Cyber-physical system shortfalls in the 2011 Brisbane flood

By Dr Giuliano Punzo

Executive summary: While fuelled by unprecedented rain, the most catastrophic effects of the 2011 Brisbane flood can be traced back to system-level shortfalls. This case study analyses the dynamics that led the Wivenhoe dam's operations to aggravate rather than alleviate the flood. Responsibilities can be mapped to three levels, and it is shown that decision making suffered from multiple pressures that had built up for more than 20 years. Ultimately, this case study shows the importance of decision-making integration across soft and hard infrastructure in cyber-physical systems, and the consequences of failing to do so.

Tags: Wivenhoe dam, Millennium drought, water infrastructure, water security, river catchment, urban planning, damage, casualties, Australia

The inquiry into the 2011 Brisbane flood revealed the role of the Wivenhoe Dam management and operations, exposing its cyber-physical nature. Cyber-physical identifies those systems where the physical components are strongly coupled to their control, which is operated, supervised or steered by humans. The naive assumption that a dam is a large, yet conceptually simple infrastructure is challenged by considering the complex system emerging from the interaction of the dam with the surrounding natural, economic, social and political environment. This case study analyses the dynamics that led the dam's operations to aggravate rather than alleviate the flood. This will be related to the multiple pressures acting on the dam and its management. Looking beyond the flood event, it is shown how failing the dam's objective of mitigating the flood had its roots in a decade of decision making that ended by cornering the dam's operators and forcing them to choose between a bad and a potentially disastrous outcome. The case study highlights the importance of the integration of decision making across soft and hard infrastructure in cyber-physical systems. This can be generalised to engineering systems that play a role across multiple complex systems, such as the climate, the natural and build environment and the dynamics of large organisations.

Section 1: Background and information

The events that led to the second highest flood in Brisbane in 35 years, on 13 January 2011, started much before the January torrential rains. The events that are reported here rely on the official report by the Queensland Flood Commission [1].

Built on a flood plain, the city of Brisbane (Queensland, Australia) has a long history of flood events, with records dating back to 1841. In the January 1974 flood, the reference gauge in the Brisbane business district measured a water height of 5.45m (also known as gauge height). This prompted the building of the Wivenhoe Dam and the consequent creation of Lake Wivenhoe in the Brisbane River catchment. At Ipswich, the Brisbane and Bremer rivers merge and flow toward the estuary located in the city of Brisbane. The completion of the Wivenhoe Dam was not sufficient to avoid the 1995-96 flood and, more importantly, the flood in January 2011, which caused 24 fatalities and damage in excess of $2.55BN [4].

When conceived, Wivenhoe Dam was meant to serve the double purpose of alleviating floods in the wet season as well as droughts in the dry season. In this, it would work together with the other reservoirs under the Seqwater jurisdiction, in particular with the North Pine Reservoir and the Somerset Lake, north of the Wivenhoe Lake. The operations of the Somerset and Wivenhoe dams are coordinated during floods to maximise mitigation. All three reservoirs have flood mitigation compartments, that is a capacity dedicated to alleviating floods beyond the 100% Full Supply Volume (FSV) or Full Supply Level (FSL). Consequently, it is normal for a dam, which has a flood mitigation compartment, to exceed 100% FSL during a flood event without risking its structural integrity. However, the flood compartment of the North Pine Dam is only 0.5% of the FSV and has, therefore, no flood mitigation capabilities by design. More details for the Wivenhoe

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and Somerset dams are offered in **Table 1**, while their location is visible in **Figure 1**.

Between 2000 and 2009, Southeast Queensland suffered the most severe drought in the region's recorded history, remembered as the Millennium Drought [5]. In October 2010, the Bureau of Meteorology (BOM) notified the Cabinet about the possible end of the droughts with an exceptional wet season ahead. A 75% chance of above median rainfall was forecast in Southeast Queensland between November 2010 and January 2011. Established La Niña patterns would have brought an active cyclone season. The levels of the Wivenhoe, Somerset and North Pine reservoirs, however, were not lowered, despite being close to FSV (**Figures A1** and **A2** in the Appendix),

