Remote sensing technologies for dam design and prototype monitoring

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Dams play an important role for flood mitigation, water supply and hydropower. Climate change associated extreme rain events and subsequent flooding will increase the risk of dam releases, and the safety of the structure must be ensured even under the most extreme conditions. Many dams have insufficient flood release capacity and require refurbishment and upgrade of their spillway and energy dissipation structures. Modern design practice for such upgrades would ideally involve a combination of Computational Fluid Dynamics (CFD) and physical hydraulic modelling conducted using the highest technical standard. While physical hydraulic modelling of dams has traditionally relied on point measurement instrumentation, remote sensing technologies have recently shown to provide superior performance in terms of spatial and temporal resolution. LIDAR technology has been successfully explored in physical hydraulic modelling of aerated flows in spillways and stilling basins as well as in field measurements at a low-head weir. Recent pilot studies have also shown opportunities of video-based observations of flows discharging from a spillway at a large dam. Both LIDAR and video-based technologies are promising approaches for quantitative measurements of flows at prototype dams. Such prototype observations can provide missing validation data for both numerical and physical modelling, information on scale effects and fundamental insights into the flow behaviour at large scale. Prototype observations enable a more robust design process for dam upgrades and enhance the safety of dams. Real-time remote sensing of flows may provide additional benefits when integrated with decision support systems to identify any adverse operations during dam spilling events.

Keywords: *Air-water flows, Drones, Hydraulic structures, LIDAR, Physical modelling, Prototype validation.*

Introduction

Dams are built for water supply, flood mitigation, and generation of hydropower. Despite their critical role for society worldwide, many dams are aging, including many dams in Australia (Perera et al. 2021). Aging dams have an increased risk of failure and require refurbishment. Climate change related extreme rain events and associated flooding (Johnson, et al. 2016), pose additional risk for dams because the capacities of the flood release structures may need to be upgraded to the new hydrological realities. The safety of a dam cannot be compromised, and industry, academia and dam owners must work together to apply the highest technical standards including the use of technological advancements for the safe design of large hydraulic structures (Felder et al. 2021a). To reduce the risk of dam failure, the design and upgrade of a dam structure should be based upon state-of-the art hydraulic design approaches ideally combing both numerical and physical modelling to characterise flow performance, water levels, hydrodynamic pressures, flow velocities, among others. Such hybrid modelling provides an opportunity to improve understanding of the hydraulic behaviour and performance of a hydraulic structure across a wide range of operational and design conditions. In hybrid modelling, a Computational Fluid Dynamics (CFD) model assesses the flow performance in parallel using the physical model data for validation. Both types of modelling have their limitations (e.g., inability of Reynolds-averaged numerical models to model turbulent fluctuations, or limited measurement locations in physical hydraulic models) and the combined use of the modelling approaches can minimise these limitations. However, flow aeration is not accurately represented in both types of modelling.

Many prototype flows in hydraulic structures are aerated, however several air-water flow properties cannot be correctly extrapolated from physical models to prototype structures (Felder and Chanson 2017). This can have implications for operation of the prototype structure since entrained air leads to the bulking of the flow and the potential for sidewall overtopping if the sidewalls are not high enough. Furthermore, the presence of aeration next to a solid boundary reduces the flow resistance, and if this aeration is not correctly represented in the physical model, the energy dissipation performance of a prototype structure may not be correctly represented in a small-scale physical model, reinforcing the need for prototype validation data (Chanson, 2013, Hohermuth et al. 2021). An overview of previous successful quantitative measurements of flows in prototype hydraulic structures is presented in Appendix A.

Recent prototype measurements by Kramer and Felder (2021) and Chanson (2022) have demonstrated for the spillway of Hinze Dam, Australia, that video-based technology may be able to provide information on the free-surface velocities of prototype spillway flows. Besides video observations, another promising remote sensing technology for prototype observations is the light detection and ranging (LIDAR) technology which has been extensively explored in laboratory settings with hydraulic jumps (Montano et al. 2018, Li et al. 2021a) as well as on a low-head weir structure in the field (Li et al. 2021b). Considering both video and LIDAR technologies, this manuscript will first present the current state of knowledge of the application of these technologies in hydraulic structures engineering. Afterwards, the deployment of remote sensing technologies in prototype hydraulic structures is discussed and finally, the vision to use remote sensing technologies for improved hydraulic structures design and monitoring is presented.

