ($PTCS_0$) in the base year. Data in the table of Past Reservoir Inventory (PRI, see Table A1) are used for these calculations:

$$IFCS = \sum_{PRI\_PURP=FC} PRI\_CAPAC \quad (Mm^3)$$

$$PTGS_0 = (\Sigma \ PRI\_CAPAC) - IFCS \quad (Mm^3)$$

Table A1. List of existing reservoirs (as of 1989) (PRI table). Source: CWA 1991.

Name	Purpose PURP	Useful capacity (Mm^3) CAPAC	Surface area (ha) AREA	Water depth (m) DEPTH
Mare aux Vacoas	D	22.0	560	11.0
Mare Longue	H,I	5.7		
Tamarind Falls	H,I	2.0		5.0
La Ferme	I	11.8	227	7.3
Eau Bleue	H	6.0	92	16.7
Piton du Milieu	D	2.3	76	10.0
La Nicolière	D,I	5.2	102	12.8
Diamamouve	H	4.0	41	34.0
Dagotière	P,I	0.5		
Valetta	P,I	1.8		
Note: D domestic H hydroelectric I irrigation P private				

For each time step (every five year period), the model determines the amount of available storage and the resulting minimum sustained flow.

Step 1: Calculate present total gross storage (PTGS) by adding the newly completed storage capacities which depend on the user-specified rate of implementation to the old total storage capacity.

The user is provided with all necessary information about the potential new reservoirs that might be constructed in the future. This information is summarized in the new reservoir inventory (NRI) table in Table A2. When setting a scenario, the user simply specifies the year in the scenario period in which construction of one or more reservoirs should be started. Costs are handled in the economic scenario and the new storage capacity is assumed to be available 5 years later.

$$PTGS_t = PTGS_{t-1} + \sum_{(t-1)<NRI\_YOC\leq t} (NRI\_CAPAC) \quad (Mm^3)$$

Step 2: Calculate present total available storage (PTAS) by adjusting for the fraction of the initial (base year) flood control storage (IFCS) available for flow regulation in the present year at the current level of regulation. Only part of the IFCS is assumed to be available for flow regulation, although this fraction is assumed to be increasing as the level of regulation is increasing. The actual fraction of IFCS available for flow regulation is the ratio of the present net flow (PNF) in the previous time step to the maximum attainable flow approximated by the mean annual flow (MAF).

MAF and the initial value for PNF are derived from the historical flow data (see Table A3). These data had to be revised upwards in order to include upstream water losses due to irrigation which were not captured by historical flow records.

$$PTAS_t = PTGS_t - \left(1 - \frac{PNF_{t-1}}{MAF}\right) * IFCS \quad (Mm^3)$$

Step 3: Calculate the present gross flow (PGF) by combining the PTAS with the flow-storage function (FSF). Depending on the user-specified level of dependence (95 or 98 per cent), the model will use the appropriate flow-storage function.

The flow-storage function (see Table A4) contains revised values to account for irrigation losses in the historical observation period.

$$PGF_t = FSF\,(PTAS_t) \quad (m^3/\text{sec})$$

Table A2. List of possible future reservoirs (NRI table). Source: CWA 1991.

Name	Purpose PURP	Capacity (Mm^3) CAPAC	Surface area (ha) AREA	Water depth (m) DEPTH	Evaporation rate (mm/year) EVAPRATE	Total cost MRs TCOST	Unit Cost (Rs/m^3) HCOST	Year of con-struction YOC
Mon Vallon	D,I	4	24	50.0	2000	216	54.0	U
		5	28	53.5		271	54.2	
Black River	D,H,I	3	29	28.5	1650	340		S
		6	43	36.5		600	100.0	
Chamarel	D,H,I	1	23	14.5	1800	143	143.0	E
		2	35	17.8		176	88.0	
Calebasses	D,I	1	22	14.5	1800	143	143.0	R
		2	44	21.5		176	88.0	
La Nicolière (enlargement)	D,I	10	129	19.5	1650	156	15.6	
		14	138	22.5		236	16.9	
		18	144	25.4		326	18.1	
Midlands	D,I	5	166	16.5	1450	223	44.6	S
		10	203	19.7		334	33.4	
		15	255	22.0		431	28.7	
La Flora	D	2	18	26.1	1400	252	126.0	P
		3	23	32.5		352	117.3	
		4	26	36.6		462	115.5	
Astroea	D	2	17	36.0	1800	216	108.0	E
		3	23	41.0		312	104.0	
Baptiste	D,H	6	110	25.0	1600	407	67.8	C
		8	134	26.5		474	59.3	
Bagatelle	D,H	4	37	29.0	1650	300	75.0	I
		6	44	33.0		456	76.0	
Terre Rouge	D	6	27	74.0	1800	670	111.7	F
		8	32	80.0		805	100.6	
Cascade	D,H	3	28	31.0	1650	295	98.3	I
		4	35	35.0		385	96.3	
Soreze	D,H	8	36	64.0	1900	970	121.3	E
		10	42	69.5		1100	110.0	
Guibies	D,H	8	53	38.5	1800	655	81.2	D
		10	58	42.0		765	76.5	