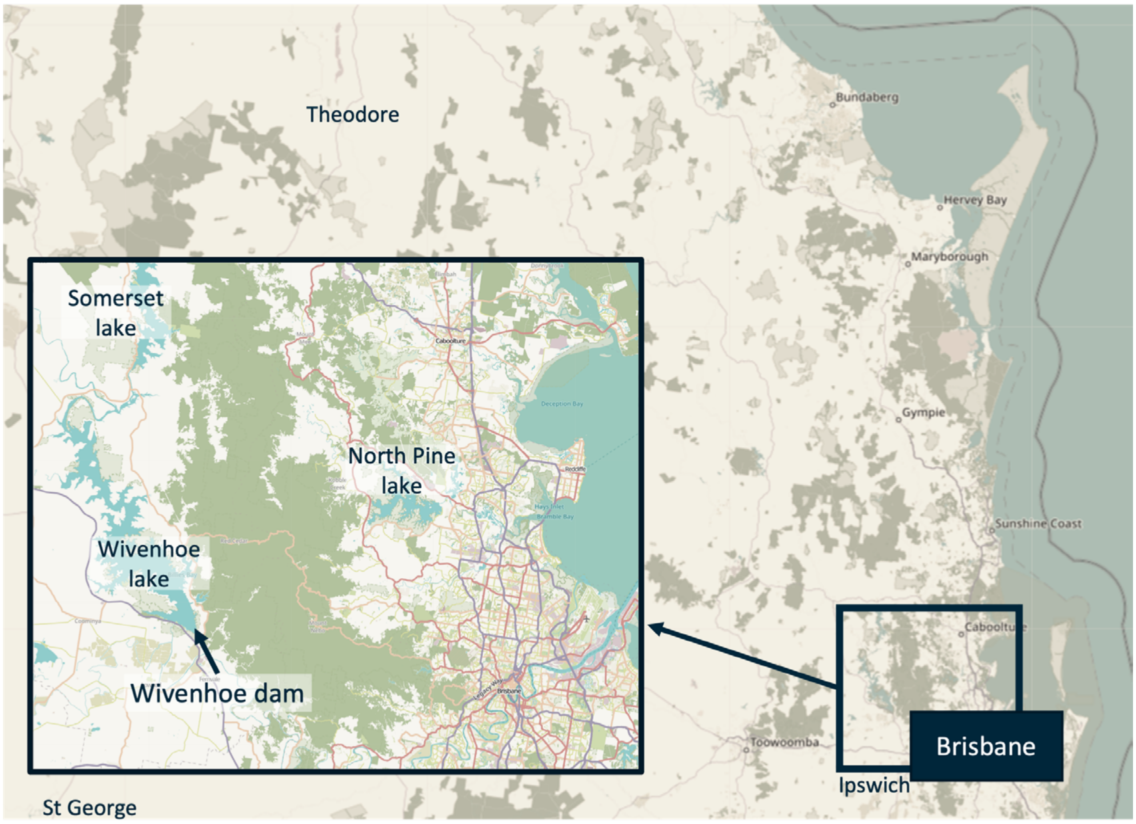

Figure 1: The city of Brisbane and the dams in the immediate vicinity providing for water security and flood mitigation (Source: Map data © OpenStreetMap HOT contributors)

Reservoirs in the immediate vicinity of Brisbane	Full supply Volume	Flood compartment	Notes
Wivenhoe	1,051,000 ML for current OFSL (EL 65.9 m AHD).	2,080,000 ML between EL 65.9 m AHD and EL 80.0 m AHD.	Controlled release through radial gates, sluice gates and fuse plugs as safety devices
Somerset	303,000 ML for current OFSL (EL 97.0 m AHD).	705,000 ML between EL 97.0 m AHD and EL 108.7 m AHD.	Controlled release through cone valves, sluice gates and crest gates. The outflow feeds into the Wivenhoe Lake
North Pine	214,302 ML full supply level, is 39.6 m AHD	the level at which gate openings are triggered, 39.65 m AHD, 1,000 ML between 39.6m and 39.65m AHD.	Not linked to Somerset and Wivenhoe.

Table 1: Characteristics of the dams in the immediate vicinity of Brisbane. The split between Water Supply and Flood compartments refer to the Operational Full Supply Level (OFSL). AHD stands for Above Australian Height Datum [2]

meaning that the only flood protection they could offer was from their flood compartments.

As the weather front approached Brisbane from the north, flood peaks occurred as early as 4-10 December in the Balonne River at St George and the Dawson River at Theodore.

By the end of December 2010, localised floods had already occurred along the Bremer and Brisbane rivers. However, the official start of the 2011 Brisbane flood main event was not until 6 January 2011. This is the date indicated in the official reports, including the Queensland Flood Commission of Inquiry report. On 12 January 2011, the 1974 flood gauge records were broken at Ipswich for the Bremer River (15,000 properties flooded) and in the business district of Brisbane, for the Brisbane River, which on 13 January experienced a major flood peak of 4.45 metres, affecting more than 14,000 properties. On the same day, the so-called strategy W4 was invoked, consisting of the full opening of the Wivenhoe radial gates, with the consequent release of water. This was triggered by the water level approaching the fuse plugs, which are safety devices meant to release water when the level puts the dam's structural integrity at risk. They are the last resort to avoid the dam collapsing. If the water had achieved the fuse plugs, the release would have happened anyway and in an uncontrollable way. Strategy W4 made this release controllable, although the volume of water released was no different as the strategy prescribes full opening anyway.

On Thursday 13 January 2011 major floods occurred throughout most of the Brisbane River catchment area, most severely in the catchments of the Lockyer Creek and Bremer River (major tributaries of the Brisbane River) where numerous record flood heights were experienced. Beyond the loss of 24 lives in the Lockyer Valley and one in Brisbane, an estimated 18,000 properties were flooded in metropolitan Brisbane, Ipswich and elsewhere in the Brisbane River Valley. A timeline of the events can be seen in **Figure 2**, where decision making milestones are also present, which are explained in the following sections.

Section 2: Analysis and insights

Four angles on the Brisbane flood

Angle 1: The joint operations of Wivenhoe and Somerset dams

On the technical side, Wivenhoe and Somerset dams are operated together to minimise the impact of floods. Starting at or close to FSL, the inflows are balanced so that both levels rise at the same rate. This is commonly known as following the target line (**Figure 3**). During the 2011 flood event, both the Somerset and the Wivenhoe dams started with empty flood compartments, but at 100% FSL. Indeed, the FSL of the Somerset Dam was 99m, one cm more than the actual level recorded on 31 December 2010. Wivenhoe Dam's FSL was set at 67.0m and the actual level was 67.69m on 31 December 2010. The fuse plugs are activated at 75.5m for the Wivenhoe Dam while the Somerset Dam cannot exceed 109.7m AHD. To avoid this, dam operators can open the gates and start the uncontrolled release to the same effect. This is triggered by a number of conditions, including but not limited to, the water level, its rising or falling trend and the precipitation forecasts. Among these, the water level at Wivenhoe should not exceed 74m AHD and, according to the manual [11], the spillway gates are not to be opened for flood control purposes prior to the reservoir level exceeding 67.25m.

