Can sustainable water monitoring be a reality?

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Abstract. In this paper, authors discuss the current methods used for surface water monitoring and the gaps left in monitoring in context of a low resourced area. Water quality monitoring [1] is a complex problem that can only be tackled through a systemic application of a transdisciplinary approach. This paper suggests use of a variety of innovative solutions adapted to the local conditions encouraging the prospect of sustainability. The approach relies on an emphasis on environmental and water quality for human life that will contribute to: 1) improved capacity building of local actors, including the role of women; 2) increased economic and social well-being at local and regional levels; and 3) protect natural capital in the region. This article reviews the state of water monitoring in low resourced area, example is taken here from Southern Arica and attempts to establish a sustainable water quality monitoring plan for application to cross-boundary water resources in the region. These are essential to diagnose and raise understanding on water quality problems in resources shared by countries with contrasting development levels. The innovative vision presented here proposes to resolve this multidimensional water quality problem by considering the broader system ranging from aquatic ecosystems providing this service to supply systems serving final consumers.

1. Introduction
The authors of this paper suggest application of a Systems Engineering approach to establish a sustainable water monitoring regime especially in low resourced areas. Such an approach is necessary because any effective solution must involve a wide range of organisations, interests and needs and the setting up of interfaces to enable efficient inter-working is a key part of this. Water resources in most of the low resourced areas like sub-Saharan Africa are not regularly monitored and many catchments are ungauged [2]. Hence, water quality problems receive attention only when very serious persistent contamination or aquatic health problems occur [3]. Under extreme climatic conditions, such as high intensity rainfall, there is a rapid propagation of water contamination [4]. This is exacerbated by difficulties in forecasting propagation and coordinating catchment management when the water resource is cross-boundary under shared international responsibility and usage.

This paper will focus on the Limpopo River Catchment, a cross-boundary basin spreading over South Africa, Mozambique, Botswana and Zimbabwe but the presented concepts can be applied to any low-resourced area. The proposed plan relies on an efficient tiered approach that may complement existing monitoring procedures where available. In each tier, levels of certain variables will be used as indicators of potential bacterial or chemical contamination triggering analysis with technically advanced methods in the subsequent tier. Guidelines for the practical implementation of the monitoring plan fitted to local water, sanitation and climatic conditions will be provided.
To achieve the mentioned aims, it is necessary to undertake a comparative multi-sensor monitoring strategy. The approach will be based on: (i) community-driven cost-effective monitoring in the form of crowdsourcing; (ii) remote online sensing, (iii) lab-based analysis and (iii) development of forecasting tools. This concept is illustrated in Fig. 1. Integration of the information produced will provide a final streamlined monitoring plan. Once established, the system will send alerts to community and other relevant stakeholders when the quality of a water body deteriorates.

2. Background

Monitoring water quality at source and in distribution systems is critical to develop adequate integrated water resources management. It enhances both domestic and agricultural water supply and safeguards environmental quality. Often in Southern Africa basic monitoring is performed at local level. However, this information is seldom integrated with techniques to diagnose the causes of water quality degradation and identify remediation and protection measures. Hence, it rarely reaches regional or national levels where it can be useful to the managers and decision makers [5]. This paper proposes a solution to promote integrated water quality monitoring in Southern Africa. Focus is being given to developing tools supporting resolution of water management problems related to severe climatic conditions and cross boundary conflicts. Table 1 below lists some major catastrophic events since 2000. These events are often followed by a disease outbreak, especially Cholera [6].

Table 1. Timeline of Catastrophic Floods and Droughts in Limpopo Basin [7]

| Year | Type of Disaster | Influenced By Cyclone | Affected Areas and Some More Details |
|------|------------------|-----------------------|-------------------------------------|
| 2008 | Flood            | Jokwe                 | Zambezi, Púngue, Búzi and Save rivers in Mozambique flooded. Zambezi |
| 2007 | Favio            |                       | Zambezi River flooded –more than 120,000 displaced and 250,000 people affected in Mozambique. (http://www.care.org/newsroom/articles/2007/02/20070223_mozambique_cyclone.asp) |
| 2003 | Floods           | Delfina               | Zambezi River flooded. Seven people died and more than 30,000 people displaced in Malawi and more than 400 homes washed away in Mozambique http://www.ncdc.noaa.gov/sotc/hazards/2003/jan |
| 2002-2003 | Drought |                       | Drought period for most of rivers on the southern east coast of Africa with some parts of Limpopo Basin affected. More than 43 districts affected in Mozambique, including those in Limpopo River Basin |
| 2001 | Flood            | Dera                  | Zambezi River flooded, with 115 deaths reported and more than 500,000 affected in Mozambique and 340,000 people affected in Malawi. (http://www.irinnews.org/report.aspx?reportid=18976) |
| 2000 | Flood            | Elaine, Gloria and Huda | Limpopo, Maputo, Umbeluzi, Incomati, Buzi and Save rivers severely flooded. Some 640 deaths recorded and more than 2 million people affected, EN1 main road in Mozambique closed for several weeks |

