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The intrinsic cybernetics of large complex systems and how droughts turn into floods

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Abstract

The cyber-physical nature of engineering systems requires the smooth integration of decision making across soft and hard infrastructure. This need is common to any systems where decision making considers multiple complex systems such as the climate, the natural and built environment, and the dynamics of large organisations.As an example, in the Anthropocene, acute droughts and floods cannot only be imputed to more extreme variations of the climate patterns, but also to the alteration of the habitable environment and of the resources that support it, hence to their governance and management. In this discussion paper we present arguments about the extent to which the natural environment is modified to support urbanisation. We expose the cyber-physical nature of large infrastructure systems taking as an example the events of the 2011 Brisbane flood and the operations of the damming system of the river Brisbane. Using literature resources and data, we show how flood defence devices had to provide for a population of almost 2 million people, while being engineered when the population was less than one million, with increase in water withdrawal mainly due to residential utilities. We show how the cyber-physical aspects of the problem materialised in moth-long delays in the governance and management structure and made the flood event transcend the boundary of a purely climatic or engineering incident. Looking beyond the Brisbane example, our conclusions point at overcoming the discontinuity between operation, management and political layers when operating on cyber-physical systems such as freshwater networks.

Keywords: systemic resilience, cybernetics, water security, Brisbane flood

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1. Introduction, objectives and contributions of this work

With the term cyber-physical systems, the scientific community often refers to those systems where the physical components are strongly coupled with their monitoring and control systems. If we consider that monitoring and control are often means for human supervision, then we can reconnect cyber-physical systems with their etymological roots. Norbert Wiener defined *cybernetics* as the study of control and communication in animals and machines [1] gaining him a parental status in the discipline. In fact, a century before Wiener, the word *cybernétique* was used by Ampère to indicate to the science of civil government [2].

Regardless of which definition of cyber-physical systems is considered, it is easy to see how critical pieces of infrastructure, including dams or power plants, belong to such a group. They may be conceptually simple, but when single pieces of infrastructures are considered in the wider context of their complex environment and interactions, they become complex themselves. Complex infrastructure assets are not just monitored and operated through ingenious pieces of control engineering. Environmental interactions as well as human supervision and management always play a determinant role.

In this discussion paper, by analysing the operations and failures of one of such complex infrastructure systems, we show how the complexity is reflected in different control layers, from operations to governance and how this layered structure is ubiquitous in large complex infrastructure systems.

The main objective of our work is presenting an angle of analysis that transcends the nature of the specific infrastructure system, being this a water supply network, a road system or any other kind. Secondly, our discussion sets the new angle on the background of previous research, with the objective to show that specific, detailed analysis of specific infrastructure are not in contrast with it. We do so by looking at the emblematic case of the freshwater system in the Brisbane river basin and the events leading to the 2011 Brisbane flood.

We achieve our objective by analysing historic data, relevant literature and some official documentation, conciliating our angle with the literature which studied the specific aspects of the events. This approach contributes elements to our discussion, leading to novel conclusions.

Our work contributes to knowledge by presenting an original, system-wide, angle of analysis, which puts under new lights the chain of events leading to the 2011 Brisbane flood. Such an analysis casts the Brisbane events into a more general problem of governance and management of complex cyber-physical systems, to which large infrastructures belong.

This paper is organised as follows. In section 2, background to the problem of complex socio technical system governance is provided with particular attention to freshwater systems. Sections 3 and 4 analyse the emblematic case of the 2011 Brisbane floods before the discussion in section 5 reconnects the analysis of the specific example to the general problem of cybernetics and complex systems governance. Finally, the conclusions summarise the main points of this work.

2. Background

2.1. Infrastructures and fresh water systems in the Anthropocene

Worldwide, both urbanised areas and the population living in it have experienced a continuous growth. Projections would see the current 4.2Bn people living in cities surging to 6.6Bn by 2050, more than 2/3 of the global population [3, 4]. In cities, where a large demographic growth is taking place, it will be increasingly more difficult to satisfy the residents' demand for freshwater while preserving the functional state of ecosystems. This puts water security under threat, with climate change exacerbating the problem [5].

It is now accepted that climate change will impact both droughts and flood occurrence [6, 7, 8]. However, extreme weather events only account for some of the pressures under which water infrastructures operate, albeit representing the main source of exogenous pressure. The growing demands from wider and more populated urban areas can be considered as the endogenous stresses to which water infrastructures are subject. Yet, at the same time, they are the reason for commissioning such infrastructures.

Water security encompasses both aspects of water provision and defence from floods [9]. Within limited natural and economic resources, having a single reservoir to provide for both require such a reservoir to be both full and empty at the same time. In practical terms, rather than how big a reservoir is, it becomes more important to know how much spare capacity it has, beyond the need for water provision, to mitigate the impact of intense precipitation. The same could be said about energy or transport capacity as they would be asked to provide for the increasingly frequent and sharper peaks of demand.

