Managing River Basins with Thinking Machines

Dedicated to the loving memory of Prof. Masood Ahmed (1959-2007), for showing me how to control chaos, both in machines and in life.

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***Abstract*—** This paper analyzes the onset of cybernetic revolutions such as smart infrastructures, agricultural robotics and information automation for the management of water resources. Large basins such as those of the rivers Indus, Ganges, Amazon, Brahmaputra, Nile and Mekong constitute the backbone of agrarian and developing economies. Such river basins are extremely complex systems of systems. The complexity is not only due to the intricate interplay of physical elements but also because of human behavior at multiple levels. Interacting components of these systems are prone to many types of uncertainties and variability, such as climate change impacts and demographic changes. It is increasingly being realized that many of the technical and institutional challenges of governance are really problems of scales, such as the inability to monitor and maintain geographically extensive infrastructures; the inability to collect information, reconfigure and react within short time spans and the inability to scale-up human expertise across institutions. The author shares experiences of research, development and field work in robotics and cyber physical systems for water management in the Indus basin as case studies to develop a general philosophy of scaling-up solutions to solve the various governance challenges. Thus we outline the promise of a *smart water grid* -- an internet inspired, tightly connected cyber-physical-social network of data collection systems, automated responder units, and decision support systems to address challenges in transparency, equity, devolution and variability in the basin.

Keywords*— *Large Scale Complex Systems; Social Impacts of Automation; Human-Natural Systems; Cyber-Physical-Social Systems; Hydro-informatics; Precision Agriculture.

I. INTRODUCTION

River basins around the world are facing rapid large-scale environmental changes brought about by natural forces unleashed by climate change; historical forces driven by social, political and demographic changes; and global transitions triggered by new technologies. The impact of these changes is felt most in the water sector in poor management of irrigation networks, depleting groundwater, deterioration in water quality, poor sanitation and difficulties in preservation of eco-systems [1][2]. In this paper, the challenges and opportunities related to taking care of river basins by means of cybernetics and ICT inspired technologies have been outlined. We make the case that this discussion inspires deeper thinking about the role of intelligence and information in meeting the grand challenges of human sustainability. River basins in the developing world pose a particularly unique and important class of sustainability problems. The advent of cybernetics technologies in water management inspire new ways of thinking about basin management and in turn enrich the fields of systems theory by providing a great test-bed for cyber-physical-social systems. The paper is organized as follows. The complexity of river basins is underlined first to motivate the need for cybernetics solutions for their management (Section II). Next, the grand challenges of river basin management are outlined and the importance of information in overcoming those challenges is discussed (Section III). The vision of a *smart water grid* is then given towards practical realization of information usage to solve various challenges. Two specific examples from the author's research experience are given to clarify this vision (Section IV). Finally, the hopes and apprehensions of information automation for river basins of the developing world are discussed along with the grand scientific challenge of incorporating human behavior in cyber-physical-social systems inspired by water problems.

II. RIVER BASINS AS COMPLEX SYSTEMS OF SYSTEMS

A. Physical Complexity

A river Basin is an extremely complex system of systems. As one thinks about managing the water resources in the basin for the benefit of the society, one normally pictures a *physical* water grid driven by a complex interplay of its geophysical elements: silt, salt and water. Engineers and scientists concerned with harnessing water as a natural resource, consider a river basin in terms of its hydrology such as rivers, lakes, glaciers, aquifers [3]. Therefore, they engineer solutions for water resource management in terms of physical infrastructures such as canals, barrages, reservoirs, pumps and treatment plants. The physical water grid itself is an immensely complex system. To give some idea, only one aspect of managing surface water in the Indus river basin (with 50% of the basin in Pakistan), namely the diversion of flows from five major rivers has resulted in setting up the world's largest contiguous irrigation network with over 90,000 km of watercourses, 23 barrages and 45 canal commands irrigating over 45 million acres of agricultural land in Pakistan [4]. The irrigation network (See Fig 2.) is a marvelous feat of 19^{th} and 20^{th} century civil engineering that has provides food security, GDP (25%), revenue via exports (70%) and livelihood (50%) to a nation of over 200 million for several decades. The irrigation network is tied to other complex subsystems of the physical grid. The source is an extremely complex mountainous glacial system whose hydrology is poorly understood even to this day [5]. Beneath the surface is an aquifer covering northwestern India and almost all of Pakistan, from which tens of thousands of tube-wells pump water to make-up for irrigation and industrial usage in an arid landscape. The basin drains into the Arabian Sea with extremely variable seasonable flow (swinging between drought like conditions and floods within a year) and complex dynamics related to seawater intrusion [4].