At 21:00 on 11 January 2011, the Dam Safety Regulator was asked for permission to exceed a level of 74.0m in Wivenhoe Dam for a maximum of 12 hours in an extreme attempt to avoid invoking

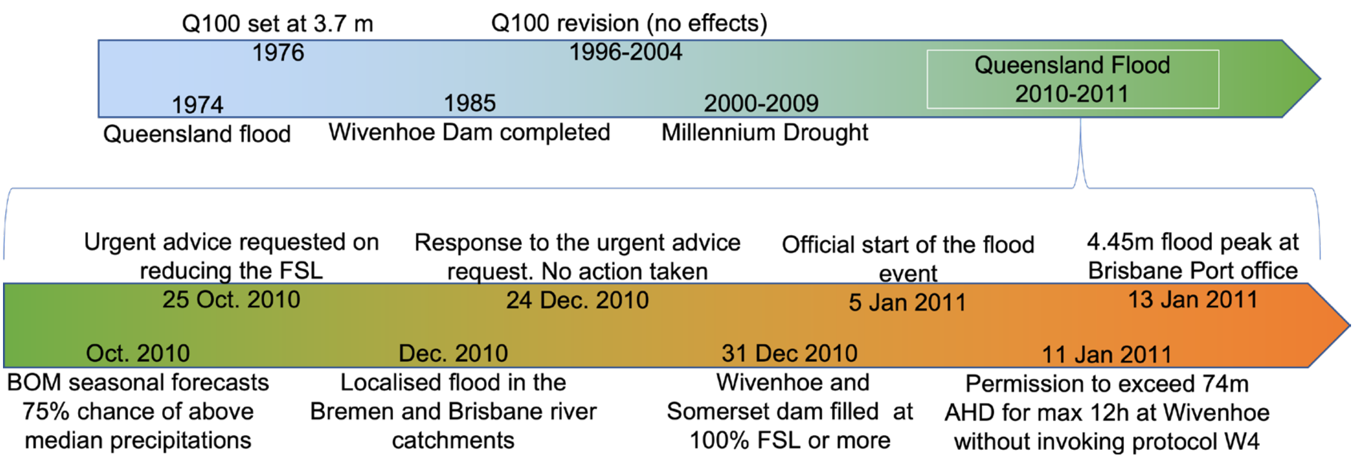

Figure 2 : Timeline of the events leading to the 13 January 2011 flood peak. Explanations about acronyms and event details can be found in the report.

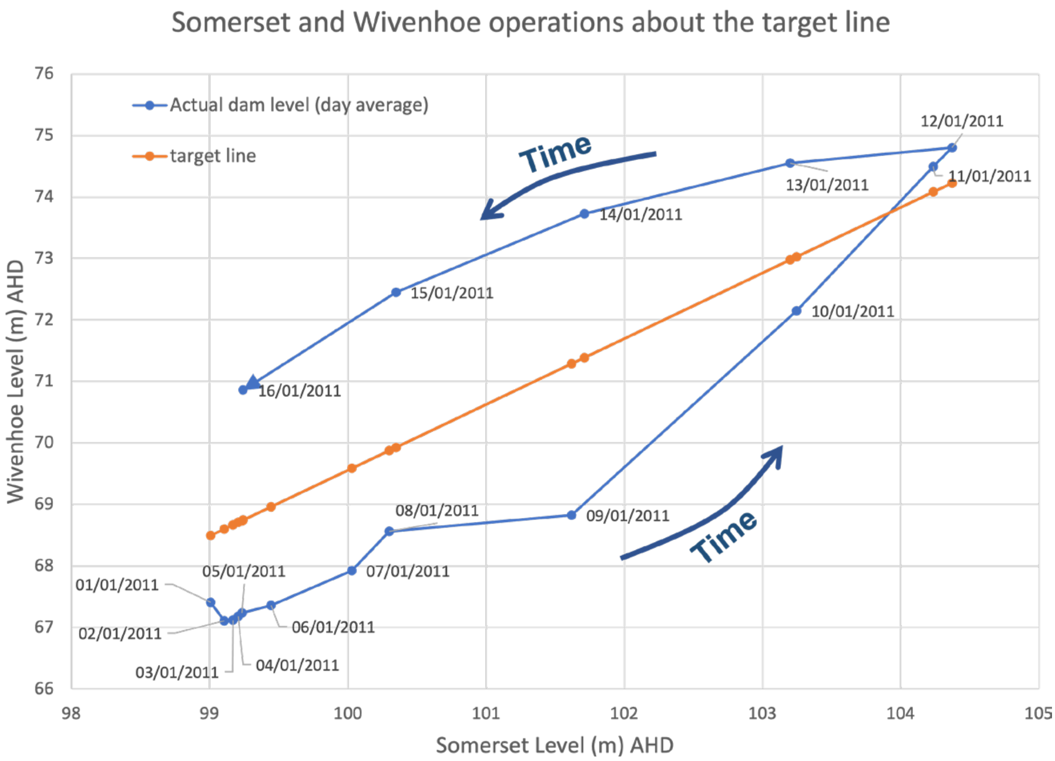

Figure 3: Target line for the levels of the Wivenhoe and Somerset dams

strategy W4 (uncontrolled release of water), provided the safety of the dam could be guaranteed. Permission was granted. The rise in the Wivenhoe Dam level was also due to the inflow from the Somerset Dam, which was already above the 102m level, meeting the conditions for which, according to the operation manual, water had to be released, flowing into the Wivenhoe Lake.