Water resources in the region are used for domestic purposes (including drinking), agricultural irrigation, small industries and mining. Table 2 below lists main uses of groundwater in the four partner countries in the Limpopo River basin.
Figure 1: 3-Tier sustainable monitoring concept

Table 2. Groundwater abstraction and uses in the Limpopo Basin

| Country      | Estimated Annual Groundwater Abstraction (Mm³/year) | Sector Use               |
|--------------|---------------------------------------------------|--------------------------|
| Botswana     | ~23.1                                            | Domestic, Irrigation     |
| Mozambique   | ~15                                               | Domestic                 |
| South Africa | 462                                               | Domestic, Irrigation, Mining, | Irrigation |
| Zimbabwe     | ~5.9                                              |                          |

(Source: Environmentek, CSIR 2003)

The range of stakeholders which rely on these rivers and groundwater resources include small scale miners, industrial operations such as the cement factory works at Coleen Bawn in the Shashe sub-catchment, gold panning and irrigated agriculture [5]. In return, these industrial and mining activities negatively impact the water quality in the basin [8]. The region is thus exposed to toxic life-threatening chemicals like pesticides and heavy metals, such as cadmium [5][9] resulting in hazards to aquatic ecosystems that endanger water quality sources and security of aquatic species. These pollutants are known for their ability to cause detrimental effects leading to oxidative stress and endocrine disruption, decreased survival and reproduction, as well as loss of food quality for human consumption [10]. Pansteatitis, in particular, has been recognised as a serious disease of unknown etiology that is affecting Nile crocodiles and catfish in the Olifants River [11]. This, yet to solve, problem has been related to altered fat oxidation processes elicited by poor water quality (cyanobacteria presence, metal contamination) and ecological changes in the trophic chain [12]. Loss of local biodiversity and negative impact in touristic activities are, thus, actual concerns, and illustrate the direct link between environmental health, social well-being and the economy.

Low aquatic health brings additional environmental degradation, water safety and public health problems. Uneven sanitation provision among the four countries, together with climatic conditions, particularly extreme events like floods, further promote the spread of bacterial contamination into local supply systems [12]. These multiple problems require a holistic integrative water quality vision and anticipation to provide fresh sustainable solutions.
3. Concept and Approach

The presented approach here relies on a multi-tier monitoring approach as shown in Figure 1.

Tier 1: Involving Communities in Water Monitoring

The Tier 1 of the sustainable monitoring programme is based on engaging and incentivising communities to support water quality monitoring within their catchment area, in source and supply systems [13]. Communities can be introduced to crowdsourcing tools, low cost, easy-to-use strip tests for physical and chemical water quality assessment (pH, phosphates, nitrites/ammonium, iron, coliforms) and the use of mobile applications to provide information on potential water contamination. The information to be presented visually through various means, e.g. hydrogeological maps. A key aspect of this task will be to develop, via a co-design approach, a context-appropriate cell phone application to support data collection [14]. The main purpose of this tier is to provide the public with the ability to engage with the relevant authorities on water quality monitoring. The design of the tools should form part of an increase in transparency and an understanding of citizenship in rural areas. Suitable selection of communities through water literacy campaigns is essential. Different demographic variables must be targeted: householders, associations promoting women’s economic empowerment, professionals linked to agricultural, industrial and economic sectors, young students, professionals in integrated water resources management, policy makers, local water management authorities and health authorities. It is important to establish a two-way communication through: (i) organisation of workshops, (ii) discussions with specific groups/stakeholders and (iii) visits to schools. Appropriate training must be given in the workshops to enhance their water literacy and collaboration.

