Water quality in the Ravi and Sutlej Rivers, Pakistan: a system view

Nicky Grigg, Mobin-ud-Din Ahmad, Saiqa Imran, Geoff Podger, Mac Kirby, Matthew Colloff

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[1]CSIRO Land and Water, Canberra ACT

[2]Pakistan Council of Research in Water Resources (PCRWR)

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Abstract

As part of CSIRO Indus Sustainable Development Investment Portfolio (SDIP) project in Pakistan, the Pakistan Council of Research in Water Resources (PCRWR) and CSIRO collaborated on a water quality monitoring program in the Ravi and Sutlej Rivers. The results revealed the state of transboundary rivers, drains and groundwater within Pakistan over a twelve-month period from August 2015 to July 2016, finding that many water quality parameters did not meet water quality guidelines. For example, the stretch of the Ravi River passing Lahore failed to meet standards for industrial waste effluent, let alone guidelines for healthy rivers. Many previous water quality assessments have given a similar picture, from which we can infer:

- The water quality situation continues to deteriorate due to industrial and municipal waste disposal and agricultural practices, and it at its worst in during dry months in the absence of diluting flows.
- The lack of improvement or management actions cannot be attributed purely to a lack of past water quality monitoring data.

These conclusions present a challenge: what is needed for water quality knowledge products to trigger and support more effective water quality management? This question requires us to look beyond the data to the decision-making context into which data is delivered. We provide a preliminary assessment in which we outline the components of a wider analysis of the Ravi and Sutlej water quality situation. This initial assessment is intended only to prompt discussion and dialogue and interested parties in Pakistan are encouraged to build upon this beginning, involve other stakeholders and take this approach further in the pursuit of meaningful change for the better. It matters because poor water quality puts lives and livelihoods at risk; the United Nations World Water Assessment Programme (2016) concluded that across all countries “investing in water is investing in jobs” and “water investments are a necessary enabling condition for economic growth, jobs and reducing inequalities”.

1 Introduction

Historically the Ravi, Beas and Sutlej rivers have contributed substantial inflows into the Indus system in Pakistan. As part of the 1960 Indus Water Treaty these rivers were left for India to develop. Since the treaty major development has occurred in India to a point where most of the water is used in that country. What is left to flow into Pakistan are largely floods, which cannot be managed, and drainage flows. Also as part of the treaty, infrastructure was developed within Pakistan to divert water from the Jhelum and Chenab rivers to the Ravi and Sutlej Rivers and these canal diversion now form the majority of the flows in these rivers.

The Ravi and Sutlej rivers carry a mix of industrial, agricultural and urban pollutants that impose health, economic and environmental costs to a region where the population is growing rapidly. This is not a new problem, and studies have pointed to water quality issues in the Ravi and Sutlej Rivers for more than two decades (Javed and Hayat, 1995; Tariq et al., 1994). Commentators in the press have expressed concern about the condition of these rivers and made strong calls for change (The Express Tribune, 2012; The Nation, 2015; The News, 2016). In this review we provide a brief overview of the current water quality situation for these two rivers. Water quality monitoring data is central to the review, but reporting water quality alone will not bring about the development and implementation of improved water management options. For this reason our review also considers the complex mix of social and biophysical influences on water quality and options for improved management.

1.1 Water quality in the Ravi and Sutlej Rivers

As part of CSIRO Indus Sustainable Development Investment Portfolio (SDIP) project in Pakistan, the Pakistan Council of Research in Water Resources (PCRWR) conducted monthly water quality monitoring in the Ravi and Sutlej Rivers for a year from August 2015 to July 2016. Between January and July 2016 the monthly monitoring also included samples from groundwater and drains (Figure 1). The monthly samples were analysed for physio-chemical, trace metal and microbiological parameters. In August 2016 and January 2016 samples were also analysed for organic pollutants, timed to be representative of high and low flow periods of the year. Appendix A lists the parameters analysed, and graphs of all the datasets are available in Appendix B.

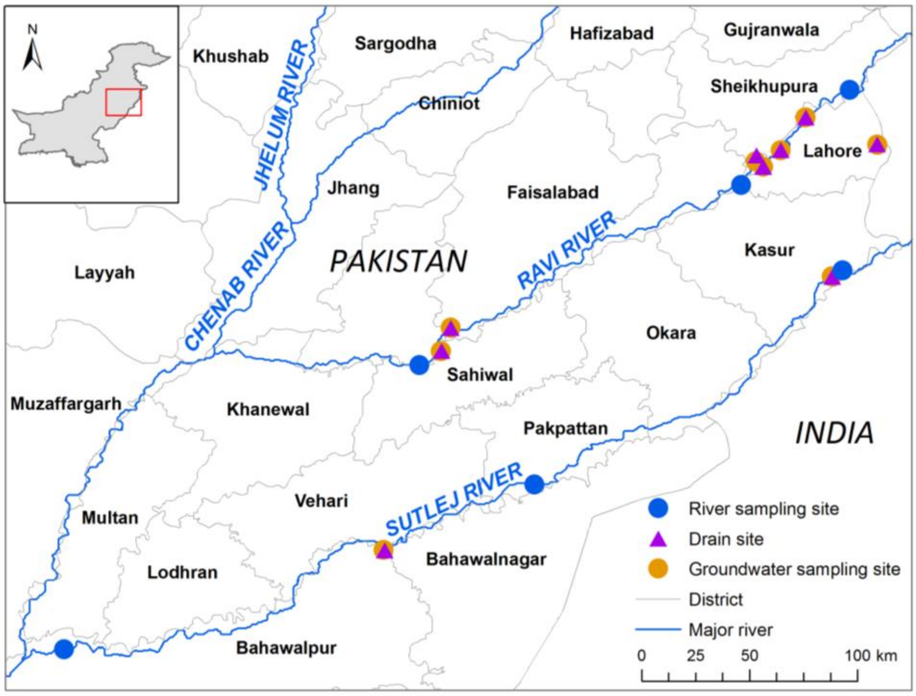

Figure 1 Sampling locations for the PCRWR monitoring program.
Samples came from river surface water, drains and groundwater locations.

The PCRWR report found that no drains complied with National Environmental Quality Standards (NEQS) for liquid industrial effluents (Government of Pakistan, 2000). Typically, physio-chemical parameters worsened and metals increased in concentration from upstream to downstream locations in the Ravi River samples. Increases in biological and chemical oxygen demand (BOD and COD), and associated decreases in dissolved oxygen (DO), all failed to meet the NEQS for liquid industrial effluents, let alone guidelines for river health. The Ravi River was more contaminated than the Sutlej for most pollutants. Persistent Organic Pollutants (POPs) were detected in all samples for rivers, drains and groundwater. In the Sutlej River during high flow conditions the concentrations of POPs were typically highest at the most upstream locations, decreasing downstream. The upstream-downstream patterns varied for different POPs in the Ravi. POPs were also detected at all groundwater sampling sites. Microbiological contamination is ubiquitous, found in all surface water and drain samples, and in many groundwater samples.

Water quality change in the Ravi and Sutlej rivers are driven by human activities shaped by social influences. Changes in water quality have social impacts and drive behaviour change and activities of their own, which in turn have biophysical impacts. It is not possible to interpret flow and water quality dynamics, or manage them, without knowing something of the human activities driving change in the system. In this review we explore these wider considerations relevant to Ravi and Sutlej water quality issues. It is a preliminary desktop review, with the intention of seeking input, critique and improvements from a range of stakeholders in Pakistan.

2 Drivers and impacts of water quality trends

2.1 Biophysical and social drivers of trends in water quality

Water quality is influenced by biophysical and social drivers. A biophysical driver is one that can be represented by a material or energy flux (e.g. a volume of water, a release of pollutants, or joules of electricity used by a pump). A social driver is one that can be characterised by social constructs (e.g. prices, laws, government policies, economic indicators such as GDP or benefit cost ratios, treaties, public health outcomes, knowledge, customs, international agreements, worldviews and mental models). Many influences on water quantity and quality, such as agricultural production, have both biophysical and social dimensions. This section provides an initial overview of relevant biophysical and social drivers.

2.1.1 Biophysical drivers

Biophysical influences on water quality in the Ravi and Sutlej catchments include agricultural and household sources of pollutants, urban and industrial waste and the infrastructure available to treat water (both natural and built infrastructure). Biophysical drivers operate at many different spatial and temporal scales. Climate and weather drive long-term inter-annual and seasonal patterns of change. Pollutant sources include readily identified point sources (e.g. particular industrial sites) and diffuse sources that are not so easily characterised and understood (e.g. nutrient and pesticide loads that are due to the accumulation of fertilizer and pesticides or sediment runoff over a large catchment area, with long time lags between cause and effect).

These biophysical drivers and their impacts can be inferred from observational datasets. For example, Figure 2 shows biological oxygen demand (BOD) increasing from upstream to downstream and worsening during dry periods (October 2015 to June 2016), pointing to sources of pollution downstream of the Syphon sampling site, and the seasonal effects of flow variations.

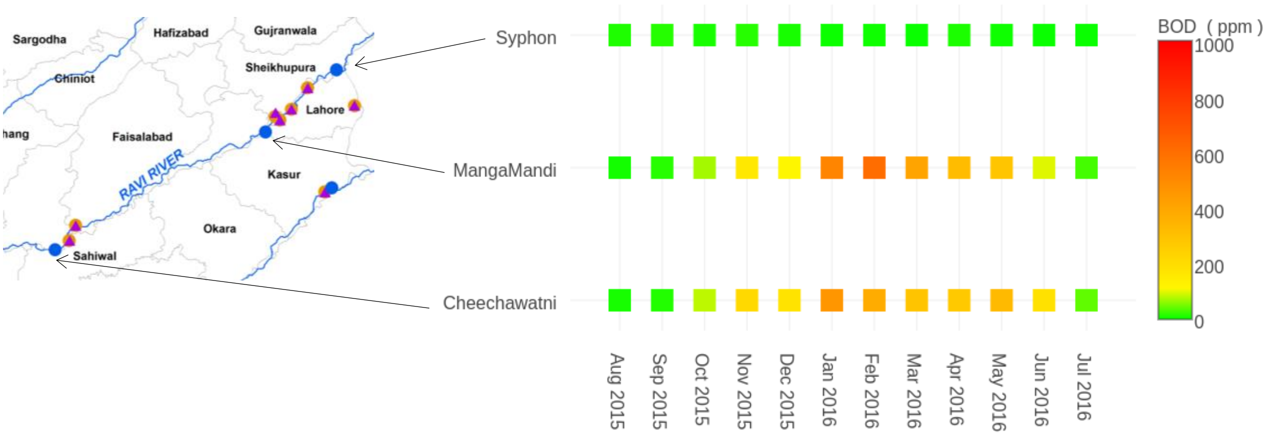

Figure 2 Biological oxygen demand (BOD) at Ravi River sampling sites (Syphon upstream, Cheechawatni downstream). National Environmental Quality Standard for BOD in effluent water in Pakistan is 80 ppm (green).

The PCRWR dataset includes measurements of BOD in drains, and these measurements confirm that the drains in Lahore are a key source of pollution, with BOD readings that exceed the NEQS throughout the year, and are considerably higher than previously reported BOD measurements for these drains (e.g. BOD data reported by (Baqar et al., 2014; Haider, 2010)).

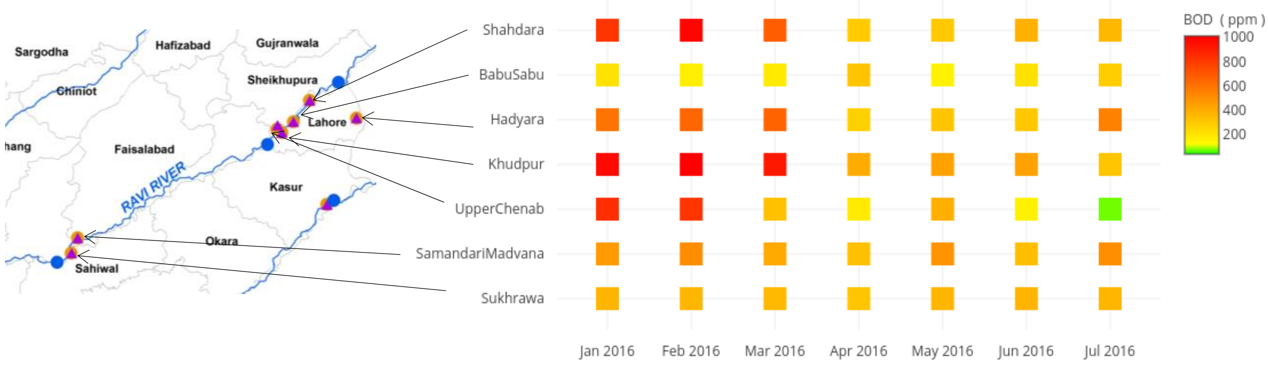

Figure 3 Biological oxygen demand (BOD) at drain sampling sites.
National Environmental Quality Standard for BOD in effluent water in Pakistan is 80 ppm (green).

A thesis by Husnain Haider (Haider, 2010), and an associated series of publications (Haider et al., 2015; Haider and Ali, 2012a, 2012b, 2010) provides a detailed working example of a model developed for the Ravi River for BOD. The model spansa 98-km stretch of the Ravi River from the Ravi Siphon to the Balloki Headworks. It combines flow and water quality data using a mass balance approach to estimate BOD loads and calibrate rate parameters for the transport-reaction processes shaping measured BOD patterns. After the model had been developed and calibrated it was used to simulate the BOD outcomes for different biophysical scenarios (e.g. wastewater treatment alternatives, flow augmentation, wastewater transportation, constructed wetlands).

2.1.2 Social drivers

The social drivers affecting water quality in the Ravi and Sutlej catchments span the following broad categories:

- Agricultural practices (crop choice, water allocation rules, irrigation decisions, decisions to apply fertilizers, pesticides or herbicides);
- Industrial practices (waste management practices in particular);
- Urban land use choices (including formal urban planning decisions);
- Social norms (e.g. hygiene practices, waste disposal practices);
- Economic drivers (e.g. prices, wealth and income levels, cost for treating sewerage, income from industrial activities, incentives to increase economic performance);
- Institutions with responsibility for water quality, and associated policies, laws or treaties. For example, The Constitution (18^{th} Amendment) Act 2010 devolved environmental responsibilities from the federal level to the provinces, with a range of impacts on environmental monitoring, and resourcing and maintenance of institutional capacities for environmental monitoring and management;
- Channels for knowledge to inform policy in a relevant way (e.g. forums for bringing researchers, water users and decision makers together, mechanisms for decision makers to access and be informed by water quality assessments and user experiences), or the absence of such channels;
- Existing knowledge about the state of the system and its impacts on different aspects of society (e.g. public health outcomes such as heavy metal poisoning), or the absence of such knowledge.

Biophysical measurements help identify significant social drivers. Measuring a wide suite of parameters, indicates where pollutants are largely derived from agricultural, industrial or household activities. Water quality monitoring by PCRWR shows industrial and urban pollutants increasing as the Ravi River passes Lahore, pointing to activities in the city as the source of pollution. Human sewage from population centres was present in all water samples, as indicated by faecal coliform measurements. The POPs data tell a more complex story. In the Sutlej River some POPs derived from agricultural chemicals had highest concentrations in upstream locations near the Pakistan/India border during high flow conditions in August (Figure 4), pointing to agricultural activities in India as the source of these pollutants.

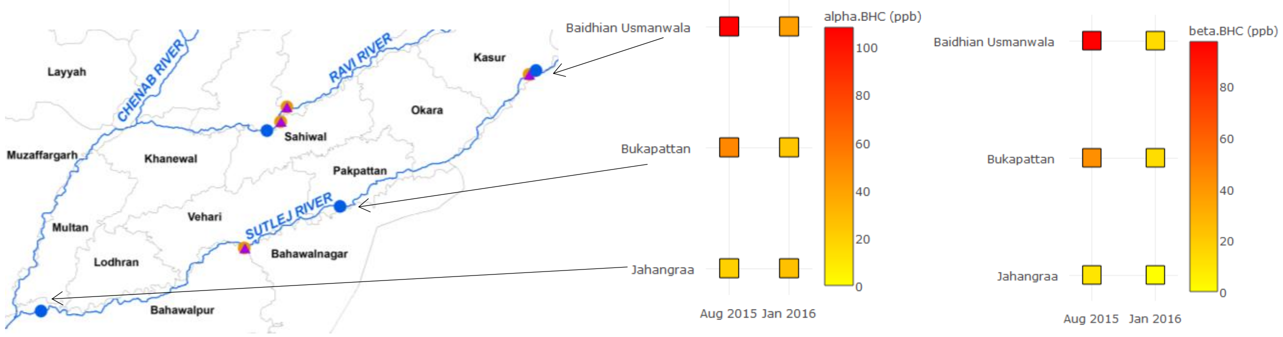

Figure 4 Example of insecticide by-products measured in the Sutlej River, where highest concentrations were measured at the most upstream location in a high flow period.
The permissible limit set by the Pakistan Standards and Quality Control Authority (PSQCA) is 2 ppb.

In the Ravi River there were also some high concentrations of POPs measured upstream during high flow periods, but in low flow periods in January concentrations typically increased downstream, pointing to sources of these pollutants within Pakistan (Figure 5). Whereas the drain measurements confirmed that drains in Lahore were a key source of physico-chemical and metal pollutants in the Ravi River, this was not the case for POPs measurements; POPs concentrations in drains were lower than those measured in the Ravi River, suggesting that there are other sources of POPs. Possible sources include the link canals taking water from western rivers, Chenab and Jhelum, which pass through agricultural areas and link to the Ravi (e.g. measurements in the Upper Chenab Canal have significant POPs concentrations). River sediments can also be a source, settling and accumulating over time to act as a reservoir of POPs which are released slowly in dissolved form to increase concentrations in the river water.