The actions taken were all in line with the Wivenhoe operation manual. This prescribes that, providing the safety of the dams is not compromised, where early opening of the gates and/or varying the operational procedures at Somerset Dam can keep the lake level below 75.5 metres, those steps should be taken to prevent fuse plug initiation. Also, the manual prescribes that the senior flood engineer may exercise reasonable discretion in moving to strategy W4 earlier if this is able to prevent the triggering of a fuse plug [11].

The flood commission inquiry concluded that, considering the flood events from 6 January onwards, dam operators took a reasonable course of action. The dam gates were operated without any impediment and both Somerset and Wivenhoe dams maintained their structural integrity. In addition to this, the Queensland Flood Commission found no evidence against the appropriate use of the operating target line [1].

Angle 2: Building and more building in a flood plain

In the past 50 years, the Brisbane population has increased at a steady rate, passing from one million in 1974 (the year of the last record-breaking flood, in the aftermath of which Wivenhoe Dam was conceived) to two million in 2011 [8]. This posed a problem which is twofold: first, the urbanisation expanded in a flood plain. This means more and more properties were built knowing about the flood risk. The second aspect to consider is the freshwater demand, which during the dry season has to be mainly satisfied through the North Pine, Somerset and Wivenhoe dams.

Given the very small flood compartment of the North Pine Dam, flood alleviation capabilities are to be sought only through the Wivenhoe and Somerset dams. Between 1974 and 2011, the flood mitigation capability leaped forward with the construction of Wivenhoe Dam. Yet, the number of properties at risk and the demand for freshwater did likewise in the 37 years separating the two events.

After the 1974 flood, the construction of the Wivenhoe Dam was seen as a definitive solution, building an 'immunity myth', hence an enabler of the urban expansion in the flood plain [12].

In fact, the increased water demand eroded the margins separating the conflicting objectives on which Wivenhoe Dam was constructed and is operated. The 2009 version of the Wivenhoe Dam manual, relevant to the 2011 flood, lists them in order [4,11]:

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.

From the list above, it is immediately obvious that there is a conflict between objectives 2 and 4.

Angle 3: The Q100

The Annual Exceedance Probability (AEP) is often indicated through the so-called Q100, that is the height of water in a flood event that is likely to occur once in 100 years and is often considered as synonymous with the height of flood water that can be recorded annually with 1% probability. This is derived using models and available information and used as a basis for flood risk management worldwide and, in particular, in Australia. The Q100 is evaluated at different geographical locations and drives planning policies. At the time of the 2011 flood, the Q100 corresponded to 3.7m at the Brisbane River Port Office Gauge [5]. This value was calculated based on the level of the flood water reached during the 1974 flood, then reduced following models that considered the mitigating effects of the Somerset and Wivenhoe dams. The higher the Q100 the more limitations are imposed on urbansiation and the kind of planning possible.

Decisions on the Q100, which must be set as a policy matter by the Brisbane City Council (BCC), are hence taken under conflicting pressures from different stakeholder groups.

In 1996, a year characterised by intense precipitations and localised floods in January and May, a revision of the Q100 was commissioned. First delivered to the BCC in 1998, the best estimate of the Q100 was 5.34m at the Brisbane port office gauge. This estimate was subject to several reservations from the BCC's Water Resources manager as it was based on the conservative assumption that the Wivenhoe and Somerset dams were at 100% FSL at the start of the flooding event. Despite two subsequent analyses that confirmed best estimates all close to 5m, BCC did not approve any changes to the Q100 and eventually left it unchanged. In 2003, a special commission was asked to estimate the Q100 again, within just five weeks and without undertaking any further modelling. The new recommended figure was 3.3m, subsequently adjusted to 3.51m and finally 3.16m in 2004. The BCC was satisfied with the figures all being below the 3.7m existing one and made no change to it. Indeed, it appears that the 2003 figure was derived on the understanding that the Wivenhoe and Somerset dams could reduce downstream peak flood flow rates between about 35% and 60%, which is far from what happened in 2011. [5,10]

Looking at the 2011 event, the peak flood level at the Brisbane River Port Office Gauge was recorded at 02:57 on 13 January 2011 at 4.45m.

The time in which the crucial decisions about the Q100 were taken, as described above, partially overlapped with the Millennium Drought (2000-2009) [9], which also witnessed an uninterrupted population growth. Both factors are likely to have pushed such crucial decisions onto a political ground, even when they should have been science based only. To this effect, it is important to report verbatim the Queensland Flood Inquiry Commission's report: "A flood study is a scientific investigation; it involves no matters of policy" [1, pg 41].

Angle 4: Inertia and (lack of) leadership

Although Seqwater kept the formal management responsibilities, it subcontracted the operational management of the Wivenhoe, Somerset and North Pine dams to Sunwater during flood events for more than 10 years up until 1 July 2011. This arrangement saw many responsibilities as operator of the dams delegated during times of flood. However, it appears that Seqwater did not ensure the continuity of the arrangement throughout the 2010/2011 wet season. The actual agreement expired on 31 October 2010 and was not extended until 24 December 2010; but no formal agreement was in place between 1 November and 23 December 2010. The flood management service by Sunwater continued nonetheless, according to the terms of the expired agreement, with acceptance from Seqwater [2]. This dangerous situation may be considered as a symptom of the intricate decision-making pathways crossing several political and technical levels and the possible lack of identified leadership in the time leading to the January 2011 flood event. The crossing of communications at different levels that resulted in no actions taken about the FSL of the Wivenhoe and Somerset dams are even more striking evidence of this.