Note: D = domestic H hydroelectric I irrigation P private

Table A3. Historical flow data. Source: CWA files.

No	Stno	River	Location	perc98	perc95	perc90	min	mean	max	code
1	a06	du rempart	haute rive	0.052	0.076	0.101	0.044	9.500	757.000	riv
2	b01	francoise	constance	0.000	0.000	0.000	0.000	0.694	3.000	riv
3	c003	rich fund canal	f.u.e.l	0.000	0.006	0.016	0.000	0.157	0.363	div
4	d01	seche	bel air	0.000	0.000	0.000	0.000	1.340	18.100	riv
5	e005	sans souci canal	f.u.e.l	0.000	0.000	0.000	0.000	0.202	0.323	div
6	e006a	eau bleue feeder	from g.r.s.e	0.000	0.000	0.045	0.000	0.330	1.420	fee
7	e008a	nicoliere feeder	la pipe	0.000	0.000	0.000	0.000	7.550	9.060	fee
8	e01	rempart	bois clair	0.000	0.091	0.122	0.000	1.190	37.000	riv
9	e010	olivia canal	olivia	0.000	0.000	0.000	0.000	0.040	0.275	div
10	e011	beau vallon canal	beau champ estate	0.000	0.000	0.000	0.000	0.124	0.238	div
11	e013	beau champ canal	beau champ	0.000	0.000	0.000	0.000	0.776	1.440	div
12	e014	vacaos div. canal	bois clair dam	0.000	0.000	0.000	0.000	0.514	3.200	div
13	e04	bateau	belle rive	0.009	0.011	0.013	0.007	0.164	1.480	riv
14	e05	vacaos	belle rive	0.000	0.000	0.000	0.000	0.039	1.990	riv
15	e06	gontran	dubreuil	0.000	0.000	0.000	0.000	0.044	1.700	riv
16	e11	deep river	pont lardier	0.714	0.875	1.030	0.263	2.800	20.000	riv
17	e13	g.r.s.e	beau champ	0.000	0.000	0.000	0.000	5.340	129.000	riv
18	e17	ruisseau chevrette	bois clair	0.024	0.041	0.061	0.084	0.327	39.000	rui
19	g07	eau bleue	cluny	0.000	0.000	0.000	0.000	0.623	19.400	riv
20	g08	ruis.tranquille	riche en eau	0.023	0.034	0.048	0.000	0.483	5.660	rui
21	g09	des creoles	riche en eau	0.000	0.657	0.923	0.000	3.710	31.400	riv
22	h02	la chaux	beau vallon	0.000	0.000	0.000	0.000	1.680	28.100	riv
23	j001	tatamaka feeder	arnaud	0.000	0.038	0.065	0.000	0.405	4.880	fee
24	j01	citron	nouvelle france	0.043	0.056	0.074	0.022	0.382	28.300	riv
25	j04	du poste	la flora	0.014	0.028	0.054	0.000	0.776	33.200	riv
26	l01	dragon	batymarais	0.000	0.000	0.004	0.000	0.487	7.840	riv
27	m01	des anguilles	riv.des anguilles	0.177	0.231	0.321	0.113	3.640	127.000	riv
28	p01	des galets	chamouny	0.088	0.113	0.159	0.000	1.380	56.600	riv
29	pac	parc aux cerfs	inflow parc cerfs	0.000	0.000	0.000	0.000	0.057	1.950	fee
30	q01	baie du cap	chamarel	0.001	0.004	0.008	0.000	0.074	1.300	riv
31	r01	black river	gorges	0.068	0.097	0.138	0.000	0.986	1170.000	riv
32	s11	des aigrettes	inflow to t.falls	0.034	0.037	0.045	0.000	0.392	4.760	riv
33	t03	du rempart-west	henrietta	0.000	0.000	0.000	0.000	0.181	2.920	riv
34	t04	papayes	henrietta	0.007	0.012	0.017	0.005	0.202	4.940	riv
35	t12	st.martin	solferino	0.022	0.028	0.047	0.128	0.246	6.490	riv
36	v05	pierrefonds tunnel	pierrefonds	0.000	0.000	0.000	0.000	0.209	0.934	tun

