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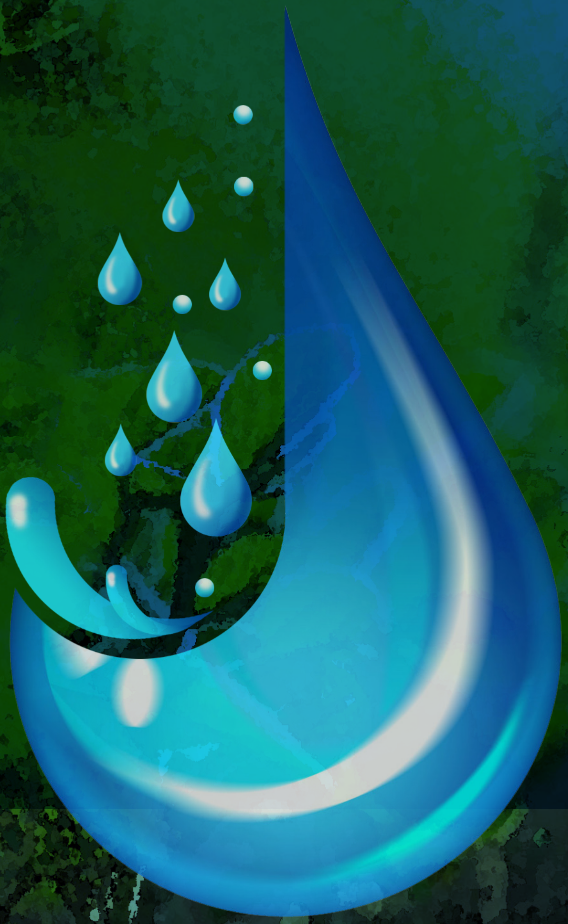
WATER QUALITY IN AGRICULTURE: Risks and risk mitigation



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Chapter 9

Water quality management in the context of river basins

Hugh Turral

As pointed out in previous chapters, the management of water quality extends beyond the farm, and has to consider upstream and downstream linkages within a catchment or water basin, where agriculture may be both a possible cause and a possible victim of water quality changes (FAO, 2018). This chapter briefly summarizes approaches used to analyse, monitor and manage water quality in its larger geographical context.

9.1. From source to sink

Within a hydrological system, pollution is classically described in terms of sources, pathways and sinks, where pollutants eventually accumulate and cause negative impacts. Easily identifiable sources with relatively high concentrations of pollutants, such as human settlements and industries located at water ways, are known as point sources. Most sources of agriculturally derived pollutants (e.g. agro-chemicals and eroded soils) are more diffuse, with small, episodic contributions across large areas, and are described generically as non-point-source pollutants.

Point-source pollutants from agricultural activities are also generated by intensive livestock and aquaculture units or from large-scale processing of agricultural products (e.g. milk factories, abattoirs and sugar cane mills).

A qualitative assessment of the relative contributions of cropping, livestock production and aquaculture to the generation of non-point source pollutants is given in Table 9.1:

Table 9.1. Relative contribution of agricultural production systems to non-point source pollution

	Nutrients	Salts	Sediments	Pesticides	Pathogens	Metals	Organic carbon	Pharma-ceuticals
Crop production	***	***	***	***	*	*	***	–
Livestock	***	*	**	–	***		***	***
Aquaculture	**	*	–	–	*		**	**

Source: Modified from FAO. 2018. More people, more food, worse water? A global review of water pollution from agriculture. FAO, Rome and IWMI, Colombo

The impacts of pollutant generation may be local or felt many hundreds of kilometres downstream and out to sea (e.g. nitrate runoff effects on coral bleaching in the Great Barrier Reef, Australia) (McCook *et al.*, 2010). Impacts may occur at interim points in the landscape and along hydrologic pathways, where pollutants accumulate, can be absorbed and "neutralised", or also be remobilized and exported downstream. The duration of impacts at such points can be very long, depending on patterns and the continuity of incoming loads and processes governing fixation, possible remobilization and transport downstream. Humans and animals also function as biological sinks, especially for toxins and microplastics that slowly accumulate in the food chain. However, the primary sinks for agricultural and other pollutants are soils, groundwater and the ocean.