Tier 2: Applying Mixed Sensor Approach to Surface and Groundwater Monitoring

Tier 2 and will use a mixed sensor approach for continuous monitoring of water bodies in the Limpopo River Basin. A range of well-established and innovative sensor systems can be used: (1) online monitoring setups (for basic parameters like Dissolved Oxygen (DO), Temperature, Conductivity, pH, Chlorophyll, Turbidity); and (2) manual sample collection for accurate physical and chemical characterisation of groundwater using spectrophotometric methods. The latter will provide an understanding of groundwater and surface water interactions. Remote monitoring setups will include the use of existing online sensors and the addition of new monitors where a gap is identified. Novel techniques will be piloted, such as the use of drones [15] to collect information on water body vitals and online tryptophan fluorimeters [16] for indicating bacterial activity. Device options include the use of normal 6-head probe typically measuring DO, Temperature, Conductivity, pH and Ammonium; Optical information from the drones can be related to chlorophyll, algae, turbidity, while commercially available novel online fluorimeters will be used for measuring biological oxygen demand (BOD), Tryptophan.

Tier 3: Lab-based evaluation of water quality and health status of aquatic ecosystems

Tier 3 is the final level in monitoring and most resource intensive tier. Information from the Tier 2 will indicate the presence of major organic/inorganic pollution that needs to be analysed in each catchment, for correlation with biological effects measured. This tier will be triggered to experimentally confirm the finding of the previous tiers. These are useful to anticipate detrimental effects at the population and ecosystems levels before it becomes too late to implement mitigation measures. Examples include toxicological assays with embryos or larvae may be conducted when required for in-depth hazard characterisation.

Modelling propagation of water contamination in surface water

Data from the three tiers will be used to model the propagation of contamination in the water system. Data mining techniques like clustering and Neural Networks will be used to develop the model (see for example [17]). The main outcome will be a model to predict water contamination outbreak and/or propagation of contaminants along the waterbody [18]. This will build on the sensor data collected and it will in addition collect climate data such as temperature, rainfall and water discharge levels. These data together with sensor information will feed into an interactive map of the water body showing the contamination status and threshold ranges for main outbreak-related variables. The system will also allow new data to be added by key stakeholders. It will also correlate and integrate the crowdsourcing data to enable understanding of indicative parameters to be measured on a continuous basis and alert thresholds. The use of this integrated technology will act as an “early warning device”, alerting the
relevant stakeholders of the possible presence of contaminants in the systems. The developed model will primarily work on two levels: (1) act as an alert system and (2) indicate the spread of contamination in a cross-boundary context.

**A Sustainable and Integrated Water Monitoring Plan**
This comprises the final aspect of this proposed plan and it will devise an integrated approach for the effective monitoring strategy of the water system in Limpopo basin. It will use the results and data collected to get a comprehensive understanding of the system, the range and magnitude of hazards that may be present and the ability of existing processes and infrastructure to manage actual or potential risks. These assessments will be combined with the participatory development of scenarios for strategic planning of the water quality monitoring system. This will require a complete multi-criteria decision analysis (MCDA) of the system and the use of tools like Cost Based Analysis (CBA) and Principal Component Analysis (PCA) as inputs. The wealth of data will be pruned through comparative evaluations through the successive iterations. The iterations will be set to achieve a balance among type, time consumed, and least number of measurements needed to be employed for effective sustainable monitoring and management by external stakeholders. This approach will thus produce tools and products, adapted to local conditions that will support: (i) better identification of water vulnerability by policy makers; (ii) operational application of integrated water management; (iii) implementation of advanced regulatory and economic instruments in the water sector.

**4. Impact**
Water quality is a basic requirement for social wellbeing and economic development. Poor water quality leads to an increase in water-borne and other communicable diseases and pollution-related death or illness. It impairs other ecosystems’ services impacting agriculture, industrial production and tourism. Solving these problems involves high health and economic costs. Integrated early-warning systems for monitoring of drinking water quality and ecosystem health will provide a critical basis for implementation of protection and/or remediation measures anticipating such problems, before they become so severe that any intervention is hopeless.

*Improved health outcomes:* This will seek to achieve a reduction in cholera, diarrhoeal disease, typhoid fever and other water-borne diseases within Limpopo populations. In terms of its public health impact, we anticipate that the immediate beneficiaries of the project will be households reliant on surface and groundwater for drinking and cooking. Within the Beitbridge District of Zimbabwe for example, the district approximating to the Umzingwani sub-catchment, there are 1,600 such households [19], using surface water, as well as a smaller number of such households in Limpopo Province in South Africa. The 11,000 households using piped water in Beitbridge District and equivalent populations in Limpopo Province, South Africa and in Mozambique will also stand to benefit from reduced disease risk via water safety planning. Such households remain a priority under proposed targets and indicators for post-2015 monitoring, specifically via proposed target 2.1 [20]. This will promote safer and informed use of water and aquatic food resources, contributing to reduced disease burden and exposure to chemical contamination. They will also benefit health care providers, saving money in treatments and medication to affected citizens that can be allocated elsewhere. Local, regional and national health statistics will provide a quantification of this impact.