LIDAR measurements in hydraulic structures engineering

Traditionally, free-surface elevations in physical hydraulic modelling have been measured with pointer gauges, pressure tappings, wire gauges and Acoustic Displacement Meters. These instruments measure mean elevations and free-surface fluctuations at a fixed measurement point providing an incomplete understanding of complex air-water flow processes characterised by unsteady and spatially varying flow behaviour. In air-water flows, phase-detection intrusive probes are considered as the most reliable air-water flow instrumentation, but these devices provide characteristic elevations based upon time and depth averaging and are also limited to fixed point measurements. As proposed in this paper, LIDAR technology is a promising alternative for free-surface measurements of air-water flows. A LIDAR device estimates the distance based on the travel time of the laser transmitted by the sensor to a target surface (Gokturk et al. 2004; Bufton et al., 1991; Blenkinsopp et al. 2012).

Over recent years, researchers at the UNSW Water Research Laboratory have pioneered the use of LIDAR technology in the measurement of free-surface motions of air-water flows in hydraulic structures engineering including classical hydraulic jumps, hydraulic jumps in stilling basins and high-velocity flows in spillways in the laboratory, as well as on a low-head weir and a river rapid in the field (Figure 1). While different LIDAR sensors have been explored, the standard LIDAR device that was used is a two-dimensional SICK LMS511 LIDAR instrument (Figure 1a and c) operated with a sampling rate of 35 Hz and with an angular resolution of 0.25 degrees over a 180-degree sampling range. The LIDAR device can be used in rainy conditions and can measure fluctuating surfaces of air-water flows over distances of up to 80 m.

Figure 1. LIDAR measurements of free-surface motions of air-water flows in hydraulic structures engineering at the UNSW Water Research laboratory: (a) fully aerated hydraulic jump; (b) high-velocity air-water flows on a spillway; (c) low-head weir at Manly Creek, NSW.

Montano et al. (2018) conducted a first study in fully aerated hydraulic jumps (Figure 1a) showing that LIDAR can provide novel information on the flow processes including the simultaneous recording of jump toe and free-surface motions, as well as their characteristic frequencies (Figure 2). This research highlighted the LIDAR capabilities to record free-surface elevations continuously and with high spatial and temporal resolution. Figure 2a shows typical instantaneous free-surface elevations d/d_1 along the hydraulic jump x/d_1, where d is the free-surface elevation, x is the distance from the mean jump toe and d_1 is the supercritical conjugate inflow depth. For each of the instantaneous surface profiles shown in Figure 2a, the LIDAR instrument was able to capture the unstable free-surface transition from supercritical to subcritical flows which was characterised by spikes and waves, emphasising the strong variation in free-surface elevations with time. Simultaneously the LIDAR sensor captured the jump toe motions showing strong variations in the jump toe positioning over the 5 s interval shown in Figure 2a. Figure 2b shows the resulting median free-surface elevations of the hydraulic jump as well as the standard deviations of the free-surface motions d'/d_1 together with the 10th and 90th percentiles of the elevations. The LIDAR sensor was also able to capture other hydraulic jump characteristics such as free-surface time and length scales due to its ability to record free-surface elevations continuously (Montano and Felder 2020).