The ability to define pollutant pathways between source and impact is essential due to the varying intersections of hydrology and human activity (e.g. food marketing) at different points along the flow paths and food chain. Quantifying these pathways and food consumption provides an opportunity to predict impacts on environmental and human health, and to identify entry points for monitoring and risk mitigation.

A sink, in simple terms, is a point in the landscape or water system where pollutants accumulate and may cause negative impacts. This accumulation may be temporary or permanent, depending on the position in the landscape, the loading, frequency, management, chemical and biochemical transformation, and secondary export of pollutants further downstream. Removing and remediating pollutants is costly and can be hazardous, therefore the most effective and economic approach to managing pollutants is to minimize their generation at source. This can be achieved through water treatment at point-pollution sources or through the adoption of less polluting agricultural practices in areas known for non-point pollution.

The impacts of agricultural pollution range from environmental degradation to health risks and industrial costs that are often borne by society as a whole. These include:

- water treatment costs (protecting public and environmental health);
- market costs on agricultural production (mitigating lowered productivity);
- non-market and market costs on fishing (damaged habitat, migration to better habitats and lowered productivity);
- market costs on industry (sediment, salt and others);
- market costs to hydropower and dam operators (sediment removal);
- non-market costs on recreational and amenity uses.

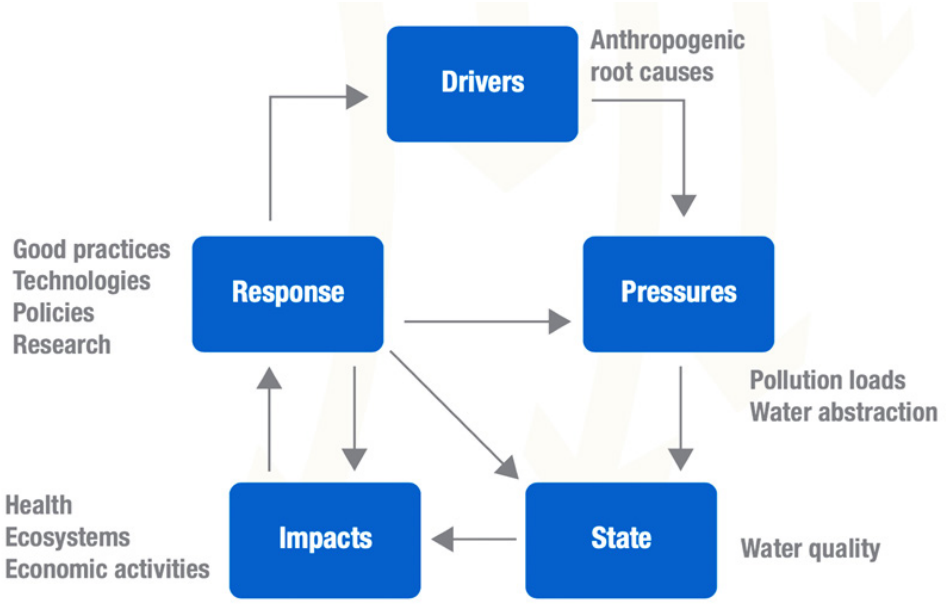
9.2 Adaptive pollution management across scales and sectors

One of the main challenges associated with managing pollution from human activities in a larger geographical context is the need to link preferences and perceptions with human actions and the consequent impacts on ecosystem services and health. One example is the (perceived) need of hillslope farmers to burn their fields, which can heighten runoff and siltation of downstream reservoirs used for irrigation or hydropower. An integrated management response ideally links scales, sectors and stakeholders, combining social and biophysical perspectives and their dynamics over time and scale. Such issues can be termed complex or “wicked” problems (Patricio *et al.*, 2016). Two common approaches to address this challenge are the DPSIR (Drivers, Pressures, State, Impact, Response) concept at the conceptual level and AM (adaptive management) at a more operational level.