B. *Socio-Economic Complexity*

The physical water grid is however only one perspective for appreciating a river basin complexity. An alternative and even more complicated picture emerges when one prefers to look at human interactions with the physical water grid. Refer to Fig. 1, as a model for that alternative. The river basin can be understood as a complex historical and cultural process in continuous evolution [6]. The basin is no longer defined by its hydraulics but by the people whose livelihood on a ubiquitous entity in nature and society. This allows us to review the aforementioned engineering feats of irrigation canal networks and large reservoirs as projects of conflict or cooperation, imperialism or social change [7]. The physical interaction circuits are completed by feedback loops with regulatory institutions, treaties, culture, values and beliefs.[1]

A basin manager's job therefore is not just to maintain set-points of certain physical variables. The liters and cusecs of the system need to be given economic value, to justify service to seemingly non-productive usages such as aquatic ecosystems. They also need to be examined in the light of legal treaties, where liters and cusecs become water rights and public trusts. Even beyond this, the aesthetic and cultural value of water in certain situations is beyond economic value or physical quantification. The basin manager therefore not only tries to solve a complex optimization problem for physical and economic variables but is also required to satisfy constraints imposed by treaties, institutional code of cooperation and cultural norms. The uncertainties in correctly formulating a cost function (be it measured in cusecs, dollars or cultural correctness) can be physical or otherwise. While the physical variability can be a complex phenomenon such as climate change effects or the onset of droughts and floods, the non-physical uncertainties manifests in even more complex ways as political uncertainty, conflict and even war [8].

C. *Towards Cyber-Physical-Social Systems*

These considerations allow us to think of the river basins as extremely challenging examples of complexity. The appreciation of this complexity allows us to graduate from thinking of river basins as mere food production economies on a physical water grid -- a modern 19th century perspective -- to providers of livelihood and sustainability in a socio-economic grid, which is a postmodern 20th century *water management* perspective [8]. We will now make the case that the advent of cybernetics or Information & Communication Technologies (ICT) add another dimension to this complexity which allows us to further graduate to the concept of river basins as *cyber-physical-social systems* or as 21st century *smart water grids*. While this adds structural complexity to the system, it also holds great promises to manage the demons of complexity and uncertainty in unprecedented ways. We will also see that the ability to measure, compute and manipulate a basin at hitherto impossible scales allows us to propose new philosophical frameworks for looking at river basins as *sentient* cultural and historical organisms with the ability to nurse, sustain, heal and reflect on its elements.

Figure 1. A Moghal-era water garden in Pakistan (Shalimar garden, Lahore) . In addition to a physical perspective, complex river basins can be seen in a cultural and historial perspective.

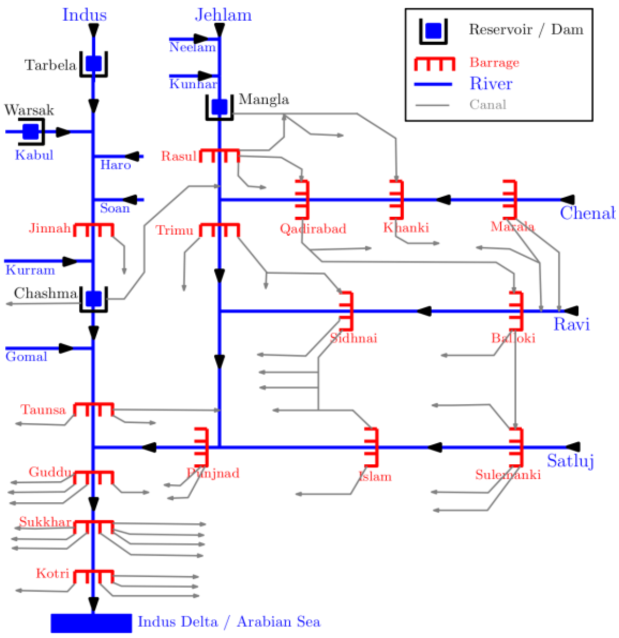

Figure 2. The world's largest contiguous irrigation canal network, in the Indus.