37	w01	seche	allee brillant	0.029	0.038	0.048	0.165	0.346	5.330	riv
38	w013	terre rouge canal	trianon	0.000	0.062	0.113	0.000	0.976	28.300	div
39	w03	plaines wilhelms	belle rose	0.062	0.093	0.125	0.000	0.448	20.300	riv
40	w04	terre rouge	reduit	0.327	0.332	0.341	0.270	0.674	20.000	riv
41	w05	cascade	reduit	0.099	0.123	0.139	0.000	0.611	17.700	riv
42	w08	profonde	le bocage	0.060	0.079	0.099	0.000	0.329	14.300	riv
43	w10	moka	river baptiste	0.102	0.133	0.161	0.000	0.684	19.500	riv
44	y01	labourdonnais	old flacq road	0.006	0.011	0.017	0.000	0.246	19.200	riv
45	y02	calebasses	calebasses	0.099	0.119	0.142	0.017	15.050	28.600	riv
46	z01	citron (north)	moulin a poudre	0.006	0.009	0.011	0.000	0.232	6.040	riv
			TOTAL	2	3	4	1	67	2740	

Table A4. Flow-storage function (95 per cent reliability).

% MAF	Flow (m^3/sec)	Storage (Mm^3)
5.6	12.43	61.2
10	15.36	83.0
15	18.70	105.7
20	22.02	128.4
25	25.36	151.1
30	28.70	173.8
35	31.90	196.5

Step 4: Calculate the present net flow (PNF) by adjusting the PGF value for the increasing evaporation losses from the new storage reservoirs. Evaporation losses from existing reservoirs (from those completed before the base year) are already captured by the historical flow data. The evaporation loss rate is calculated by deducting the basic evapotranspiration rate of the vegetation cover before the reservoir was constructed from the reservoir evaporation rate.

$$TEVAP_t = \sum_{t_0 < NRI\_YOC \leq t} (NRI\_EVAPRATE * NRI\_AREA) \quad (m^3)$$

$$PNF_t = PGF_t - TEVAP_t / SECYEAR \quad (m^3/\text{sec})$$

SECYEAR is a constant ($31.536*10^6$) to convert annual data to secundum basis.

In order to make it possible for the user to study impacts of exceptional drought periods, the long term PNF_t value can be reduced according to a user-specified ratio (assumed reduction inflow--ARP). The actual present net flow ($APNF_t$) in this case will be:

$$APNF_t = PNF_t * (1 - ARP/100)$$

The APNF value in each time step will be used in the water balance computation to establish whether the amount of APNF is sufficient to satisfy water requirements calculated in the demand part of the water model.

A2. Water Requirements Model

Two components of the water requirements are considered in the Mauritius model: Losses from withdrawal uses and the dilution flow required to keep the water quality in streams and rivers above the user-specified standard values. The total water requirement is expressed in terms of stream flow:

$$TWR = TWL + RDF \quad (m^3/sec)$$

(total water requirement = total withdrawal losses + required dilution flow)

Withdrawal losses

There are two components of losses associated with water withdrawals for industrial, agricultural, or domestic purposes in Mauritius. First, the net water consumption (NWC), that is the amount of water not returned to the natural watercourse because it was evaporated, transpirated by plants, incorporated into products, etc. Second, the direct discharge (DD), that is the amount of waste water which was discharged into receiving media other than streams and rivers (e.g. lagoons, or deep ocean).

$$TWL = NWC + DD \quad (m^3/sec)$$

NWC is derived from the I/O table. Table A5 presents amounts of water delivered to various sectors of the economy to produce 1 Million Rupees worth of output, hereafter called specific gross intake (SGI). The last row shows the amount of water delivered to households per person. Combined with the actual values of output and actual number of people, the total amount of water (gross intake - GI) diverted from the natural watercourse, surface or underground, for the economic and domestic sectors can be calculated.

$$GI(j) = OUTPUT(j) * SGI(j) \; ; \; j = 1,16$$

where OUTPUT(j) is:
for j = 1,...,15 MRs of output in the given year (I/O model)
for j = 16 number of people (total population) in the given year (POP model).