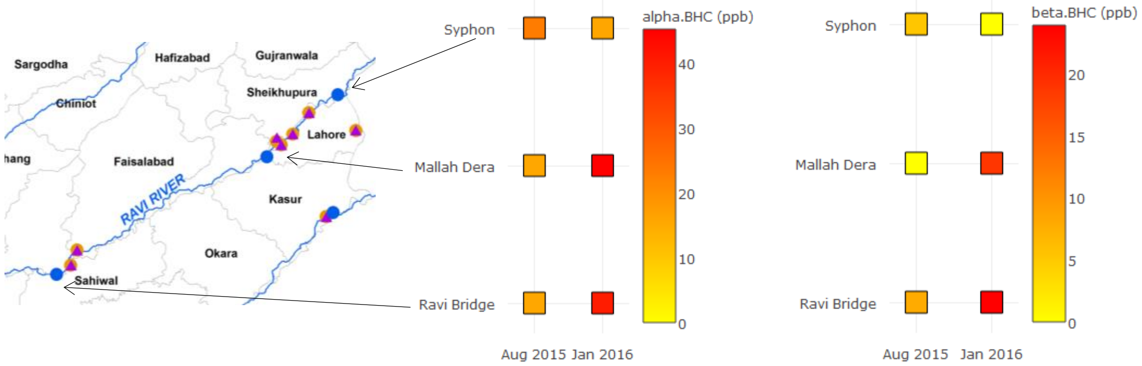

Figure 5 Example of insecticide by-products measured in the Ravi River, where highest concentrations were measured at downstream locations during a low flow period.
The permissible limit set by the Pakistan Standards and Quality Control Authority (PSQCA) is 2 ppb.

These data are valuable for identifying the industrial, agricultural and household activities that are leading to pollution, however they do not inform us about the social and institutional influences on those activities.

As with biophysical drivers, social drivers operate at a range of spatial and temporal scales, and there are equivalents of 'point source' and 'diffuse' influences. For example, the Water Apportionment Accord (Indus River System Authority, 1991; IUCN, 2010) or the Indus Waters Treaty (1960) are single documents with significant basin-level outcomes. On the other hand, social norms around household hygiene or waste disposal practices also have a significant influence at the basin scale, but there is no equivalent central intervention point; the scale at which behavioural changes would take effect (i.e. at individual and household level) is insignificant at the basin scale and it is only the collective cumulative impact that is observed.

While biophysical influences can be characterised by quantified dynamic mass balances, social influences are not so readily described in an unambiguous and quantified way. One approach to doing so is the Institutional Analysis and Development Framework (IAD) (Ostrom, 1990; Polski and Ostrom, 1999). The IAD

Framework has been used to analyse the governance of different common pool resource (CPR) systems, and has allowed the identification of common attributes of successful, long-term common pool resource management, supported by a strong evidence base (Cox et al., 2010; Ostrom, 1990). Irrigation systems are common pool resource systems, and Kamran and Shivakoti (2013) applied Ostrom's IAD framework to characterise and compare state-administered and tribal irrigation systems in the Dera Ghazi Khan District in Punjab. The authors used the analysis as a way to assess the two irrigation systems against the design principles identified in long-enduring CPR institutions. This is one of the few published attempts to characterise social systems in Pakistan using the IAD framework.

An example that is more relevant to water quality management was a study by Farooqi (2016) of initiatives conducted by City District Government Lahore (CDGL) and City District Government Faisalabad (CDGF) within the Changa Pani Program (CPP). The CPP was developed under the Punjab Urban Water and Sanitation Policy and is a strategy for delivering water and sanitation services through collaboration between the public, community and private sectors. The CDGL and CDGF initiatives have been designed and implemented differently, and Farooqi (2016) used the IAD framework to assess, compare and contrast these initiatives to see what can be learned about effective co-production for the delivery of water and sanitation services. The core of the analysis focused on 'action situations', which is where 'actors' in the system (individuals and agencies) interact and implement actions, shaped by biophysical and social context. For example, the key actors in the CPP project in CDGL included local community representation (Union Council 60), a non-government organisation (Anjuman Samaji Behbood) and government agencies (the Urban Unit of the Government of Punjab and the Water and Sanitation Agency (WASA) Lahore), with a steering committee tasked with project management and conflict resolution. By interviewing key actors and discerning the 'rules in use' in action situations, the authors had a basis for comparing the CDGL and CDGF initiatives and drawing some preliminary conclusions about factors that help and hinder the co-production of water and sanitation services. For example, they found that the CDGL initiative benefited from the existence of formal structures and processes such as a Memorandum of Understanding, a steering committee, conflict resolution and decision making processes, and these were designed in a way that allowed the public sector to be more flexible in its interactions with the local community and NGO. Political and bureaucratic commitment combined with community willingness to participate were vital requirements, and the participation of an NGO brought in valuable technical skills, such as mapping and surveying and practical social skills in community mobilisation and communication.

More generally, recent publications have outlined the state of environmental impact assessment (EIA) and regulation in Pakistan, providing current and useful descriptions of policy and legislative arrangements (Ali et al., 2012; Nadeem et al., 2013; Nadeem and Hameed, 2008a; Naureen, 2009).

We are not aware of more specific institutional analysis for water quality management in the Ravi or Sutlej rivers and associated groundwater and drains. Any attempts to address water quality problems cannot rely solely on improved technical information. Institutional analysis could be helpful for identifying institutional changes that would enable more effective responses to available water quality information, and ensure ongoing high quality future water quality monitoring. A reason to characterise the social influences is in order to identify the important intersections where social and biophysical processes affect each other, which is the topic of the following section.

2.2 Impacts of water quality change

Impacts are felt across different sectors of society, in different locations to the source of the water quality changes (e.g. downstream of upstream polluting activities) and at different times (e.g. future generations may inherit degraded groundwater reserves). Health impacts are among the most commonly cited direct and immediate impacts of poor water quality, pointing to incidence of water-borne diseases and associated mortality rates, particularly for children. Despite the clear interest in these impacts in media reports, good quality data on specific health impacts of poor water quality in these rivers are hard to come by. Figures are reported, but with inadequate references to sources. For example, PCRWR (2007) stated "It is estimated that around 40% of all reported diseases and deaths in Pakistan are attributed to poor water quality in the country. Moreover, the leading cause of deaths in infants and children up to 10 years of age, is that of contaminated water. The mortality rate of 136 per 1,000 live births due to diarrhoea is reported, while every fifth citizen suffers from illness caused by unsafe water. In Karachi, more than 10,000 people die annually of renal infection due to polluted drinking water", citing a 2004 news article as the source. Azizullah et al. (2011) conducted a comprehensive review of the water quality related health risks in Pakistan, and while they could draw on several datasets quantifying levels of a wide range of pollutants, they reported "comparatively little data are available regarding water-related disease due to the lack of diagnostic facilities and maintenance records".

There is widespread recognition that water sources are polluted, but the extent of the health impacts is unknown, and there is a general reliance on health impacts characterised elsewhere. For example, Bhowmik et al. (2015) used international guideline values to derive human health risk maps from exposure to trace metals in drinking water in Pakistan.

Ecological impacts can also be measured and used as indicators of river health. For example, Shakir and Qazi (2013) measured impacts on carp at four sites along the Ravi River between the Siphon and Balloki. In addition to being valuable as indicators of river health, the species of carp in the study are favoured for human consumption. The authors concluded that carp condition is best upstream of Lahore, worst in the reach immediately downstream of Lahore, with some evidence of recovery of condition downstream of Balloki. Such studies tend to be isolated initiatives and there is no ongoing long-term monitoring of ecological impacts, even though these are useful indicators of the effects of pollution.

Inferring indirect impacts is difficult, but attempts to do so are valuable because the impacts are real. For example, an overview of economic impacts of inadequate sanitation in Pakistan estimated a total cost of 343.7 billion Pakistan Rupees (PKR; $US 1 = 85 PKR at 2011 exchange rates), or close to 4% of GDP in Pakistan (World Bank, 2011). These were estimated by considering both direct and indirect costs in four areas (World Bank, 2011):

1. Health-related costs (premature death, costs of health care, lost productivity-time, and time lost to care of sick household members);
2. Drinking and domestic water related costs (household treatment of drinking water, use of bottled water, piped water costs, and time spent hauling water from cleaner sources);
3. Welfare costs (time costs associated with absences from work or school due to inadequate or unavailable sanitation facilities, particularly for women and girls)
4. Tourism costs (lost tourism income, health costs of sick tourists)

The methods used to make these estimates were not described by the authors, and nor was a more complete report available. An earlier World Bank study had concluded that public expenditure on health is relatively low, with most health costs borne by affected individuals, and estimated that 4% of the population falls into poverty each year because of health costs: "The impoverishing impact of health shocks is also increasing over time. While in the early nineties, an estimated 3% of the population became poor per year because of health payments, the proportion of the population is now close to 4%." (World Bank, 2010). Again, it is unclear how this estimate was arrived, and nor is it clear how to interpret this statement given that World Bank World Development Indicators show declining poverty rates for Pakistan, falling from 58% of the population in 1998 to 29% in 2013 (http://data.worldbank.org/share/widget?locations=PK&indicators=SI.POV.NAHC).

Human sewage is a ubiquitous pollutant in the Ravi and Sutlej Rivers, as indicated by high faecal coliform measurements at all sites in all seasons, making matters of sanitation and hygiene a particular priority. Chambers (2009) identified Pakistan as a leader in Community-Led Total Sanitation (CLTS) initiatives, in which communities are empowered to take responsibility for their personal hygiene and sanitation practices. In reviewing community led sanitation initiatives, Chambers (2009) provided a diagram showing how improvements in sanitation can contribute to the Millennium Development Goals (MDGs). In reviewing the status of health in Pakistan, Afzal and Yusuf (2013) also referred to the MDGs as a useful international benchmark. The MDGs were eight goals for 2015, set in the year 2000. Pakistan documented improvements against the goals, including better access to improved water sources, however it did not achieve most of the MDGs (Government of Pakistan, 2013).

The message is that while qualitative links between water quality and its health, ecological and economic impacts are being made, the methods for characterising these impacts reliably are still developing and there have been few applications in Pakistan. More could be done to shed light on the particular impacts on women and children; poor water quality stands to impact disproportionately on women because they are primary carers for children and ill household members (Khan et al., 2013). Characterising the economic impacts need not be limited to costs of inadequate access to clean water. For example, Akram and Olmstead (2010) surveyed residents of Lahore and learned that households are willing to pay more for a clean, drinkable water supply than their current monthly water bill, and this higher price still falls well below the World Bank's benchmark for affordable water service (4% of monthly household income).

A UN water assessment concluded that across all countries "investing in water is investing in jobs" and "water investments are a necessary enabling condition for economic growth, jobs and reducing inequalities" (United Nations World Water Assessment Programme, 2016). An earlier report by the Organisation for Economic Cooperation and Development (OECD) drew a similar conclusion: "*in developing countries, WHO has estimated that almost 10% of the global burden of disease could be prevented through water, sanitation and hygiene interventions. Health benefits are only a small portion of overall benefits, however. WHO estimated that meeting the water and sanitation Millennium Development Goals (MDGs) could generate about USD 84 billion per year in benefits, with a benefit to cost ratio of 7 to 1. Of those benefits, three quarters would stem from time gains, the rest being driven by reductions in water-related diseases.*" (OECD, 2011a)

2.3 Path dependence, lock-in and amplifying impacts

Unwanted trends in water quality can be locked in because of the different rates and time scales over which different processes operate. For example, if an industrial waste stream has released pollutants into rivers over years and pollutants have accumulated in the river sediments, even if industry changes its practices and no longer releases any waste to the river, the store of pollutants in the sediments may continue to release harmful material into the river for many years. This is an example of path-dependence, in that contingency on past events makes the future trajectory difficult to change. Work by Ali et al. (2015) provided an assessment persistent organic pollutants (POPs) in sediments in Mehmood Booti Drain in Lahore, Pakistan, estimating both deposition fluxes and mass inventories for these pollutants. Because these chemicals are so stable and persistent, inventories in the sediment act as an ongoing source of pollution. There has been little analysis of water quality dynamics in Pakistan along these lines, identifying the stocks and flows of pollutants, their stores and resulting system inertia or lock-in. Such analyses are helpful for identifying damage that will be difficult or impossible to remediate rapidly, even if there are no institutional or financial barriers to doing so.

If all water and sediment currently in the Ravi and Sutlej rivers and drains were to be cleaned instantly through some extraordinary (impossible) one-off intervention, but then current business-as-usual practices were to resume unchanged, we would not consider the water quality problems to be "solved". Polluting behaviours would continue and it would be a short period of time before the rivers and drains would again carry contaminated, unsafe water. Similarly, even if there are investments in water quality improvement and prevention of polluting behaviours, if these improvement activities are overwhelmed by increases in polluting industries and behaviours then the problem will worsen, despite investments in prevention or remediation. Paying attention to rates of change can identify thresholds beyond which investments can lead to lasting improvement, and not only to slowing the rate of decline.

Water quality trends can become locked in when the impacts of water quality degradation themselves become causes of further water quality problems, which then reinforce or amplify unwanted consequences. The impacts described in Section 2.2 were the impacts of water quality on environmental, social and economic outcomes. A feedback loop is where a driver of change is itself affected by the changes, and feedback loops between biophysical and social processes can reinforce or accelerate change. Hypothetical examples of unwanted reinforcing feedback loops ('vicious cycles') are given in Figure 6.

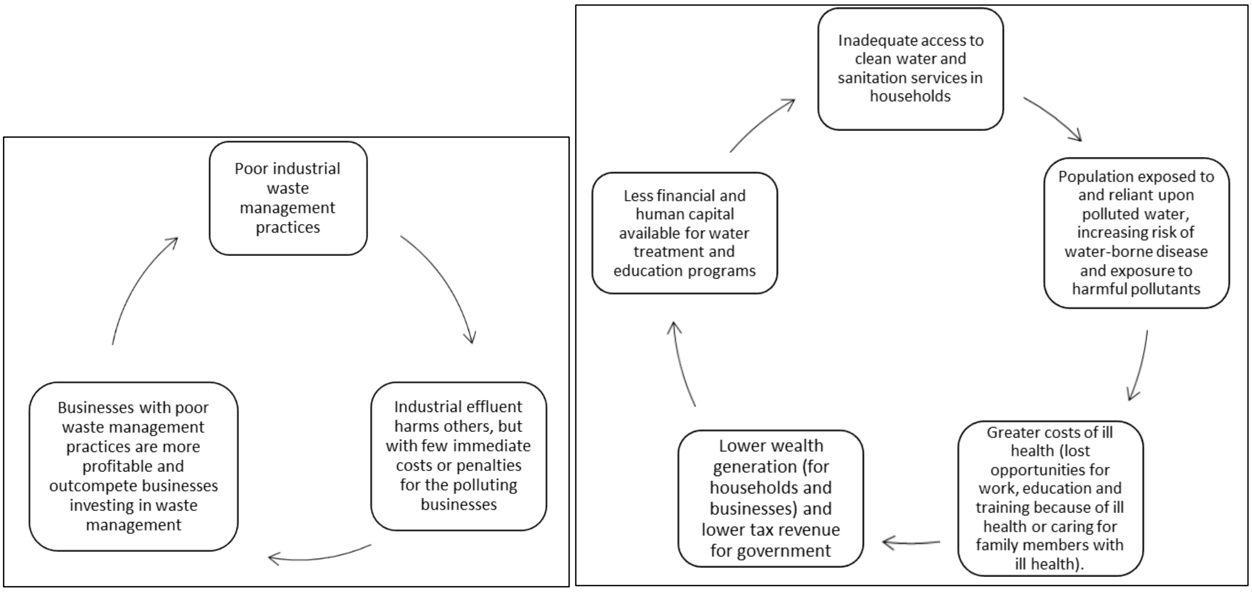

Figure 6 Hypothetical feedback loops that serve to reinforce unwanted water quality outcomes.

Reinforcing feedback loops can also work as 'virtuous cycles' that reinforce or amplify desirable changes. For example, an OECD assessment of benefits of investment in water and sanitation identified a "value chain of sustainable water and sanitation services" in which investments in water quality are supported by, and support, effective integrated water resource management with multiple benefits across sectors (OECD, 2011b). This message was reinforced by a UN Water assessment demonstrating the jobs and wealth creation enabled by investment in safe water, which in turn creates opportunities to sustain water quality improvements (United Nations World Water Assessment Programme, 2016).

Being aware of ways in which water quality outcomes are locked in can be helpful for comparing and contrasting different potential interventions, and more reliably distinguishing between interventions that provide temporary improvements only (because long term business-as-usual practices have not changed), versus improvements that appear to be more modest, yet are enduring because the business-as-usual practices no longer make matters worse.

2.4 Summary of data on drivers and impacts

Table 1 summarised the types of data on drivers and impacts available to inform water quality management in the Ravi and Sutlej rivers. More evidence for impacts of water quality decline would be helpful for involving a wider range of affected stakeholders. Furthermore, more explicit consideration of the informal and formal institutional context and stakeholder values would reveal barriers to and entry points for more effective water quality management practices.

