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Building resilience in the water supply network of Mauritius

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Abstract: In Mauritius, surface water is abstracted through rivers and stored in reservoirs across dammed rivers, while groundwater is harnessed through some 120 boreholes. During heavy rains, the aquifers are recharged, and unless pumping is carried, the ground water will flow to the sea. There are two inherent problems with borehole pumping in Mauritius: water levels may vary widely - as much as 20 metres – during the dry and wet seasons and the risk of a power supply breakdown during cyclones. These two issues have been addressed by installing a second borehole and a standby generator. As previous droughts have indicated the need of possible interconnections between networks - which work independently - a few interconnections are gradually being made, so that should a network suffer a shortage of supply for various reasons, there is a possibility of recovering from the shortfall. Thus, the overall water network is acquiring a certain degree of resilience which helps provide water satisfactorily during the whole year.

Key words: Water Supply, Planning, Vulnerability, Resilience, Conjunctive use

1. INTRODUCTION

The island of Mauritius is situated in the Southwest Indian Ocean between longitudes 57˚18′ and 57˚ 46′ East and latitude 19˚ 59′ and 20˚ 32′ South. It lies at about 800 km east of the Republic of Malagasy as shown in Figure 1.

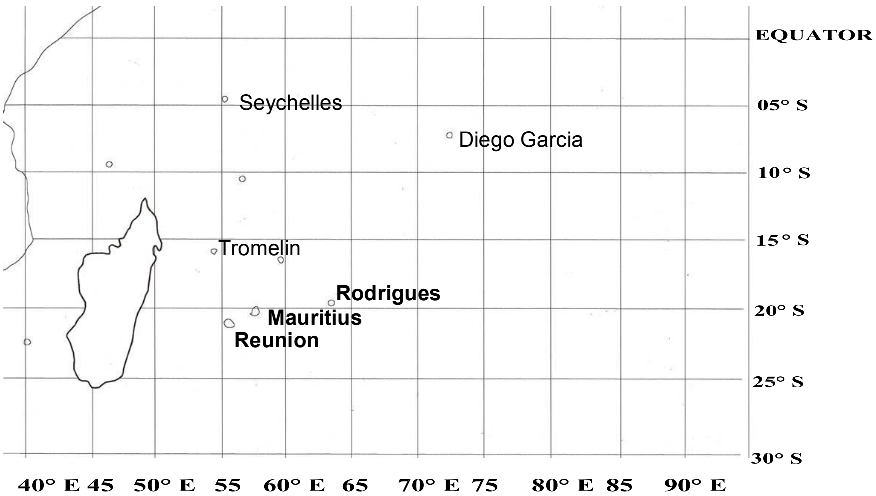

Figure 1. Location of Mauritius

The geology of Mauritius consists basically of basalt rocks only. The complex nature of its formation has given rise to basalt of various densities: the impermeable compact basalt to highly porous basalt. The latter acts a water collector; thus aquifers of Mauritius have a high permeability in excess of 10^{-5} m/s.

The texture and type of formation from the different volcanic activities would thus determine the natural infiltration rates, the contribution of rainfall recharge to aquifers and also the amount of runoff.

The rainfall pattern of Mauritius is strongly influenced by topography. The average annual precipitation over the island is 2120 mm, varying from 1500 mm on the East Coast to 4000 mm on the Central Plateau and 900 mm on the West Coast.

The surface and groundwater regimes are closely related, although aquifer and water catchment boundaries do not necessarily coincide. Groundwater plays a major role in sustaining flows in the rivers.

Regularly, throughout the year, there are several problems which occur:

1. Cyclonic events or heavy rains bring heavily silt laden water to the filters, with a consequential break down in water supply
2. Water tables go up significantly (up to 20 metres), and the boreholes pumps operate at a lower efficiency (lower head and higher flow).
3. Droughts may deplete the groundwater aquifers, or the impounding reservoirs.
4. Power cuts (after cyclones) affect the operation of pumping and other equipment.

The present water supply system thus has some inherent vulnerabilities arising from extreme climatic events.

This paper explains how, gradually, some form of resilience has been added in the different network components to address these problems. After a presentation of the existing water supply system and some relevant definitions, the paper details the solutions adopted, followed by methods which could be used to measure resilience quantitatively. The problems encountered in Mauritius are similar in other islands, and the solutions or variations thereof could be usefully shared.