In fact, water shortages and floods are closely related and often areas which are prone to one, are also subject to the other [10]. Excess precipitations, which would normally be associated to flood events, can be linked to drought as well, and vice-versa [11]. Hess et al. [12] highlighted the mechanisms by which increased precipitations can threaten water security supporting their findings through a hydrological analysis. While a lack of datasets and analytical tools may prevent a full investigation of this [13], detrimental feedback can be identified that involve relying on reservoirs to mitigate water shortages. Two of these are

- the spiralling up of the supply–demand cycle, where increasing water supply enables the development of economical activities and urbanisation relying on freshwater supplies [14] and
- the *reservoir effect* [13], by which the perceived water security given by the presence of water reservoirs disincentives parallel adaptation actions. This means that the reservoir needed for everyday life as opposed to a device meant for mitigating exceptional droughts and/or provide buffer for floods.

Clearly, how cities develop impacts their infrastructures, and vice-versa. This has been part on the debate of densification [15, 16, 17] and land cover in the urban fabric [18], which could easily change the ranking of the factors affecting flood vulnerability [19]. Once again, climate change exacerbates the effects of urbanisation on the depletion of natural resources and the decline of natural ecosystems, through increased and more variable demands for energy, food and water.

While infrastructure planning has a timescale of decades, ensuring access to resources, and to water in particular, involves processes that develop over months to years. Meanwhile the decisions and actions delivering flood defence and mitigation happen in days or even hours. Yet, the ability to mitigate floods and ensuring freshwater supply is recognised to be one of the focusses that should drive planning [20, 21]. This bonds together three delicate dynamics on very different timescales.

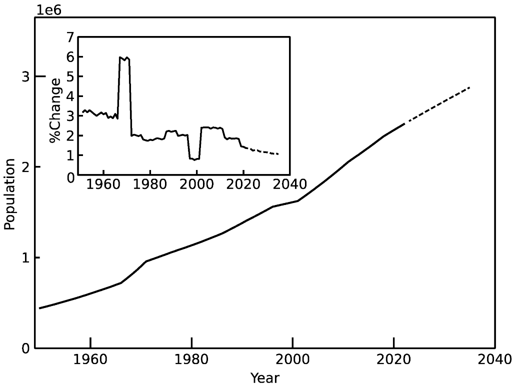

Figure 1: Population growth and percentage growth rate (inset) in Brisbane from 1950, with projections up to 2035. Data from [26]

2.2. An emblematic case

Consider the case of Brisbane, where the last 50 years of urban development are a dramatic example of urban expansion. In this time, the population grew on average 2% annually, more than doubling the population in 1972 (Figure 1). The consequent increase in the built up area, which between 1991 and 2001 swallowed one fifth of the available land, mainly concentrated in the suburbs where flat land was abundant and was not always accompanied by policy interventions aimed at making such developments sustainable [22]. The arguments about densification have traditionally pivoted around economic performance (see for example [23, 24] and [25, pp.223-244]). However, in the context of the Brisbane river and South-East Australia, the economic drive to densification is strengthen by ecological rationales. In practice, urban expansion happened in the flat, low-lying areas, does not just contrast with the current economic understanding of productive cities, but also represents a liability in terms of flood defence and a missed opportunity for dedicated recreational use or ecological conservation.

When these problems first became apparent in the wake of the 1973-74 Queensland flood, the ”engineering” solution was the first and only one identified. It materialised in damming the Brisbane river, and so creating lake Wivenhoe. Despite taking almost ten years to complete, the design capacity to mitigate floods showed its limits already in 2001 [27, 28]. The “engineering first” approach was not just of little effectiveness, but could in

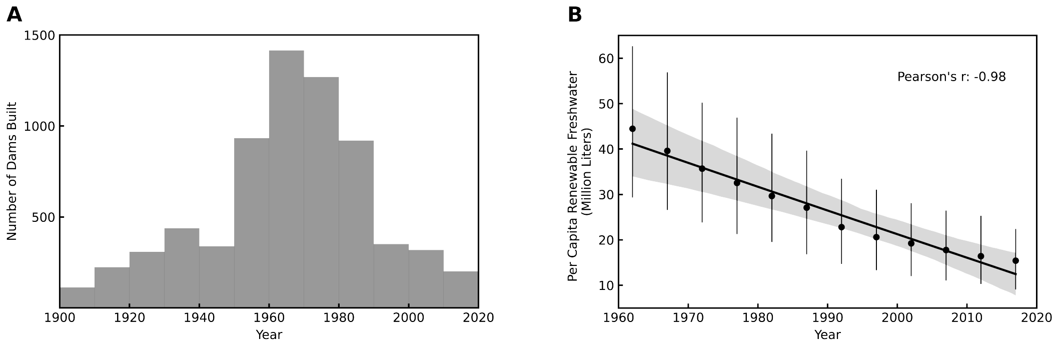

Figure 2: Number of dams built across the world (A) and per capita water availability for 155 countries showing mean and 95% CI at 5-year intervals from 1962 (B). Data from `http://globaldamwatch.org`, `data.worldbank.org`

fact act as a flood effect amplifier. This was not an isolated occurrence. In the second part of the 20^{th} century, the building of new engineered assets was identified as the solution to water security problems. This translated in increasingly higher numbers of water infrastructure, and in particular dams, being built across the world [29] (Figure 2A), while the per-capita fresh-water availability kept on declining (Figure 2B).