9.2.1. DPSIR

The DPSIR concept helps develop an understanding of human impacts on natural systems. It was adopted by the EU as part of the Water Framework Directive (European Commission, 2000) and has been recommended more broadly for developing countries (FAO, 2018). The concept provides a logical connection between the various components of cause and effect in pollution, in general, and encompasses management of water quality from field to ocean (Figure 9.1). It has been widely used to transform unstructured problems into ones that can be effectively addressed within a broader analysis for longer-term management of ecosystem-society dynamics, needs and trade-offs. This approach works best when there is sufficient understanding of all biophysical processes, as well as the required data and techniques to quantitatively combine biophysical and socio-ecological information within a given or changing political economy.

Figure 9.1. DPSIR cycle and connections



Source: Modified from European Commission. 2002. Guidance for the analysis of pressures and impacts in accordance with the Water Framework Directive. Common Implementation Strategy. Working Group 2.1. Brussels, Office for Official Publications of the European Communities

Table 9.2. The DPSIR framework: terms and definitions

Term	Definition
Driver	An anthropogenic activity that may have an environmental effect, such as agricultural intensification or a change of diet.
Pressure	The direct effect of the driver on water quality (e.g. higher siltation rate through increased erosion).
State	The resulting condition of water quality (i.e. physical, chemical and biological characteristics).
Impact	The effect of the water quality change on environmental health including human and aquatic life.
Response	The measures taken to improve the state of the water body.

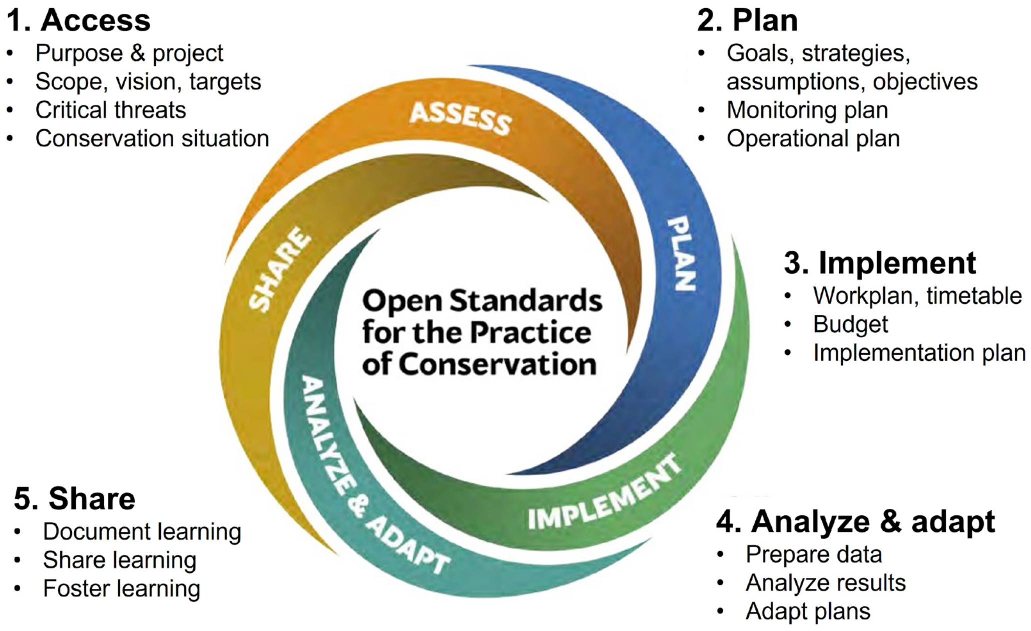
Source: Modified from European Commission. 2002. Guidance for the analysis of pressures and impacts in accordance with the Water Framework Directive. Common Implementation Strategy. Working Group 2.1. Brussels,Office for Official Publications of the European Communities