2. EXISTING SITUATION

2.1 Present Water Demand and Supply

The whole population of Mauritius has access to piped potable water, distributed from the six water supply zones on the Island of Mauritius as shown in Figure 2.

Figure 2. The Six Water Supply Zones of Mauritius (Source: CWA, 2004)

- Port Louis System
- North District Water System
- East District Water System
- South District Water System
- Mare aux Vacoas Upper System
- Mare aux Vacoas Lower System

Previous studies by CWA (2004) and Gibb (2007) have shown that the water supply situation in Mauritius is presently at a good standard. Nevertheless, there are certain regions in Mauritius where water supply is not sufficient in terms of quantity and pressure.

2.2 Potable Water Requirements

According to the Central Statistical Office (CSO), the population of the island of Mauritius will grow from 1.23 million in 2007 to 1.39 million in 2025. The population trends and distribution thereof throughout the island are summarised in Table 1.

Table 1. Population Projections for the Island of Mauritius (CSO)

District Water System	Population (2005)	Households (2005)	Population projection based on CSO growth rates		
			2007	2017	2025
Port Louis	193 601	52 325	197 250	212 658	222 462
North	236 295	63 863	240 747	259 554	271 520
South	150 904	40 785	190 445	205 321	214 787
East	186 923	50 520	153 748	165 758	173 400
MAV Upper	224 976	60 804	229 215	247 120	258 513
MAV Lower	213 647	57 742	217 673	234 677	245 496
Total	1 206 346	326 039	1 229 077	1 325 088	1 386 178

3. VULNERABILITY AND RESILIENCE

3.1 Vulnerability

The concept of *vulnerability* implies some risk combined with the level of social and economic liability, and the ability to cope with the resulting event. Vulnerability has been defined as the degree to which a system, or part of a system, may react adversely during the occurrence of a hazardous event.

Thus people become "vulnerable" if access to resources either at a household, or at an individual level is the most critical factor in achieving a secure livelihood or recovering effectively from a disaster. The households with direct access to capital, tools and equipment, and able-bodied members are the ones which can recover most quickly when a disaster strikes. As such, the most vulnerable people are the poorest, who have little choice but to locate themselves in unsafe settings.

3.2 Vulnerability in the Water Supply Network System

The water distribution system in Mauritius has evolved from old systems, some dating back to more than 100 years. Major man-made water distribution systems for domestic purposes in

Mauritius dates back to 1790 with the construction of the Dayot Canal to convey untreated water from Grand River North West to the western suburbs of Port Louis. In the early 19th century, the Bathurst Canal was built to divert untreated water from Calebasses River at Terre Rouge to the eastern suburbs of Port Louis. In other parts of the island, dug-wells were popular for domestic purposes.

Subsequently, with population growth, piped systems were introduced. For example, the 450 mm and 475 mm diameters asbestos cement pipelines laid during the period 1860 to 1880 from the Municipal Dyke to supply Port Louis were still in service, until recently.

According to Gibb (2007), assuming existing water infrastructure capacity and water infrastructure efficiencies of 75%, there will be a general water deficit by 2025.

Thus, this is one of the possible vulnerabilities.

Sometimes, the vulnerability of the water network arises from a combination of several factors as indicated in Table 2.

Table 2. Vulnerability parameters to be considered

	Variables	Dependents	Vulnerability parameters
A	Resources	Climatic factors	Drought
			Heavy Rainfall
			Floods
			Change in precipitation averages and extremes
			Water Quality
B	Infrastructure	Technology	Impounding reservoir capacity
			Service reservoir capacity
			Treatment technology
			Electricity
			Manpower
C	Network		Age of network
			Pipe type (DI, uPVC, AC, HDPE, etc)
			Reticulation (branch, grid and loop system)
			Physical losses
			Pilferage
			Pressure inadequacy
D	Use	Demand v/s supply	Forward planning
			Water management strategies
			Political influence

Surface water is stored through man made reservoirs, which do not have a capacity beyond a year's supply, unless there are heavy rains throughout the year, which is rare. However, if there is abundant rainfall, or a good rainy season, the reservoirs get replenished so that supplies may sometimes be sufficient to last more than 12 months. But, this also becomes a vulnerability as an overflowing impounding reservoir often leads to premature over consumption.

3.3 Resilience

3.3.1 Resilience of systems

Imagine a car going along a bumpy road. The passengers will feel the shocks, each time the car goes over a hump or over a pothole. However, if the car damping (shock absorbing) system is very good (or should we say efficient), the shocks will be barely noticeable, or even enjoyable for children as they slowly come back to their original position. Here, the car springs have the ability to absorb and recover from the impact of the shock of an uneven road surface.