The extended timescale which water security is concerned with would have left room to more holistic approaches in the Brisbane flood. For example, in the long term, the opportunity was missed for keeping low altitude areas for recreational use as opposed to residential or economically productive neighbourhoods. In the medium term, contingency plans and communication strategies were hardly defined as the urban fabric evolved [30]. Finally, short term actions, such as increase awareness of the impact of dams were not taken to prepare the population for the disruptions from possible floods [31]. While the literature dissected the events leading to the 2011 Brisbane flood, looking at responsibilities and the events cascading in time, yet we were not able to find previous connections between the specific case and the more general problem of complex systems management and governance. This missing link is the gap we address here.

Starting from these considerations in relation to the Brisbane flood and the support these have in the literature, we provide arguments in support of 2 main points which highlight ubiquitous dynamics across different complex cyber-physical systems, achieving our objective:

1. The 2011 Brisbane flood can be mapped to a cyber-physical system failure, one that transcends the physical water infrastructure and involves the human-modified ecological balance in the region, the management of the urban expansion, the biased perception of the Wivenhoe reservoir and its management in the urban context, at different levels [28].
2. The example coming from the water infrastructure management can be generalised to any large artefact able to shift the balance of the natural environment ans well as its perception by inhabitants and decision makers.

We will show how water security strategies, where in place, were fragmented across different control layers, and often conflicting. We note how this structure is rather ubiquitous in the management of large infrastructure which, starting as engineering assets, become cyber-physical systems, as Ampère would intend them. By doing so, we add a new dimension of analysis which looks at the lack of synchronisation between the three layers of control over the Wivenhoe dam that were in place during the 2011 Brisbane flood, namely the governance, management and operation levels. We argue that these three control levels, or layers, are ubiquitous in complex cyber-physical systems.

3. The 2011 Brisbane flood

The climate in the city of Brisbane (Queensland, Australia) is affected by the alternated patterns of 'El Niño' and 'La Niña' phenomena, bringing decade-long cycles of droughts broken by months of torrential rain [32]. As such, it has a long history of flood events, with records dating back to 1841 [33]. The 1974 flood, recorded a gauge height[1] of 5.45m and triggered political decisions culminating in the creation of lake Wivenhoe by damming the Brisbane river, downstream from the Somerset lake. Downstream from lake Wivenhoe, the Brisbane and Bremer river merge at Ipswich to flow through the city of Brisbane and to the estuary. Despite the scale of the project, the flood mitigation provided by the Wivenhoe Dam revealed insufficient to avoid both the 1995-96 and the January 2011 flood, causing damage in excess of AU$2.55BN [34].

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[1] The height of the water at a specific location. In this case, it refers to the Brisbane Port Gauge

Officially, the 2011 flood event was dated 13 January, as this corresponds to the time the second highest flood in Brisbane in the past 35 years was recorded. Although exacerbated by a preceding month of heavy rain, the actual trigger was started further back in the past. Wivenhoe Dam was designed to ensure water security both against floods in the wet season and droughts in the dry season. It is operated by Seqwater in a coordinated manner with the North Pine reservoir and the Somerset lake, North from the Wivenhoe lake (see Figure 3A). In particular, close coordination is needed in operating the Somerset and Wivenhoe dams as the former feeds the latter, so their filling strategy is such that any increase of inflow or outflow is distributed between the two reservoirs, the levels of which rise or decrease consistently. Nominally, all these reservoirs feature spare capacity above the 100% Full Supply Volume (FSV) [2] , albeit the North Pine dam's flood mitigation compartment is only 0.5% above FSV, leaving the onus on the Somerset and Wivenhoe reservoirs. Levels and volumes for the three reservoirs are summarised in Table 1.

The first decade of 2000 saw the most severe region's drought ever recorded [35], which reflected in constantly low levels of the water reservoirs (Figure 4A). This is remembered as the Millennium Drought. The long observed 'El Niño/La Niña' patterns allowed the Bureau of Meteorology (BOM) to notify the authorities about the possible sudden switch from droughts to exceptional wet conditions in October 2010. The forecast was detailed to the point of mentioning 75% chance of above median rainfall on the Brisbane region in the following 3 months. Despite clear signs of an imminent cyclone season, the levels of Wivenhoe, Somerset and North Pine reservoirs were kept close to full capacity (Figure 4B) leaving only the volumes of the flood compartment to mitigate for the incoming precipitations.