9.2.2. Adaptive management

Adaptive management (AM) underpins sustainable natural resource management strategies in countries such as Australia, New Zealand and the United States. It recognizes that responses to address one set of problems may provoke unforeseen outcomes, synergies and impacts, and that coherence in policy, strategy, planning and practical activities is an iterative and often cyclical process. AM is used by communities, state authorities and independent service providers, although many examples in the literature focus on a single issue and rely heavily on data and modelling.

AM is also often described as a cyclical process, as shown in Figure 9.2, following classic expressions of the strategic management cycle, with a strong focus on learning and adaptation. It can help to address the challenges and needs identified in the DPSIR analysis from a practical perspective. An example of AM in the wastewater and sanitation sector is 'sanitation safety planning' (WHO, 2022).

Figure 9.2. An example of the adaptive management cycle in the context of environmental conservation measures



Source: CMP. 2020. Open standards for the practice of conservation: Version 4.0. The Conservation Measures Partnership (www.conservationmeasures.org)

AM is designed to address uncertainty or disagreement about underlying system dynamics or the expected effects of management and is useful when management decisions are taken over a time frame long enough to generate learning for feedback (Williams & Brown, 2012). Models can play a key role in dealing with this complexity by representing uncertainty in the description of a system and its components, dynamics and likely responses to management. The rapidly expanding set of modelling approaches include Multi-Criteria Decision Analysis (MCDA) (Gregory *et al.*, 2012) and the use of agent-based modelling in conjunction with a creative analysis of human preferences and perceptions, for example the Challenge and Reconstruct Learning (ChaRL) framework (Smajgl *et al.*, 2015). Models based on available data, concepts and beliefs can be built to predict scenario outcomes, design monitoring programmes to test those outcomes, and then compare and modify active management strategies. Scenarios can be built to represent opposing opinions or understandings and can identify supporting research and data needs as well as interventions that will generate learning and management feedback. For adaptive decision making, government agencies must transition from a traditional "top down" organizational structure to one that is more collaborative, risk tolerant, inclusive and flexible (Williams & Brown, 2012). This requires explicit community involvement in the identification of problems and solutions (Box 9.1), and is in some ways less centralized than the expert process of DPSIR.

It should be noted that most examples are found in data-rich countries, where spatial and temporal data (e.g. monitoring in-stream water quality changes over time) can be mapped within the watershed using GIS. The Wisconsin Department of Natural Resources (DNR), in the example below, offers a suite of six physically based models for management of agricultural and urban-sourced phosphorus at different scales, which require comprehensive primary and secondary data and technical/laboratory support. The Wisconsin guidance also provides considerable detail and references for a suite of best management practices (BMPs) ready for different contexts (urban and rural catchments) as well as for arable, livestock and mixed farms.

The challenges for AM in developing countries are considerable in terms of costs, the availability of data, information, technical and organizational support from "government", and the capacity and motivation in communities to tackle these issues beyond managing their own needs.

Box 9.1. Examples of adaptive management approaches

The following two examples describe the key steps of an AM plan. The first example concerns the management of pollutants and water quality according to the Australian Water Quality Management Framework of which the key steps are outlined below (Water Quality Australia, n.d.):

1. Examine current understanding
2. Define community values and management goals
3. Define relevant indicators (ecosystem condition, pollutant loads, input use)
4. Determine water/sediment quality guideline values
5. Define draft water/sediment quality objectives
6. Assess if draft water/sediment quality objectives are met
7. Consider additional indicators or refine water/sediment quality objectives
8. Consider alternative management strategies
9. Assess if water/sediment quality objectives are achievable
10. Implement agreed management strategy.