[1] M. Gorbachev has reflected on water in a most remarkable way: "*Like religion and ideology, water has the power to move millions of people… People move to settle close to it. People move when there is too little of it. People move when there is too much of it. People journey down it. People write, sing and dance about it. People fight over it. And all people, everywhere and every day, need it*." *Civilization Magazine of the US Library of Congress*, Oct 2000.

III. Data-Driven Governance of River Basins

A. Governance Practices and Institutional Challenges

The governance challenges faced by river basin managers can be catalogued in alternative ways. Using the prevalent perspectives of water researchers, the challenges are listed topically as irrigation efficiency, urban water quality, ground-water management etc. Focusing in particular on the Indus basin (and noting that issues for other basins are very similar), experts have listed three main themes [4] that cut across such topical challenges:

1) Equity:

Entitlements are defined either by legislation or via treaties and accords at trans-boundary, national, provincial, regional or farm levels. Beneficiaries require both ethical frameworks and scientific evidence to support legal claims or to negotiate equitable positions in a treaty.

2) Devolution:

Driven by the desire to involve all stakeholders and end-users in decision making as well as constitutional developments that devolve power to lower levels, there is a dire need to enable decision making bodies of smaller capabilities to analyze scientific data and implement decisions.

3) Transparency:

Once entitlements are sanctioned and decisions made, any deviations, misappropriations, conflicting claims or systemic failures need to be analyzed for past and future scenarios. Thus tools for ensuring accountability and conflict resolution are required.

Solutions to these grand challenges require both technical solutions in the form of physical infrastructures and technologies as well as institutional setups to regulate human behavior. However, the extents of the problems are so large that most attempts in setting up physical or institutional structures quickly crumble under the exponential growth of scales.

B. A Problem of Scales and Information Automation

In work done recently by the author, it has become apparent that many of the technical and institutional challenges are really problems of scales, particularly:

1) Spatial scales:

The inability to monitor and maintain geographically extent infrastructures (e.g. the world's largest contiguous irrigation network running over tens of thousands of km of open channels)

2) Time scales:

The inability to collect information, reconfigure, and react within short time spans (e.g. irrigation rosters issued once in a cropping season despite the fact that water demand and supply varies over much shorter time spans)

3) Human scales:

The inability to scale human expertise across institutions (e.g. compare the resources and responsibilities of a local farmer organization with that of a federal agency.)

The only technology that can match such explosion in problem dimensions by an exponential scaling up of solutions is information based automation or *cybernetics*. Whether manipulated by humans or machines, information has the potential to become a key component of the system, at par with the physical elements manipulated by other machines and mechanisms.

There has been great interest in introducing such automations in the water sector and a discipline by the name of *hydroinformatics* caters to the role of information technology in water resources research [9]. However, engineers, computer scientists and systems analysts must pay attention to understanding these issues more deeply. *Digitlization* as understood in today's agriculture and water sectors is only a primitive step in deploying information automations. Towards this goal, a dictionary must be developed (see Table 1) between basin managers and scientists on the following translations between various governance challenges and ICT enabled solutions [2].

Table 1. A governance-to-cybernetics dictionary for river basins.

Requirements on tackling	translate to cybernetics (ICT) solutions in
rapid changes	real-time ubiquitous sensing and data collection systems.
large-scale uncertainties	analysis of large data sets, models for complex systems.
institutional reforms	new architectures for decision support.
enforcement of entitlements	monitoring and control technologies.
accountability and conflict resolution	data preservation and dissemination.

A framework given in the schematic of Fig 3 captures the above considerations at two levels. First, the use of hydro-informatics technologies to generate data, invent methods and deploy machines for understanding key topical problems in river basin management. Monitoring, modeling and control technologies are of central importance. At a second level, there is the promise of using systems theory and data analytics to derive or compare policies, technology interventions and institutional reforms. Innovations in algorithms and architectures are common in both aspects of this framework.