Table 1 A summary of relevant data for Ravi and Sutlej assessing the water quality drivers and impacts

Data	What does it contribute?	Availability
Water quality datasets	Biophysical knowledge of the key pollutants, sources of pollution and trends over time	Recent and historical datasets measuring key water quality parameters exist. There is less data available on • Sediments • Fluxes and rates of changes
Water quality models	Characterisation of the biophysical processes and an ability to estimate responses to different future scenarios	A model for oxygen dynamics (DO, BOD etc) exists for a stretch of the Ravi River. Limited modelling studies for other water quality parameters.
Data on health, economic and other impacts	Knowledge of the health and economic impacts	Limited data specific to Pakistan.
Institutional analysis	Characterisation of the institutions, the formal and informal rules that shape activities, as well as the values and principles underpinning these rules.	Analyses of environmental governance in Pakistan have been published (Ali et al., 2012; Nadeem et al., 2013; Nadeem and Hameed, 2008a; Naureen, 2009). Very limited available data specific to water quality management, but particular individuals would have high levels of tacit knowledge.
Stakeholder values	Understanding of different stakeholders' values, and how these values are represented in or affected by water quality management practices.	Very limited available explicit data, but particular individuals would have a high level of tacit knowledge and there are universal values such as access to clean, safe water.

3 Opportunities for water quality improvement

3.1 Social drivers of water quality improvement

Section 2.1.2 referred to social drivers of water quality decline. If water quality is to improve it will be due to new social drivers of water quality improvement. Consider two contrasting examples in Pakistan. The first is an example of water quality monitoring that is having an impact on daily decision-making. The Prime Minister and Cabinet directed the Ministry of Science and Technology to conduct high-quality water quality measurements of bottled drinking water being sold in Pakistan and to make the reports publicly available (http://www.pcrwr.gov.pk/bottle.html). Given that access to high quality drinking water is a core value shared by all people, it is an effective mechanism for empowering individuals to ensure their choice of bottled water is informed by water quality analysis.

In general, there is more potential to make more use of water quality data to raise awareness among the general public. For example, public signboards could display near real-time water quality along with World Health Organisation (WHO) standards for comparison. The data need to be communicated in ways that are meaningful to people and where links to health and livelihoods impacts are clear to all.

The bottled water monitoring and reporting is providing a valuable service that supports decision-making among citizens and companies and empowers a wider range of actors to influence the situation. The monitoring has altered the decision-making context by making more knowledge available, and represents an example of a Government decision that has the effect of distributing responsibility across a broader range of actors. Monitoring has also triggered follow-up water quality interventions. A potential disadvantage of this arrangement, however, is that it privileges those who can afford bottled water and who have access to the Internet to download the water quality reports. It does not help those who have few options other than to use publicly available water sources. Inherent in the Government directive is an intention for the Government to “follow up with punitive/legal action”, with the intention of acting to protect all from unsafe bottled water. Each report since testing began in 2005 has identified a set of companies selling unsafe water. Mandatory reporting over the past seven years, and any follow-up action, has not been sufficient to end the sale of unsafe bottled water. A perusal of the archive of published reports reveals that at least one company reported to be selling unsafe water in 2009 continued to sell unsafe water in 2016. These observations indicate that while the bottled water reports have made an important contribution to changing the decision-making context, other influences make it possible for unsafe bottled water to be sold in Pakistan despite public monitoring and reporting.

The second example is Haider’s comprehensive body of work that uses water quality analysis to calibrate and test a quantitative water quality model used to assess management options in Ravi River (Haider et al., 2015; Haider and Ali, 2012a, 2012b, 2010). Here there is research knowledge, compiled and presented in a way to be useable by decision makers. But it is not clear whether this work has been taken up and used. If it has not, it could be valuable to review and better understand the barriers and challenges to implementing the recommendations of this work, because lack of knowledge is not the primary barrier to change in this case.

Gorddard et al. (2016) recognise that knowledge of the kind presented in the bottled water reports or Haider’s modelling is only one input shaping human decisions and activities. Decisions and actions are also strongly shaped by values and rules. The authors refer to the interacting systems of human values, societal rules and scientific and tacit knowledge (*vrk*) as shaping the ‘decision context’. Characterising the decision context can offer some insights for management. Commonly where there is a well-researched body of knowledge, and yet little action or change informed by that knowledge, the barriers to action are not due to a knowledge deficit. Rather the barriers are likely to lie in the realm of the rules or values shaping the decision context, and the specific interactions between different values, rules and knowledge of the decision makers.

In the case of water quality in bottled water, or in the Ravi and Sutlej rivers, there is no ambiguity in the values at stake: availability of high quality water is a core, high priority value common to all people (although as described earlier, more could be done to more fully substantiate the wider impacts of poor water quality in the Ravi and Sutlej). The *vrk* perspective would point to societal 'rules' as a critical part of the decision context. 'Rules' refers to both formal rules, the in-practice 'rules-in-use' and informal norms. The practice of emptying waste into an open drain, for example, is a social norm and considered a 'rule' in this framework. It is reinforced by a value system in which the action is deemed acceptable, even necessary. The *vrk* approach is a useful way to draw attention to what changes can be made in order to change the decision context, and this becomes very important when working with stakeholders to explore scenarios, options and pathways for action. While more water quality data and analysis is always helpful in the quest for improved water quality, these social influences on water quality governance warrant attention to secure better outcomes.

3.2 Resilience and adapting to change

Any efforts to improve water quality will take place in a rapidly changing Pakistan and wider world. For improvements in water quality to be lasting, the changes will need to be resilient to all manner of possible future events, with capacity to adapt to the unexpected. Resilience and adaptive capacity refer to the capacity of people and organisations to respond to shocks and changes. For example, a population in good health has a better ability to adapt and cope with a large range of unexpected changes than a population with poor health.

Duh et al. (2008) reviewed water quality and air quality trends in cities around the world and explored their resilience to urbanisation rates. They found there was no simple relationship between population growth and water quality. Improvements in water and air quality were more strongly associated with the introduction of environmental policy and new technology rather than with population trends, which led the authors to believe that water quality can be resilient to population increases and increased urbanisation. The authors recommended considering a broad suite of "resiliency factors" when managing water quality in urbanising locations, and when interpreting many interacting, rapidly changing factors affecting water and air quality.

Malik et al. (2012) developed and calculated an indicator for adaptive capacity for agro-ecological zones in Pakistan, which was combined with indicators for exposure and sensitivity to climate change to infer climate-related health risks for different regions of Pakistan. The authors used an index for adaptive capacity that included socioeconomic factors only: employment rate and literacy rates, percentage of children aged 12-23 months immunised against major diseases, percentage of births attended by skilled birth attendants and household consumption per capita. Adaptive capacity can be characterised more broadly than this. Factors that build resilience and adaptive capacity vary depending on the context, however Carpenter et al. (2012) provide some generic insights on the attributes of systems with high adaptive capacity. Table 2 lists the attributes used by Carpenter et al. (2012), and we have illustrated these with examples and questions that are relevant to water quality in the Ravi and Sutlej catchments.

Table 2 Examples of conditions that provide adaptive capacity, and questions that can be helpful for identifying these conditions (based on Carpenter et al. (2012)).

Condition	Examples	Questions
Diversity	Diverse ways to provide an essential function, or diverse ways to respond to the loss of an important function Cultural diversity	Are there diverse sources of clean, safe water? Can different people and organisations respond in different ways to potential future shocks (e.g. pollution events, floods)?

Condition	Examples	Questions
Modularity	Protection mechanisms for sources of clean water People with different approaches to problem-solving Independent organizations capable of providing clean, safe water	Are sources of clean water (e.g. groundwater) protected from sources of contamination? Do people and/or organisations have different ways to provide or access clean water (e.g. rainwater tanks, municipal piped water, communal groundwater pumps, bottled water)? Do water protection mechanisms or different ways of responding create inequities in access to clean water (e.g. only wealthy households have access or response options)?
Openness	Strength of connection with neighbouring systems	Are there good working relationships with neighbouring systems? What unwanted impacts does the system have on neighbouring systems? Are there ways to dampen unwanted shocks that originate from neighbouring systems? What are the trade-offs between openness and modularity?
Reserves	Capacity to recover from losses thanks to good reserves (e.g. a healthy population will recover from water borne disease shock better than an unhealthy population; financial reserves or insurance mechanisms aid recovery from disaster)	What can be done to restore water quality once it has been degraded? What allows health to recover quickly after exposure to unsafe water? What financial or insurance mechanisms are available in the event of an emergency?
Feedbacks	Decision makers feel the full consequences of decisions	Do polluters face any unwanted consequences, e.g. are they required to pay compensation for damage caused?
Nestedness	Upstream-downstream interactions District, province, national and global interacting levels of governance systems	Can the societal response be tuned to be relevant to the different scales of the situation and work with cross-scale interactions?
Monitoring and learning	Regular, transparent, and shared measurements of social-ecological variables	How much do people know about the status and trends in water quality and the impact on lives, livelihoods and society?
Leadership	Recognition of barriers and bridges that could change resilience Building networks	What existing experience of effective action in complex social-ecological contexts can we draw upon?
Trust	Development of trust in repeated interactions	Can people collaborate effectively in the presence of uncertainty?

3.3 Principles and indicators for guiding management

The previous sections of this review have referred to drivers, impacts and opportunities that could also inform principles and indicators for guiding water quality management and tracking progress. For example, Table 2 could be used to derive potential indicators of adaptive capacity that would be relevant to water quality management. These could be a useful addition to existing water quality guidelines developed by organisations or governments to assess and monitor water quality.

As another example, Ostrom's frameworks for institutional and social-ecological system analysis (Ostrom, 2009, 1990; Polski and Ostrom, 1999) have been applied in many systems and used to identify governance properties that provide effective stewardship of common pool resources (e.g. water resources). These properties informed a set of eight design principles (Ostrom, 1990) that have since been further tested and expanded upon (Cox et al., 2010; Wilson et al., 2013). These eight principles are listed in Table 3. The common pool resources in our context are the waters of the Ravi and Sutlej Rivers, and we provide hypothetical descriptions of what each principle could mean for managing Ravi and Sutlej water quality. These principles could be used to derive relevant indicators of effectiveness of water quality governance, and also to identify opportunities to design more effective governance mechanisms.

Table 3 Design principles for managing common pool resources, as initially presented by Ostrom (1990) and further explored by Cox et al. (2010) and Wilson et al. (2013).

Principles for managing a common pool resource	Example description of what it could mean to have the principle met in managing water quality of the Ravi and Sutlej Rivers.
Clearly defined boundaries	The sources and destinations of clean water resources are well defined, and those using or dependent upon them are identified.
Proportional equivalence between benefits and costs	Users of water resources operate in a system that recognises and rewards those preventing pollution. High status or other disproportionate benefits are earned, and unfair inequality minimised.
Collective-choice arrangements	Users of water resources, and those affected by water use decisions, have been instrumental in shaping the rules of access to the resource and regulations limiting polluting activities.
Monitoring	Monitoring allows detection of non-compliance with rules.
Graduated sanctions	Larger transgressions from the collectively-agreed rules are subject to larger penalties.
Conflict resolution mechanisms	Where there are disagreements in the creation, interpretation or application or rules, there are timely and effective ways to mediate these disagreements.
Minimum recognition of rights to organise.	Local water resource management solutions are respected, and not over-ridden by externally imposed rules or prescriptions that are insensitive to local institutional arrangements.
Nested (polycentric) governance	Given the multiple scales (basin, nation, province, district, household), there are appropriate governance arrangements "organised in multiples layers of nested enterprises" (Ostrom, 1990).

3.4 Options and pathways for water quality improvement

3.4.1 Adaptation pathways

The previous sections have provided a preliminary review only, requiring deliberation and input from a broad range of stakeholders. This section offers an outline of what could be involved in developing options and pathways for water quality improvement in the Ravi and Sutlej rivers. A good place to start it is to refer again to Haider's work (Haider et al., 2015; Haider and Ali, 2012a, 2012b, 2010). Having developed the biophysical model of water quality in the Ravi River he integrated it into a broader assessment process that evaluated different water quality management options. His sustainability evaluation considered many criteria, including monetary cost, land requirements, operation and maintenance issues, environmental impacts and socio-economic impacts, and he provided a clear set of processes for evaluating these different criteria with decision-makers and establishing a ranking of water quality management options. It provides a rational, transparent way to proceed with water quality management planning.

There are very real uncertainties and barriers that decision makers face, however, even when they have good water quality monitoring data and recommendations to inform them. We can learn more about this by asking stakeholders questions not just about the water quality knowledge, but the decision-making context (e.g. using the *vrk* framework of Gorddard et al. [2016]). These are questions that go beyond characterising the water quality problems and technological solutions, and are more about the operating environment in which decision makers are trying to make a difference. Taking this approach acknowledges, without blame or judgment, the challenges in implementing evidence-based recommendations and offers the potential to identify actions that better account for and respond to these challenges and operational uncertainties. Prevailing decision contexts that are resilient to change are also a form of path-dependency that can be included in the analysis of system drivers and impacts (Section 2.3).

Different kinds of options are helpful:

- Short-term options for protecting people from harm while longer term interventions are developed (e.g. individual education so people can minimise their own exposure to unsafe water; monitoring and communicating information so that all are aware of the impacts);
- Building resilience to avoid crossing thresholds (e.g. identifying and targeting 'hot spots' of concern, setting up insurance mechanisms, designing incentives for maintaining existing infrastructure so that it is in good working order);
- Supporting and enabling more transformational shifts (e.g. bringing in more sectors and designing more effective governance mechanisms for working in a more integrated way and changing the decision-making context);
- Distinguishing between options for large point sources of pollution (which can be targeted by specific management interventions at that site), and options for managing diffuse sources, where household or site-level interventions will only be effective if they can be scaled up to system level;
- Distinguishing between urban and rural options, and account for shifting urban/rural demographics. As highlighted by this review, water quality in urban areas is deteriorating, and impacting the lives and health of urban populations. In Pakistan and around the world there is a growing migration of people from rural to urban locations, placing further pressure on access to clean and safe water.

Reality will differ from even the best-prepared plans, so monitoring and learning from progress is needed when identifying and implementing options to bring about change. 'Adaptation pathways' approaches (Haasnoot et al., 2013; Wise et al., 2014) make ongoing learning a priority, so that new learning triggers revisions to the system description, assessment and change pathways.

In designing options and pathways it is worth noting the following caution from Kamran and Shivakoti 2013 in an assessment of Pakistan irrigation systems:

> *CPR [Common Pool Resource] management institutions implemented by external agencies are often not successful because their designers fail to understand local norms and culture … Previous*

attempts by states to craft institutional changes have failed for numerous reasons, including: resource users resisting the externally imposed institutional changes, viewing them as a resource grab; overestimation by the state of its own management capacity; and the establishment of faulty enforcement mechanisms and pervasive corruption. … There is no panacea for crafting institutions, as the success of these institutions depends on many contextual factors. However, the creation of appropriate institutional arrangements must respect local customs and the constraints of local people, whose needs are specific to the conditions.

Their caution is consistent with Ostrom's seventh design principle given in Table 3 ("minimum recognition of rights to organise").

3.4.2 Sustainable Development Goals

Clear goals are vital when designing options and pathways. The UN Sustainable Development Goals (SDGs) contain the recognition the environmental services underpinning human health, wellbeing and prosperity. SDG #6 is 'clean water and sanitation' and can be a starting point for exploring how progress towards improved water quality management can contribute to achieving goals in other sectors. There are many challenges in characterising the links between the SDGs, but at a high level it is possible to identify ways in which progress towards this goal could support, and be supported by, other SDGs (Figure **7**). SDGs can also be a useful entry point for discussions on trade-offs. For example, if more money is to be spent on clean water and sanitation, some might argue that the money could be spent on quality education or health services instead, and yet it is mistaken to frame it as an either/or trade-off. Some investments in education can enable better water quality outcomes and vice versa, and some investments in water quality prevent health costs. Similarly, it can also bring to light where progress towards one goal risks hindering progress towards another goal. For example, pursuit of SDG#9 (industry, innovation and infrastructure) can enable great advances in the provision of clean water and sanitation, but it is not guaranteed because many industry and infrastructure developments add to water quality problems through industrial or urban waste. Similarly, access to clean water and sanitation supports SDG#2 (zero hunger) because high incidence of diarrhoea is one of the large health impacts of unsafe water in the region, preventing affected individuals from being adequately nourished. On the other hand, pursuit of SDG#2 without awareness of water quality impacts can harm progress towards SDG#6 through agricultural and food processing waste streams as well as altered hydrology and sediment loads from land use change. If ministries responsible for different sectors pursue goals in isolation then these beneficial or harmful interactions with other sectors fail to be recognised and handled appropriately.

In this way the SDGs can be used as a framework exploring links between social and biophysical processes. These descriptions need not have all data and models integrated into one all-encompassing description to be useful. Rather, it is possible to start by identifying links that are known to be important and work with a minimal description. These small beginnings can allow some awareness-raising and reflection on social-biophysical interactions.