The second example presents the key steps of an AM plan to limit phosphorus exports from a catchment in Wisconsin, US (Wisconsin Department of Natural Resources, 2013). The purpose is to improve water quality within watersheds and receiving surface water bodies to eventually comply with state in-stream phosphorus targets and standards.

1. Identify representative partners (from all stakeholders)
2. Describe the watershed and set load reduction goals in line with state standards
3. Conduct a watershed inventory and identify critical source areas
4. Identify where reductions will (or can) occur
5. Describe management measures to be implemented at different sites
6. Estimate load reductions expected by permit term (load reduction target)
7. Measuring success
8. Financial security
9. Implementation schedule with milestones.

9.3. Modelling and decision support

The previous section and the example of phosphorus management in Wisconsin indicate the central importance of simulation modelling in evaluating and testing water quality management strategies and actions. It is difficult to observe all components of complex hydrological cycles and the processes that govern the transport of solutes and particles through land and water systems.

Models approximate these processes to varying degrees and substitute or augment observations but they cannot replace observation; and the more sophisticated a model, the more intensive the requirements for data, as well as for calibration and validation: there is little point in predicting the outcomes of future management activities if a model cannot replicate current and historic conditions.

Regardless of scale, the key processes to be modelled for water quality management begin with the hydrologic cycle and the pathways and flows of water through soil, groundwater, open channels and open water bodies. The transport of solutes is modelled by advection and dispersion, mediated by chemical models of sorption, desorption and chemical reactions, and changes in soils and suspended particles. Sediment transport in surface water flows is a complex process but can be modelled simply in relation to hydraulic (slope, bed condition, flow rate) and material characteristics (particle size and type).

On farms, the physics of the underlying processes are modified by management practices. For example, in order to determine the likely export of nitrogen from fertilizer application, it is necessary to consider the type of fertilizer, the timing and rate of application, the rainfall before during and after application, soil type and physiographic conditions (slope, uniformity), irrigation application (amount, method, duration, excess as drainage) and whether fertilizer is incorporated or broadcast.

At catchment scale and above, the impacts on an aquatic habitat or the state of a water body are influenced by many factors, which also require observation and research to understand the process and quantify cause and effect. The formation of algal blooms in water ways and along coasts is a good example, especially where less common toxic algal blooms form that kill fish, aquatic fauna and livestock. Multiple pollutants (N,P, sediment) are key factors but do not cause blooms without the right mix of enabling conditions of temperature, flow rate and flow depth, salinity and BOD. Furthermore, the activities that generate low flows could be natural or due to excessive diversion of water for other uses (irrigation) or a combination of the two. Similarly, sediment could be generated by forest clearance, the aftermath of a fire, construction activity, or be a consequence of rainfed or irrigated cropping.

Over recent decades, research has contributed to the development and use of models by understanding and parameterising fundamental processes, and through developing new techniques and instrumentation to record the required data. Hydrological models have increased in complexity and effectiveness at the "cost" of data demands over time and space. In most developing countries, the institutional capacity exists to build, refine and use models for water quality management, but contemporary data collection, coverage and availability, as well as data transmission and storage, are typically problematic and require further investment and attention.

Table 9.3 attempts a broad summary of the types of modelling, their purposes and data requirements, and examples of software, with some comments on their appropriateness for application under low developing country (LDC) conditions. A more comprehensive compilation of models for water quality simulation can be found in FAO (2018); however, socio-hydrological models that combine or link biophysical and socio-economic indicators to better understand the human–water system in a holistic sense remain a challenge (Blair & Buytaert, 2016).