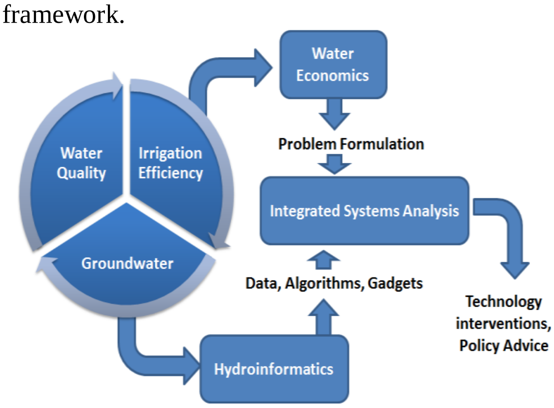

Figure 3. A framework for data driven governance of river basins.

IV. The Promise of a Smart Water Grid

A. An IoT / CPS Perspective

In order to meet the technical challenges of scaling time, space and expertise in a problem as complex as water, *cybernetics* based solutions hold the key. An internet inspired system, envisioned as a tightly connected network of sensors, automated actors and local decision support systems may address problems of large scales, provide services amidst the general breakdown of governance structures and uphold entitlements and accountability. This is the vision of an ICT inspired *Smart water grid*.

Specific problems that a smart water grid proposes to solve, include increases in water distribution efficiency, demand based water delivery, control of nontechnical losses, detection of leaks or breaches, system health monitoring, flood control, real-time scheduling and planning .

Three cybernetics based technology areas have received priority in setting up such smart infrastructures. First, the development of ultra-cheap, robust and non-invasive sensory data collection networks for real-time monitoring of water resources. This fits well in the *wireless sensor networks* (WSN) or *Internet of Things* (IoT). Second, the development of decision support tools for analyzing sensor data, surveys and scenario forecasts. This falls under the category of *large-scale optimization*, *integrated systems analysis* and *big data analytics*. Third, the capability to intervene in a distributed and pervasive manner to manipulate physical variables with the help of information. The fields of *cyber-physical systems (CPS)*, *robotics* and *smart infrastructures* fall under this category of solutions.

The CPS paradigm is especially pertinent for setting up smart water girds in river basins (See Fig 4). The *physical* elements of a river basin may contain both natural and man-made components including rivers, watercourses, barrages, weirs, gates, pumps. The *cyber* elements of a smart water grid would include sensors, controllers, communication networks, and autonomic software services. A true river basin-level cyber physical system does not exist at the scale mentioned in previous sections. However, if conceived such CPS would make excellent test-beds for testing algorithms and architectures in distributed control, optimization, data analytics and general systems theory.

Control engineering technologies lead the way in setting up such cyber physical systems. There exists a vast body of literature on modeling the flow of water in open channels and controlling water levels in an irrigation canal network using methods of feedback control [16][17]. An exhaustive survey of control technologies in water resources is beyond the scope of this article. However, it should be pointed out that various low-level control theoretic problems have been addressed and solved by researchers related to modeling and controller design [19] covering issues of decentralization [17][18], security [16] and practical implementation issues [19]. In the context of Indus river basin, the author's group

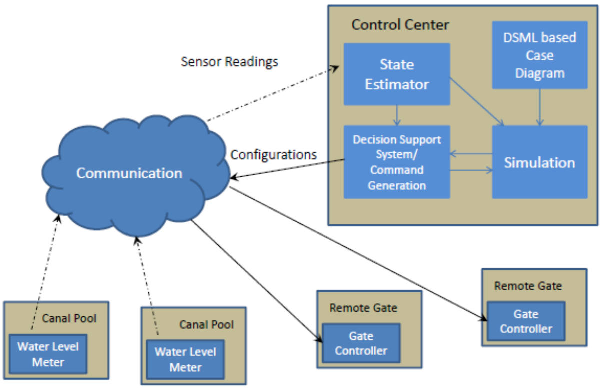

Figure 4. Smart water grids as cyber-physical systems [14].

has conducted a series of studies to determine the feasibility of a fully automated CPS [10][11][12][13][14][15].

This is a very promising start in the direction of realizing full basin level CPS covering many other hydrological variables and enabling solution to more complex problems than physical regulation.