In October 2010, the Minister for Natural Resources, Mines and Energy, Stephen Robertson, launched an inquiry into the possibility that the full supply level of Somerset, Wivenhoe, North Pine and Leslie Harrison dams might temporarily be lowered. Indeed, the Bureau of Meteorology had warned the Cabinet about the forecast for an unusually intense wet season ahead, with a 75% chance of above median rainfall in South-East Queensland and of an active cyclone season. The forecasts were based on evidence of established La Niña patterns, expected to persist until at least

March. Such events are historically correlated with tropical cyclones in the Coral Sea, leading to above normal rainfall persisting over Queensland.

As a result of this, the Water Grid Manager and the Minister agreed on a formal letter in which the minister asked the Water Grid Manager's urgent advice about options for, and benefits of, releasing water from 'key storages' – at a minimum, Wivenhoe, North Pine and Leslie Harrison dams – in anticipation of major inflows over the coming summer. This correspondence was dated 25 October 2010. Although anticipated through informal briefings, an official response to the letter was dated 24 December 2010. In essence, the response suggested that the benefits of a temporary reduction in the level of Wivenhoe and Somerset dams (to 95% of the combined full supply level) would have been negligible as protection against medium and major flood events. To improve flood mitigation, the release should have been as great as 16% or more. However, it should be noted that on 24 December, Queensland had already suffered increased precipitations and localised floods and on 25 December, Category 1 Cyclone Tasha crossed the coast. The minister eventually decided that no actions should be taken.

On 20 January 2011, when the scale of the devastation was apparent, the minister requested that Seqwater's report on the recent flood events at Wivenhoe and Somerset dams include considerations on the effect of the full supply levels. After maintaining the 'no action' line and noting that the tension to ensure water security motivated the FSL decision on policy grounds, on 13 February 2011 Mr Robertson had to reconsider his decision. He issued a media statement in which he announced that Seqwater had formally recommended that Wivenhoe Dam should be temporarily reduced to 75% of its full supply level as a precaution against the 'second strongest La Niña pattern in history'. The impact of this decision is visible in the volume reduction shown on the right side of **Figure A1** in the appendix.

The inertia that emerges at this level of control over the dam operations saturated the ability of the engineering level of control and is striking evidence of the cyber-physical nature of the system.

A complex system framework for safety

The Wivenhoe-Brisbane case can be illustrated through the Complex System Safety framework [6] which provides a conceptual arrangement of the elements in a complex system that lead to its systemic failure. Such elements are the exacerbating factors; the causes of complexity; the consequences of complexity; the design-time controls; and the operation-time controls. In the Wivenhoe-Brisbane case, the failure is not the physical collapse of the dam but can be found in the system-wide issue of failing to conciliate the needs of a growing population with long term management strategies of the whole cyber-physical system, including the urbanisation as well as the green and blue infrastructures and the people. This eventually led to the uncontrolled release of water from the dam, which is the physical and visual aspect of the systemic failure.

Based on the description of the events and the analysis of the different dynamics, the opacity of the decision-making process is the common trait to all the exacerbating factors, which became explosive when projected in highly expected and highly uncertain La Niña patterns.

The Wivenhoe system presents complexities on all levels. Technical complexities are linked to the fact that the reservoir is part of the network of reservoirs meant to provide relief from both floods and droughts. Moreover, it feeds into the Brisbane River, which has tidal characteristics. This, in turn, links to the governance and management complexities as the dam serves the interests of diverse stakeholders, who exert pressure at different levels of governance and management.

The networked nature of the reservoirs implies the need for coordinating their operations. It is impossible to discharge water from the Somerset Dam without filling the Wivenhoe Dam. Decision makers at governance and management level are therefore presented with a multifaceted problem as the solution has to satisfy more than one objective and more than one group of stakeholders.

Design time controls in the system were made ineffective by the large population growth in Brisbane, making such controls outdated and unable to cope.

On the other hand, operation time controls had to deal with a system composed of subsystems that move at different speeds. The physical perturbation to the system, i.e., the inflow of water, has a time scale of hours and is well matched by the reactiveness of the dam's operations. However, more effective operation time controls – those that should operate ahead of a catastrophic event – have been shown to belong to higher control authorities that move on a longer-term timescale of months to years.

Figure A3 in the appendix uses the York University framework [6] to report in a schematic way the above considerations.

In the case of the Brisbane flood, however, while some of the factors can be framed within a single layer, their interaction cannot be captured in this way. As becomes clear in the following section, the different speed at which the different layers moved, from many months to hours before the uncontrolled release of water, determined the catastrophic failure that the Brisbane flood is mainly remembered for.

Section 3: Discussion and transferable learnings

Looking at the structural integrity and functionality of the gates, there is little that can be imputed to the Wivenhoe and Somerset dams and their operations from 6 to 13 January 2011. However, those operations have been the focus of long investigations as the dams are the main flood mitigation devices for the city of Brisbane. This concentrated the attention on technical aspects, looking at possible engineering failures, unsuccessfully. Although left with a large degree of discretion, and with several data sources to interpret about the flood development, the engineers did what they could within what was allowed by the manual of operations to mitigate the flood. As a matter of fact, the outflow from the Wivenhoe and Somerset dams never matched or exceeded the inflow during the flood event [3].

If any early water release to free capacity were to be attempted, this should have happened in December 2010. The choice, however, to keep the reservoirs at 100% FSL determined the limited ability to mitigate the flood effects.

This was, in turn, due to the long delay between the flagging of an intense rain season and the decision on the FSL. The decision was taken on political ground, rather than technical or scientific, and it can be argued that the final decision was biased by the recent memories of the hardship caused by the Queensland's Millennium Drought (2000-2009). Nevertheless, the slow pace of the process, starting with the request for urgent advice on28 October 2010 that only received a response on 24 December, would have made any lowering of the FSL too little and/or too late.