Figure 3C shows a timeline of the events just described, with decision points that are explained next. The weather front crossed the coast North of Brisbane where the first floods peaks were recorded, in the Balonne and Dawson rivers in early December[30].

In the following weeks, the Bremer and the Brisbane rivers experienced

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[2] The full supply volume is the volume of water a reservoir can hold before it start filling the flood mitigation compartment

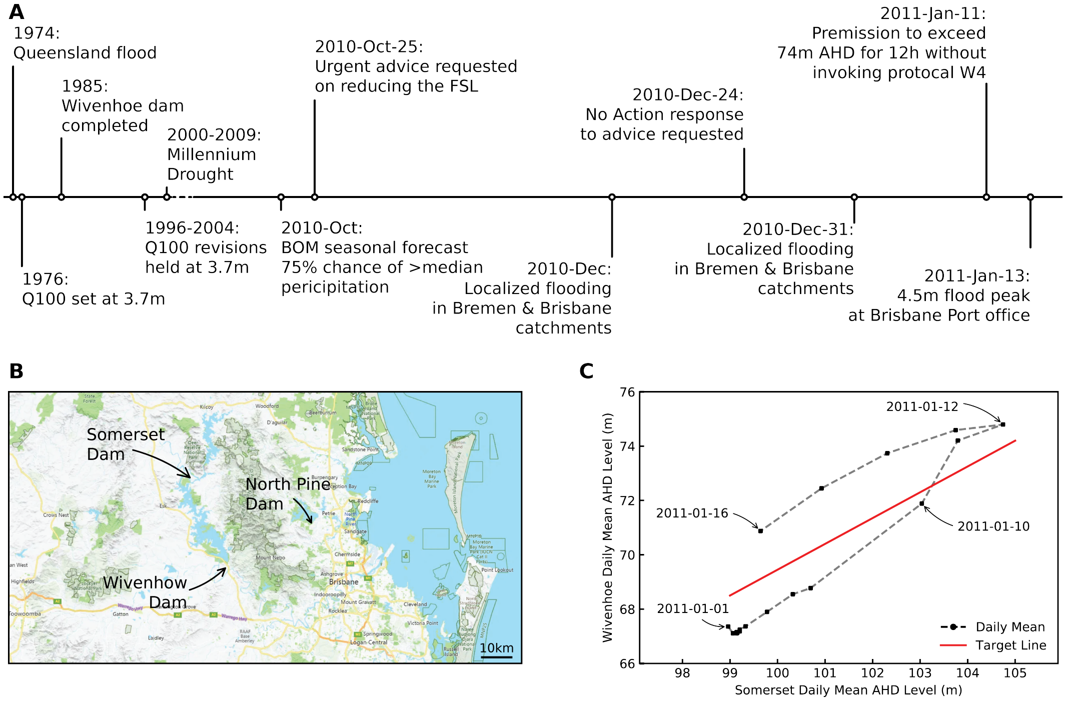

Figure 3: The city of Brisbane and the dams providing for its water security and flood mitigation (A), the target line for the water levels at the Wivenhoe and Somerset dams (B) and timeline of events from the 1974 Queensland flood to the 2011 Brisbane flood (C). Data from the Australian Bureau of Meteorology `http://www.bom.gov.au/water/index.shtml`.

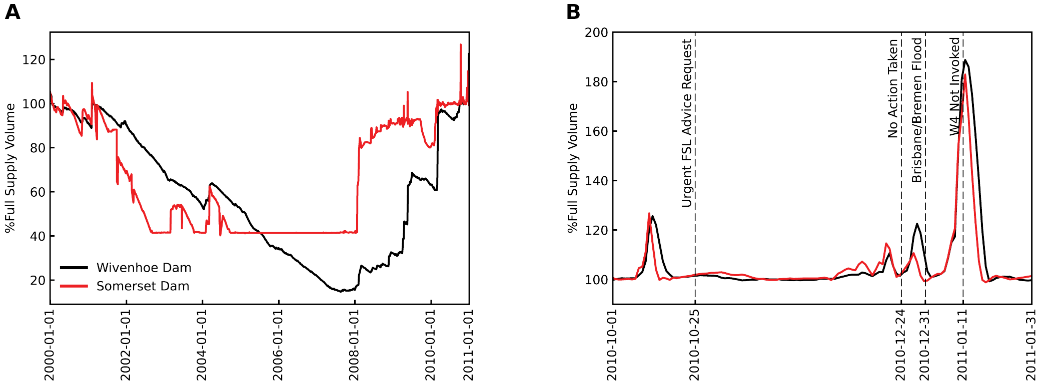

Figure 4: Water level at the Somerset and Wivenhoe dams throughout the Millennium Drought (A) and in the months before and after the January 2011 floods (B). Data from Australian Bureau of Meteorology `http://www.bom.gov.au/water/index.shtml`

Table 1: Characteristics of the dams in the immediate vicinity of Brisbane. The split between water supply and flood compartments refer to the OFSL. Capacity is in million litres (ML). The level, is indicated as EL and is reported in reference to the AHD [36].

