Doing Science That Matters to Address India's Water Crisis

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India is one of the most water stressed countries in the world. However, despite appreciable increase in funding for water research, high quality science that is usable by stakeholders remains elusive. I argue that this can be attributed to the absence of research on questions that actually matter to stakeholders, unwillingness to transcend disciplinary boundaries, and the demise of field-work research culture in favour of computer simulation.

Conventional wisdom is these trends are driven by what is publishable. However, there is an increasing interest in the international community in interdisciplinary, problem driven, empirical research. Using examples of my own research in Chennai and Bengaluru, on water scarcity in urbanising watersheds, I offer some methods and insights.

1. India's Water Problem

No matter how it is measured – water poverty, water vulnerability, water scarcity, water risk, water insecurity, or environmental water scarcity – by every measure, India is one of the most stressed countries in the world.

Research funding in the Indian water sector is actually quite robust for a developing country. Based on preliminary calculations, Government of India's research spending on water research has been increasing steadily. Yet, India produces very few high-quality scientific publications and the trajectory of the country towards a doomed future seems to be accelerating, not slowing down. There are several reasons why this might be happening.

1.1 Narrow Focus, Incorrect Framing

First, there is no direct link between the science being done and the real-world conditions in which it is applied. Research studies in individual disciplines have become increasingly specialised, and are limited to very narrow subject areas. But the real-world is not neatly divided into disciplines. Moreover, decisions made by people with narrow expertise have wide reaching impacts. At the undergraduate level, most engineering courses do a poor job of training students to think critically about the broader social implications of engineering design decisions. Thus, a civil engineer may be trained to write an equation for loss from an irrigation canal, or to write a programme to 'optimally' manage a reservoir; but often they are completely blind to the social implications of a particular dam or canal design such as – "who are the winners and losers if one design is chosen over the other?" "Does one caste always benefit?" "Are the implicit assumptions about human behaviour valid?" "Who gets to decide what goes into the optimisation objective and constraint equations?" "Should aquatic species be included?" and "what are the concerns of the landless?"

But doing this would call for some understanding of the fields of economics, ecology, sociology, political science, and anthropology which scientists and engineers aren't trained to do. How are these considerations to be brought into the thinking of science and engineering graduates, if they don't even know what they don't know?

Worse still, this blinkered approach to research and education carries over into the bureaucracy. Postings in the Irrigation Department start from Assistant Engineer and go all the way up to Chief Engineer. There is simply no place in the hierarchy to employ an anthropologist, sociologist, or an expert on negotiations with tribal communities. The net result is that many infrastructure projects, even basically sound ones, are mired for years in litigation; after which they finally get shoved down the throats of the protesting communities. But once constructed, they are operated by engineers based on the dictates of local politics; rarely are the rule books adhered to. In the absence of monitoring, many so-called beneficiaries of the project may never see the water. Indeed very few post-facto analyses of dams exist in India, making it virtually impossible to validate or rebut claims.

1.2 Demise of Field Work

The conventional approach to deciding if a dam must be built, or how it must be operated is to develop a 'model of the system'. This involves writing a set of equations that govern energy and water fluxes, and then coding them in a computer programme. The purpose of computer simulation is to be able to predict how the dam, irrigation canal, or piped water network would behave under different conditions.

The problem is, in reality, the equations are highly dependent on assumptions that the modeller makes. For instance, we know in theory that streamflow depends on stream roughness and soil hydraulic parameters. In practice, we can never measure the stream roughness in every section of the stream, or the soil types in every square inch of the watershed. Instead, we 'guess' these parameter values, and then keep adjusting the guesses so that the streamflow values predicted by the model matches what is observed in the real world. This may be done manually, or using sophisticated computer algorithms, through a process called model calibration. But frequently, the models don't even aim at realism; the watershed is simply modelled as if humans never existed. Even large dams or sewage treatment plants may be completely ignored. To reconcile the model world with the real world, model parameters are set to absurd values to force the simulated streamflow to match what has been observed in the gaging stations.

A bigger problem is that sometimes the measured streamflow values are simply wrong (e.g., due to unit conversion errors or faulty sensors), or at least not what the modeller thinks they are (e.g., in many urban streams, 'streamflow' is just sewage). In many parts of India, humans have altered watersheds so much so that the original equations don't even hold. A cursory visit to the field would reveal this; but many water researchers no longer visit the field so they have no way of knowing that the data and equations they have assumed are incorrect. Additionally, the fashion is to work on large scale, national or global models that work off data downloaded from hundreds of stream gages. So the models can end up being garbage-in-garbage-out!