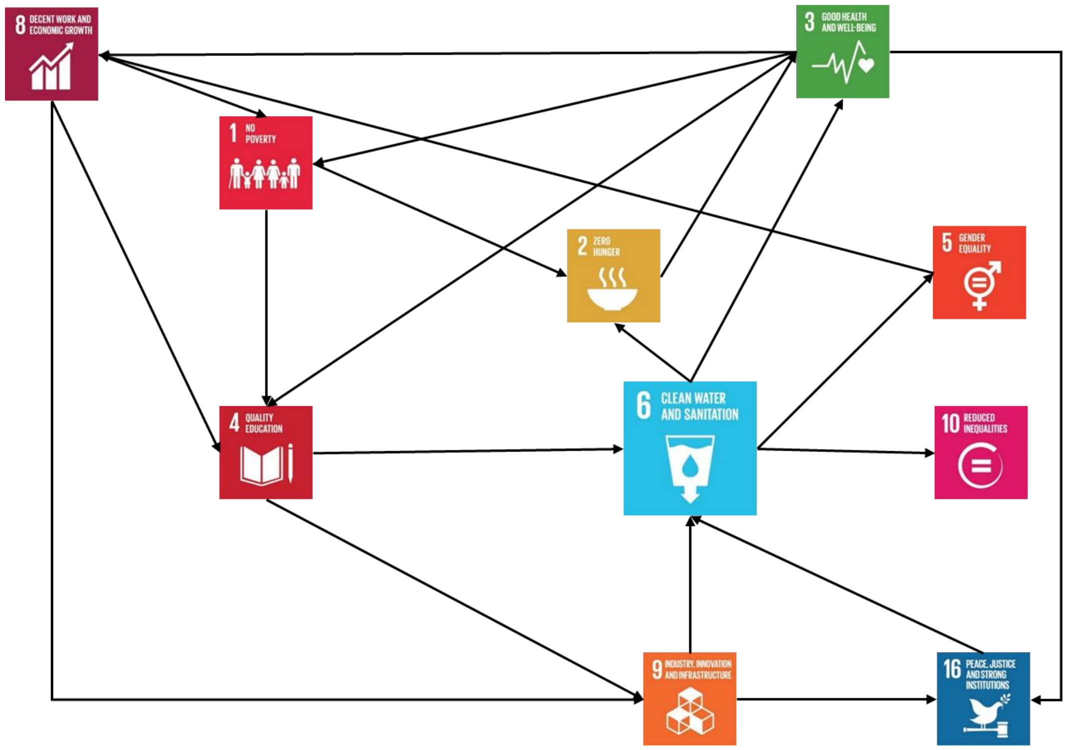

Figure 7 A network view of a subset of Sustainable Development Goals with SDG#6 (clean water and sanitation) as the primary focus. Note that there are many more links than indicated here (e.g. SDG#5 and SDG#10 support many other SDGs).
A link indicates where one goal can support another. The diagram is intended only as an indicative starting point for conversations between sectors and stakeholders, and would be replaced by a network diagram informed by comprehensive analysis and evidence base. Explanation of links: 6→2 (clean water and sanitation enables safe food preparation); 6→3 (clean water and sanitation prevents health impacts of unsafe water); 6→5 (women bear disproportionally high impacts of unsafe water and would experience relatively larger gains from clean water and sanitation); 6→10 (absence of clean water and sanitation further marginalises already disadvantaged groups and reinforces poverty traps); 3→8 (good health enables productive employment); 3→1 (good health prevents high medical bills and other health-related costs, including lost income due to sickness or caring for sick family members); 3→4 (good health enables participation in education activities); 4→6 (good education enables more informed water management practices); 8→1 (productive work provides household income); 1→2 (absence of poverty increases ability to buy food); 8→4 (income from productive work can fund education activities); 4→9 (good education supports advances in industry, innovation and infrastructure); 8→9 (productive workforce is needed for advances in industry, innovation and infrastructure); 9→6 (advances in industry, innovation and infrastructure make technologies for water treatment and water management infrastructure more available); 9→16 (strong institutions are supported by knowledge infrastructure and can be forms of social innovation); 3→16 (good health enables a focus on broader goals of peace, justice and strong institutions); 16→6 (water resources are common pool resources and equitable access requires strong governance institutions that foster peaceful and productive interactions among multiple users).

3.5 Summary

In summary, there is the potential to develop and draw upon a wider range of components to inform better management of water quality in the Ravi and Sutlej Rivers, recognising that water quality trends are just one outcome of a more complex system (Table 4).

Table 4 A summary of components for assessing and informing water quality management in the Ravi and Sutlej rivers.

Component	What does it contribute to the water quality assessment?	Availability
Biophysical indicators and standards	Indicators capturing assessment criteria, and associated thresholds or quality standards against which to evaluate measurements	NEQS exist No indicators/thresholds for other aspects
Water quality models and assessment frameworks	Ability to compare different water quality management options and evaluate their performance under alternative future scenarios or anticipated shocks.	A model and framework for oxygen dynamics exists for a stretch of the Ravi River (Haider et al., 2015; Haider and Ali, 2012a, 2012b, 2010). Limited modelling capacity for other water quality parameters. Considerable work on Environmental Impact Assessment (EIA) frameworks in Pakistan (Fischer and Khanum, 2014; Saeed et al., 2011)
Reinforcing or dampening feedback loops, path dependence, lock-in	Highlights where system characteristics create barriers to change, or where there are potential leverage points for effective change.	Very limited or non-existent in any formal documentation, but would exist as tacit knowledge by some individuals.
Indicators for sustainable common pool resource management, resilience and adaptive capacity	A set of assessment criteria against which options can be evaluated. These criteria could include: indictors that inform resilience assessment; and evidence-based design principles for water quality management against which current or proposed practices can be assessed.	Very limited or non-existent for the specifics of Ravi and Sutlej water quality management, except as tacit knowledge by some individuals. Evaluation frameworks for environmental impact assessment more generally have been developed and applied in Pakistan (e.g. Nadeem and Fischer, 2011; Nadeem and Hameed, 2008b). There are high-level goals and indicators such those for the SDGs, generic considerations for designing resilience indicators (e.g. Table 2) and generic design principles for common pool resource management (e.g. Table 3).

4 Conclusions and recommendations

4.1 Past recommendations

Water quality analyses in Pakistan are typically accompanied by recommendations, and these span three general categories:

1. Recommendations for more information gathering, assessment and monitoring, e.g. ongoing water quality monitoring programs.
2. Calls for improved infrastructure and operations, e.g. wastewater treatment, infrastructure modifications such as concrete lining for drains, or changed pumping behaviour.
3. Argument for changes to policy and legislation, accompanied by higher levels of enforcement of regulations.

Such recommendations reflect an awareness that decisions and actions by individuals, businesses, communities and governments are primary determinants of water quality now and in the future. For many water pollutants, Pakistan is not the passive recipient of events outside its control, and decisions and actions by people in Pakistan determine whether water quality is healthy or dangerous.

On the other hand, there is substantial inertia in the system. Polluting behaviours are the norm and it is difficult to change the status quo even though water quality problems are common knowledge and of concern to all. There is relatively little analysis on the societal structures and processes that reinforce polluting behaviour and so maintain this inertia. Social and institutional analysis and awareness could inform more effective interventions that would support previous water quality management recommendations.

There are also drivers of water quality change that lie outside Pakistan's jurisdiction, and any transboundary conversations about water quality would also benefit from being underpinned by well substantiated evidence (e.g. water quality data) as well as a broader assessments that consider social and environmental drivers and impacts.

The preliminary overview provided in this review highlights a complex picture worthy of deliberation by a range of actors in Pakistan in the quest for improving water quality outcomes in the Ravi and Sutlej catchments. The available water quality data are valuable and could be used to develop more useful knowledge products for informing water quality management options. For such data products and options to be effective, however, better understanding of the decision-making context is needed so that these knowledge products can be developed in ways that have more impact. Suggested next steps involve building on past work, and in particular, identifying useful responses to previous recommendations in order to improve their chances of being implemented (e.g. Table 5).

Table 5 A subset of common recommendations from past reports and potential next steps in response to previous recommendations

Previous recommendations	System-level considerations	Potential next steps in response to this recommendation	Who can take these next steps
Ongoing measurement and monitoring of biophysical parameters	Biophysical measurements are core to ongoing assessment of water quality management. Knowledge products in isolation will not be effective unless there is demand and support for ongoing knowledge generation and uptake so that results are communicated widely and are useful to people across all impacted sectors of society.	Multi-stakeholder dialogue to gauge cross-sectoral demand and support for continued and expanded monitoring. Questions for cross-sectoral dialogue include: • What benefits do different sectors see in water quality monitoring data programs? • Where has previous water quality data monitoring has been used to good effect (e.g. published assessments of bottled water on the market), what can we learn from such successes and how can we build upon them? The goal is to identify how water quality monitoring can be communicated effectively so it is connected to decision making, whether it is government policy decisions or decisions of individuals in businesses and households.	A range of stakeholders could be included in the deliberations. It can be hosted by any number of actors in Pakistan, whether from government, private or community sector, or by international agencies working in the region. PCRWR hosted such a workshop in September 2016, inviting participants from multiple sectors.
Water quality standards should be fully enforced	This recommendation is consistent with Ostrom's design principles about collectively agreed rules and graduated sanctions to enforce rules. Guidelines, standards and rules exist. What is the demand and support across sectors for these standards to be enforced? What are the competing interests that create barriers to enforcement?	Undertake an institutional analysis, informed by different stakeholder groups, and assessed and evaluated according to criteria that can reveal opportunities for improved enforcement of existing guidelines and standards (e.g. criteria informed by Ostrom's design principles for common pool resource management, Table 3).	The analysis could be undertaken by an independent body that is trusted by all stakeholders.

Previous recommendations	System-level considerations	Potential next steps in response to this recommendation	Who can take these next steps
More effective operations of water supply infrastructure. For example: • Pipeline infrastructure and sanitation management systems should be designed and run to minimise cross-contamination between waste and freshwater sources. • Water supply agencies to filter and treat water to meet water quality standards.	Such fundamental operational requirements are likely to be uncontroversial across stakeholders, suggesting that institutional capacity or resource constraints are significant.	Work with those responsible for providing and maintaining water supply infrastructure, assess the resourcing requirements for improved operations. Engage in dialogue with a wider range of stakeholders (especially in the private sector) to develop options for financing these improvements.	The assessment of resourcing needs requires a high level of specialist, technical input. The development of financing options needs wider engagement.

4.2 Conclusion

In Table 5 we suggest potential next steps for building upon previous studies and recommendations to more fully benefit from past work. These steps acknowledge the importance of data, but recognise that data is not enough. There is a good history of water quality monitoring in Pakistan thanks to the work of PCRWR, WAPDA and others. Past recommendations have included monitoring, technological solutions and policy recommendations. The sizeable challenges in implementing such changes point to the need to place more emphasis on the decision-making context, and identifying what factors help and hinder water quality improvement. Institutional analysis, and broader assessments more generally, could reveal useful pathways for more effective water quality management. There always is a need for regular monitoring and reporting (like meteorological services), however this overview has pointed to the potential to build on such monitoring and assess water quality in a way that goes beyond biophysical measurements to include a range of broader, relevant components (Table 4).

Our review was informed by the Resilience, Adaptation Pathways and Transformation (RAPT) approach, which is a framework for applying concepts of resilience and adaptation in practical ways in pursuit of sustainability goals (O'Connell et al., 2016). Our preliminary review is offered as a starting point for further conversations with stakeholders in Pakistan. PCRWR has taken first steps in this direction by hosting a cross-sectoral workshop on water quality, its impacts across different sectors, and the opportunities for improved water quality management. Participants of the PCRWR workshop, and other interested actors in Pakistan, are invited to provide feedback on our review. We encourage feedback and strong critique because we would like to be a part of a constructive, challenging dialogue in which there are many difficulties, no easy answers and yet all want the same outcome: cleaner water for all, now and in the future.

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Appendix A PCRWR water quality monitoring program

A.1 Water quality parameters

Table A.1 The months and locations in which each parameter was measured in the PCRWR water quality monitoring program. R: river sample; D: drain sample; G: groundwater sample.

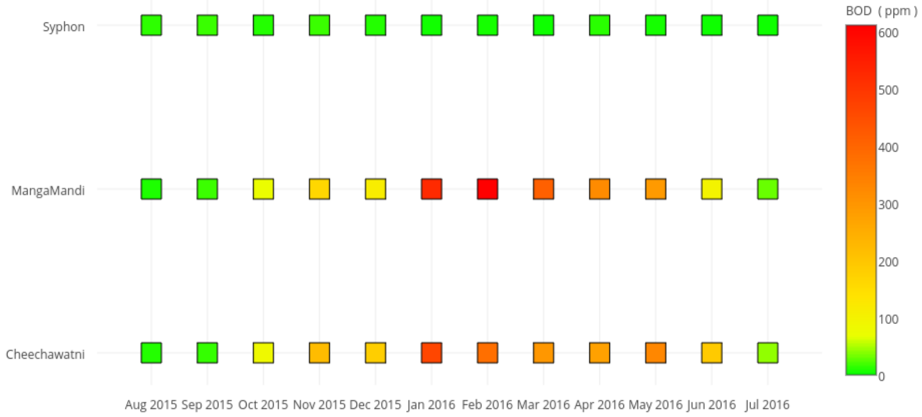
Parameter	August 2015	September 2015 to December 2015 (monthly samples)	January 2016	February 2016 to July 2016 (monthly samples)
Physico-chemical				
EC	R	R	R,D,G	R,D,G
pH	R	R	R,D,G	R,D,G
TDS	R	R	R,D,G	R,D,G
Turbidity	R	R	R,D,G	R,D,G
NO3	R	R	R,D,G	R,D,G
Hardness	R	R	R,D,G	R,D,G
COD	R	R	R,D	R,D
BOD	R	R	R,D	R,D
DO	R	R	R,D	R,D
Total Nitrogen	R	R	R,D	R,D
Total Phosphorus	R	R	R,D	R,D
Metals				
As	R	R	R,D,G	R,D,G
Cu	R	R	R,D,G	R,D,G
Zn	R	R	R,D,G	R,D,G
Mn	R	R	R,D,G	R,D,G
Cr	R	R	R,D,G	R,D,G
Pb	R	R	R,D,G	R,D,G
Ni	R	R	R,D,G	R,D,G
B	R	R	R,D,G	R,D,G
Cd	R	R	R,D,G	R,D,G
Microbiological				
Coliforms	R	R	R,D,G	R,D,G
Faecal Coliforms	R	R	R,D,G	R,D,G
Groundwater				
HCO3	-	-	G	G
Cl	-	-	G	G
SO4	-	-	G	G
Na	-	-	G	G
K	-	-	G	G
Ca	-	-	G	G
Fe	-	-	G	G

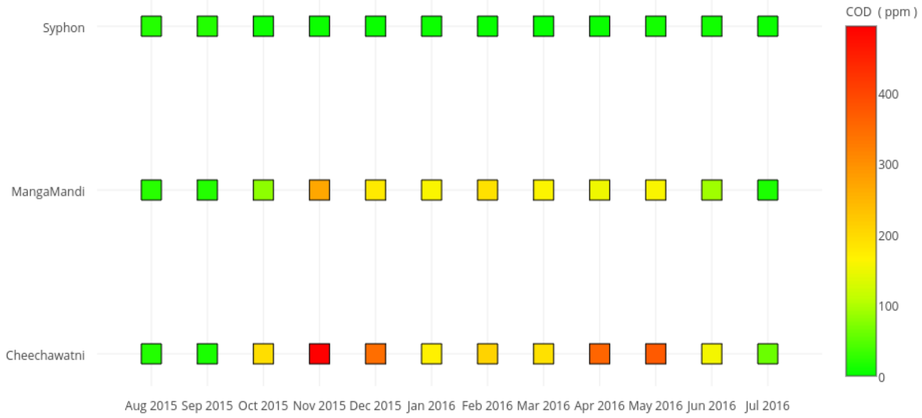
Parameter	August 2015	September 2015 to December 2015 (monthly samples)	January 2016	February 2016 to July 2016 (monthly samples)
Mg	-	-	G	G
Organic Phosphorus Pesticides				
Chlorpyrifosmethyl	R	-	R,D	-
dimethoate	R	-	R,D	-
Profenofos	R	-	R,D	-
Methamibophos	R	-	R,D	-
Monocrotophos	R	-	R,D	-
Pyretheroids				
Bifenthrin	R	-	R,D	-
Cypermethrin	R	-	R,D	-
Deltamethrin	R	-	R,D	-
Lambdacyhalothrin	R	-	R,D	-
Propathrin	R	-	R,D	-
Persistent organic pollutants				
alpha-BHC	R	-	R,D,G	-
beta-BHC	R	-	R,D,G	-
HCB	R	-	R,D,G	-
gamma-BHC7	R	-	R,D,G	-
dalta-BHC	R	-	R,D,G	-
heptachlor	R	-	R,D,G	-
aldrin	R	-	R,D,G	-
trans-chlordane	R	-	R,D,G	-
o,p-DDE	R	-	R,D,G	-
cis-chlordane	R	-	R,D,G	-
dieldrin	R	-	R,D,G	-
p,p-DDE	R	-	R,D,G	-
o,p-DDD	R	-	R,D,G	-
endrin	R	-	R,D,G	-
p,p-DDD	R	-	R,D,G	-
o,p-DDT	R	-	R,D,G	-
p,p-DDT	R	-	R,D,G	-
mirex	R	-	R,D,G	-