	Full Supply Volume	**Flood Compartment**	**Notes**
Wivenhoe	1,051,000ML for current OFSL (EL 65.9m AHD).	2,080,000ML between EL 65.9m AHD and EL 80.0m AHD.	Controlled release through radial gates, sluice gates and fuse plugs as safety devices
Somerset	303,000ML for current OFSL (EL 97.0m AHD).	705,000ML between EL 97.0m AHD and EL 108.7m AHD.	Controlled release through cone valves, sluice gates and crest gates. The outflow feeds into the Wivenhoe lake
North Pine	214,302ML full supply level, is 39.6m AHD	1,000ML between 39.6m and 39.65m AHD.	Not linked to Somerset and Wivenhoe.

localised floods too. However, the official start for the 2011 Brisbane flood main event was not until 6 January 2011. Within a week, 15 thousand properties were flooded by the Bremer river at Ipswich and 14 thousand by the Brisbane river in the metropolitan area of Brisbane, with water height reaching 4.45 metres at the Brisbane business district gauge. On the 13 January, Wivenhoe dam operators moved to the so-called strategy W4, consisting of the full opening of the dam's radial gates releasing water. Strategy W4 is in place to preserve the structural integrity of the dam ahead of the water level approaching the fuse plugs [30]. These are fail-safe devices, preserving the structural integrity of the dam against excessive pressure or overtopping. If the water had reached the fuse plugs, the same volumetric release would have happened in an uncontrollable way. Strategy W4 just made this a controlled release.

The coordinated operations of Wivenhoe and Somerset dams along the target line (Figure 3B) made the two reservoirs having empty flood compartments yet being both filled at 100% Full Supply Level (FSL)[3] on 31 December 2010. These correspond to 67m for the Wivenhoe and 99m for the Somerset dam, while fuse plugs are engaged at 75.5m and 109m, respectively.

Anticipating the release of the water, before it reaches the flood plugs, can be triggered by combinations of water level, precipitation forecasts, and other parameters monitored by the dam's operators. In particular, the operation manual states that the water level at Wivenhoe should not exceed 74m above the Australian height datum (AHD) and that opening of the radial gates should not be triggered for flood control, unless the level exceeds 67.25m [37].

As the water level quickly approached 74m threshold, at 21:00 of 11 January 2011, permission was sought from the Dam Safety Regulator to temporarily exceed such a threshold in Wivenhoe Dam for 12 hours, invoking strategy W4, provided that the security of the dam was maintained. The permission was granted but this extreme attempt revealed in vain as strategy W4 was eventually invoked, also pushed by the rise in the Wivenhoe dam level due to the inflow from the Somerset Dam. By that time, Somerset lake was already above the 102 m level, meeting the conditions for which, water had to be released downstream, into the Wivenhoe dam. This happened during the peak of the flood, with devastating consequences. The events on 13 January 2011 concerned severe floods in the catchments of the Lockyer Creek and Bremer River causing the loss of 23 lives in the Lockyer Valley and 18,000 properties flooded in the Brisbane urban area, including Ipswich.

The operation manual allowed for the anticipated opening of the radial gates when the fuse plugs are expected to be reached by the water anyway. Likewise, the manual allowed some discretion to the senior flood engineer on when invoking the strategy.

It comes with no surprise that the Flood Commission concluded that the dam operators took a reasonable course of action, having preserved the structural integrity of both Somerset and Wivenhoe dams [30].

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[3] The height of water in a reservoir at FSV measured at a reference gauge.

4. During, before and long before: exacerbating circumstances, concurring events and seeds.

4.1. Inertia to action

At the time of the 2011 flood, the management of the Wivenhoe, Somerset and North Pine dams was delegated by Seqwater to Sunwater, with an arrangement meant to last to the Summer 2011. The arrangement however appears to have been discontinued in the autumn 2010 and only re-activated in December 2010, with no formal agreement in place from November 2010 to the reactivation date [36].

The discontinuity in the dam management was not an isolated episode of what appeared a systemic reluctance to action, which is even more evident in the lack of decisive actions about the filling levels of Wivenhoe and Somerset Dams.

The official report by the Queensland Flood Inquire commission [30] accounts for the timeline of the communications and decision taken before and during the flood event. An inquiry by the then Minister for Natural Resources, Mines and Energy Stephen Robertson into the possibility of temporarily lowering the full supply level of the three reservoirs, launched in October 2010, shows awareness was present at the highest possible level. In fact, a correspondence dated 25 October 2010 from the minister to the Water Grid Manager sought urgent advice on the matter. An official response was only delivered on 24 December 2010, albeit anticipated through informal briefings. Such a response suggested that a FSL reduction of at least 16% was needed for it to be meaningful. Yet by the time the response arrived, localised floods had already happened following intense precipitations and, on 25 December, category 1 Cyclone Tasha crossed the coast. No action was taken.