A second contribution of the proposed methodology will be an enhanced understanding of the vulnerability of such populations to pollution spikes associated with climatic events. This includes notably high intensity rainfall events, as well as droughts with consequent salinity intrusion. Although there is now more widespread use and guidance on the development of water safety plans for the management of piped supplies [21], more specific guidance and academic literature is lacking on cross-boundary catchment characterisation and management. Techniques for estimating gridded counts of population using different water source types can be taken up beyond the study area, contributing to health risk management.

*Maintenance of environmental resource quality:* Beneficiaries in this area will be local populations, decision-makers at Environmental Agencies, Catchment Management Commissions, Integrated Water Resources Managers, and researchers linked to environmental quality. Ecosystems functioning and health are at the core of the global water cycle. Their degradation undermines benefits to humans,
including water purification and food provision. Integrated evaluation and diagnosis of ecosystems status and the linkages to final end-users is now recognised as necessary to produce adequate solutions to water problems. Local populations will benefit profiting from drinking water supplies and ecosystems services (water, fisheries, agriculture and industrial activities, cultural and spiritual values) in the Limpopo. It will also provide information benefiting the work and decisions of environmental agencies and management commissions mentioned above.

In the long-term this proposed strategy will reduce the high costs of mitigation and remediation interventions to solve severe contamination problems and deteriorated ecosystems. They will also enlarge the scientific knowledge-base on methods to assess ecosystem health. Furthermore, this approach will be build-up on concerted operation of inclusive participation of stakeholders from Limpopo WASH and environmental health sectors of South Africa, Mozambique and Zimbabwe. This process to achieve a harmonised sustainable monitoring plan can ease communication among the African countries to solve transboundary water management problems.

**Water Literacy and Capacity Building:** Beneficiaries in this area will be medium to high-school students, citizens from all activity sectors, technical professionals and higher level decision-makers. In low and middle income countries, public perceptions of drinking water safety are relevant to promotion of household water treatment and to household choices over drinking water sources. Nevertheless, in South Africa, perceived drinking water safety is primarily related to organoleptic qualities rather than socio-economic or demographic characteristics [22]. More important, this perception has remained relatively stable over time, even after a large cholera outbreak took place [7]. A similar trend is to be expected concerning ecosystems health. They are expected to increment water literacy and promote informed citizens, more responsible and better equipped to take knowledgeable decisions. They will also improve knowledge of natural resources and best practices applicable to food systems and water resources, and their economic and social value to countries. These impacts are aligned with Post-2015 Sustainable Development Goal 6 (6.b support and strengthen the participation of local communities for improving water and sanitation management) of the Global Goal for Water and Rio+20 follow-up [23].

Technical-oriented training will benefit professionals at Environmental Agencies and Southern African Universities applying water quality monitoring tools and techniques. It will improve their qualifications and innovation-capacity to support their countries in evaluation of water quality, sanitation and ecosystems health, in line with Post-2015 Goal (6.a). Communication of information through various channels can also impact decision and policy makers at regional, national and supranational decision levels.

**5. Conclusion**

In this paper, authors have proposed a sustainable water monitoring strategy that builds on an effective utilisation of existing resources, avoids ‘over monitoring’ and empowers the citizens and stakeholders by engaging them in data collection. On a higher level, among all, the innovation lies on using a Systems Engineering approach to produce a high-end business model tackling a long-known problem. Water is a multidimensional asset in nature, scale and repercussions. However, water problems are commonly approached in isolated pockets, with division of knowledge, resources and energy. These may act as barriers and limitations that hamper their solution. Occasionally, the solutions given act as quick band aids until a new focus appears or a regulatory standard cannot be met. The systemic approach presented here will produce an effective monitoring tool, with reliable optimisation of available resources that can act as a ground base for water quality sustainability and early diagnosis of potential cross-boundary water problems requiring specific management strategies in African developing countries. The well balanced, hand-in-hand transdisciplinary approach will ensure this systems approach implementation, fostering the essential link between water, environmental health and human economic and social wellbeing.

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