This behaviour is in contrast to a boxer's practice sand bag, which barely moves under the boxer's fists hammering it, just as a brick wall will not move at all.

In each of the above examples, the system (car, sand bag, brick wall) has some characteristics which enable it to return (or to recover) to the original state. This is what is denoted by the resilience of a system. This is illustrated in Figure 3, which shows how a shock may affect a system's performance.

Thus, the concepts of resilience take two broad forms:

a) hard resilience : the direct strength of structures or institutions when placed under pressure, such as increasing the resilience of a structure through specific strengthening measures to reduce their probability of collapse.
b) soft resilience: the ability of systems to absorb and recover from the impact of disruptive events without fundamental changes in function or structure, which depend on the flexibility and adaptive capacity of the system as a whole, rather than simply strengthening structures or institutions in relation to specific stresses, as in the hard resilience approach.

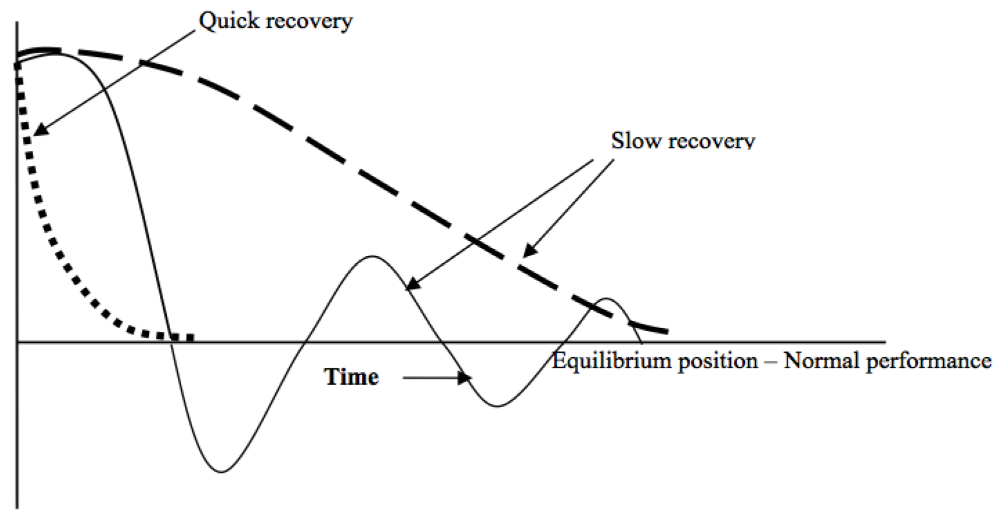

Figure 3. How a system returns to normal performance - equilibrium position

If the system behaves in one of the ways illustrated in Figure 3, it is very likely because the system has been purposely designed to do so, and not just by chance.

3.3.2 Definition of resilience

The definition of system resilience follows from the above as:

A system is usually designed to behave in a certain way under normal circumstances. When disturbed from equilibrium by a disruptive event, the performance of the system will deviate from its design level. The resilience of the system is its ability to reduce both the magnitude and duration of the deviation as efficiently as possible to its usual targeted system performance levels.

Figure 3, showing slow and quick recoveries, fully illustrates this definition. Can the water system network be designed/adapted to become more resilient?

3.4 Assessing Resilience and Remedial Measures

3.4.1 Assessing Resilience

Table 3 explains the steps that can be carried out for assessing the resilience of the water network. System resilience will depend, at least, partly on inherent properties of – or those inbuilt in

- the system. In particular, three such properties or capacities are used to define, quantify, and design for better resilience:

1. *absorptive capacity*, or the ability of the system to absorb the disruptive event;
2. *adaptive capacity*, or the ability to adapt to the event; and
3. *restorative capacity*, or the ability of the system to recover.

Table 3. Assessing resilience of the water network

Steps	**Explanation**
System definition	understand the components of the system and how resilience applies to the system
Identify critical resilient components	demarcate the boundaries of the system, identify appropriate scales to examine resilience, and identify the variables of concern
Identify sector resilience needed	identify external shocks and relevant internal parameters, through stakeholders and historical log
Identify stakeholders	identify the key players and the external critical parameters
Assess resilience	identify the recovery path and recovery efforts, through models
Management implications	inform policymakers/ managers how the system might react to shocks.
General assessment of resilience	synthesize the findings of the previous steps

The solutions that are identified can be further elaborated by examining the technical features (a simple design may be more robust, be easier to adapt, and easier to repair) and the organisational aspects (the costs of recovery need to be compared against the speed of recovery).