B. Smart Water Girds in Developing World Settings

One thing to note about the CPS / IoT paradigms summarized in the previous section is that they are primarily engineered to improve upon the operation of developed world physical infrastructures. Developing countries have their own set of unique challenges (refer to our discussion on scales above) that dictate the deployment of large-scale cyber physical systems in other ways. For water resources, in particular, such CPS based solutions must demonstrate:

1. Applicability to geographically extent networks.
2. Design and testing in low-cost (preferably virtual) laboratory settings.
3. Decentralization to allow flexibility in governance and scalability.
4. Fitness for unreliable energy and communication infrastructures.

Two examples from the author's research group are given below that demonstrate the unique challenges and opportunities of working with CPS based solutions for water in a developing world setting.

1) Low-power Hydrometry of Canal Flows

In the context of irrigation networks and water resources in general, telemetry systems and hydrological observatories are of great interest to relay real-time information to decision support systems or water managers. In a recent work, we have focuses on automating the hourly-to-daily measurement of canal water discharges at the level of distributary and branch canals of irrigation networks in the Indus. It is important to understand the scale and hierarchy of such networks (Fig. 2) to appreciate the relevance of this work as compared with previous research in irrigation automation. Measuring flows in open channels is one of the most critical requirements of automation in the Indus basin due to the following reasons. First, the scale of such measurements, even at a local canal command is very large.

The scale enormity when combined with the manual nature of daily flow measurements poses obvious logistical problems in data collection, dissemination and interpretation. Second, the fidelity of manual measurements is questionable due to deteriorating infrastructure and human factors in gauge reading. Third, there is a need to give near real-time picture to basin managers (the provincial irrigation departments, area water boards, farmer organizations) to perform situation assessment and planning, resolve conflicts, ensure transparency and maintain equity amongst users. The manual operation allows no quicker than daily updates. Lastly, automated flow measurements will be the first step towards installing even higher levels of automation such as controlled gates and other active structures.

Keeping in mind these motivations, we have developed a fully functional, field deployable, stand alone and weather proof canal flow measurement system [12][13]. The design is inspired from wireless sensor network (WSN) technology and most suitable for installation on branch canals and distributaries at irrigation canal networks of the Indus river basin. A high level diagram of the proposed automation is shown in Fig. 4. A stilling well is constructed in close proximity to the canal. At the top of the stilling well is installed a battery powered wireless sensor node that samples the level of water using the principle of ultrasonic distance measurement. The measured water level is time-stamped and then transmitted to a central office at regular intervals using GPRS/GSM based services. Here, a computer server receives the raw water level data, calibrate them, convert them into discharge (in cubic feet per second, cfs) using a predefined rating curve and then file them in a database. Subsequently, the data is made available for dissemination in the form of graphs, time series and text using various standard web and mobile based services.

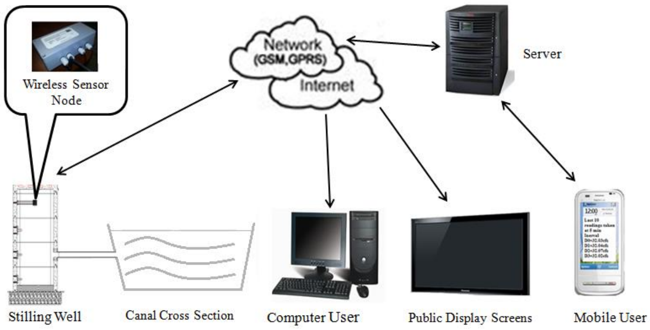

Figure. 4. Overview of a hydrometry network for canal flow measurement.

Such a technology helps the three pillars of governance, namely equity, transparency and devolution all at once. The data recorded from the sensors have helped us analyze the fairness in water distribution across all channels of the network. The data is disseminated in real-time to farmers, irrigation officials and the general public providing openness and transparency to canal operation. Lastly, such low-cost sensor networks enable local farmer organizations to manage the irrigation network by themselves, encouraging devolution of power and providing the needed scientific support.