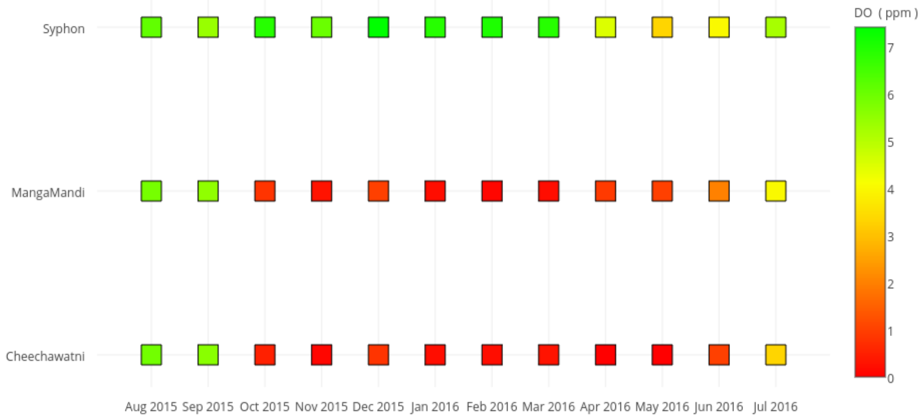
A.2 Water quality results

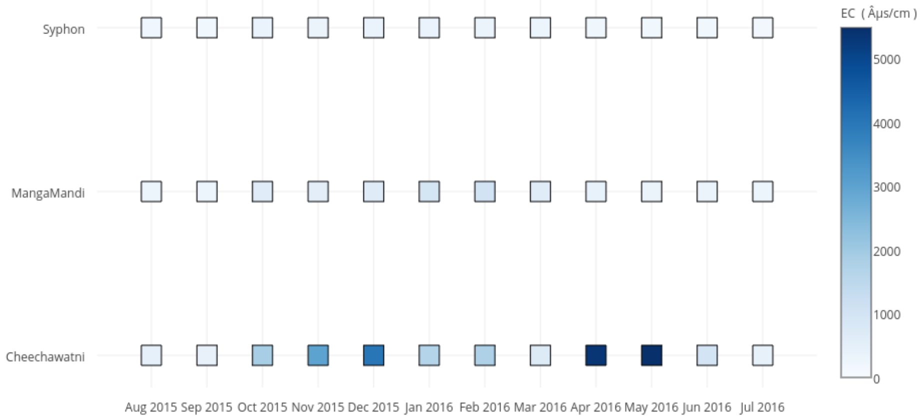
A.2.1 Physico-chemical and wastewater parameters

Ravi River

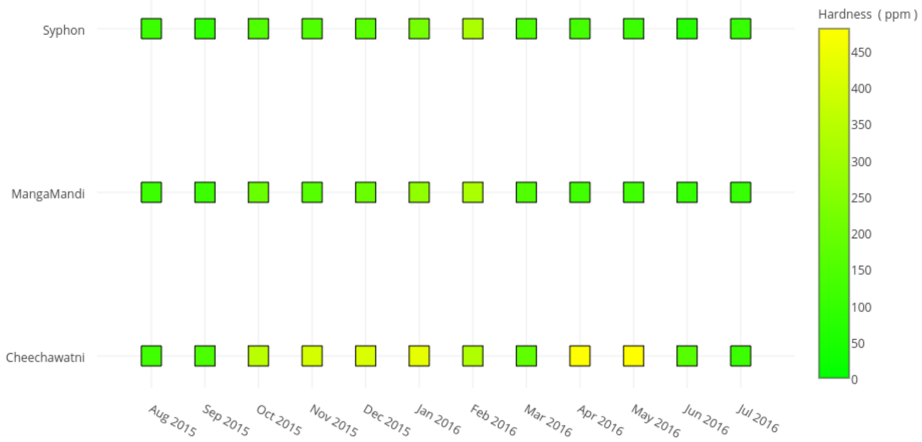




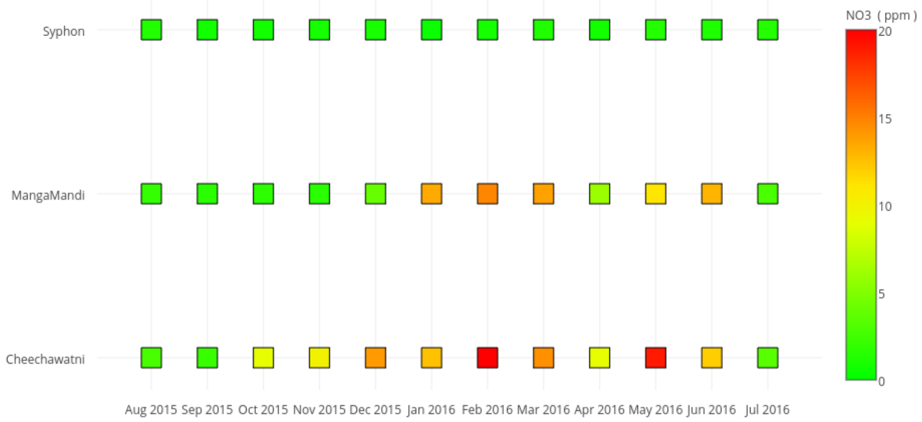




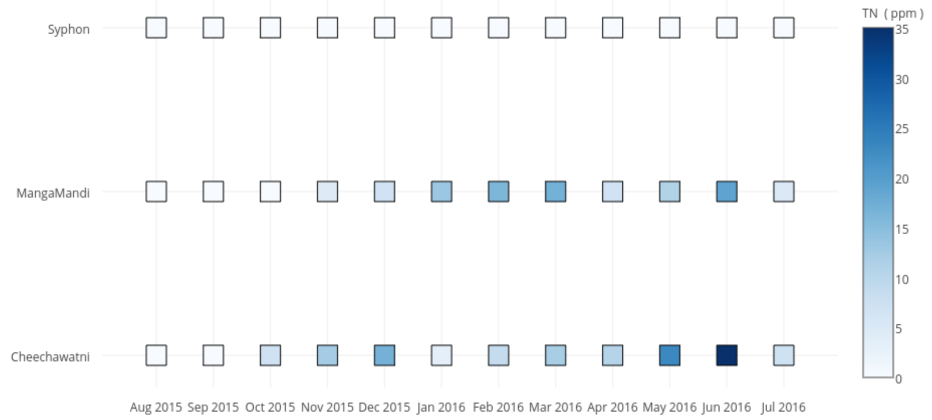
Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
EC (Âµs/cm)
5000
4000
3000
2000
1000
0



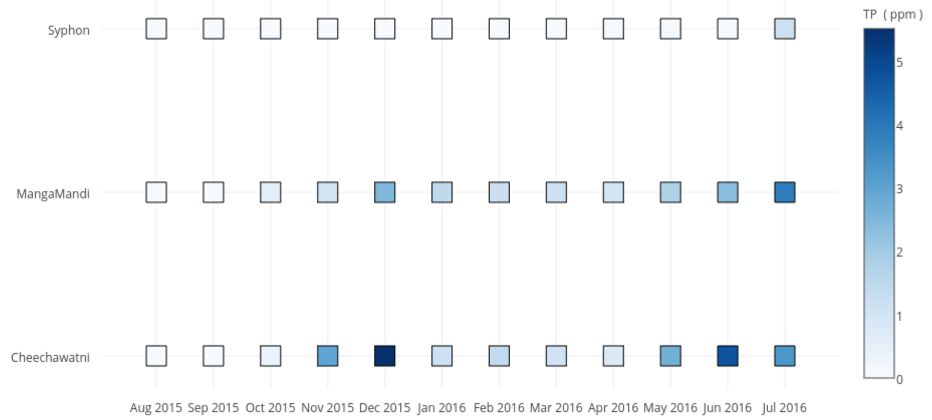
Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
Hardness (ppm)
450
400
350
300
250
200
150
100
50
0



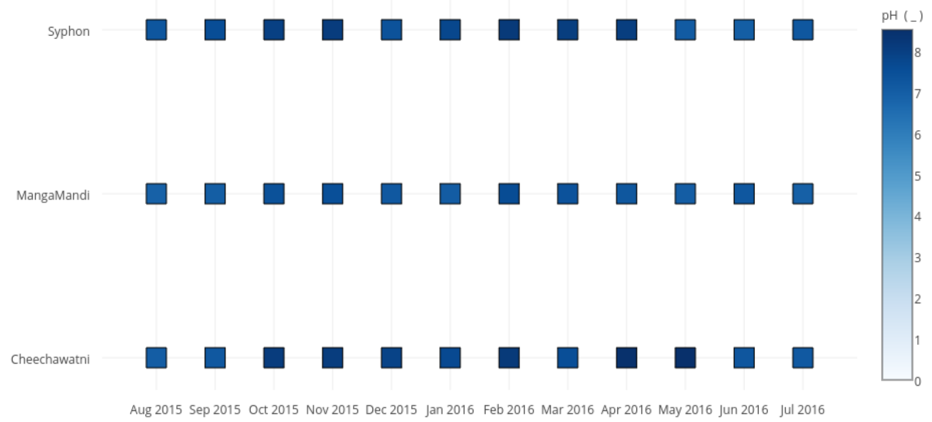
Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
NO3 (ppm)
20
15
10
5
0



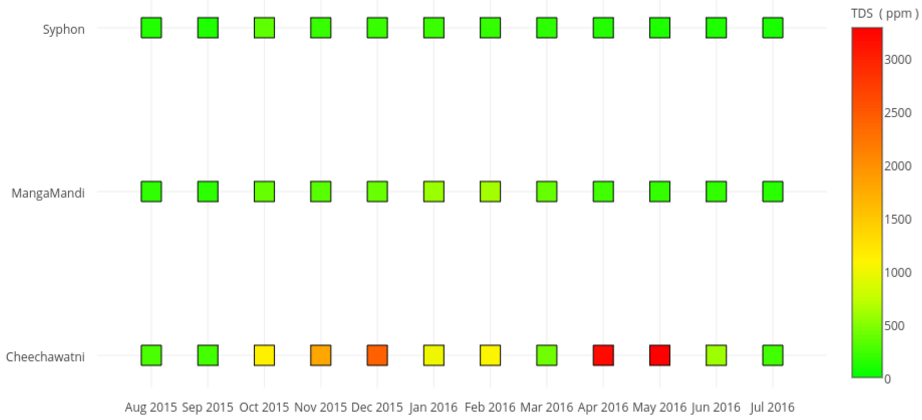
TN (ppm)
Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
35
30
25
20
15
10
5
0

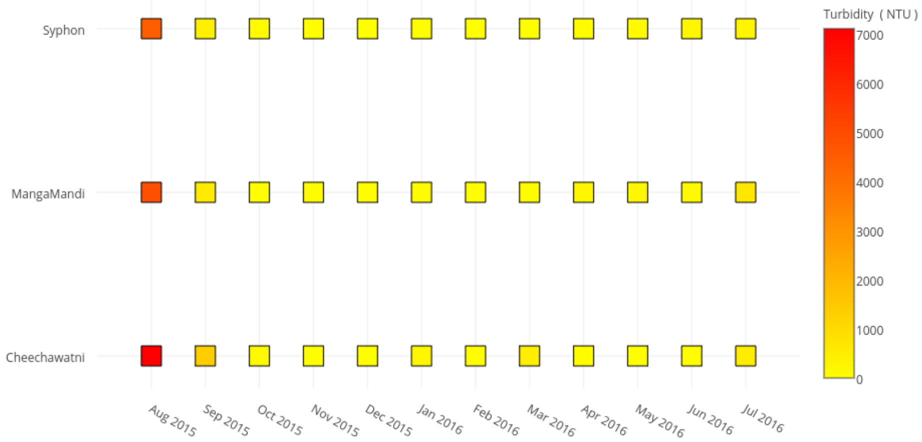


TP (ppm)
Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
5
4
3
2
1
0

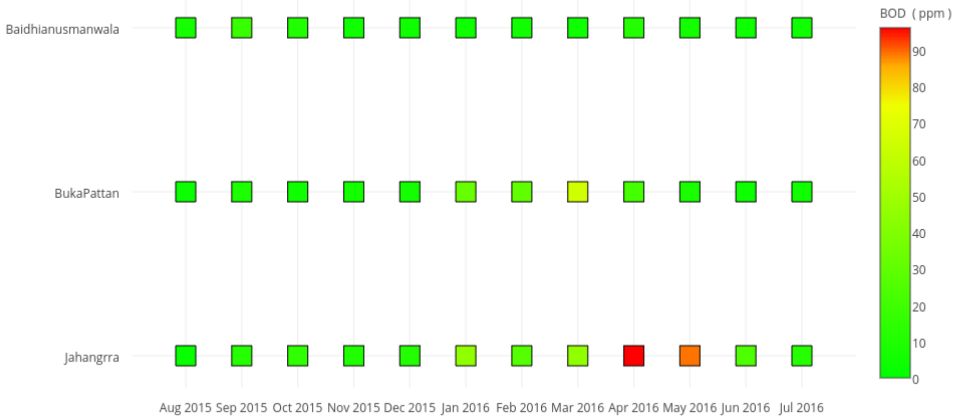


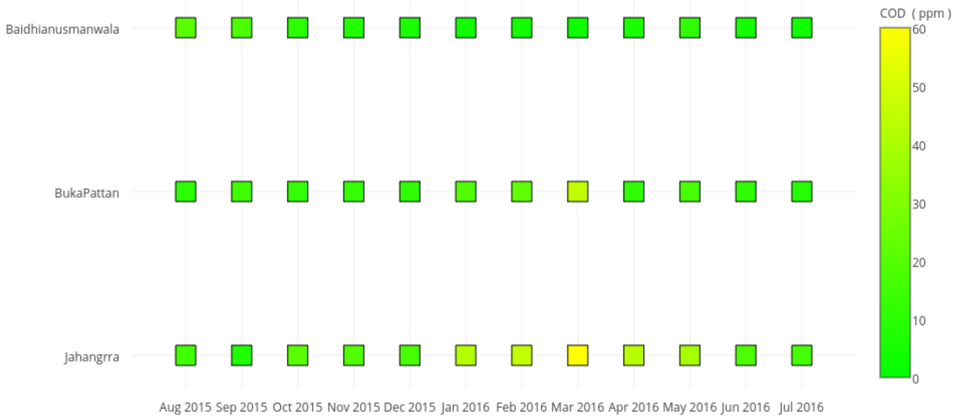
pH (_)
Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
8
7
6
5
4
3
2
1
0

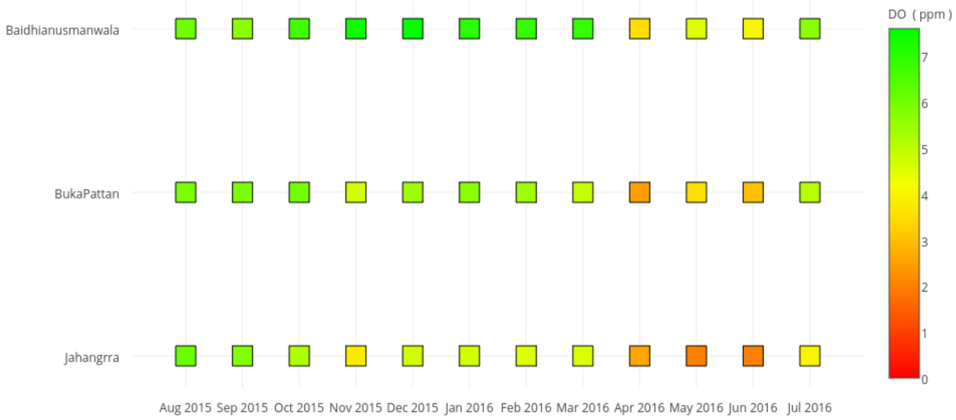


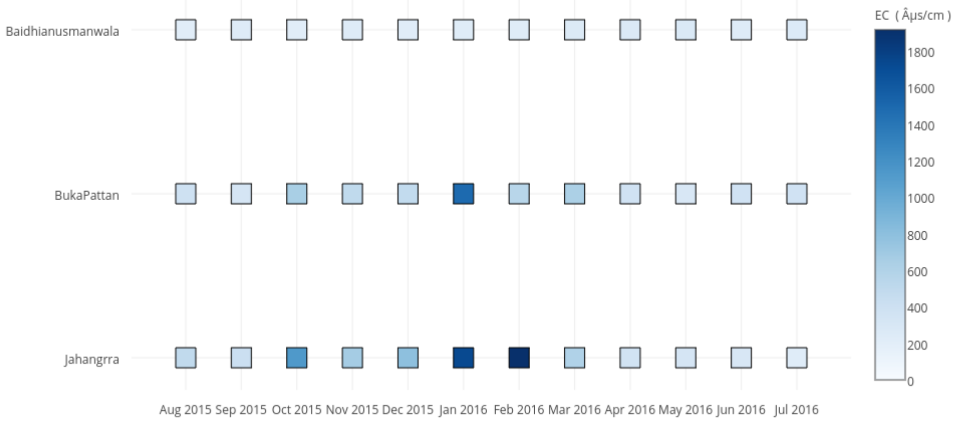


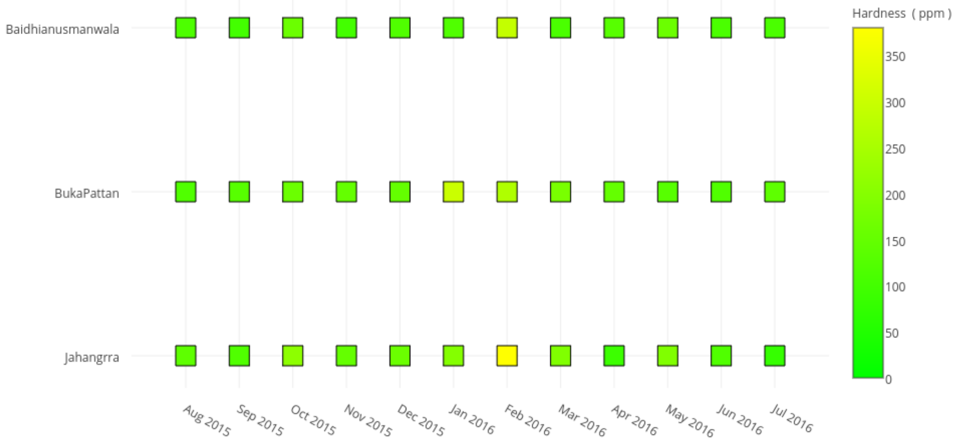
Sutlej River

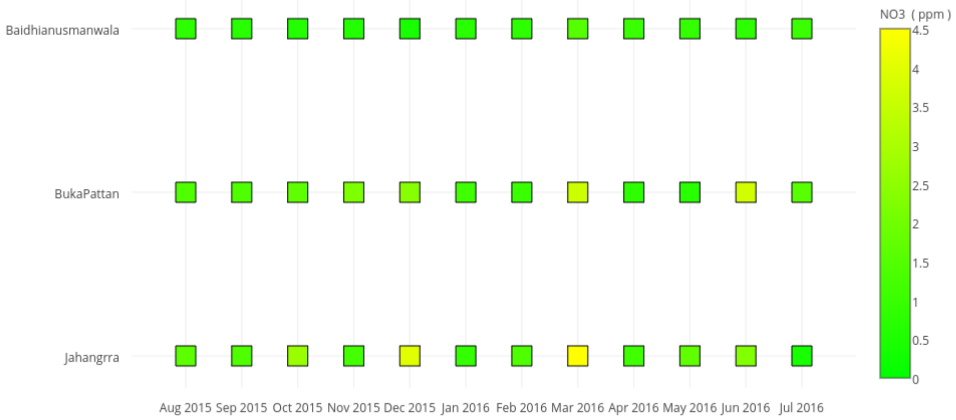


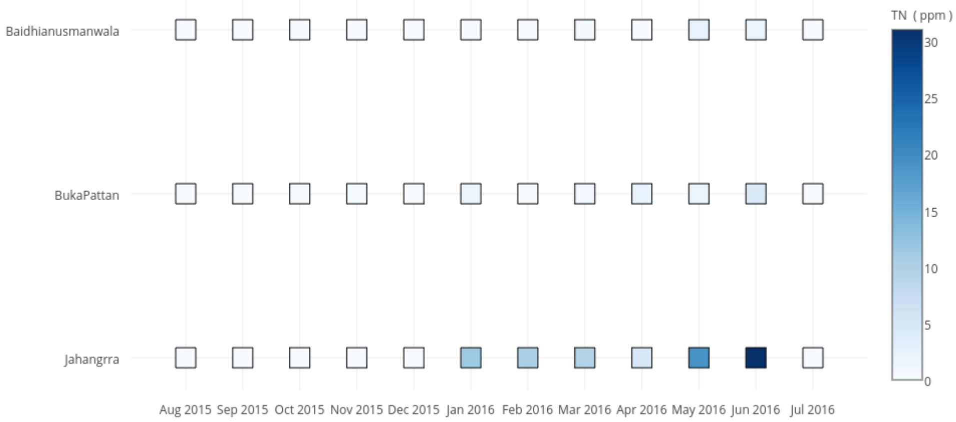

Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
COD (ppm)
60
50
40
30
20
10
0