Table 9.3. Examples of models for managing water quality by scale, purpose and data needs

Model scale	Model purpose	Model types	Data requirements	Applicability in LDCs	Examples of software
Farm management	Management of constraints: salinity, waste-water quality, incoming non-point source pollutants	Salinity balances Nutrient balances Static lumped models Dynamic process models	Local sampling and analysis Record keeping Survey and sample data Detailed soil, water, atmosphere parameters*	**High** Possible via student work (local universities)	Water Productivity Function (WPF) model, NUTMON, MOPECO-Salt, SWAP, DSSAT, APSIM, SaltMod
	Management of agronomic inputs and minimization of exports: N, P, sediment, pesticides, salt	Nutrient budgets production function models, Crop-soil-water models • Point • Spatial	Yield records, prices, "efficiencies". Detailed soil, water, plant, atmosphere, data: primary and secondary.	**High** Consultants and governmental institutions	LIMDEP, SWAP, DSSAT, APSIM
Integrated river basin and coastal zone management	Formation, persistence and dynamics of eutrophic conditions in estuaries, coastal zones and the ocean	Complex integrated models – surface and groundwater hydrology, coupled with coastal hydraulic models and solute and sediment transport models linked to ecological models and socio-economic factors	Extensive – the data needs of all component models plus coastal data on undersea topography, currents and flows, wind, tides, salt-freshwater mixing. At a minimum, "simple" regression models of algal growth	**Limited** Challenging for normal research purposes; specialist support needed	Mike 21 FM-ECOLab
Principal agent modeling; game theory	Human action and preferences: managing conflicting stakeholder needs	Scenario modelling Risk modelling Decision support systems	Extensive social survey and or stakeholder meetings.	**High** Generally undertaken through academic/research cooperation	Challenge and Reconstruct Learning (ChaRL), Multiple-criteria decision analysis (MCDA), Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)

Source: Author's own elaborations

9.4. Options for data-scarce regions

Data availability for modelling remains a challenge in many parts of the world, highlighting the need for alternative approaches for evidence-based basin-wide water quality management.

9.4.1. Geographical Information Systems (GIS) and remote sensing

Over the past 20-30 years, the emergence of GIS and remote sensing have had a profound impact on the ability to map, undertake simple processing of limited spatial and temporal data, and determine changes in the state and trends of natural anthropogenic processes.

GIS has been widely adopted throughout the developing world, where extensive capacity exists to establish and maintain such systems and process the data. Many simple modules for specific analysis are available commercially and as open-source tools.

Remote sensing data can provide effective estimates of some forms of data (Table 9.4), especially in relation to improving the description of catchments, river basins and stream networks. Remote sensing provides consistent spatial and temporal coverage of land surface characteristics and can infer environmental conditions such as algal content, soil moisture and salinity in conjunction with field validation.

Table 9.4. Remote-sensing applications in water quality management

Category	Application	Type of data*	Resolution	Focus
Catchment and river basin management	Catchment delineation (DEM, stream paths, water bodies)	SRTM, VNIR and Interferometric SAR data	~10 m (Sentinel) to 1 km (MODIS)	Base maps for 1) monitoring and 2) catchment model parameterization
	Land cover classification Infrastructure mapping	VNIR, SWIR, Pan SAR	10 m to 1 km (free data)	
	Phytoplankton/algal bloom mapping in streams and water bodies	VNIR, SWIR (Sat) Hyperspectral (Airborne/UAV)	10 m to 1 km (free data) 3-30 m	Monitoring Research
	Sediment mapping in rivers, freshwater bodies, estuaries, CZ	VNIR/SWIR (Sat) Hyperspectral (Airborne/UAV)	10 m to 1 km (free data) 3-30 m	Monitoring, model calibration Research
	Salinity mapping	(VNIR/SWIR) Hyperspectral	10 m to 1 km (free data) 3-30 m	Water balance components in hydrological models /calibration Interpolation of ground data
	ET estimation Rainfall	VNIR +TIR Geostationary instruments – TRMM, GMS	30 m to 4 km	Management, monitoring. Dryland salinity monitoring/trends Research
Environmental Management	Habitat delineation, dynamics and composition	VNIR, SWIR, SAR Hyperspectral	10 m to 1 km 30 to 90 m 3 to 30 m	Project studies and research Research
	Pollutant load estimation (N, P)	Hyperspectral	3 to 30 m	Model parameterization and research
Field applications – farming	Soil mapping, crop mapping, crop health/ NPP; irrigation monitoring	VNIR/SWIR/TIR**	1 m commercial to 10 m (Sentinel) – 100 m (LS 8 TIR)	Precision agriculture (fertilizer and pesticide management; irrigation scheduling and management) System performance assessment
	Soil Salinity Assessment	VNIR Hyperspectral***	1 m commercial 10 m to 1 km (free data) 3 to 30 m	(Farming, system planning) and modelling Research
	Crop productivity and water use	VNIR/SWIR correlation to vegetation indices VNIR/SWIR/TIR energy balance	1 m (commercial) to 10m + (free) 30 m to 100 m	Commercial management services Water rights adjudication Research