1.3 Modelling vs. Hypothesis Testing

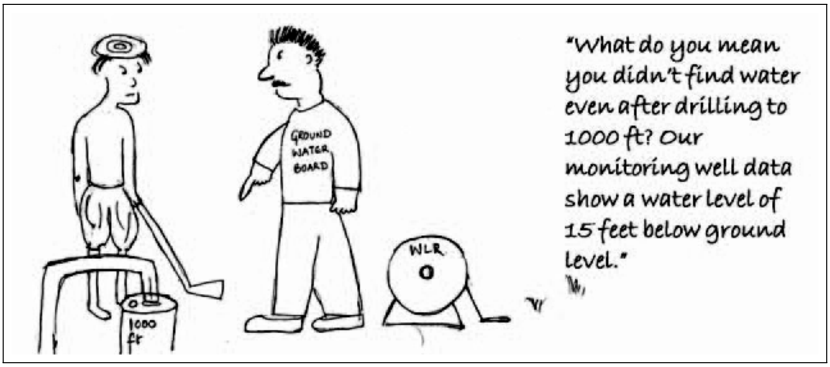
One barrier that hampers collaboration between disciplines is that water resource researchers often build computer simulation models whereas, social scientists test hypotheses. If you have been exposed to any philosophy of science, perhaps you might have learnt that scientists add to knowledge by advancing hypothesis about how the world works, followed by collecting data to try and disprove the hypothesis. If the hypothesis can't be disproved, it stands.

By this yardstick, how is model building science? After all, a model only gives you what you put into it. This objective and rationale of computer simulation modelling is never taught in undergraduate civil engineering or water resource courses. A model is NOT science in the sense that it does not create new knowledge about processes. New knowledge about how the world works is still generated by hypothesis testing. What a model does is to help understand the cumulative effect of hundreds of unrelated processes, which can't be guessed from understanding the individual processes.

Even so, no model can ever capture every single process – we don't model every leaf fall, gust of wind, bug, or human walking across the landscape. Rather we make judgements about which elements matter and which ones do not. This makes modelling an art rather than a science. In fact, models are frequently built without much thought to what processes are to be included and excluded and why. Individual model equations are not validated separately. Hydrologic researchers in the data-dense Western countries have shown that many models with wildly different assumptions can all replicate observed historical streamflow quite well. So why do we believe that any one model is 'the model' of the system?

2. The Case For Problem-Driven Science

No model is ever a perfect representation. Models are only useful for specific purposes within a limited range of conditions. Therefore, to start answering scientific questions that actually matter, we need to start with a problem, identify the knowledge gaps, and



seek to address them. We also need to understand the rationale and limits of the tools used.

It is therefore critical to not ignore real world conditions and to acknowledge that there is no such a thing as 'a model of the river basin'. There are many possible models, and they each serve different purposes with different implications. Ideally, a researcher should talk to people to understand how different problem framings will affect different groups of people. Additionally, if scientists can pay attention to the policy debate and talk to civil society groups and policy makers, it will increase the chances of science being useful.

The idea of stakeholder inclusion has been around since the introduction of Integrated Water Resources Management (IWRM) in the early 1990s. But IWRM implementation projects required that the scientists would build 'a model of the river basin', and then hand it over to the community or decision makers to use. But I am proposing something quite different; that for the science to be usable and believable, the models themselves need to be built and validated by consulting stakeholders. This idea is relatively new and is gaining prominence in international literature. However, it requires a fundamental rethinking of how science is done; a change in mindset and willingness to tolerate 'messiness'. It requires natural scientists to be willing to see economists, sociologists, and anthropologists as people with valuable expertise. It also requires that each researcher be willing to make their work comprehensible, and be willing to listen to others.

3. What Are the Barriers?

While the idea of usable science is gradually gaining popularity, there are still many barriers to overcome within the Indian research community.

3.1 Claim 1: The Science is Settled

Some argue that scientists already know what to do; it is the job of social scientists to understand it and 'convince the people'. In other words, knowledge is not the barrier to sustainable water management. The scientists know what to do; it is just politics and interdepartmental bickering that gets in the way.