A striking piece of evidence of the over reliance on technical solutions for complex (beyond technical) problems is apparent in the contrast between the extremely detailed guidelines from the operation manuals of the dams and the extremely vague prescribed timeline in which the decision process on the FSL is supposed to take place.

The politicisation of decision making was at the root of the discretionary discarding of three Q100 assessments higher than the current one. This allowed continued urban growth in the Brisbane flood plain. While politics has to balance conflicting instances and be able to compromise on different stakeholders' objectives, scientific assessments should be taken as inputs to policy making. In the Brisbane case, it appears that the separation between policy decisions and technical/scientific assessments was either blurred or the two were looping onto each other. Policy making is, and should be, guided by scientific evidence, but closing the loop, i.e., allowing policy to steer scientific assessments in return, introduces a complexity-enabled fragility, as highlighted by the Q100 determination in the Brisbane case.

Finally, the Brisbane/Wivenhoe case teaches us that the boundary of complex systems is not just difficult to draw on the geographical map (what dams, what catchments, what weather patterns) or on the engineering blueprints (what technical features of the dams, what element of the basin). The analysis of the Brisbane-Wivenhoe complex system, even when confined to the spatial extent between the Brisbane urbanisation and the Wivenhoe Lake, presents poorly defined time limits. These could start from the design specifications at expectations in the building of the Wivenhoe Dam (1985), as well as from the revision of the Q100 for Brisbane (1996); from the start of the Millennium Drought (2000); from the issue of the seasonal forecast for Queensland (October 2010); from the start of the torrential rain and from the (non-) decision about the FSL (December 2010); or from the declaration of the flood event (6 January 2011). The latter was chosen as the starting time point in the official flood commission report [1]. Furthermore, such a complex system presents poorly defined limits on the systems governance and management charts. This allowed for discarding scientific evidence for the new definition of Q100 but did not compel anyone to take a timely decision about the dam's FSL.

What was well defined is the sequence of operations and discretion that the dam's operators have when a flood event is declared. This appears once again to stem out of considering engineering as the solution to policy, governance and management flaws. It is now clear that, rather than looking for a single culprit, the causes of the failure lie in the cyber-physical nature of the Brisbane Wivenhoe system, that is, in the interwoven layers of physical infrastructure, their management, the political decisions that determined the Q100 for Brisbane, etc. This is the focus of the next and final section.

Generalised learning and how we can leverage it

The government of the engineering and the science of the civil government

Norbert Wiener defined Cybernetics as the study of control and communication in the animal and the machine. Before him, André-Marie Ampère used the word Cybernetique with reference to the science of civil government [7].

The term Cyber-physical systems nowadays identifies those systems where the physical components are strongly coupled to their control, which is operated, supervised or steered by humans.

The case of Wivenhoe Dam exemplifies a class of engineering systems which are, per se, conceptually simple, but become complex from the time they are inserted in a complex environment. An element that is always present in these cases is the human action, which makes most complex systems cyber-physical.

The popular image of a dam as a concrete wall might not be easily identified with a complex engineering system. However, the resulting engineering of the natural environment in which the dam sits becomes a complex engineering system and therefore must be treated as such. This changes completely the safety requirements of the system, from a purely structural angle to one of operation management. Similar considerations extend to systems large enough to impact people who feed back into the systems via political representation. In essence, any large infrastructure project can be subject to the same considerations. Examples of this are the projects currently shaping developing countries, such as the logistic corridors in East Africa, including the transport infrastructure, as well as oil ducts from South Sudan to the Kenyan coast; the Grand Ethiopian Renaissance Dam, raising the complex geo-political issue of limiting the flow of the river Nile to Egypt while being built completely outside its borders; the Gwadar port city in Pakistan, or in the developed world, the smart motorway system in Britain. All of these have the potential – and some have already proven it to be the case – to shape society, urbanisation and resource utilisation and therefore cannot be expected to deliver, and deliver safely, just by means of engineering.

Static procedures in a highly dynamic environment

The idea of static operation procedures to regulate a system in an extremely dynamic environment is a liability to the safety of the system. For such long-living systems, design-time control's effectiveness fades in time as it is dwarfed by the lifespan of the designed object.

In the case of Wivenhoe Dam, the rapid reaction and revision was relegated to the dam operations. However, when the whole system includes the urbanisation and the natural environment, the dynamic components of the system become much more heterogeneous. The increased demand for water provision in the 30 and more years of expanding urbanisation eroded the safety margins that could have provided a buffer for the contradiction in the system objectives (i.e., having the dam both full and empty). At the same time, the dam was seen as the green light to virtually unconfined urban development. In transport systems, this is known as induced demand, meaning the increase in demand for some transport modes or routes fuelled by their increased capacity. While engineering cannot solve this fundamentally social problem, the use of common infrastructure, it can indeed help by supporting existing assets with demand management strategies, which are at the heart of systems engineering. As with every ecosystem, the built environment has to fare within the resources available, meaning that managing infrastructure's user load can be considered as the built environment equivalent of thriving within the resources of the natural environment. This could be achieved by implementing control and feedback strategies to include the users in the design and management process. The alternative is the reactive fashion with which policy has invested the engineering of the iterative solutions of iteratively generated problems. Unfortunately, such an alternative is flawed.