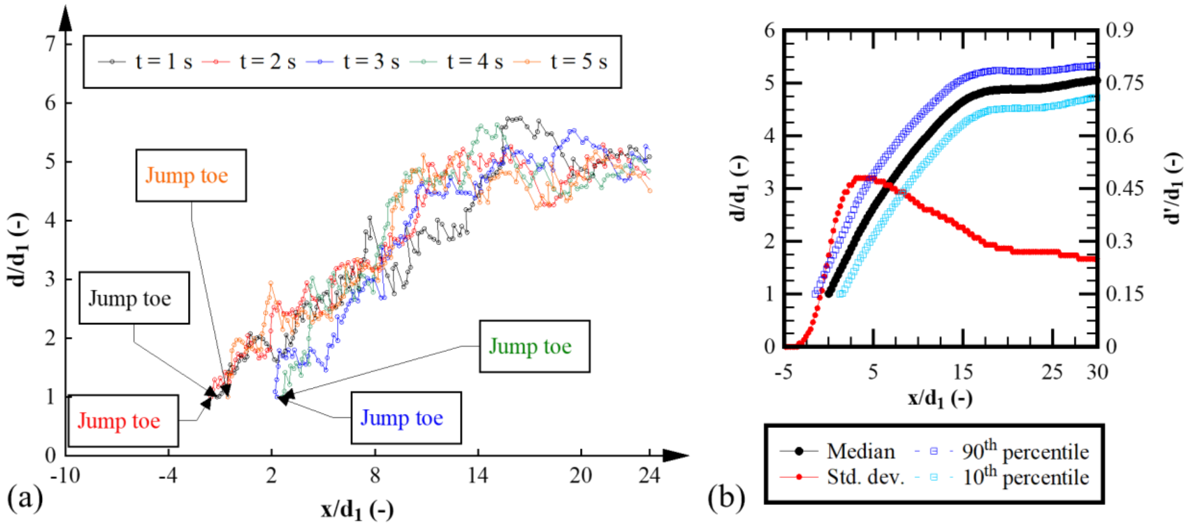

Figure 2. LIDAR observations of the free-surface motions in a fully aerated hydraulic jump; (a) Instantaneous free-surface elevations with time steps of 1 s between profiles; (b) Median free-surface profile together with 10th and 90th percentiles and standard deviation of the free-surface elevations (raw signal recorded for 30 mins).

Subsequent research on hydraulic jump behaviour used the LIDAR capabilities to highlight the effects of the development of the supercritical inflow conditions upstream of hydraulic jumps on the free-surface motions (Felder et al. 2021b) and linked the previously reported scatter in hydraulic jump data to missing considerations of the jump toe motions (Li et al. 2021c). Comparative analyses of the LIDAR observations with data from acoustic displacement meters and wire gauges showed that the LIDAR data provided similar elevations when all elevations were adjusted to the jump toe location measured with the LIDAR sensor (Li et al. 2021c). A comparison of characteristic air-water flow elevations measured with an air-water phase-detection intrusive probe showed that the mean elevations measured with the LIDAR sensor correspond to the location with the maximum number of air bubbles in the flow column at an elevation with air concentrations of 50% (Montano 2019, Li et al. 2021a). This agreement between elevations recorded with the LIDAR sensor and the phase-detection intrusive probe is important for the consistent interpretation of the free-surface elevations across any air-water flow.

While this research was focussed on classical hydraulic jumps, Li et al. (2021a) and Modra et al. (2018) used LIDAR technology to record the free-surface elevations and fluctuations of a hydraulic jump in a stilling basin with and without super-cavitating blocks. Li et al. (2021a) showed that a single 2-dimensional LIDAR sensor can be used to create a free-surface map of the mean elevations illustrating the three-dimensional motions of flow within a stilling basin. Such free-surface maps can be used for improved stilling basin design since they can show potential asymmetry in the flow behaviour within a stilling basin.

LIDAR technology was also tested in aerated flows on a stepped spillway (Kramer et al. 2019) highlighting the general suitability of LIDAR technology to record the elevations and other free-surface properties in high-velocity air-water flows. The measured elevations were consistent with the characteristic air-water flow depth with 50% air concentration measured with an air-water phase-detection intrusive probe. These observations suggested the general suitability of LIDAR devices to remotely measure the internal air-water flow properties. This aspect was further explored by Li et al. (2022) and Li (2022), who introduced an angle correction method for observations of air-water flows on a spillway with bed macro-roughness (Figure 1b) which enables the recording of free-surface properties on spillways irrespective of the positioning of the LIDAR sensor.

In parallel, Li et al. (2021b) used the same LIDAR device to record the flow profiles upstream and downstream of a low-head weir in the field during a 48-hour overtopping event (Figure 1c). The LIDAR was able to record the upstream non-aerated flow depths due to the strong turbidity of the water and free-surface ripples enabling a remote gauging of water level and flow rate. Downstream of the weir, the LIDAR device was used to capture the highly three-dimensional aerated flow motions (Li et al. 2021b).

Considering these extensive LIDAR tests on a range of air-water flow phenomena in hydraulic structures engineering, LIDAR technology appears to be well suited for use in both hydraulic laboratory settings and field situations to provide advanced engineering design capabilities for hydraulic structure design prior to construction or for the upgrade of an existing structure. The research at the UNSW Water Research Laboratory has now advanced to a stage where LIDAR technology is ready for testing on larger scale hydraulic structures.