The no-action line was only abandoned on 13 February 2021 when Mr Robertson acknowledged Seqwater recommendation to lower Wivenhoe dam's FSL to 75%, following a report requested on 20 January 2011 on the ongoing flood event, which included considerations on the FSL.

4.2. The fallacy of Q100

While often understood as the height of flood water that can be recorded annually with 1% probability, the Annual Exceedance Probability (AEP) indicated by the Q100 is the height of water expected in a flood event that is likely to occur once in 100 years. The Q100 is evaluated at various points in a region for planning purposes and, at the time of the 2011 flood, the Q100 at Brisbane Port Office gauge was set to 3.7m [35]. This was based on the experience of the 1974 flood, although the actual figure was lowered after including the mitigating effects of the Somerset and Wivenhoe dams.

As a fundamental policy item for urban development, setting the Q100's official figures is a policy matter, hence responsibility of the Brisbane City Council (BCC). As such it is influenced by conflicting pressures from different stakeholders groups. These include property owners and developers as well as the general public for which an expansion of the flood zone, where development is not allowed, means increasing the premium on the remaining available space [35]. Such pressures conflict with the need to ensure water security against both floods and droughts.

Years before the 2011 events, this problem had already presented itself. In fact, heavy precipitations in 1996 led the BCC to commission a revision of the Q100.

The first estimate delivered to BCC in 1998 set the Q100 to 5.34m at Brisbane port office gauge. This estimate included the conservative assumption that both the Wivenhoe and Somerset dams were at 100% FSL at the start of the flooding event, which did not satisfy the BCC's Water Resources Manager. Two subsequent iterations of the Q100 estimation process delivered a figure close to 5m, which BCC did not approve. The Q100 was hence left unchanged until 2003, when a special commission was asked for a new estimate to be delivered in 5 weeks, without undertaking any further modelling. The new recommended figures, none higher than 3.51m, left the BCC satisfied that the existing 3.7m figure required no change. Subsequent analyses suggested that the 2003 figure included a flood mitigation capacity from Wivenhoe and Somerset dams available only if the reservoirs were at about 35% and 60%, at the beginning of the flood event, far from their state in December 2010 [35].

These figures were all lower than the 4.45m flood level recorded on 13 January 2011.

The rejections of more conservative estimates of the Q100 may be understood looking at the 10 consecutive years of drought Queensland experienced between 2000 and 2009, remembered as the Millennium Drought [38], accompanied by uninterrupted population growth. Changing the Q100 means, as previously noted, changing the constraints to urban development, which inevitably affects the electorate. In this respect, motivations pivoting around flood risk mitigations would have been difficult to accept and make popular amongst a population living through the Millennium drought. The fallacy of the Q100 is hence rooted in the anomaly of a technical evaluation being guided by political will. To this respect, the Queensland Flood Inquire commission, who noted how "A flood study is a scientific investigation; it involves no matters of policy"[30, pg 41].

4.3. Continued development on flood plains

Wivenhoe dam was built in the aftermath of the 1974 flood, when Brisbane population was about 1 million people. Since then a steady increase of 20- to 25-thousand people a year, resulted in the city having doubled in size by the time of the floods in 2011 [26].

The population growth meant urbanisation expanded in the flood plain. Moreover, this increased the freshwater demand, imposing further strain on the North Pine, Somerset and Wivenhoe dams. The more stringent flood mitigation requirements were however to be satisfied through the flood compartments of the Wivenhoe and Somerset dams only.

The increased flood mitigation capacity obtained through Wivenhoe Dam was hence completely erased by the time the 2011 flood hit, leaving a higher number of properties at risk compared to the 1974 event.

The construction of the Wivenhoe dam was meant to alleviate both floods and droughts, hence its operations had to be regulated with conflicting objectives. In the 2009 version of the operation manual, these were listed as [34, 39]:

1. Ensuring the structural safety of the dams;
2. Providing optimum protection of urbanised areas from inundation;
3. Minimising disruption to rural life in the valleys of the Brisbane and Stanley Rivers;
4. Retaining the storage at Full Supply Level (for water supply purposes) at the conclusion of the Flood Event;
5. Minimising impacts to riparian flora and fauna during the drain down phase of the Flood Event.

In fact, the conflict between objectives 2 and 4, acceptable for the time Wivenhoe Dam was constructed, could no longer be tolerated since the increased water demand eroded the margins separating them. The construction of the Wivenhoe dam was seen as a definitive solution to the devastation caused by 1974-like events, and had the effect of promoting the continuous urban expansion in the flood plain.

5. Discussion: The many Wivenhoes around the world

The shortfalls highlighted in the governance and management of the water resources in the Brisbane river catchment are in fact common to a wide range of complex cyber-physical systems, as Ampère would define them. We shall now show how this is the case and how this allows to map the events in Brisbane to a framework more general than water resource management. This corresponds to the novel contribution we offer to the ongoing discourse and articulate our point in the following three sections.