But this claim doesn't bear scrutiny. When one does a SciSearch or Google Scholar query to answer basic questions on virtually any water crisis or conflict in India, it becomes apparent that answers to most questions do not exist. For instance, in the case of the contentious inter-state Cauvery River (which originates in the Western Ghats and flows through Karnataka and Tamil Nadu states into the Bay of Bengal), do flows in the various tributaries show a declining trend over time? Has rainfall in the Western Ghats, which provide most of the river flow, declined? How do deforestation and urbanisation affect the flows in the river system? Has irrigation area in Karnataka and Tamil Nadu increased or decreased?

I would encourage young scholars to explore for themselves. Compare results on hydrologic studies from the Cauvery river basin with similar Google Scholar searches on the Mekong, Murray Darling or Colorado river basins. It will be obvious that there is a big disparity in both the number of papers and their usefulness in public discourse.

3.2 Claim 2: Not 'Real' Science

This is one of the biggest barriers in the current mind-set. Scientists argue that by definition, reductionist science can only tackle one small question at a time. Collaboration between departments to answer larger questions is hampered by the lack of understanding of what other researchers actually do! Not only is there a lack of communication, there is snobbery too. Undergraduate courses have a clear hierarchy. Engineering/Medicine is still considered more prestigious than a Bachelors in Science, which in turn is more prestigious than a Bachelors in Commerce. The Humanities are at the bottom of the heap! But if compartmentalisation were not bad enough, hierarchy is even worse because it prevents any dialogue between students of different disciplines. Moreover, this hierarchy is carried over into government departments.

Cross-discipline learning is virtually impossible in a system where colleges are segregated by discipline. Engineering undergraduates (who might listen to a TED talk on economics by a Harvard professor) will rarely engage with their own friends from other colleges on debates over matters of public interest. But even when cross-disciplinary research is done, many natural scientists feel that it is a dilution or weakening of 'real science'. This attitude carries over into journal publications.

3.3 Claim 3: Such Works Are Not Publishable

Another claim is that interdisciplinary, problem-driven work is not done because it is not publishable. During my field research in drought-stricken Chennai, I met some who justified the absence of water research in India by arguing that working with foreign datasets was preferable because 'Indian data is unreliable' and can't be published in international journals; a claim that was simply not borne out by my own experience.

To some extent, data access, despite improvements over the years, remains a barrier. IMD datasets are very expensive and beyond the reach of most student researchers. Even where states like Karnataka has invested in high density network of weather stations, the data is not placed in a searchable portal with metadata (although the agencies do make data for selected stations available by email on request). Data on water use is completely unavailable. Data collected by local agencies tend to be fragmented, and the researcher must visit dozens of offices to create a usable dataset. There is no unified platform for data dissemination, and lot of time is wasted in repeating data collection activities again and again, instead of progressing the science.

Moreover, the fear of using unconventional sources of data is not entirely unfounded. Some Indian journals do not in fact recognise certain types of data as 'valid'. A review comment in an article submitted (by me) to an Indian journal for instance argued that government data were beyond question, citizen collected data were not admissible, and farmer survey data even when systematically done could not be used in a scientific paper!

There are glimmers of hope though. While the Indian research community is still catching up, top field journals like *Water Resources Research*, Hydrology and *Earth System Science*, and *Journal of Hydrology* are showing interest in field based, interdisciplinary studies that ask real-world questions versus studies that make small tweaks to Western models, or blindly apply a methodology developed elsewhere to an Indian river basin. Independently, the research community must continue to push for open access to data.

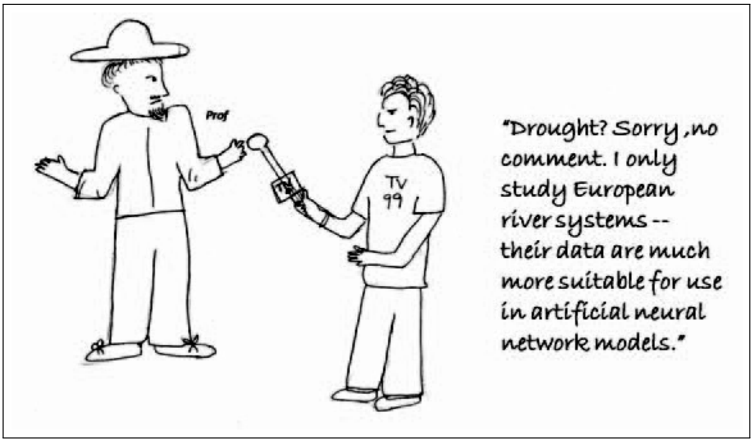
4. Lessons From My Research

I have unfairly painted all the Indian researchers with the same broad brush. In fact there are many excellent examples of high-quality, problem driven research in India both from academic and government institutions. In this article, I draw on my experience from my own work in Chennai and Bengaluru, not to imply that others have not done good work, but merely because I am most qualified to write about my own work.