Video observations in hydraulic structures engineering

Visual documentation of flows in hydraulic structures has been conducted for decades and has become ever more common and sophisticated with the evolution of camera and mobile phone technology. In recent years drone-based camera use has also become popular. Most of the documentation of spilling events of dams have however been qualitative (Figure 3a) without the objective of documenting the flow processes quantitatively for engineering design or improvement of the understanding of the flow behaviours and processes.

In contrast, photography and video-based observations of flow phenomena in laboratory settings have been more targeted towards the understanding of flow patterns (Figure 3b and c) and the quantitative documentation of flow processes. In non-aerated flows, the use of particle image volumetry (PIV) has become a standard method to measure the non-aerated flow velocity fields and associated turbulence properties including in hydraulic structures engineering (e.g., Amador et al. 2006, Lennon and Hill 2006). In fully aerated flows, PIV is not suitable and bubble image velocimetry (BIV) has been applied through the glass sidewall of laboratory channels to record the flow velocity fields in hydraulic jumps (e.g., Leandro et al. 2012) and of spillway flows (e.g., Bung 2011).

More recently, researchers have implemented optical flow methods through the sidewall to observe the flow field and air concentration distributions of spillway flows (Bung and Valero 2016; Kramer and Chanson 2019) and in hydraulic jumps (Kramer and Valero 2020). While BIV and optical flow methods provide improvements to the characterisation of the velocity fields, both methods have been applied through the sidewall which itself affects the velocity distributions due to the presence of a sidewall boundary layer. Furthermore, the use of sidewall images is not practical for observations of flow processes in prototype structures.

Figure 3. Photos of air-water flow phenomena in field and lab: (a) Air-water flows on spillway of Manly Dam, NSW, Australia in February 2020; (b) side-view of air-water flow processes on spillway (video sequence used for optical flow analysis); (c) side-view of hydraulic jump in the laboratory

Promisingly, researchers have recently explored the measurements of free-surface velocity fields with camera technology from a top-view perspective. Bung et al. (2021) used a stereoscopic camera positioned above the flume to record the free-surface profile of hydraulic jumps in the laboratory, while Macian-Perez (2020) used a LIDAR camera from top-view to measure the hydraulic jump profile in a fully aerated stilling basin model. These attempts suggest that camera technology from a top-view perspective may offer new opportunities for physical hydraulic modelling of energy dissipation basins.

In high-velocity air-water flows on spillways, Kramer and Felder (2021) piloted the use of high-speed camera technology from top-view for the recording of free-surface velocities. In a comparative study with air-water phase-detection intrusive probes in a laboratory flume, they showed that a camera from top-view may be able to measure the flow depth and flow velocities enabling the estimation of flow resistance and energy dissipation. Using a drone-based video of the spilling Hinze Dam, Australia, Kramer and Felder (2021) highlighted new opportunities for remote sensing of the velocity fields in prototype spillways, demonstrating that it is possible to measure the inception point location, the free-surface velocities and the residual energy at the downstream end of the spillway. Chanson (2022) used videos from downstream of Hinze Dam for the analysis of free-surface characteristics in prototype spillway flows, confirming the earlier observations of Kramer and Felder (2021).

Opportunities of remote sensing of flows across prototype hydraulic structures

As outlined, in the previous two sections, there have been substantial new developments in instrumentation suitable for remotely measuring key flow properties in air-water flows in hydraulic structures including surface elevations, flow velocities and other parameters. Opportunities to remotely measure free-surface motions with LIDAR devices have been demonstrated for classical hydraulic jumps, hydraulic jumps in stilling basins and air-water flows on spillways at laboratory scale and low-head structures and river rapids in the field. The suitability of top-view video-based instrumentation has been demonstrated for making observations and measurements of flow behaviour on spillways and in hydraulic jumps in the laboratory as well as on one prototype structure. The laboratory-based studies have been conducted systematically, using validation against other instrumentation, previous studies, and fundamental theories. All research has been published in high-quality journals with a robust peer-review process providing confidence in the new state-of-knowledge for the use of such remote sensing technologies for physical hydraulic modelling and field observations of flows in hydraulic structures.