* SAR: Synthetic aperture radar; SRTM: Shuttle Radar Topographic Mission (90 m global DEM); SWIR: Short Wave Infrared; TIR: Thermal infrared, used in ET and NPP/Yield estimation; TRMM: Tropical Rainfall Measuring Mission, GMS: Geostationary Meteorological Satellite;UAV: Unmanned aerial vehicle (drone); VNIR: Optical remote sensing in the Visual (Red, Green, Blue) and Near-Infrared wavebands

**VNIR/SWIR/TIR data – increasingly available for free at useable resolutions (10 m to 5 m with Pan sharpening and other interpolation techniques) – processed or with accessible online processing (GEE).

*** All hyperspectral data have an associated cost of flying an aeroplane or UAV, as there is no Hyperspectral Satellite in orbit at the moment. Coverage by Hyperion (the only hyperspectral satellite to have been in orbit) was very selective with a narrow field of view (18 km swath width).

Source: Author's own elaborations

Case study 6 in the annex presents a range of salinity mapping projects and programs realized in Australia.

9.4.2 Citizen science approaches

As outlined above, the involvement of basin stakeholders in analysing upstream downstream water quality challenges and possible solutions is central to any basin-wide management approach. This involvement can extend beyond decision-makers. Involving citizens in data collection has the potential to increase data, create awareness about water quality issues and help in the formulation of citizen-backed community action plans (UN Water, 2018; Quinlivan, Chapman & Sullivan, 2020). Such an approach can also help overcome possible disconnection between civil society and its institutions and/or complement the efforts of authorities, which might not have sufficient capacity to monitor water quality in vast basins.

The underlying idea is that citizens hold immense potential to increase temporal and spatial data availability, and therefore could bridge existing data gaps while enhancing their awareness of environmental issues (Carlson & Cohen, 2018; Walker *et al.*, 2016; Buytaert *et al.*, 2014). However, citizen-derived data may also be selective and biased, requiring attention to effective design principles for successful citizen science projects (Brouwer *et al.*, 2018; Crall *et al.*, 2011). When well-designed, citizen science projects have been very successful in analysing pollution (Capdevila *et al.*, 2020), for example through adopting biological water quality indicators, ranging from insects to the incidence of aquatic pests in fresh water systems, or the use of simple water quality test kits in school programmes (Ballard, Dixon & Harris, 2017) to generate data and increase awareness about catchment health and resilience.

In order to harness the rising enthusiasm from a wide range of participating groups, citizen science projects should go beyond data collection and try to understand social change models with the ultimate aim of developing community-driven water quality solutions. In South Africa, for example, a suite of tools was packaged into an integrated water resource and catchment monitoring toolkit, known as “Capacity for Catchments”, for roll-out within South Africa and neighbouring countries (Graham & Taylor, 2018).