The difference between the amount of water removed from and returned to the natural watercourse is the net consumption. For each (present and future) sector of the economy, a rate of loss (RL) value was estimated that indicates what fraction of the water intake will be "used-up" by that sector:

$$NWC = \left[\sum_{j=1}^{16} GI(j) * RL(j)\right] / SECYEAR \quad (m^3/sec)$$

Table A5. Water use and waste water discharge coefficients.

(j)	RL (%)	SGI (m^3/MRs) (m^3/person-year)	SGDB (kg/MRs) (kg/person-year)	BOD to N ratio in waste water	BOD to P ratio in waste water
1	0.75	106,018	0	0	0
2	0.75	39,254	0	0	0
3	0.20	1,176	1,155	60	200
4	0.10	415	264	35	27
5	0.10	678	132	7	40
6	0.12	576	141	7	40
7	0.10	44	2	18	33
8	0.10	44	2	18	33
9	0.10	134	7	18	33
10	0.10	147	7	18	33
11	0.35	1,562	625	6	27
12	0.10	79	4	18	33
13	0.10	34	2	18	33
14	0.10	272	14	18	33
15	0.10	282	14	18	33
*16	0.25	46	20	6	27

Note:
RL = Rate of loss
SGI = Specific Gross Intake
SGDB = Specific Gross Discharge of BOD

DD accounts for the amount of water which is not returned to freshwater course (streams, lakes, rivers), but rather discharged into brackish or salty waters. In Mauritius, a considerable part of waste water is directly discharged into the lagoons. This water is lost as freshwater, therefore the appropriate flow data must be reduced by:

$$DD = \left[\sum_{j=1}^{16} (GI(j) * (1 - RL(j)) * (1 - DISP(1,j) - DISP(4,j))\right] / SECYEAR \ (m^3/\text{sec})$$

where DISP is a 4 * 16 matrix indicating for each sector (j) the fraction of waste water discharged into the ground (e.g. soak pits; i=1), into the lagoon (i=2), into the deep ocean (i=3), or into streams/rivers (i=4) (see Table A6).

Table A6. Fraction of waste water discharged into each of the 4 receiving media (DISP).

j	Ground	Lagoon	Ocean	Rivers
1	.95	.01	0	.04
2	.90	.01	0	.09
3	.50	.15	0	.35
4	.17	.75	0	.08
5	.17	.75	0	.08
6	.17	.75	0	.08
7	.17	.75	0	.08
8	.17	.75	0	.08
9	.17	.75	0	.08
10	.17	.75	0	.08
11	.38	.62	0	0
12	.17	.75	0	.08
13	.17	.75	0	.08
14	.17	.75	0	.08
15	.17	.75	0	.08
*16	.81	.18	0	.01

Dilution flow

RDF is calculated from the amount of pollutants discharged into the streams and rivers after various levels of treatment (pollutant removal) and from the specified water quality standards. Three types of pollutants are considered: Biochemical Oxygen Demand

(BOD), Nitrogen (N), and Phosphorous (P). RDF is calculated for each (QB, QN, QP, respectively) and the largest of the three RDFs becomes the ruling dilution flow:

$$RDF = \max\{QB, QN, QP\}$$

BOD

Table A5 includes data related to the amount of organic wastes generated and discharged with waste water by each sector. Organic waste load is measured in terms of BOD and it depends on the technological coefficients, the structure of the economy and the level of activity in each sector in the economic model and on the size of population in the demographic model. Numbers in Table A5 indicate for each sector the amount of organic wastes (kg BOD) generated in producing each 1 Million Rupees worth of output. For the domestic sector they show the amount of BOD per person-year. Figures are called specific gross discharge of BOD (SGDB). Gross discharge of BOD (GDB) from each sector is then calculated as follows:

$$GDB(j) = SGDB(j) * OUTPUT(j) \; ; \; j = 1,16$$

where OUTPUT(j) is:
for j=1,...,15 MRs of output in the given year (I/O model)
for j=16 number of people (total population) in the given year (POP model).