5.1. The Governance of engineered systems and the science of the civil governance

The complexity of an engineering asset such as the Wivenhoe dam is different from that arising from millions of identical assets connected in a telecommunication systems. While in the latter the complexity arises from the collective functioning of many assets each almost irrelevant on its own, in the former the complexity arises from the interactions of three very different systems: the dam (intended as the concrete wall retaining the water), the natural environment, which includes the climate, and the social environment, that is the urbanisation. Note that the cybernetic aspects, those related to the science of civil govern, are still ubiquitous as much as the human aspects of the infrastructure management, which include the decision making at various levels. When considering all these elements and the variety of outcomes that can come out of their interplay, it becomes clear that the image of a dam as a concrete wall is nothing short of deceiving. The dam, as embedded and interacting with its surrounding natural and built environments, becomes a complex engineering system. More than that, as the human element is present both as governance, management and users, the dam is a cyber-physical system. It should be looked at through the science of civil governance before engineering.

The social component of the Wivenhoe dam system is one characterised by different stakeholders each exerting pressures to drive the system in different ways. An equivalent environment can be found into many infrastructure systems impacting people to the point that the impact is fed back to the infrastructure management and governance via political representation. This applies to large infrastructure projects, with many of these currently shaping the development of countries in the global South. Examples include the logistic corridors in East Africa [40], the Grand Ethiopian Renaissance Dam changing the flow of the river Nile in Egypt while being built outside its borders [41] and the smart motorway system in Britain with its safety implications [42]. Such examples, while being designed in response to some societal needs, can redefine the needs shifting the demand patterns of logistics, water withdrawal and travel. By doing so, they shape the society, the urbanisation and the resources in response to which they were built. They do so to the point that the governance and management of such large complex systems becomes as important as their engineering.

5.2. Static operating procedures for highly dynamic systems

The operations, management and governance of Wivenhoe dam are three levels of control of a system that steer three different dynamics: the dam itself, the short term water security and the long term demand, respectively. These can be generalised to operations, management and governance of any large complex systems as those previously discussed. In the 2011 flood events, the lower level (operations) appeared to be fast enough to compensate for the variability of inputs (inflow and demand) that the system was subject to. However, this relied on a set of static procedures influenced by the upper levels, which turned out to be a liability to the system safety. What was designed for a population of 1 million people would hardly adapt to 2 million people with a different spatial distribution.

The top-down stratification of control levels generated discontinuity at the interface of governance, management and operations, with the three levels pursuing often conflicting objectives and making impossible to converge towards a consensual approach, informed by scientific evidence and previous events [27].

Systems designed to outlive their designers should be able to adapt not just to stresses of larger magnitude than those they were designed for, but also occurring more frequently and suddenly. In the 2011 Brisbane flood, such stresses interested the whole water security system, of which the dam is just a component. Unfortunately, that was also the only component of the system designed to react in a timely manner. Other parts of the system, including the urbanisation and the natural environment, suffered from being managed

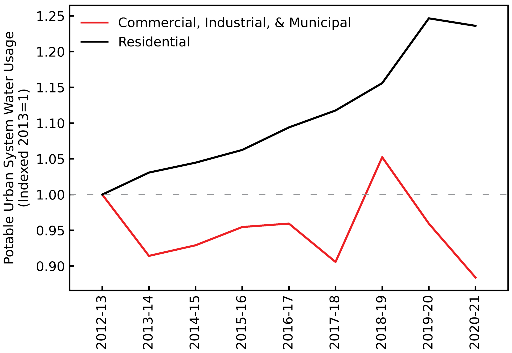

Figure 5: Water withdrawal from the urban water system by end-use utility. Data obtained upon request from the Australian Bureau of Meteorology

and controlled through slower and at times uncoordinated policy and decision making mechanisms, whose effectiveness faded away in the 30 and more years of expanding urbanisation. The safety margins in the engineered side of the system, that could have provided a buffer for the contradiction in the system objectives (i.e. having the dam both full and empty) were eroded over time.

Water demand grew as the population did, and in fact is continuing to do so under the pressures of residential utilities (Figure 5). With no plan to limit population growth, a seamless management of the water resources across the different power levels is non optional. This must encompass not just the reservoirs, but also the whole water security problem in the Brisbane area.

The weaknesses in managing the whole system made the dam a liability as it was seen as the enabler to virtually unconfined urban development. This is alike to the induced demand phenomenon in transport engineering where extra capacity added to a route or mode of transport to ease congestion promotes the increase in demand along that route or mode of transport [43]. This parallel makes clear how engineering assets cannot solve, on their own, the fundamental societal problems, or, in fact, those concerning cyber-physical systems, as Ampère defined them.

Opening up the water security problem to collaborative water governance is a way to minimise the possibility that lessons learned get overlooked under specific stakeholder interests or biases. When concerning urban planning, such an approach requires iteratively posing the water resource management problem, finding solutions in a participative way [44, 45]. However, we note how such an approach is viable in pre-empting threats well before they manifest themselves. Clearly, in the autumn 2010, embarking the decision makers in the process of listening to several stakeholders would prove belated.