In a next step, remote sensing technologies must be systematically explored at prototype scale on spillways and energy dissipators to confirm the results from the laboratory in flows at larger scale and with larger Reynolds numbers. Figure 4 illustrates potential installation locations for fixed LIDAR devices or fixed cameras for the monitoring of the flows across a large spillway with a downstream stilling basin. The LIDAR SICK LMS511 sensor is suitable for distances of up to 80 m. For larger distances, an alternative LIDAR sensor would need to be used (e.g., SICK LIDAR MRS6000 with a range of up to 200 m). In addition to measurements with cameras and LIDAR devices at fixed sampling locations, both video and LIDAR-based observations with drones could provide additional flow observations at all desired locations during an actual spilling event (Figure 4).

Fixed installations of LIDAR devices and cameras are more reliable since drone-based observations require the presence of a drone pilot as well as permissions for drone flights. In addition, drones can only fly in favourable weather conditions. Fixed LIDAR devices and camera installations will initially require some manual handling, but they can ultimately be set up to be operated remotely. A substantial disadvantage of camera-based observations is that these will not work during rain events and darkness. In contrast, LIDAR devices can operate during both day and night. The 48-hour continuous field test by Li et al. (2021b) showed that the LIDAR LMS511 sensor is unaffected by rain and can collect equally good data during rain and dry periods. Measurements of air-water flows in laboratory settings show that the laser pulses emitted by the LIDAR sensor are reflected by air bubbles entrained into a water phase and not by droplets alone. However, unrelated research of the effects of rain on the quality of the performance of LIDAR devices has shown that heavy rain with large drops can affect the signal quality (Ryde and Hillier 2009; Filguira et al. 2017) and systematic testing of the operation of LIDAR devices in prototype spillways and energy dissipators is needed under a range of weather conditions to identify any weather-related limitations. Similarly, spillway flows on large dams create strong mist, and any adverse effects of mist on reliable measurements of the flow properties need to be investigated.

Remote sensing of prototype flows will have many advantages that are currently not available to design experts of hydraulic structures. The capability of the LIDAR to record instantaneous elevation profiles continuously from a safe distance provides valuable information about flow processes in the real-world structure including spatial distributions of free-surface elevations, free-surface fluctuations and jump toe motions. This information is critical for the design of stilling basins including training wall and side wall heights, stilling basin length, as well as to better understand the hydraulic jump toe stability and overall hydraulic jump behaviour. Herein, prototype observations could provide dam owners with real-world information on how the flood release and energy dissipation structures perform under flood conditions less than the design standard and could flag potential aspects of concern should a larger flood release event occur one day. At the same time, prototype observations can provide invaluable validation data for numerical and physical models. For example, should a dam be considered for refurbishment, prototype observational data from that dam could be used to validate physical and numerical models during the investigation process for establishing the feasibility of upgrading an existing discharge facility. More generally, prototype data are needed to better understand the significance of scale effects which would benefit all operators and designers by improving the reliability of physical and numerical model predictions.