Only a part of this amount of total generated BOD will reach one or another component of the water system, because part of the waste water will go through treatment processes. The link between gross discharge figures and the actual net discharges of pollutants was established by introducing a treatment matrix (T) and a treatment efficiency vector.

Elements of the 4 * 16 matrix T indicate what fraction of waste water is subject to one of four levels of treatment: i=1 indicates raw discharge (no treatment); i=2 means primary treatment (removing a portion of the suspended solids by plain sedimentation, Imhoff tanks, sedimentation lagoons, etc); i=3 is the fraction undergoing secondary treatment (involving biological processes which satisfy the O_2 demand to decompose part of the organic matter in the waste water); and i=4 indicates tertiary treatment (additional polishing by further stabilizing/removing pollutants). Note that BOD discharge from sectors 1 and 2 is negligible, therefore the corresponding elements in all treatment-related arrays will be 0. The 16-sector arrangement was kept for technical reasons.

The four elements of the treatment removal ratio vector (TRRB) show the average efficiency of BOD removal for each of the four treatment levels listed above. For example, TRRB(2)=0.30 means that given the typical primary treatment technologies in a specific year, they provide an average of 30 per cent BOD removal.

The T and TRRB matrices are updated in the model as technologies are developing and new user-specified investments are made in waste water treatment plants. The treatment section of the model consists of two parts. The first part updates the treatment capacity matrix based on investment costs and the user's decision to invest into building new treatment facilities. The second part is calculating current values of T from the amount of BOD produced and from the currently available capacity at each treatment level.

The first task is to update the treatment capacity matrix (TC) over time. In each time step, the treatment capacity is increased by the amount of new treatment capacity (NTC) completed in the previous period (5 years):

$$TC_t(i,j) = TC_{t-1}(i,j) + NTC_t(i,j) \quad i=2,3,4; \quad j=3,\ldots,16 \quad (m^3)$$

NTC depends on two factors: the cost of building and operating new treatment facilities and how much money the user is allocating for constructing these facilities. Treatment costs are defined to include both construction and operating costs so that elements of the COT(4,16) matrix (see Table A7) indicate the total costs of 1 m^3 of waste water treatment capacity to handle sewage from sector j at the given level (primary, secondary, tertiary) of treatment.

Table A7. Cost of treatment (Rs/m^3 treatment capacity).

	Levels of treatment			
j	Raw discharge	Primary	Secondary	Tertiary
1	0	0	0	0
2	0	0	0	0
3	0	88	313	348
4	0	172	604	741
5	0	145	507	551
6	0	145	507	551
7	0	145	507	551
8	0	145	507	551
9	0	145	507	551
10	0	754	1451	1738
11	0	754	1451	1738
12	0	754	1451	1738
13	0	754	1451	1738
14	0	754	1451	1738
15	0	754	1451	1738
16	0	754	1451	1738

Given the amount of money allocated by the user for investments in treatment and the COT matrix, the new treatment capacities (NTC) will be (note the 5-year delay to complete construction):

$$NTC_t(i,j) = \frac{INV_{t-1}(i,j)}{COT(i,j)} \quad i=2,3,4; \; j=3,...,16 \quad (m^3)$$

Based on the updated inventory of treatment capacities, we are now in the position to construct the T matrix. Full capacity utilization is assumed when calculating what fraction of waste water is going through each of the four different treatment levels. For each sector (j) of the economy, the amount of treatment at the highest level (tertiary treatment) is calculated first.

For each sector (j=3,...,16), the amount of waste water discharge needs to be determined:

$$RET(j) = GI(j) * (1-RL(j))$$

Then:

$$X4(j) = RET(j) - TC_t(4,j) \quad (m^3)$$

$$\begin{aligned} &if \;\; X4(j) > 0 \quad then: \; T(4,j) = \frac{TC_t(4,j)}{RET(j)} \\ &else: \; T(4,j) = 1; \; T(3,j) = T(2,j) = T(1,j) = 0 \end{aligned}$$

In the first case, the full amount of waste water is not treated at the tertiary level, therefore the ratio corresponding to the tertiary treatment capacity will show up in the T matrix. In the second case, there is sufficient capacity to clean all the waste water from the sector at this level, thus other elements in the appropriate column of the T matrix will be zero.