Table 4 illustrates the system dependencies across systems which can affect resilience capacities.

Table 4. Relationships between system capacities, performance, and recovery

Capacity	Relationships
Absorptive	If system A (pump) is dependent upon system B (electricity) to operate, then this relationship will lower system A’s absorptive capacity in scenarios that negatively affect system B (power failure).
Adaptive	System A (pump) may have adaptive capacities that allow the system to reorganize (using standby generator) to reduce its dependency upon system B (electricity grid)
Restorative	The operation of system A (gravity pipeline) may not depend upon the functionality of system B (electricity supply), but the repairs to system A may require system B to be operational. Difficult coordination may further reduce institutional restorative capacity

3.4.2 Remedial Measures

From the above, resilience can be improved by acting on different parameters, as shown in Table 5.

3.4.3 Resilience Features in the Water Supply System

Over the course of time, the Central Water Authority (CWA) has developed several strategies to improve the resilience of the water supply network, such as:

a) Pumping heavily during heavy rains
b) Digging a second borehole
c) Installing a standby generator to address the issue of a power breakdown
d) Interconnecting different networks

Table 5. Characteristics which influence resilience

Characteristic	Wrt Event	Reason
Robustness	Ex-ante	In the design or retrofit phase, to increase infrastructure resistance to extreme events or impacts.
Redundancy	Ex-ante	In the design or retrofit phase, when increasing redundancy options might be cheaper than increasing robustness options.
Reliability	Ex-ante	In the design or retrofit phase, so that infrastructure is reliable under all conditions, even extreme events.
Resourcefulness	Ex-ante	Resourcefulness can be increased through preparedness and recovery service organisations, to restore infrastructure performance.
	Ex-post	Depends on decisions (e.g., through distribution of available resources in post-disaster situations), to restore infrastructure performance.
Rapidity (Response and recovery)	Ex-ante	Rapidity can be increased ex ante (e.g., through design changes, preparedness, and recovery service organisation), to overcome disruption and to restore infrastructure performance.
	Ex-post	Depends on decisions (e.g., through distribution of available resources in post-disaster situations), to overcome disruption and to restore infrastructure performance.

a) Pump heavily during heavy rains: Surface water is stored through man made reservoirs, which do not have a capacity beyond a year's supply, unless there are additional heavy rains during the year. During the same heavy rains, the aquifers are recharged, and unless pumping is carried, the ground water will certainly go to the sea. One idea has been to pump heavily during the rainy period so as to abstract a maximum amount of water from underground, thus saving on the amount of water which needs to be extracted from the reservoirs.
b) Digging a second borehole offers two advantages: firstly, in case of a pump breakdown or maintenance, a immediate relief is available with the second borehole and secondly, given that water levels may vary widely - as much as 20 metres – during the dry and wet seasons, the two pumps may be chosen to operate more efficiently, one at the dry season level, and the other at the wet season level.
c) Installing a standby generator, with an automatic start in case of electricity supply breakdown increases the resilience of the network.
d) Interconnecting different networks: Any of the networks mentioned above in para. 2.1 is, in principle, independent. However, previous droughts have brought home the need of possible interconnections. Gradually a few interconnections are being made, so that should a network suffer a shortage of supply for various reasons, there is a possibility of damping the shortfall through an intake from another system.

Thus, the overall water network is acquiring a certain degree of resilience which helps providing water to the population satisfactorily during the whole year.

A summary of these different strategies adopted and to be developed is presented in Table 6.

While output measures performance, it can be appreciated that the recovery time to normal performance can be another measure of resilience, as well as the effort required to do so. A simple example: a damaged house does not offer the same facilities as before the disaster. How much time and effort (cost) does it take to get the house performing as before? The absorptive, adaptation and restorative capacities of a system influence its resilience. Just as efficiency is defined as the ratio of output to input, one can imagine defining resilience efficiency as:

$$\text{Resilience efficiency} = \frac{\text{Output under Shock}}{\text{Normal Output}} \qquad (1)$$

Variations based on this defining equation will be discussed further down when dealing with quantitative assessment. A form of quantitative assessment may be useful when evaluating different alternatives of providing resilience to the network.