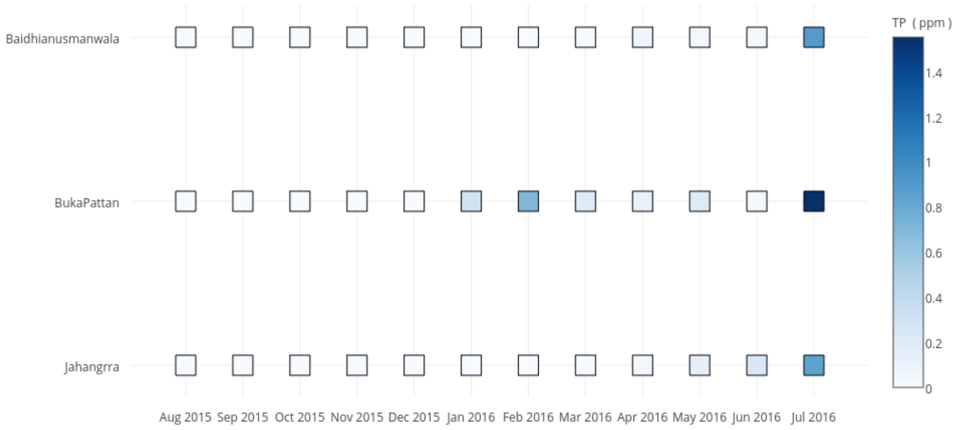

Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
DO (ppm)
7
6
5
4
3
2
1
0

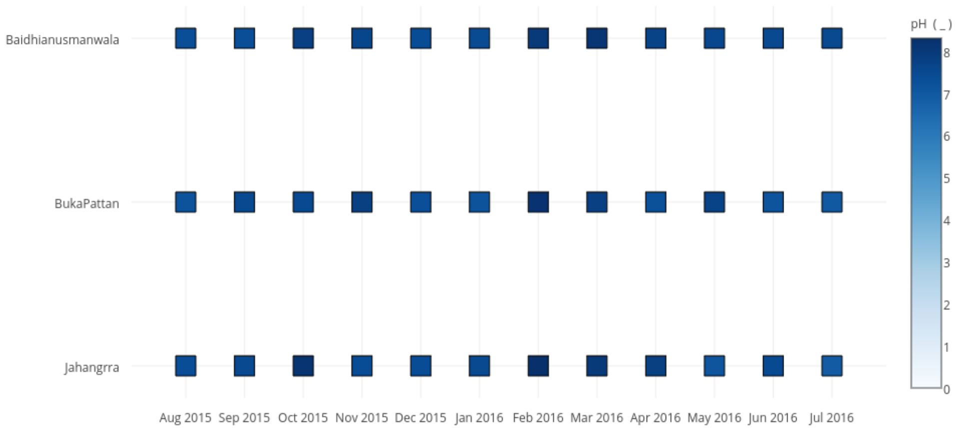

Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
EC (Âμs/cm)
1800
1600
1400
1200
1000
800
600
400
200
0

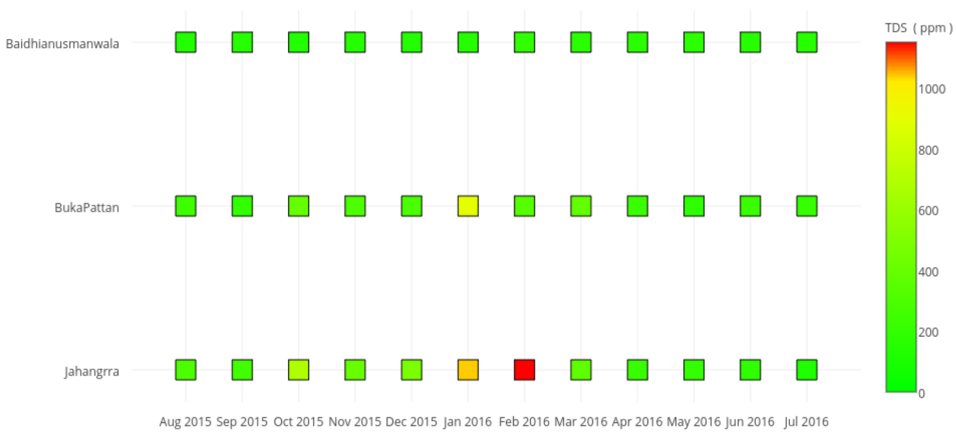

Hardness (ppm)
350
300
250
200
150
100
50
0
Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016

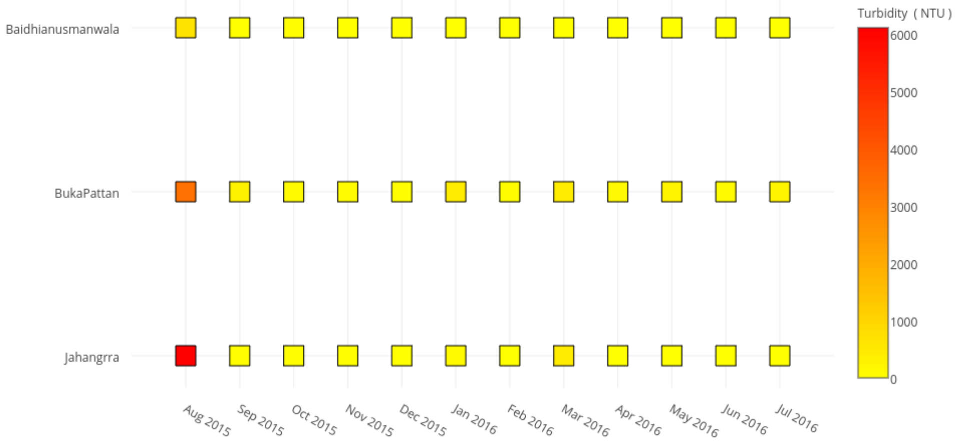

NO3 (ppm)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016


TN (ppm)
30
25
20
15
10
5
0
Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016


Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
TP (ppm)
1.4
1.2
1
0.8
0.6
0.4
0.2
0

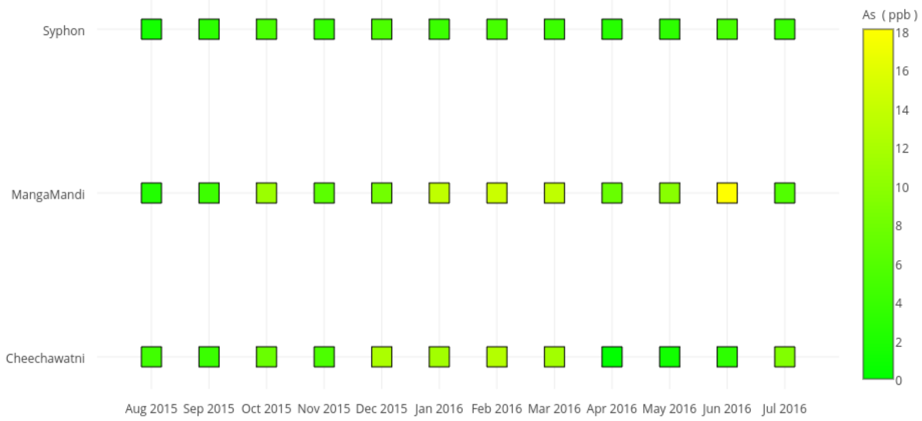

Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
pH (_)
8
7
6
5
4
3
2
1
0

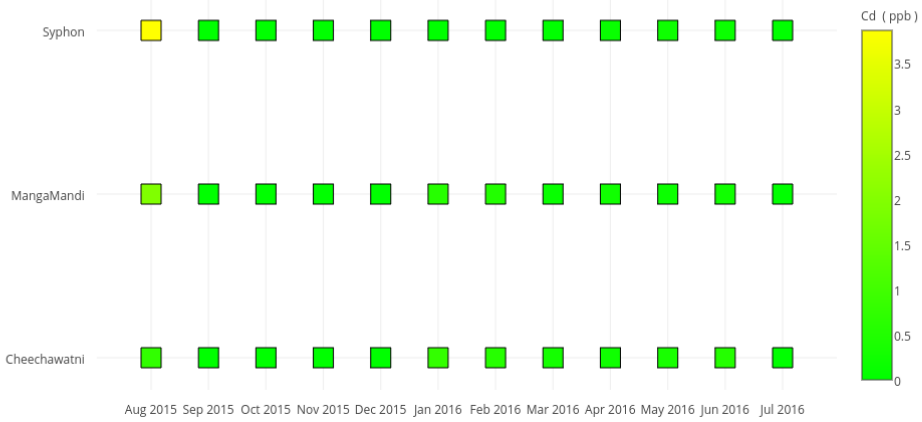

Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
TDS (ppm)
1000
800
600
400
200
0

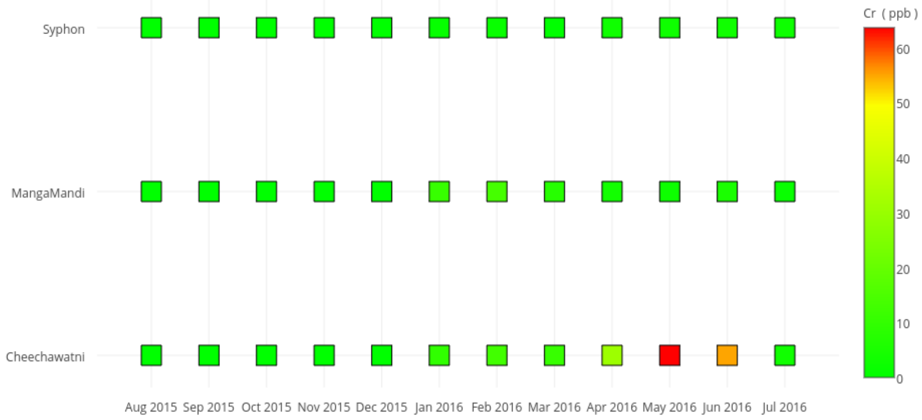


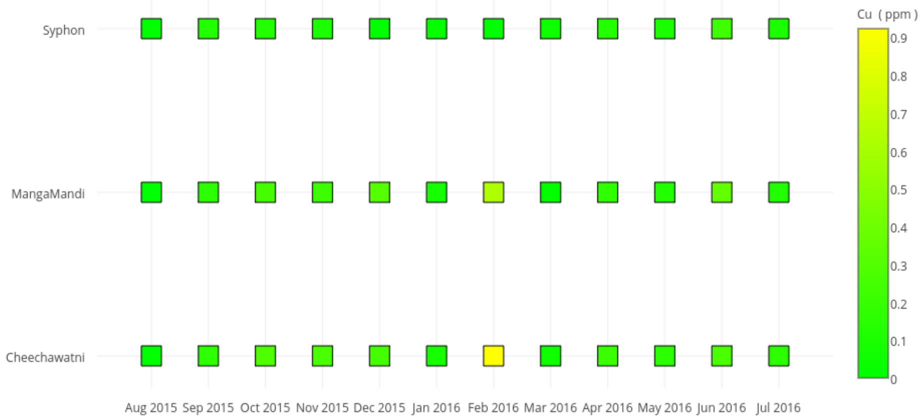
A.2.2 Metals

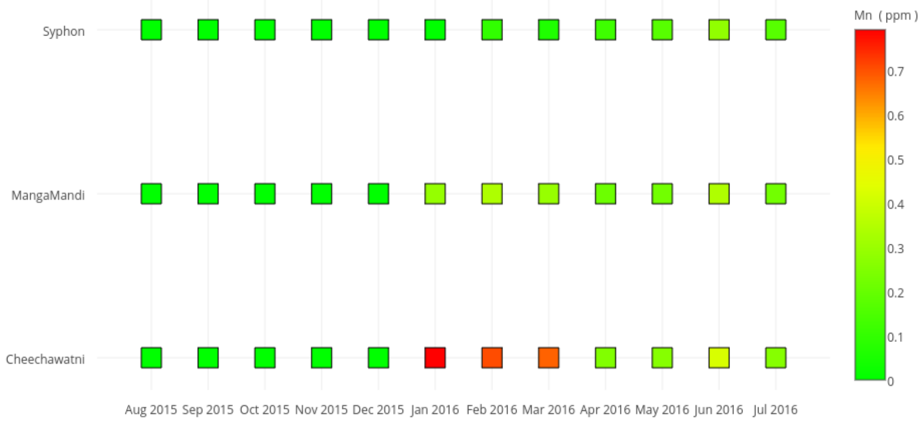
Ravi River

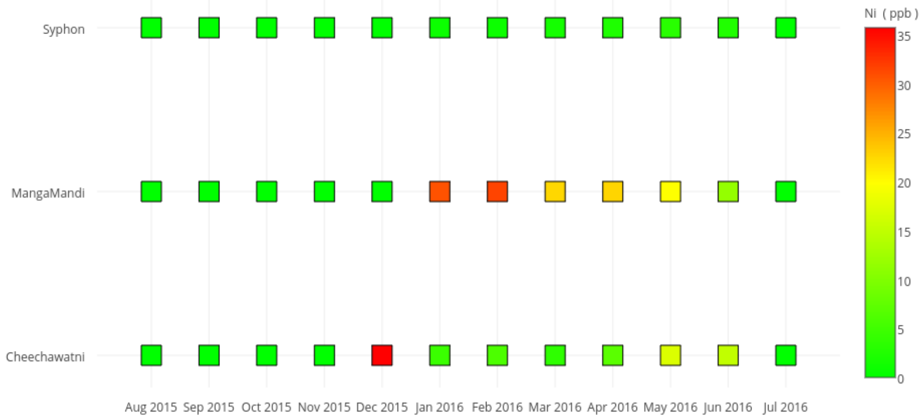


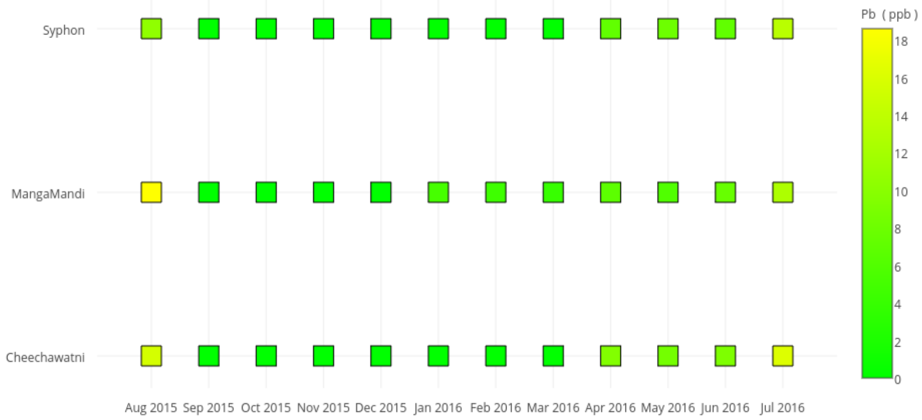


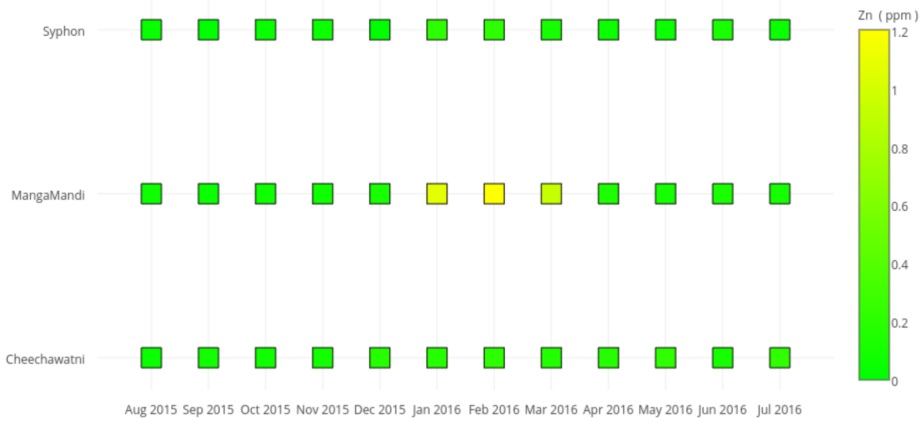

Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
Cr (ppb)
60
50
40
30
20
10
0


Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
Cu (ppm)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

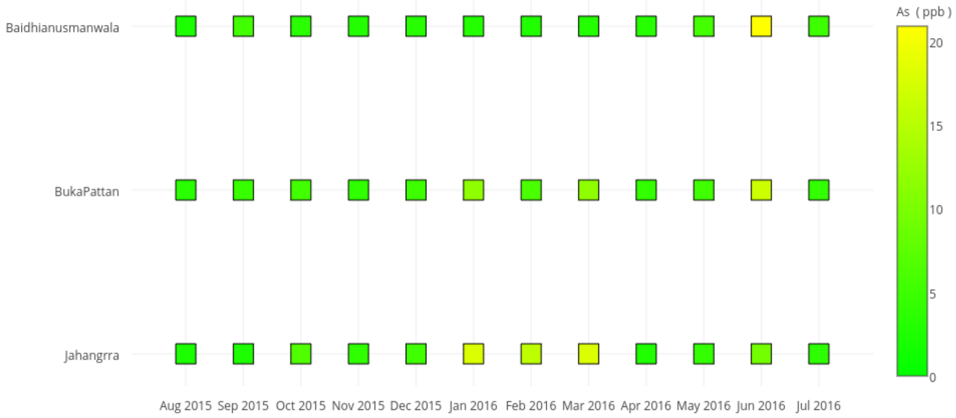

Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
Mn (ppm)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

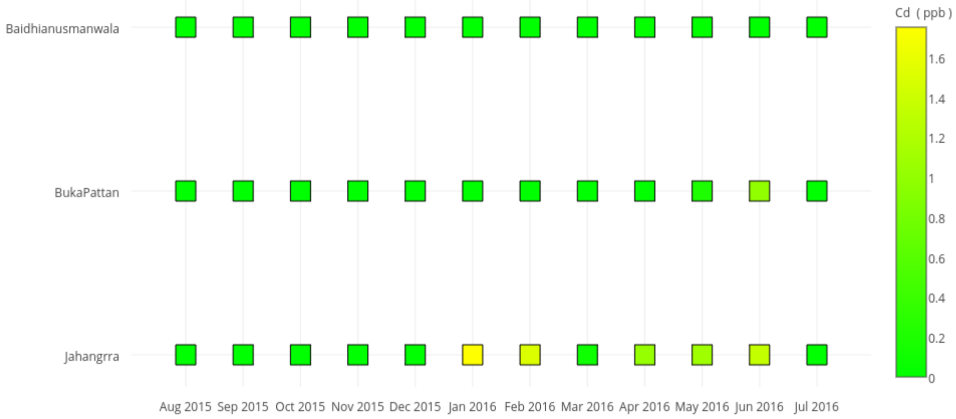

Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
Ni (ppb)
35
30
25
20
15
10
5
0

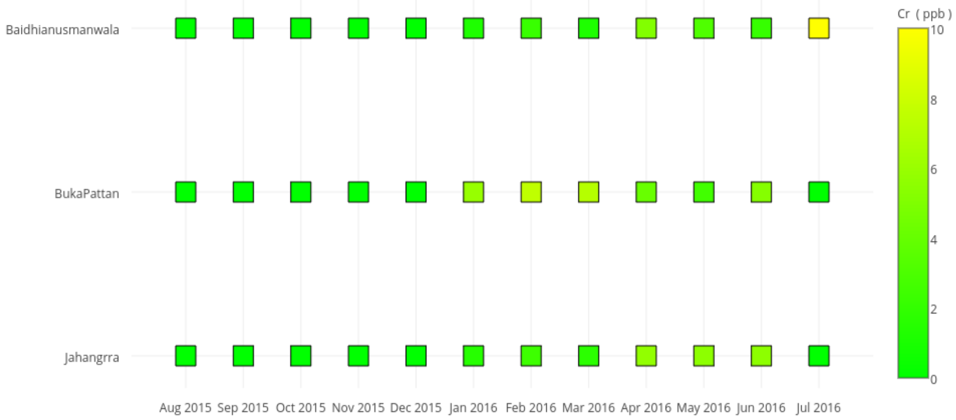

Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
Pb (ppb)
18
16
14
12
10
8
6
4
2
0

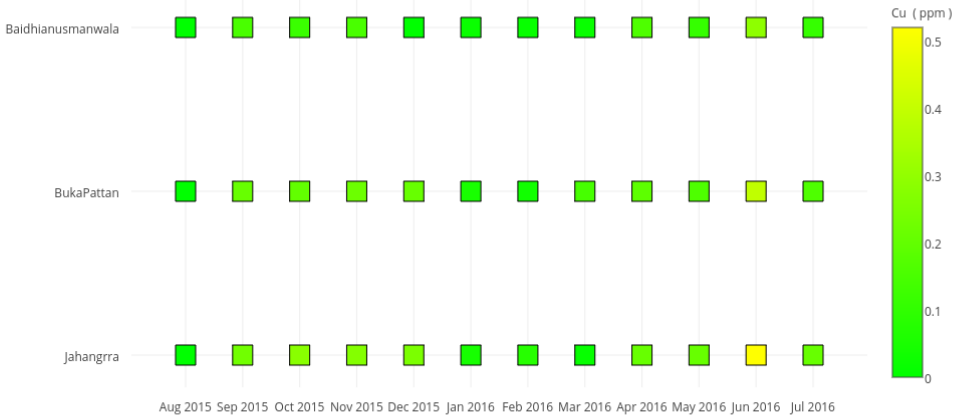

Syphon
MangaMandi
Cheechawatni
Aug 2015 Sep 2015 Oct 2015 Nov 2015 Dec 2015 Jan 2016 Feb 2016 Mar 2016 Apr 2016 May 2016 Jun 2016 Jul 2016
Zn (ppm)
1.2
1
0.8
0.6
0.4
0.2
0

Sutlej River

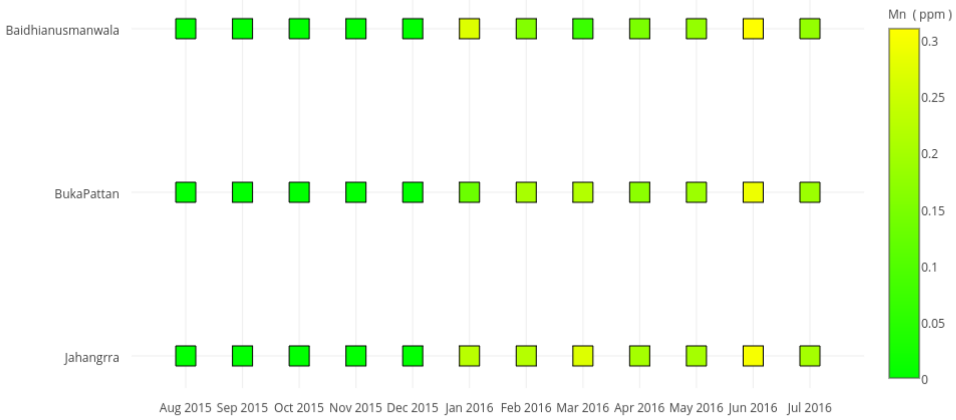




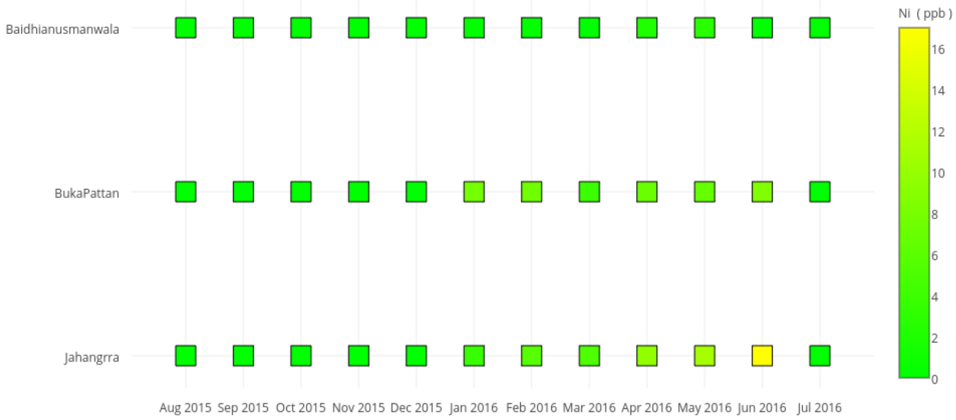




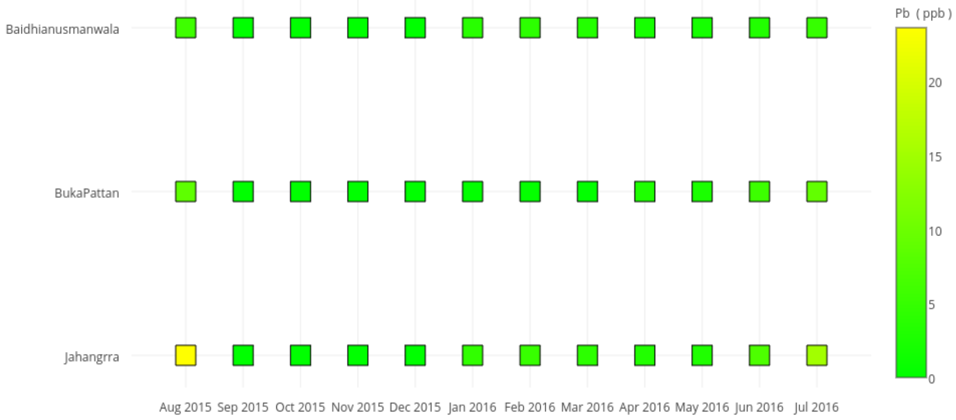
Cu (ppm)
0.5
0.4
0.3
0.2
0.1
0
Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016

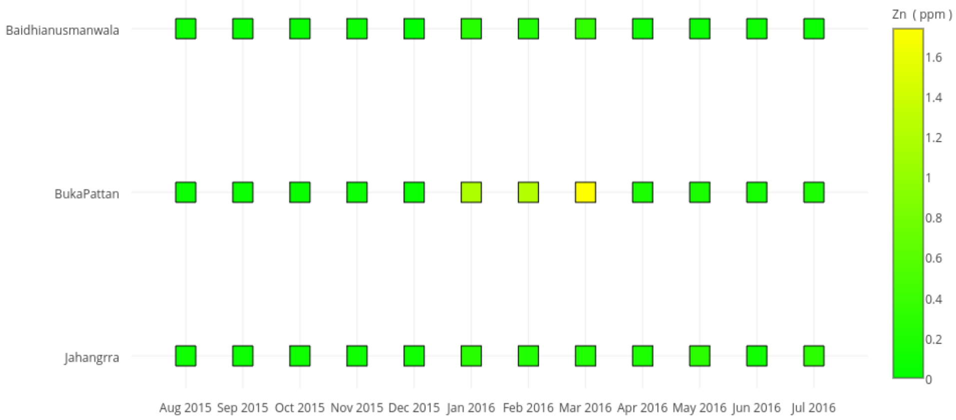


Mn (ppm)
0.3
0.25
0.2
0.15
0.1
0.05
0
Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016



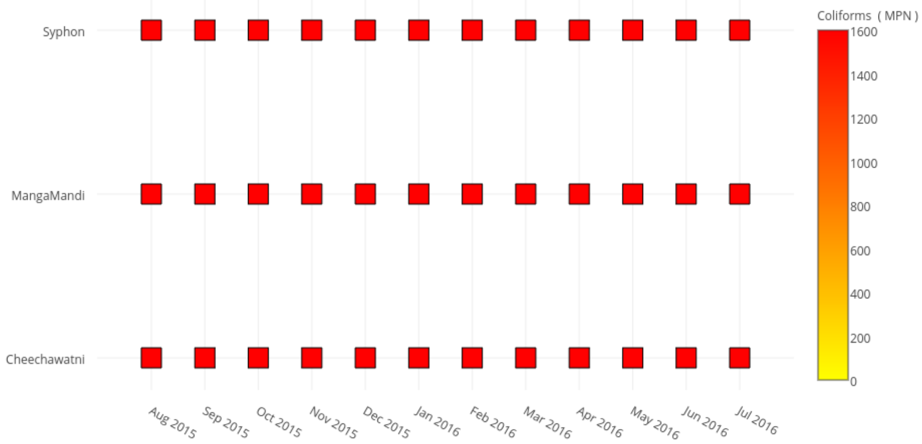
Ni (ppb)
16
14
12
10
8
6
4
2
0
Baidhianusmanwala
BukaPattan
Jahangrra
Aug 2015
Sep 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016

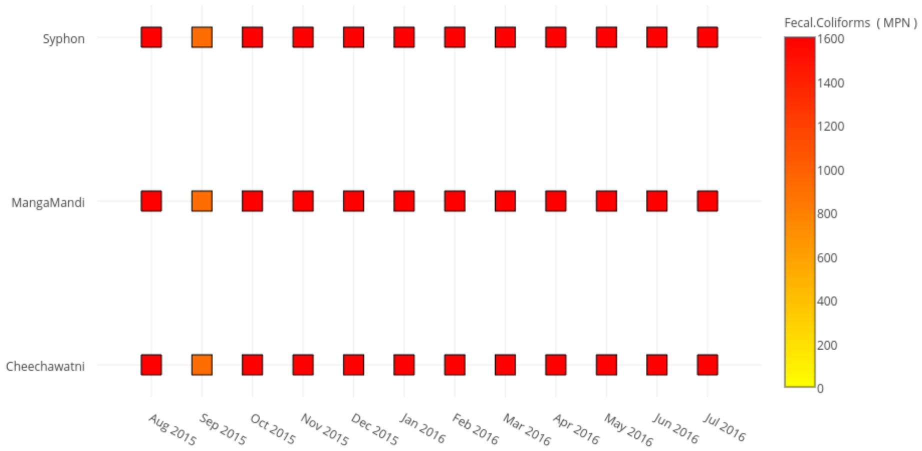




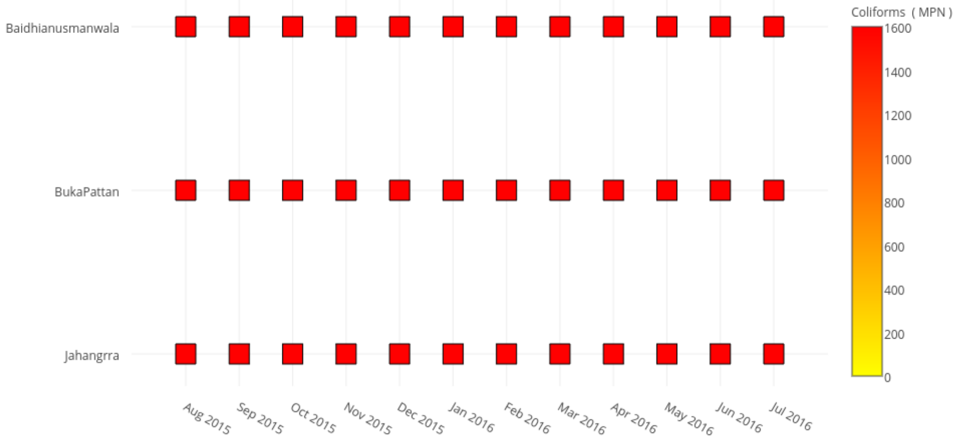
A.2.3 Microbiological parameters

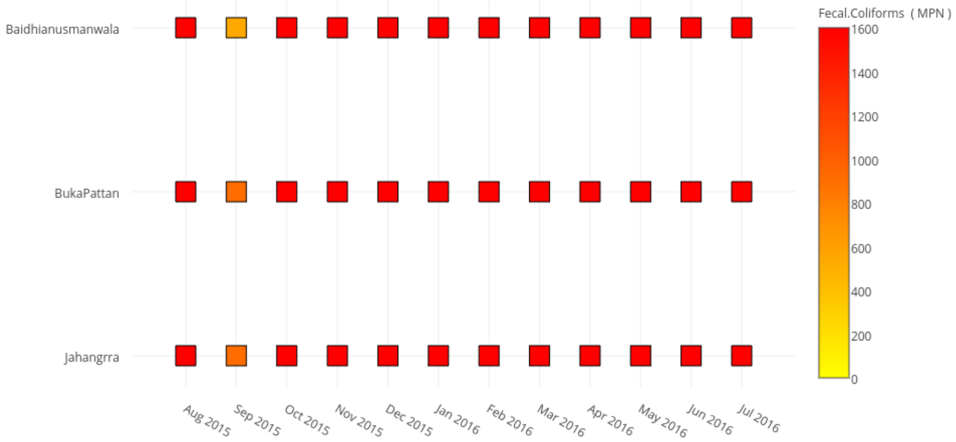
Ravi River





Sutlej River

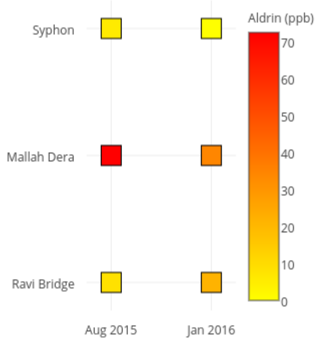


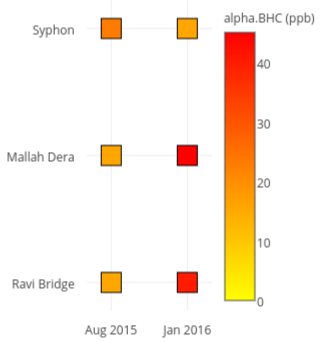


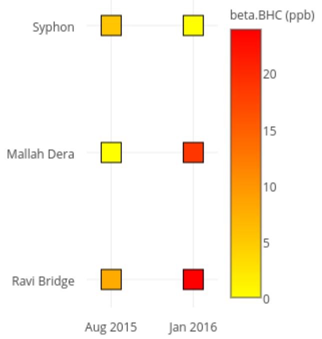
A.2.4 Organophosphorous Pesticides and Pyrethroids