We have the same procedure at the secondary treatment level:

$$X3(j) = RET(j) - TC_t(4,j) - TC_t(3,j)$$

$$\begin{aligned} &if \;\; X3(j) > 0 \quad then \;\; T(3,j) = \frac{TC_t(3,j)}{RET(j)} \\ &else \;\; T(3,j) = 1 - T(4,j); \; T(2,j) = T(1,j) = 0 \end{aligned}$$

All waste water which was not cleaned at the tertiary level and exceeded the capacity available at the secondary level, might be subject to primary treatment:

$$X2(j) = RET(j) - TC_t(4,j) - TC_t(3,j) - TC_t(2,j)$$

$$\begin{aligned}&\textit{if}\ \ X2(j) > 0 \quad \textit{then}\ \ T(2,j) = \frac{TC_t(2,j)}{RET(j)}\\ &\textit{else}\ \ T(2,j) = 1 - T(4,j) - T(3,j);\ T(1,j) = 0\end{aligned}$$

X2(j) > 0 for any sector indicates that part of its waste water could not be treated even at the primary level. This part counts as raw discharge:

$$T(1,j) = 1 - T(4,j) - T(3,j) - T(2,j)\ \ .$$

Treatment efficiency

Another factor determining the actual pollutant removal from the waste water is the efficiency of treatment called treatment removal ratio (TRRB) in the model. In order to keep the model simple, we assume that, with proper investments into the maintenance of treatment capacities already existing or created during the model's life-time, there will be a slight improvement in the efficiency of pollutant removal for each type of treatment. The slow increase in the average efficiency reflects the improvements resulting from the renewed older capacities and the higher efficiency of the newly established plants. The actual rate of improvement is specified by the user in order to make it possible to test different assumptions.

The corresponding equation for updating the TRRB vector will be:

$$TRRB(i)_t = TRRB(i)_{t-1} * (1 + EFFIMP) \quad i = 2,3,4$$

where EFFIMP shows the average efficiency improvement (e.g. 0.003 means 0.3 per cent improvement in each five year period).

BOD discharge

The above additions make the treatment part of the water requirements model complete. The net discharge of BOD from each sector [NDB(j)] is now calculated as follows:

$$NDB(j) = GDB(j) * \sum_{i=1}^{4} T(i,j) * (1 - TRRB_t(i))$$
$$i = 2,3,4,;\ j = 1,\ldots,16\ \ (kg/year)$$

Finally, the DISP matrix shows proportions of the various receiving media (ground, lagoons, ocean, streams/lakes) as discussed above. Only the fraction discharged into streams/rivers is considered for calculating the required dilution flow. The net BOD load to the freshwater system is:

$$NLB = \sum_{j=1}^{16} NDB(j) * DISP(4,j) \quad (kg/year)$$

Our objective is to determine the amount of water that is necessary to dilute the NLB amount of BOD (considering natural regeneration processes) so that the required water quality standard for BOD will be met.

The required dilution flow (QB) is calculated from a simple biodegradation model. The model assumes uniform load and no regeneration which means purification of only one discharge is taken into account:

$$QB = \left[\frac{NLB/10}{r * k2 * D}\right] * \frac{10^3}{YEARSEC} \quad (m^3/sec)$$

where
k2 = reaeration reaction coefficient
r = reoxygenation efficiency term
D = DOS - RQSD
DOS = D.O. saturation level at a given temp (Mauritius average) (mg/l)
RQSD = required quality standard for dissolved oxygen (mg/l) -- user-specified

Nitrogen

The amount of N discharge from various sectors of the economy is derived from the parameters of BOD discharge. Given the typical technologies in various economic sectors, ratios of BOD to N (CRN) per unit of waste water discharged can be determined. These ratios are listed in the CRN vector for each sector in Table A5.