4.1 Chennai

When I began my PhD field work in 2004, Chennai was in the throes of one the worst droughts ever. The reservoirs had dried up, piped supply had been shutdown for almost a year, and the whole city was dependent on tanker water. Groundwater tables had been in continuous decline for almost a decade at that point. The city had signed an agreement to buy water from peri-urban farmers. There were protests from landless labourers in those villages; they had lost their wages but were not benefiting from the water purchase agreements. The situation presented an ideal topic for a thesis on water scarcity. Just six months later, by the time I passed my qualifying exam and arrived in Chennai to start field work, the situation was dramatically different. Chennai was experiencing one of the worst floods on record and was submerged under water for several days. As the flood water infiltrated and recharged the aquifer, groundwater levels reached historic highs; the reservoirs were full, piped supply was restored. Overnight the tanker market disappeared. There was nothing left for me to study!

While this threw my carefully laid out research plan on drought and acute scarcity out of the window, it raised questions about why the narrative on water scarcity in Chennai (claiming that the city would always be water scarce) had been so wrong. The state government was proudly claiming credit for constructing the Veeranam project and announc-



ing several desalination projects to avert a similar crisis in the future. The World Bank was back to bemoaning the lack of metering and pricing of water and high leakage rates, arguing that if less water was lost in leakage, then the system would be more resilient. Meanwhile, environmental NGOs were claiming credit for pushing the 2004 rainwater harvesting regulations, which required every building to have a rainwater harvesting recharge pit.

I wanted to know why the crisis had occurred and which of the suggested measures would make Chennai more water secure in future. I wanted to know whether, if rainwater harvesting was strictly implemented, we could do away with the need for two desalination plants. I was also curious whether all options affected different categories of users (rich vs. poor, domestic vs. commercial, high rises vs. independent houses) in the same way. In other words, I wanted to know if there were equity implications to policy choices.

As a hydrologist/water resources engineer, I was qualified to build a model of the watershed, the aquifer, and even the piped supply system. But that would not answer my research questions. The main difficulty was that there were no physical links between desalination plants (that increase piped water availability), rainwater harvesting (that raises groundwater levels), and metering (which gives water users a signal of how much water they are using). Luckily, my dissertation advisory committee, representing the fields of hydrogeology, economics, law, and engineering, encouraged me to take a holistic rather than a fragmented view of the system.

The key to solving the puzzle was the discovery that it was the water user who links all the other elements together. Water users in Chennai (unlike the Western world) have adapted to acute scarcity by building sumps to store water, drilling borewells, and buying tanker water if needed. If I could model this 'consumption from multiple-sources' behaviour, this would help me understand how a given water user would benefit from improvements in any one of the systems – the reservoir system, the aquifer, and the piped system, and thus compare these options.

By linking a 'user agent' model to hydrology and engineering models, it became possible to address the policy questions. Methodologically, each link in the model was established separately through statistical or qualitative methods through methods that those disciplines consider valid, before linking everything together in a single integrated model.

My research showed that a combination of rainwater harvesting, waste water recycling, pricing, and efficiency would be more cost effective than building desalination plants. In effect, these options controls the demand and make use of the buffering capacity of the urban aquifer. However, these options only worked up to a certain level of growth. If the population density increased beyond a tipping point, then depending mostly on local resources became infeasible.

4.2 Arkavathy

My Chennai work was accomplished as a single doctoral researcher advised by a multidisciplinary advisory committee. In my current professional life as a career researcher, I am unlikely to work alone. Instead, a more likely scenario is 'team science', where a group of researchers work together towards a set of shared research goals.