C. Aerial Robots for Inspection of Siltation in Waterways

We now provide a second example of thinking machines in the service of a river basin to enable a smart water grid. Silt accumulation and sedimentation in canal beds leads to deterioration of watercourses over time. Every year a forced closure of the canals in the Indus basin is inevitable for canal cleaning, entailing a very large scale and costly operation. Silt removal precision is prone to inefficiencies due to subjective decision making in the cleaning process. In a recent work [10], we have mapped the semi-structured (emptied) canal bed terrains with an Unmanned Aerial Vehicle (UAV) system for quantitative inspection of deposited silt. As mentioned above, the motivation for our work comes from a desire to map the vast irrigation canal network in the Indus basin running tens of thousands of kilometers. The author's group has developed a semi-autonomous robotic profiling system to increase the efficiency of this process. It consists of a 3D perception system, deployed on board an aerial robot to assist the human operator in cleaning the canal effectively. Technical challenges in deploying such a system involve precise localization, accurate mapping, autonomous navigation and systems engineering of the aerial system. The system envisages efficient cost effective cleaning, reduced water discharge variability, and enhanced agricultural productivity.

While the technology used in this project is standard robotics, the lessons are very general. Once again a cybernetics technology demonstrates how to scale complex operations. While it was not possible to measure siltation in hundreds of channels using manual inspections, this technology allows us to scale space (the large geographical extent), time (ability to finish the task within the tight canal closure period) and expertise (ability to measure precisely and accurately with minimal human intervention). It also helps the three pillars of river basin governance (transparency, devolution and devolution) along the same lines as the canal telemetry network examples cited above. These examples collectively demonstrate the potential of a cyber-physical systems approach towards river basin management and the ability to match explosions in problem complexity with appropriate interventions. This indeed is the promise of a smart water grid for these river basin dependent developing countries.

V. THE WAY FORWARD – LEARNING FROM WIENER

"*The thought of every age is reflected in its technique*," wrote Norbert Wiener [20] -- a pioneer, mathematician, engineer and philosopher of cybernetics in the mid 20th century. Wiener was excited about the endless possibilities for his new science of cybernetics and control. But like Goethe, the sorcerer was mindful of his apprentices[2]. He foresaw unpredictable results in mindless automation.

[2] J. W. von Goethe, *Der Zauberlehrling*.

Wiener specifically warned about extending the tools of cybernetics to socio-economic systems and beyond.

In developing countries like Pakistan, reducing or replacing the human factor in a system via automation would invariably result in unwanted or unintended distortions associated with social engineering [21]. Therefore, cybernetic solutions must be generated and thought out carefully in consultation with stakeholders. In previous sections, we pointed out the socio-economic and cultural aspects of river basins. Unfortunately, sensors networks and aerial robotics do not speak the language of sociology. But there is both a great need and a desire to look at such large scale systems as cyber-physical-social systems. Hence the need to incorporate human behavior in system theoretic frameworks. This is easier said than done since the language to incorporate sociological factors in cyber-physical systems does not exist yet.

It is interesting to compare and contrast the current views of introvert cybernetics and extrovert ideas of sustainable development for water. When we take a cybernetic view of machines, it also allows one to ponder on the miracle of life, even from the limited mechanistic perspective just as measuring cusecs connects us to civilization. There are fantastic parallels and common implications. In some sense, the inner reflective viewpoint of robotics complements and completes the outer pragmatic viewpoint of sustainable development. As long as we view humans as machines mechanically connected in society, we will continue to treat sustainability problems in a similarly incomplete way.

Going forward, there will be a realization that complex societal problem like water need wholesome multidisciplinary approaches. Human factors are a source of incompleteness in our models that must be freely admitted, embraced and incorporated. When we are able to crack this problem, will also say something profound about man, mind and machines, their relation to society and why life can’t be just a purposeless swim against the entropic arrow of time. As Wiener would say, *it will be the thought of a new age and will be reflected in its technique*.

VI. CONCLUSIONS

It has been argued that river basins, when equipped with smart infrastructures, are complex cyber-physical-social systems with a unique set of CPS problems and IoT inspired solutions. Water problems can inspire a range of ICT inspired systems engineering, informatics and systems analysis solutions that challenge the state of art in both theory and practice. Our work for managing irrigation networks in the Indus inspires interesting problems with an important and unique socio-economic context for developing countries like Pakistan. Scalable cybernetics technologies are the key to making complex decision support systems. There is both a need and a market for it.

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