The challenge of dynamical systems in a highly dynamical and uncertain environment

Having the cyber (intended as human) and physical (intended as hard infrastructure) parts of a system efficiently working together presents as many challenges as opportunities. The challenges of defining the FSL as early as October for the Wivenhoe Dam is comparable to allocating space in refrigerated warehouses for the food supply chain or to secure stocks of personal protection equipment for health operators. While accountability requires a human sign-off, 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 (not just the level) or a warehouse's floorspace would face the challenge of integrating the right information in the right amount, which would still imply human decisional intervention. Yet, achieving such a level of unbiased directions would enable accountability across the system with neater contours than is currently possible.

Complex systems, when considered holistically, are evolving systems [13]: the time factor is pivotal. The image of the giant, monolithic Wivenhoe Dam as an engineered artefact, static in space and time, is in this sense deceiving. As soon as we extend the system to the natural and built environments surrounding the dam, the stakeholders, the governance and management, the imposing Wivenhoe Dam is scaled down from the system to a component of it. Strikingly, the engineered artefact is likely to become the most static part of all the system components. Every other component in the system moves, changes and gets transformed in time. Capturing these parallel evolution patterns and how they impact on the entire system can be the key to safer complex engineering systems.

Appendix

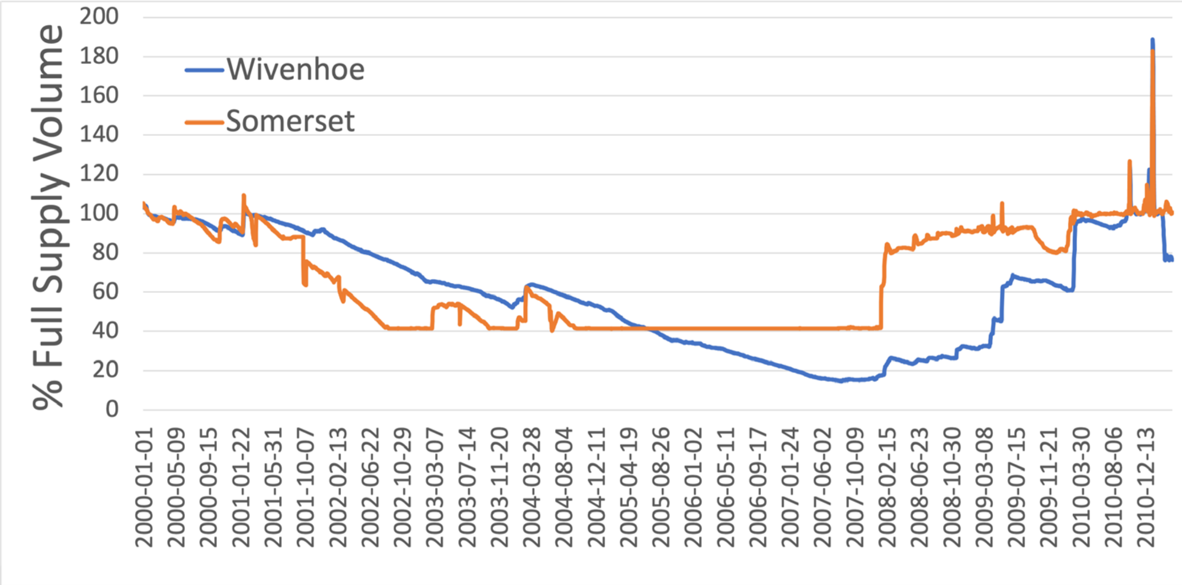

Figure A1: Percentage of full supply volume for the Brisbane and Wivenhoe dams from the start of the Millennium Drought (200) to March 2011. Note the reduction in volume decided for the Wivenhoe dam after the 2011 Brisbane flood to the right of the diagram. Data by Seqwater.