The Arkavathy river lies to the west of Bengaluru. It originates at Nandi Hills, north of Bengaluru, and flows *via* a series of cascading tanks to join the Kumudavathy, where a reservoir called the Thippegondanahalli (TG Halli) was constructed in 1935. Once a major source of water to Bengaluru city, the reservoir no longer supplies any water to its residents. Inflows into the reservoir have gradually declined to a trickle today. When we asked different stakeholders why they thought the river was drying, every NGO and state department had a different explanation. Not only that, they were basing their course of action on their beliefs about the science. Our approach was then to develop a set of hypotheses of all the possible factors which might be contributing to drying using the available data – was it declining rainfall, rising temperatures, groundwater pumping, eucalyptus plantations, or stream fragmentation? The historical data clearly showed that changes in rainfall and temperature could not explain the sharp declines in streamflow.

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Having broadly established that groundwater pumping, stream fragmentation and eucalyptus were responsible for the river drying, the next task was to understand how much each of these factors contributes. To do this, we embarked on an intensive three year field study to test various hypotheses such as – what is the process by which run-off is generated? Where does the water in streams originate from? Where does it end up? Is the water that enters the ground surface the same as the water that is being pumped from deeper fractures? What is the time-lag for water infiltrating the surface to reach deeper fractures? Is the groundwater local, or does in move over a large area? How deep do the eucalyptus roots go, and how much of the infiltrating rainwater are they able to capture?

We did this by running isotopic studies, analysing satellite imagery, setting up field instruments to measure streamflow, water in tanks, and soil moisture. We also set up weather stations and monitored groundwater levels through a participatory groundwater monitoring programme. With the help of social scientist colleagues, we asked questions about water use by conducting household and farm surveys. We wanted to understand how much do farmers pump? How has this changed over time? What motivates farmers to make the choices they do, and so on.

The farmer survey showed clearly that as the city grew, it made no sense for farmers to stay in rainfed agriculture. They were better off either putting their land under eucalyptus and going to work in the city, or drilling deep borewells to grow irrigated high-value crops that could be sold in the city. The hydrologic studies showed that pumping was causing groundwater to decline sharply. The eucalyptus trees were taking up much of the infiltrated water and decreasing recharge. The response to declining groundwater was to set up check dams to boost recharge; but the check dams did not create new water, all they did was to reduce streamflow.

The research led us to conclude that ultimately groundwater only acts as a buffer storage. It stores rainfall in wet periods so that it can be used in dry periods. Ultimately rainfall remains the limiting factor. Currently, because electricity is free and borewell drilling is relatively affordable, there is no limit on how much water humans are extracting. Effectively, free electricity allows farmers to mine recharge that occurred over many decades, and the only way out is to regulate extraction.

The research also shows that most of the available water resources are used by just a handful of large irrigators. The current system of water use is neither sustainable, nor equitable. In the long term, we have to stay within the water resources available through some sort of water budgeting exercise.

4.3 What is Different?

The research was interdisciplinary and problem driven from the start. The 'framing' of the research and formulation of the hypotheses was based on iterative discussions with stakeholders. Primary data collection was targeted to test rival hypotheses regarding each link in the model separately with no *a priori* assumptions about which biophysical and social processes were dominant. Human alterations to the system were explicitly included and measured. Where necessary, model parameters were validated with survey data, interviews, and oral histories.

The model was then linked using equations for each process allowing for 'two-way feedbacks' between the natural and human subsystems; i.e., after each period, human agents are allowed to respond to the hydrology and change their behaviour in response. This would drive water use and management in the next period.

The Chennai model for instance, showed that leaking pipelines were contributing to almost half the groundwater recharge in the city. The Arkavathy model showed that watershed development activities, undertaken to address groundwater depletion, were changing the infiltration and run-off characteristics of the watershed.

The model was used to develop a narrative of change that could be communicated back to stakeholders through water literacy meetings, short films, opinion pieces, and newspaper stories. One insight that emerges from both the case studies is that the hydrologic system cannot be explained without accounting for human activity. A purely hydrologic model would have to make absurd assumptions to capture these effects.

5. Concluding Thoughts

I hope this article will encourage budding water researchers (indeed all young applied scientists) to avoid jargon filled papers and ask simple fundamental science questions in ways that a lay person can understand. Don't let the disciplinary boundaries stop you from exploring questions that matter and collaborating with other young researchers when appropriate. Respect all forms of knowledge. Don't blindly go after the next hot tool, or software, or algorithm; match the tool to the question. Finally, communicate your results clearly and constantly to diverse audiences. If your parents or friends can't understand your findings, then the local politician will not either. Interdisciplinary, problem driven research that answers salient questions of interest to society is publishable and will eventually lead to career success. Most importantly, it is the only way to address the looming water crisis.

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