The development, and in some cases, the adaptation of the tools was based on the review and assessment of key water resource types, such as rivers/streams, wetlands, estuaries, springs and rainfall. This resulted in the following tools:

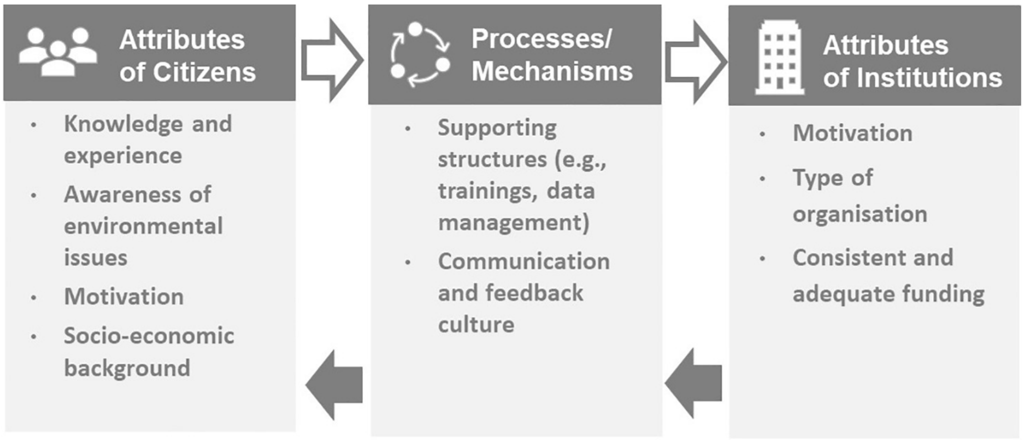
- Aquatic Biomonitoring including an associated phone Apps
- The Riparian Health Audit
- The Water Clarity Tube
- The Transparent Velocity Head Rod
- The Wetland assessment tool
- The Estuary tool
- The Spring tool
- Weather monitoring tools, including Citizen Science Rain Gauges
- The Enviro Picture Building game to investigate catchment issues.

School lesson plans were developed as a component of the toolkit and these materials were integrated into the school curriculum (Graham & Taylor, 2018).

Many of such tools allow for web-based monitoring to share and compare data, including the use of mobile phones. For example, Smart phones for Water (S4W) in Nepal (Davids, 2019) mobilizes a combination of young researchers, citizen science and mobile technology to generate water data. S4W's citizen scientists use an Android phone application called Open Data Kit or ODK to collect data about water (including flow gauging, sediment and water quality). GPS readings and cameras were used to verify the reliability (and error rate) of citizen science observations. All data collected by S4W are open source and freely available (https://data.smartphones4water.org).

Based on a literature review, Capdevila *et al.* (2020) identified three sets of factors for successful citizen science projects in water quality monitoring (Figure 9.3): (i) the attributes of citizens (knowledge and experience in collecting data, awareness of environmental problems, motivation and socio-economic background), (ii) the attributes of institutions (motivation, type of organization, consistent and adequate funding), and (iii) the interactions between citizens and institutions (supporting structure, communication and feedback).

Figure 9.3: Factors steering the success of citizen science projects for monitoring water quality



Source: Capdevila, A.S.L., Kokimova, A., Ray, S.S., Avellán, T., Kim, J. & Kirschke, S. 2020. Success factors for citizen science projects in water quality monitoring. Science of the Total Environment, 728: 137843.

Motivation was also highlighted as a key challenge in the smartphone study in Nepal, where different approaches were tested for different target groups. According to Davids (2019), an important aspect of sustaining citizen science efforts is funding: all efforts to minimize the costs per observation (CPO) while maintaining data quality will lead to lower funding requirements and greater chances of sustainability. In this case, incentives seemed to motivate students to participate in citizen science projects, including (i) the opportunity to use data for their research projects (e.g. bachelor's theses); (ii) lucky draws (i.e. raffles or giveaways); and (iii) receiving certificates of involvement. However, student turn-over remains an issue that needs addressing, and in rural areas with limited student populations and relatively low scientific literacy levels, payments may be the most effective near-term incentive to ensure continuity of observations over time.

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