In a systems' view, managing infrastructure's user load requires acting within the limitedness nature of the system. In other words, this should be pursued through control and feedback strategies, designed to include the users as part of the system, rather than changing and expanding the it beyond its limits. Participative approaches advocated earlier on for water governance are a concurrent aspect of this which could be part of a system-level multi-criteria analysis. This kind of analysis proved useful in deciding amongst different alternatives [46, 47, 48], any of which becomes viable only if considered within and not above the limits of a rigorous technical assessment, as in emphasized in the emblematic setting of the Q100. Moreover, evidence from the literature suggests that presenting such a technical assessment at a level to which decision makers can immediately relate to, has direct effects on the decisions to be taken [49]. We also note that multi-criteria analysis as a singular approach remains a time-discrete exercise performed at a specific time in the system's life. Complex systems failures exemplified by the Brisbane floods, arise from the continuous evolution of a system ending up to operate close if not beyond its design envelope. An analysis carried out at a specific time would hardly capture this evolution, in particular when the analysis pertains to the design phase.

The popular approach, focussed on increasingly more refined engineering solutions to increasingly more challenging issues pushes complex systems to the boundary of their safe envelope, with always narrower room for manoeuvre and adaptation. This is regardless of whether such solutions follow from the rigorous technical assessment earlier invoked.

A sustainable development approach must consider the management of natural resources and land-use, where classical requirement-based solutions are challenged and urged in the era of climate change, which is contingent to and exasperated by continually growing demands for water, energy, and food security[50, 27].

5.3. Dynamical systems in highly uncertain and dynamic environments

The operations of connected water reservoirs are a classic example of engineering systems (see for example the Ksetibios' water clock [51]). When keeping the water level to some target value is challenged by variable inflows, controllers are engineered which can achieve this. However, hardly any examples include controllers challenged by other controllers, yet this is what appears to have been the scenario in the 2010-11 operations of the Wivenhoe Dam. Defining the FSL for Wivenhoe and Somerset dams as early as October was not going to be an easy task as both the drought and flood protection had to be pursued. Yet the multiple, conflicting levels of control where often biased by external pressure on their human component. While accountability requires a human sign-off, yet decision support tools may and should stay separate from human biases. A decision support tool that, on a day by day basis forecasts a dam's FSL may still require human operators to choose which data to account for, but would clearly operate without external pressure where high uncertainty may influence human perception. At the same time it would neatly bound accountability.

Resilience is the key performance for a safety critical system operating in a highly uncertain environment and this requires the learning from the past for the system to bounce back to its performance (in this case provide flood defence) when diminished in its capabilities [52].

The image of a giant, monolithic engineered artefact, as the Wivenhoe dam, is at the opposite of the dynamic environment in which it sits and shapes. This includes natural and built environment surrounding the dam, as well as its human components composed of stakeholders, governance and management. All of these as significantly more dynamic than the engineering artefact (the dam) invested of the task to compensate for the pressure they exert on the other components of the system.

The system view that was missed in the 2010-11 Brisbane flood, where different levels of control affected the operations negatively, may not offer the solution to a better management of the dam. Yet it would better inform the governance of the water resources as both flood protection and drought mitigation, alleviating the dam from a task which became too onerous since its construction.

6. Conclusions

The engineering-first approach, which led the development of technological solutions for societal challenges around the globe, which include water security solutions in the second part of the 20^{th} century, revealed its fragility when looked from the perspective of larger, complex systems. In these, only few parts are designed and operated based on specifications.

In this discussion paper, we have shown how a shift is needed where the through-life management becomes as important as the initial specifications and design requirements. This would include system wide approaches which become participative in nature when population and human decision makers are included within the system's boundaries. More important, this inclusion makes the systems cyber-physical demanding solutions beyond technical, and adaptable through time, on the basis of scientific evidence.

While technical, social and scientific components all must take part in the cybernetics of complex systems, societal pressures should not feed back onto scientific assessment. Yet societal elements, including elected governance should be able to capture the pressures engineered systems undergo in highly dynamic environments (both social and natural) and compensate for them avoiding the building up of unsustainable demands.

As a discussion piece, this work used empirical evidence and compelling literature to support the points made a above. Yet, the very nature of a discussion paper means that primary data collection, modelling, analysis and data processing are all beyond the scope of the work. While their absence is a limitation to the arguments presented, we trust we have opened the way to more applied studies through our arguments.

Despite the limitation above, our contribution lies in the identification of common traits to large infrastructure projects which, by their extent, become cyber-physical in nature. We proposed approaches by which such systems can be control to avert catastrophic failures. We argue how large infrastructure systems present a control that is distributed amongst various actors, which in turn can be grouped into either governance, management or operations layers. In doing so, we provided the scope for further research into the governance of large complex systems.

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