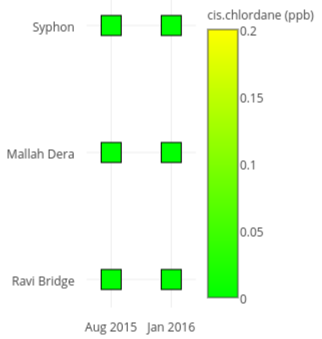
A.2.5 Persistent Organic Pollutants (POPs)

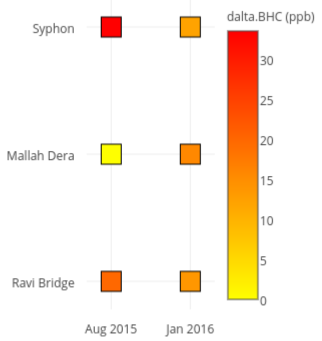
Ravi River

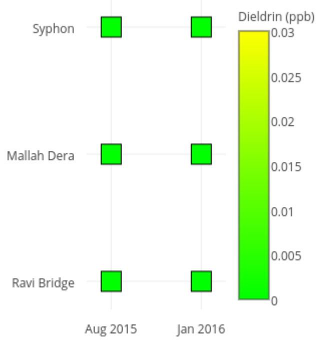


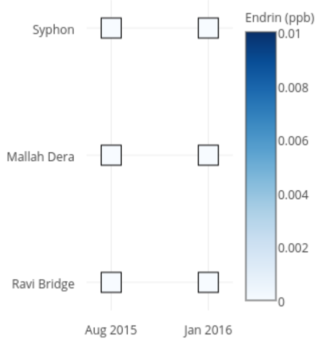


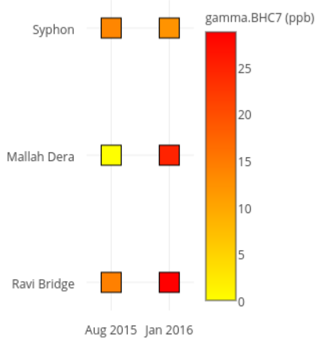


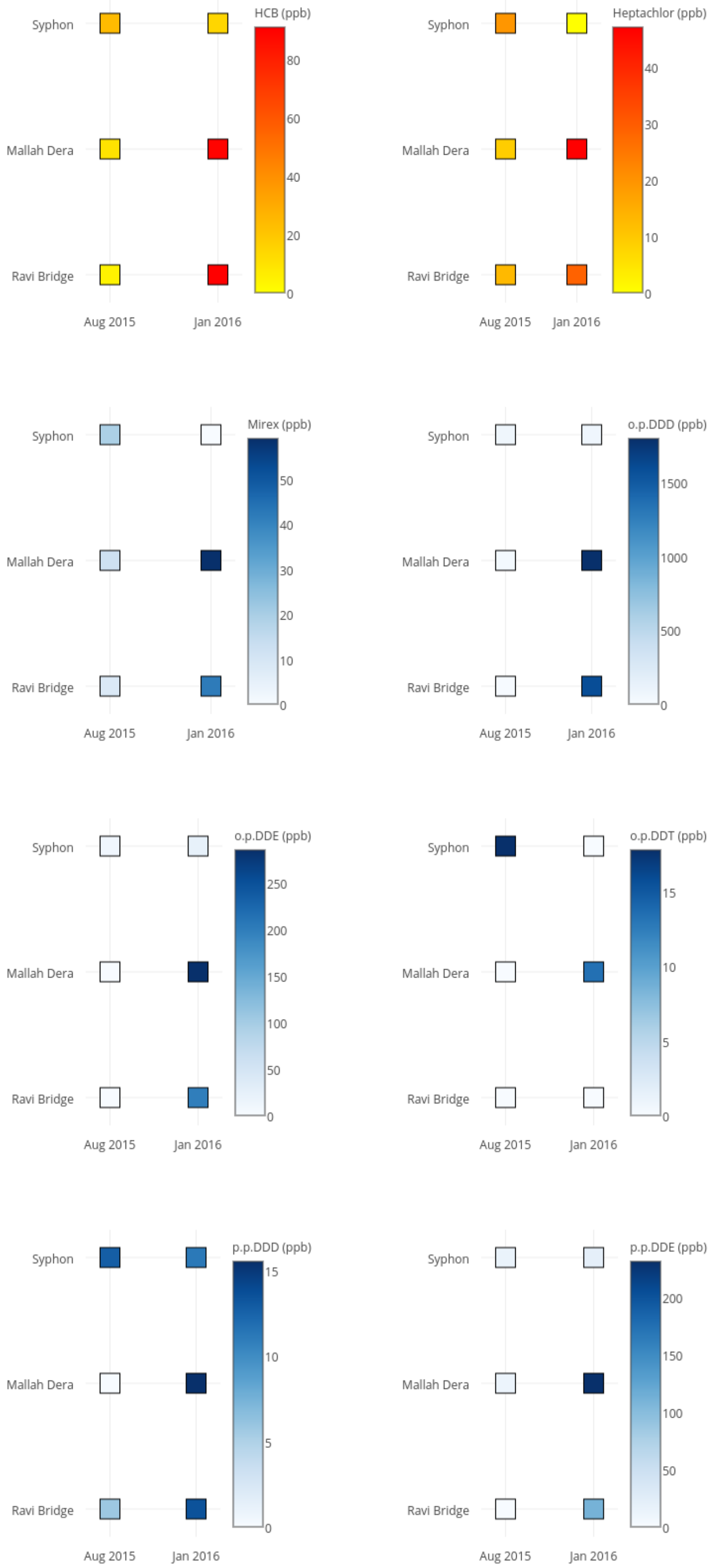


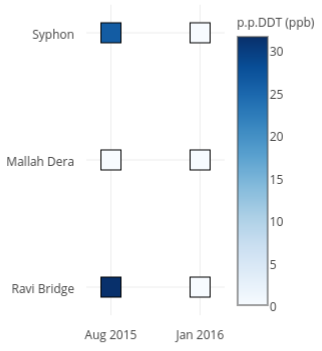


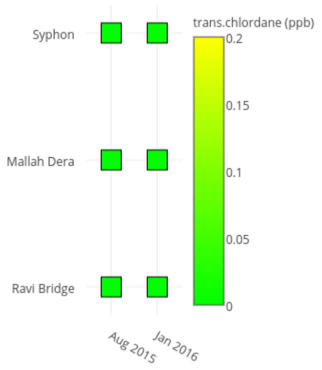




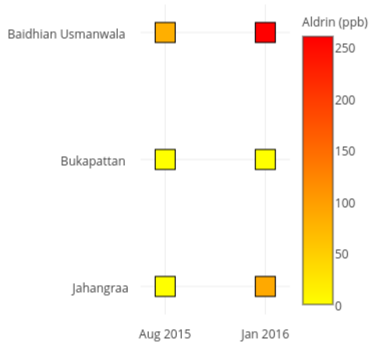


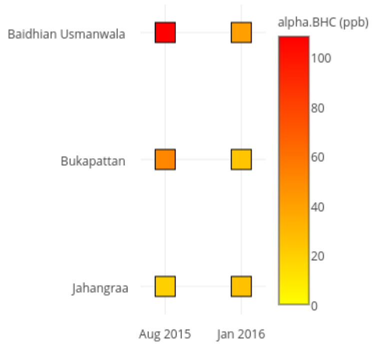

HCB (ppb)
Heptachlor (ppb)
Mirex (ppb)
o.p.DDD (ppb)
o.p.DDE (ppb)
o.p.DDT (ppb)
p.p.DDD (ppb)
p.p.DDE (ppb)
Syphon
Mallah Dera
Ravi Bridge
Aug 2015
Jan 2016

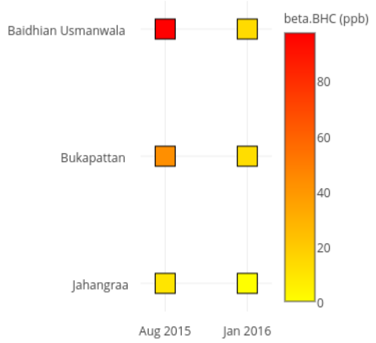


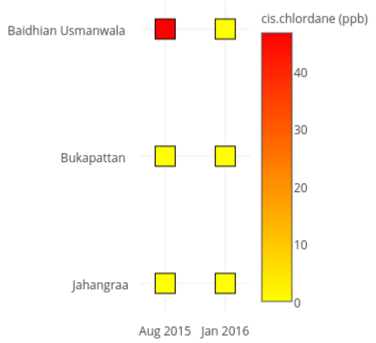


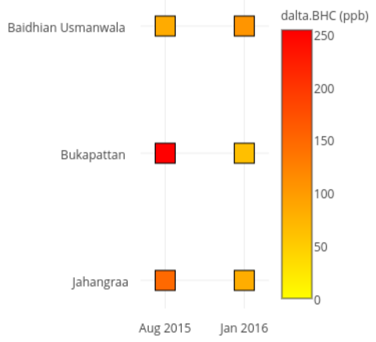
Sutlej River

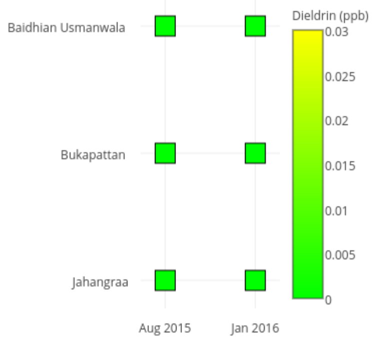


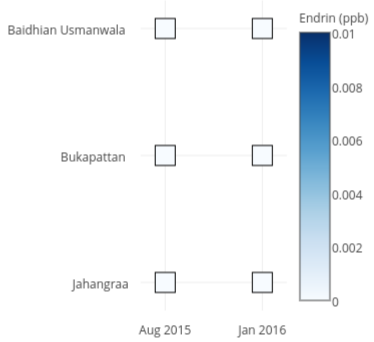


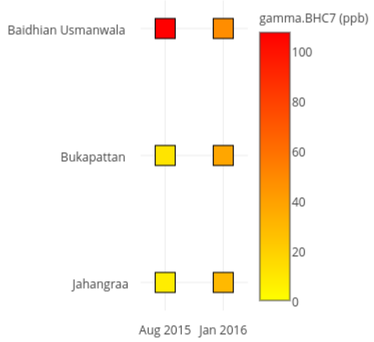


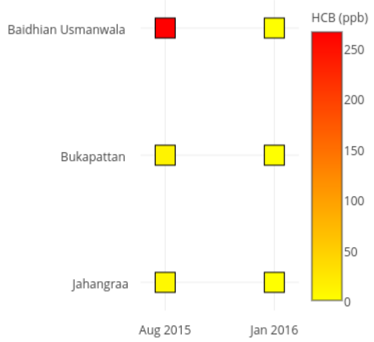


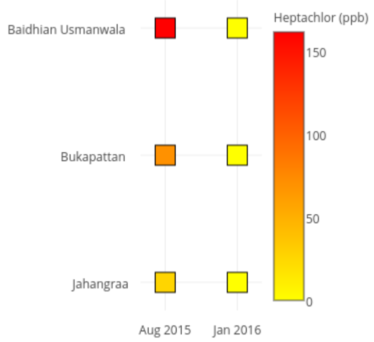


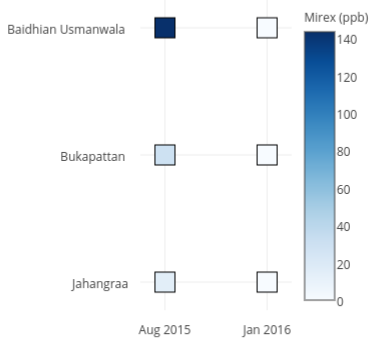


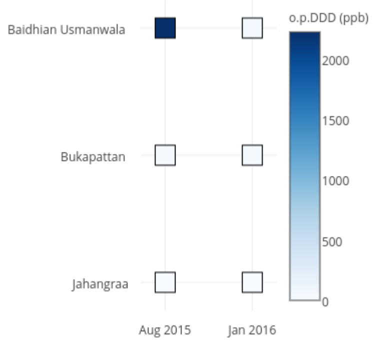

Endrin (ppb)
0.01
0.008
0.006
0.004
0.002
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016

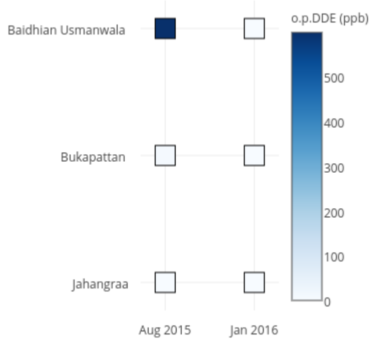

gamma.BHC7 (ppb)
100
80
60
40
20
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016

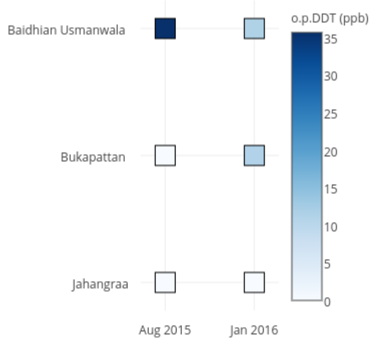

HCB (ppb)
250
200
150
100
50
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016

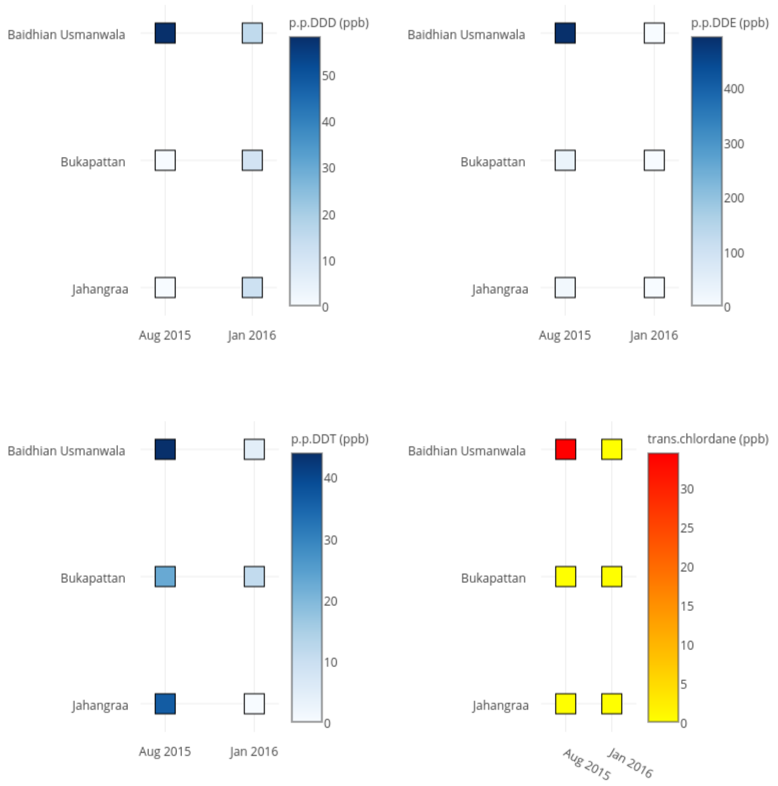

Heptachlor (ppb)
150
100
50
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016


Mirex (ppb)
140
120
100
80
60
40
20
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016


o.p.DDD (ppb)
2000
1500
1000
500
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016


o.p.DDE (ppb)
500
400
300
200
100
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016


o.p.DDT (ppb)
35
30
25
20
15
10
5
0
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016



p.p.DDD (ppb)
p.p.DDE (ppb)
p.p.DDT (ppb)
trans.chlordane (ppb)
Baidhian Usmanwala
Bukapattan
Jahangraa
Aug 2015
Jan 2016

CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

FOR FURTHER INFORMATION

CSIRO Land and Water
Dr Nicky Grigg
t +61 2 6246 5569
e nicky.grigg@csiro.au

CSIRO Land and Water
Dr Mobin-ud-Din Ahmad
t +61 2 6246 5936
e Mobin.Ahmad@csiro.au