The gross discharge of N now can be calculated as follows:

$$GDN(j) = GDB(j)/CRN(j) \quad j=3,\ldots,16 \quad (kg/year)$$

Sectors 1 and 2, the two agricultural sectors, represent a special case in this respect. Except for animal husbandry which is part of Sector 2 and its relative weight cannot be determined from the economic model, there is practically no discharge of BOD from these sectors, but considerable amounts of Nitrogenous fertilizers are washed to the streams and rivers from the fields. This N load is calculated from current rates of fertilizer use, but the model also allows for changes in fertilizer application:

$$GDN(1) = (1 + PCHN/100) * 2.689 * SUGAR\ AREA$$

$$GDN(2) = (1 + PCHN/100) * 2.689 * OTHER\ AG.AREA$$

where SUGAR AREA AND OTHER AG.AREA represent land under sugar cane and other crops, respectively. These values are taken from the land use module. PCHN is the per cent change in N fertilizer application from starting conditions (1987 levels). For example, PCHN = -10 implies a 10 per cent decrease in the use of N fertilizers relative to the 1987 per hectare figure. The constant 2.689 (kg/ha) is the average amount of N reaching surface waters under 1987 conditions.

The amount of gross discharge is reduced by various treatment processes. The model is using the same T matrix as in the BOD section to show what fractions of the total discharge are subject to various levels of treatment. The 4 elements of the TRRN vector show the average efficiency of N removal for each of the four treatment levels. The net N discharge (NDN) for each sector is:

$$NDN(j) = GDN(j) * \sum_{i=1}^{4} T(i,j) * (1 - TRRN_i(j)) \quad j = 3,\ldots,16 \quad (kg/year)$$

Elements of the TRRN vector are updated to reflect improvements in the removal efficiency due to technological development. The corresponding equation is the same as the one for BOD and is not repeated here.

Only part of the waste water is discharged into the streams and rivers (see above), and only this part requires the appropriate dilution flow to be considered in our water demand model. Using the same DISP matrix as above and adding agricultural N load we get the total net load of Nitrogen (NLN):

$$NLN = \sum_{j=3}^{n} NDN(j) * DISP(4,j) + \sum_{j=1}^{2} GDN(j) \quad (kg/year)$$

Part of this net N load will be consumed in biodegradation processes. This amount depends on BOD availability and on the BOD to N combining ratio (BNCR). Thus, the excessive N (EXN) requiring dilution will be:

$$EXN = NLN - \frac{NLB/10}{BNCR} \quad (kg/year)$$

The required dilution flow now depends on the prescribed water quality standard for N (RQSN):

$$QN = \left[\frac{EXN}{RQSN}\right] * \frac{10^3}{YEARSEC} \quad (m^3/sec)$$

Phosphorous

Similarly to Nitrogen, the amount of P discharge from various sectors of the economy is derived from the parameters of BOD discharge. Given the typical technologies in various economic sectors, ratios of BOD to P (CRP) per unit of waste water discharged can be determined for each of them. These ratios are listed in the CRP vector for each sector in Table A5.

The gross discharge of P (GDP) now can be calculated as follows:

$$GDP(j) = GDB(j)/CRP(j) \quad j=3,...,16 \quad (kg/year)$$

Here again, the two agricultural sectors require special treatment. Following the logic of the N section above, P load from agricultural sources will be:

$$GDP(1) = (1+PCHP/100)*0.103*SUGAR\ AREA$$

$$GDP(2) = (1+PCHP/100)*0.103*OTHER\ AGAREA$$

where PCHP is the per cent change in P fertilizer use and 0.103 (kg/ha) is the average amount of P reaching surface waters under 1987 conditions.

The amount of gross discharge is reduced by various treatment processes. The model is using the same T matrix as in the BOD section to show what fractions of the total discharge are subject to various levels of treatment. The 4 elements of the TRRP vector show the average efficiency of P removal for each of the four treatment levels. The net P discharge (NDP) from each sector is:

$$NDP(j) = GDP(j)*\sum_{i=1}^{4} T(i,j)*(1-TRRP_t(j)) \quad j=3,...,16 \quad (kg/year)$$

Elements of the TRRP vector are updated to reflect improvements in the removal efficiency due to technological development. The corresponding equation is the same as the one for BOD and is not repeated here.