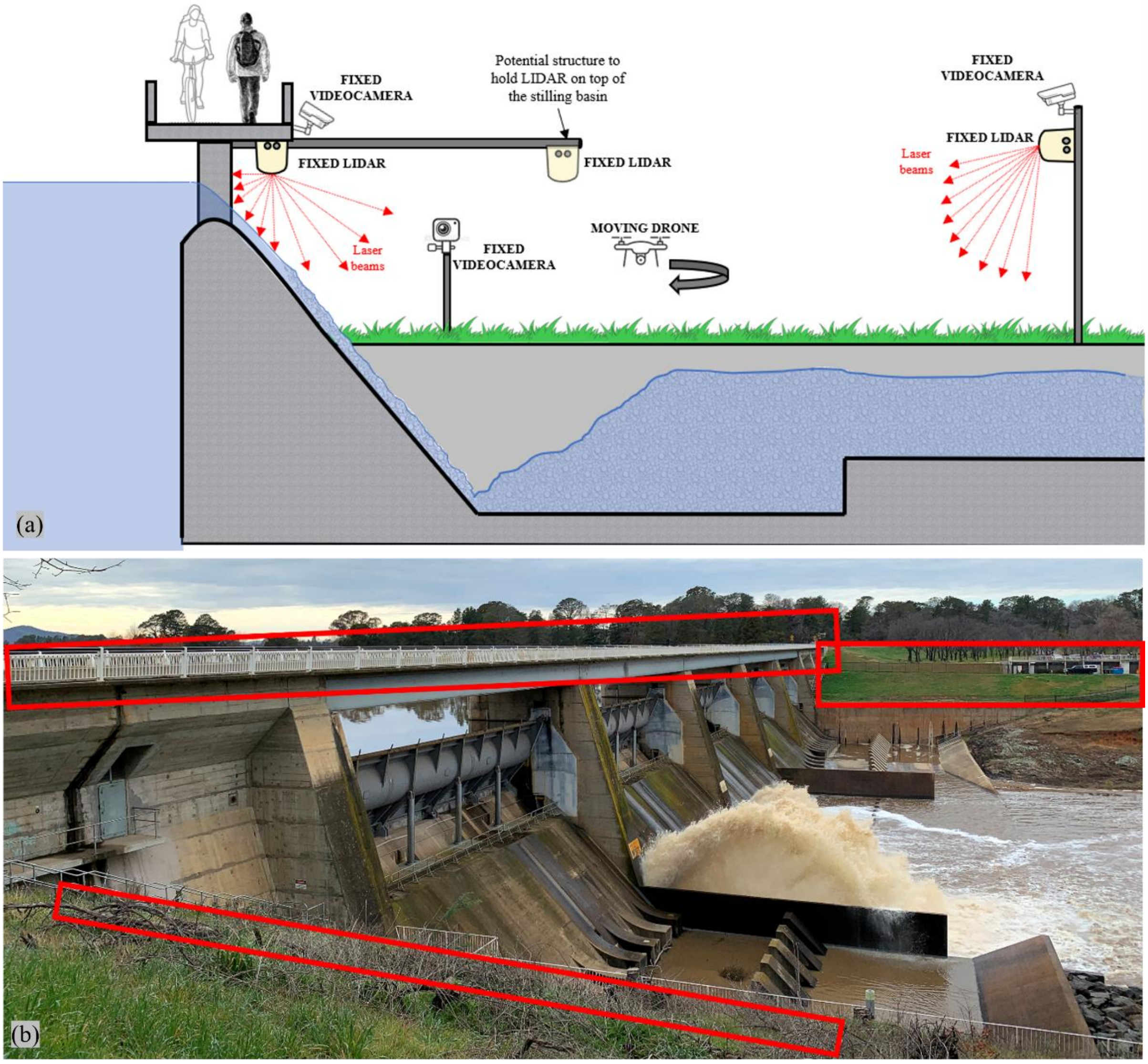

Figure 4. Positioning of LIDAR devices and video cameras for remote sensing in prototype hydraulic structures (a) Conceptional sketch of dam with possible fixed installation locations and drone operation (not drawn to scale); (b) Potential fixed installation location (red boxes) on Scrivener Dam, ACT, Australia.

Remote sensing of prototype structures potentially provides a valuable tool for assisting with the management of the safety of dams and flood release facilities. The use of stationary cameras and LIDAR devices could be combined with the monitoring of the structures when not exposed to floods (e.g., structural monitoring) as well as for the monitoring of flow behaviour and performance during flood events. Combining these observations with a decision support system could provide an enhanced level of safety which could alert dam operators of any adverse flow performance of the hydraulic structure. For example, if remote monitoring devices with an associated decision support system had been installed on the Oroville Dam spillway (France et al. 2018), the initial changes in flow patterns that occurred on the spillway when the erosion of the spillway started could have triggered an alarm to the relevant authorities to allow the earliest possible intervention in such an adverse event.

In contrast to flow observations in controlled conditions in the laboratory, remote sensing of flows in prototype structures requires the spilling of a dam. Such events may be sporadic and cannot be reliably predicted unless a controlled release occurs. Often a spilling event coincides with extreme weather and flood conditions and a dam site might not be accessible. Therefore, the use of permanently installed stationary cameras and LIDAR devices is preferred. These devices can be installed and operated as standard dam safety equipment that allows routine structural health monitoring as well as quantitative flow observation in case of a spilling event. This will ensure that the remote sensing devices are fully operational and routinely maintained. Drone-based observations are however more dependent on the weather conditions and can only be conducted when it is safe. Often a dam spills for several days after a flood event and drone-based observations could be conducted when the weather permits.