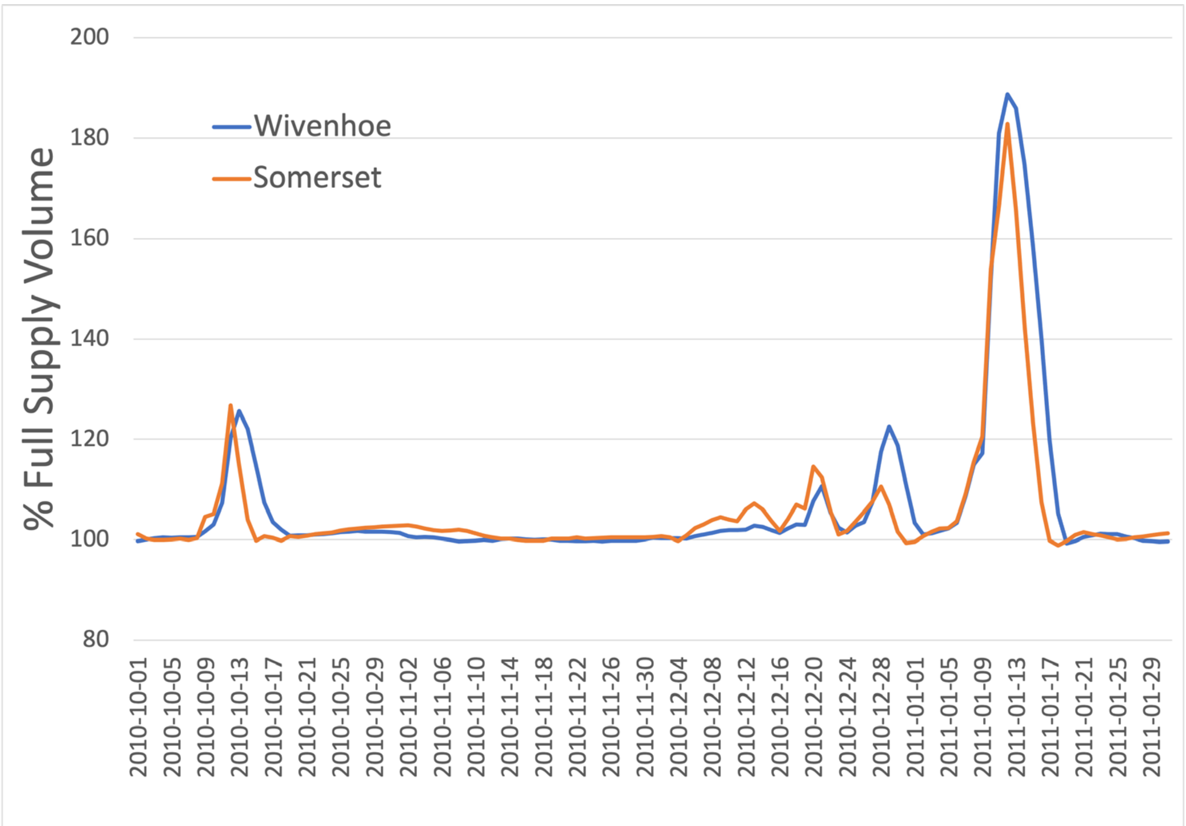

Figure A2: Percentage of full supply volume for the Brisbane and Wivenhoe dams from October 2010 to January 2011. Data by Seqwater.

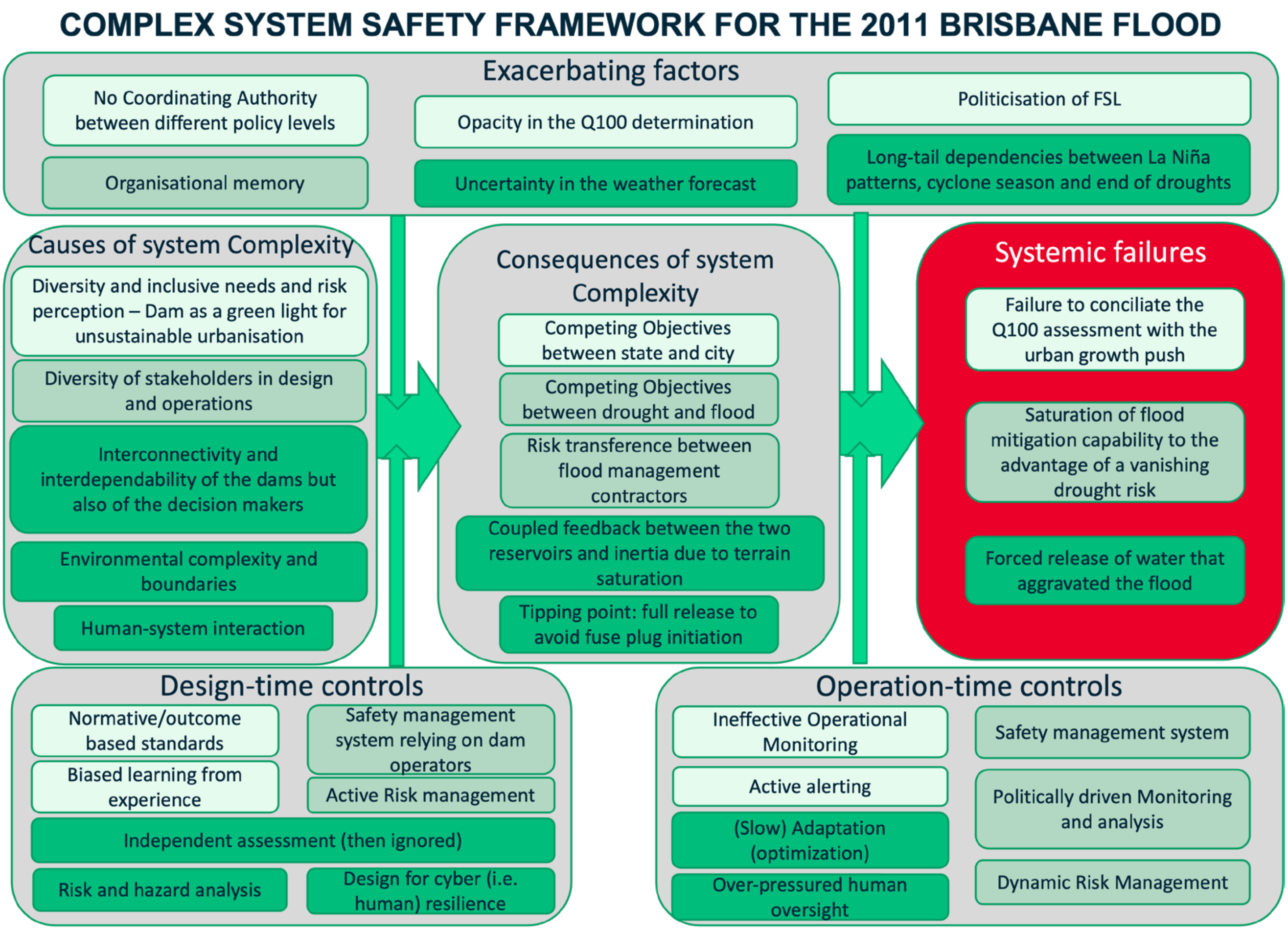

Figure A3: Complex system safety framework, as developed by the University of York [6], applied to the case of the 2011 Brisbane flood. The three shades of green correspond, from pale to dark, to the governance, management and task/technical layers to which the different factors/approaches belong. The framework groups the factors in 'elements', here, represented as boxes with a grey shade.

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