Table 6. Adding resilience to the water supply network of Mauritius

	Robustness	Redundancy	Reliability	Resourcefulness	Response after event
Surface water / Ground water conjunctive use	♦	♦	♦	♦	
Double borehole	♦	♦	♦		
Standby generator	♦		♦		♦
System Interconnection	♦	♦	♦		♦
River (surface) pump				♦	♦
Water Rights use during drought				♦	♦
Tanker service during drought				♦	♦
New impounding reservoirs	♦	♦	♦		
New service reservoirs	♦	♦	♦		
Local / domestic storage tanks	♦	♦	♦		
New treatment plants	♦	♦	♦		

4. MEASURING THE RESILIENCE ACHIEVED

4.1 Quantitative assessment

4.1.1 Resilience efficiency

While output measures performance, it can be appreciated that the recovery time to return to normal performance can be another measure of resilience, as well as the effort required to do so.

If we define the concept of resilience efficiency (Eq. 1), it is logical to start working along these lines to introduce the recovery time and the effort required in an attempt to measure resilience. The concepts of resilience quality, effort resilience, cost resilience and even time resilience are explained below.

4.1.2 Resilience quality

If two similar systems are equally damaged, the time it takes for them to recover back to normal performance can be a simple measure for resilience (cf. Figure 3). The longer time it takes, the less resilient it is.

However, during this recovery period, it may also be imagined that the system is partly functional, say y %. If this percentage is plotted during the recovery period, the area under this curve gives a measure of the product (performance x time). If there had been no damage, the area under this curve would have been 100 % x recovery period. Thus, the ratio of the former to the latter can give a quantitative measure of resilience that could be termed as resilience quality.

4.1.3 Effort (cost) resilience

Another measure that can be developed would rely on the effort (cost) (Y) required to build a new system. This can then be compared to the effort (cost) (X) required to recover to an equivalent system (as performing previously).

The effort (cost) resilience could then be expressed as effort (cost) resilience = (Y-X)/Y

This ratio would give 0 % if the whole system had to be rebuilt, and 100 % if no effort (cost) was required.

4.1.4 Comparison

It may be noticed that this last measure of resilience would still give 100 %, even if the system - though requiring no effort (cost) – takes a significant amount of time to recover to normal performance. It is therefore judicious to use several measures of resilience to compare or assess different systems. The benefits of having a resilient system are obvious – recover more quickly from a disturbing event. But, at what cost?

4.2 Cost of providing resilience

Resilience can only be provided by adding another link to a network component, be it a second borehole, a standby generator, etc. These different forms of resilience added to the network have a cost. For example,

1. During the drought of 1999-2000, the cost of providing water tanker service and other facilities, amounted to some Rs 50 million (2.5 million Euros, at that time).
2. The interconnection between Mare Longue reservoir and La Marie filters cost Rs 50 million (1.25 million Euros, at the present exchange rate), for an addition of 20,000 m^3/d, which is lost for hydropower and irrigation.
3. The interconnection between Midlands reservoir and Piton du Milieu reservoir is estimated at a cost of Rs 400 million (10 million Euros, at the present exchange rate), for an addition of 20,000 m^3/d.

This may be compared to an average selling price of water of Rs 9/m^3, for a total sold volume of about 90 Mm^3, annually. A cost benefit exercise could be carried to determine the feasibility of adding such resilience. Some methods of adding resilience, though initially expensive, might provide a cheaper long term solution than other possible alternatives. Thus, having quantitative methods of measuring resilience may be a useful guide.

4. CONCLUSION

Very often, the quick development of the water supply network - often in a haphazard way on small islands - brought inherent vulnerabilities, which need to be removed gradually. Some resilience has gradually been introduced into the system, sometimes at high cost.

This paper has explained the concept of having resilience in a water supply network and the ways of introducing or adding such resilience. The problems encountered in Mauritius are not unique, but do apply to many islands (Réunion, Rodrigues, Fiji among others). Hence, the solutions shown here are probably applicable, with some variation, if necessary.

Measuring resilience is not easy as this depends on the system under study. It is important to look at the ways resilience is being considered and use these as a method to measure resilience, either qualitatively and quantitatively. In most cases, the systems are rarely totally down. While qualitative assessment is useful to understand how bad things are, quantitative measures give quantified estimates of performance, time and effort (cost) that are more meaningful to stakeholders (consumers, fund providers), and decision makers.

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