Only part of the waste water is discharged into the streams and rivers (see above), and only this part of P discharge requires the appropriate dilution flow to be considered in the water demand model. Using the same DISP matrix as above, and adding agricultural P load we get the total net load of Phosphorous (NLP):

$$NLP = \sum_{j=3}^{n} NDP(j)*DISP(4,j)+\sum_{j=1}^{2} GDP(j) \quad (kg/year)$$

Part of this net P load will be consumed in biodegradation processes. This amount depends on BOD availability and on the BOD to P combining ratio (BPCR). After the necessary conversion to inorganic P, the excessive P (EXP) requiring dilution will be:

$$EXP = \left(NLP - \frac{NLB/10}{BPCR}\right)/3 \quad (kg/year)$$

The required dilution flow now depends on the prescribed water quality standard for P (RQSP):

$$QP = \left[\frac{EXP}{RQSP}\right]*\frac{10^3}{YEARSEC} \quad (m^3/\mathrm{sec})$$

A3. Lagoon Model

The Surface Water Model (SFM) keeps track of the pollutants (BOD, N, P) as they are generated, treated, and discharged (see Section A2). The DISP vector shows what fraction of the waste water is discharged into one of the four disposal locations (ground, lagoon, ocean, rivers). The pollutant load of the lagoons (PLL) thus stems from two sources: direct discharge into the lagoons and indirect load of pollutants carried by rivers.

$$PLL = LNDLB + LNRILB$$

Using the notation introduced in SFM above, the direct BOD load of the lagoons (LNDLB) will be:

$$LNDLB = \sum_{j=1}^{16} NDB(j) * DISP(2,j)$$

Indirect load, the amount of BOD delivered by the rivers (LNRILB), is calculated from SFM and a simple first order biodegradation model:

$$LNRILB = NLB - DECRIV$$

where DECRIV is the amount of BOD lost in biodegradation in rivers and

$$DECRIV = NLB*(1 - e^{-k_1 t})$$

where
t = travel time
k_1 = decay rate (rate of oxidation of organic material in the river).

Environmental quality of the lagoons is characterized by the quality of the water and by the accumulation of pollutants in the sediment. Thus we have a two-box model (water, sediment) linked via the processes of sedimentation and release from the bottom sediment. Other processes affecting water quality of the lagoons include decay, the impact of throughflow, and dilution (water exchange between the lagoons and the deep ocean). The present version of the model includes BOD as the only pollutant.

Water quality (WQ):

$$WQ_{t+1} = WQ_t + \textit{NEW LOAD (direct, indirect)} - \textit{BIOLOGICAL DECAY} - \textit{SEDIMENTATION} - \textit{OUTFLOW} - \textit{SEDIMENT RELEASE} - \textit{TIDAL EXCHANGE}$$

The corresponding equation takes the following form:

$$\frac{dC}{dt} = \frac{PLL}{V} - k_d C - \frac{A}{V} v_s C - \frac{1}{V} Q_{OUT} C - k_e (C - C_s) - \frac{1}{V} Q_e C \quad (kg/m^3)$$

where:

C = concentration of BOD in the water; kg/m^3
PLL = total new load (direct and indirect); kg/day
V = volume; m^3
k_d = biological decay rate; 1/day
A = lagoon surface area; m^2
v_s = deposition rate; m/day
Q_{OUT} = amount of freshwater inflow m^3/day
k_e = sediment release rate; 1/day
C_s = concentration of the given pollutant in the sediment; kg/m^3
Q_e = exchange flow rate related to tidal motion and wind impact; m^3/day

Sediment quality (SQ):

$$SQ_{t+1} = SQ_t + SEDIMENTATION - ACCUMULATION - DECAY - SEDIMENT\ RELEASE$$

The corresponding equation will be:

$$\frac{dC_s}{dt} = \frac{s}{h} - \frac{\Delta h}{h} C_s - k_s C_s + k_e (C - C_s) \quad (kg/m^3)$$

where:
s = sedimentation rate; kg/m^2/day; equal to $v_s C$ above
h = mixing depth; m
Δh = accumulation; m/day
k_s = decay rate; 1/day

The above two differential equations constitute a first order inhomogeneous system. Introducing the standard notation, we get:

$$X'(t) = AX(t) + F(t)$$

where:
X is the vector of concentration values (C and C_s)
A is the matrix of coefficients
F is the inhomogeneous term

and the solution is:

$$X(t) = e^{A(t-t_o)} X(t_o) + e^{At} \int_{t_o}^{t} e^{-As} F(s)\, ds$$

For t = 0 and F(s) = b we get:

$$X(t) = -A^{-1} b + e^{At} (x(o) + A^{-1} b)$$

For this system, the appropriate numerical solution was developed and is included in the computer model.