Ultimately remote sensing of flows across hydraulic structures may become a key component for the hydraulic design of water infrastructure. While the current practice is based upon numerical and physical modelling which are underpinned by fundamental fluid mechanics theory and hydraulic principles, quantitative prototype observations may become an overarching new pillar that can not only validate the physical and numerical models but can also support our general understanding of the fundamental flow processes that underpin the hydraulic design in the first place.

Conclusions

Dams are aging worldwide, and dam owners and engineers will remain occupied to upgrade these aging dams for a new reality of potentially stronger flood situations due to climate change. At the same time new dams will be required for pumped storage, hydroelectricity, flood mitigation and water supply. A sustainable design requires state-of-the-art technology to improve the safety of the structure. Current design practice is based upon physical and numerical modelling. However, prototype validation data are missing that would confirm design assumptions and which could be used to enhance the safety of the hydraulic design.

Prototype observations with remote sensing technology such as LIDAR and video-based observations can provide new opportunities for continuous measurements with high spatial and temporal resolution that would provide new quantitative information of the prototype flows. This has been successfully demonstrated in various laboratory applications with spillways and hydraulic jumps as well as in field applications on a low-head weir. Remote sensing with LIDAR devices and cameras provides new opportunities for prototype observations (1) that could provide currently missing validation data for physical and numerical models, (2) that could provide important new insights into fundamental flow processes, (3) that could allow for real-time continuous monitoring of flows across dams with potential connection to decision support systems, and (4) that could provide a new important tool for the design of hydraulic structures that will ultimately contribute to the safer and more efficient design of hydraulic structures.

Remote sensing in hydraulic structures engineering has currently untapped potential that should be explored by dam owners and hydraulic engineers alike. Considering that instrumentation and computing possibilities will further evolve in future, the importance of remote sensing technologies will increase and there will be enormous opportunities ahead for the hydraulic structures profession. These new opportunities should be embraced to ensure more sustainable and safe design of hydraulic structures.

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Appendix A

Despite the importance of validation data, prototype measurements in large-scale hydraulic structures have been limited (Table 1). Milestone measurements of air concentration and velocities were conducted on Aviemore Dam spillway in New Zealand by Keller (1972) and Cain (1978). Subsequent prototype measurements during the 1980$^{\text{'s}}$ failed to provide any more advanced prototype data compared to the earlier Aviemore Dam spillway measurements (Table 1). Only recently, Hohermuth et al. (2021) were able to provide novel air-water flow data in the tunnel chute of the 225 m high Luzzone Dam in Switzerland. In two measurement campaigns, Hohermuth et al. (2021) were able to measure air concentrations, interfacial flow velocities and bubble and droplet sizes under extreme flow conditions with interfacial velocities of up to 40 m/s and Reynolds numbers up to 2.4×10^7. This data set highlighted that the air concentration distributions and important design parameters can be scaled between large laboratory models with Re ~ 10^5 up to prototype structures with Re ~ 10^7. However, intrusive air-water flow measurements are complex and cannot be repeated easily. Instead, other means are needed that can provide reliable and safe alternative measurements of prototype flows such as remote sensing technologies.

Table 1. Measurements of flows in prototype hydraulic structures (adapted from Hohermuth et al. (2021))

Reference	Hydraulic structure	Location	Instrument	Variable measured
Keller (1972) Cain (1978)	Spillway	Aviemore Dam, New Zealand	Pressure & air concentration probe	Air concentration Velocities
Volkart and Rutschmann (1984)	Tunnel spillway	Grande Dixence, Switzerland	Conductivity probe Pitot tube	Air concentration Velocities
Pujol et al. (1985), Vernet et al. (1988)	Spillway with aerators	Alicura Dam, Argentina	Flat plate capacitor	Bottom air concentration
Aivazyan (1986)	Spillway	Ak-Tepe, USSR		Measurement of water saturation coefficients and velocities
Hohermuth et al. (2021)	Tunnel spillway	Luzzone Dam, Switzerland	16 double-tip conductivity probes	Air concentration Interfacial velocity Droplet sizes and numbers
Kramer and Felder (2021)	Stepped spillway	Hinze Dam, Australia	Drone video	Inception point Free-surface velocities
Chanson (2022)	Stepped spillway	Hinze Dam, Australia	Video camera	Inception point Free-surface velocities