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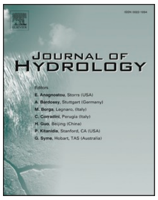

Research papers

Flume experiments reveal how beaver dam characteristics influence pond depth regulation

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ABSTRACT

Beavers act as 'ecosystem engineers' by altering watercourses through dam construction. These structures are often associated with potential hydrological benefits, including flood attenuation and drought mitigation. Previous research has largely focused on the general hydrological response of beaver dam systems, often treating the dam as a 'black box' without sufficiently considering how specific dam characteristics may influence different hydrological outcomes. This study presents the results from a systematic series of controlled laboratory testing using a hydraulic flume and model beaver dams to investigate the effects of dam type, breach area, and discharge on steady-state pond depth. The model dams were designed to encompass the range of dam types and breach areas commonly observed in natural beaver dams, as reported in previous field studies. The results revealed a diverse range of pond depth responses across the four dam types examined. In general, dam type exerted a greater influence on pond depth under conditions of low discharge and high breach area, while its impact was minimal under conditions of high discharge and low breach area. The findings demonstrate that beaver dams have the capacity to mitigate against flooding; however, this effect is variable and strongly dependent on dam type. These findings underscore the importance of considering dam type, breach area, and discharge as critical variables in assessing the hydrological effects of beaver damming, particularly in relation to mitigation of hydrological extremes.

1. Introduction

1.1. Background

Beavers act as 'ecosystem engineers' by modifying their surrounding landscape and ecosystem (Brazier et al. 2021). To create hydrological stability, they build dams on streams and rivers using woody material, stones and compacted mud. These dams raise the upstream water level, creating ponds and wetlands that provide a safe habitat from predators and access to food (Wright et al. 2002, Rozhkova-Timina et al. 2018, Brazier et al. 2021, Benke and Wallace 2010).

Beaver ponds have a positive impact on the surrounding habitat and ecosystem, predominantly through enhancing habitat heterogeneity and resultant biodiversity (Wright et al 2002, Law et al. 2019, Orazi et al. 2022). They also provide benefits for human society; for example, it has been estimated that the nature-based solutions offered by beaver dams are worth "millions to hundreds of millions of US dollars annually" (Thompson et al. 2021). They provide water storage and flow attenuation during stormflow, allowing for the slow re-release of excess floodwaters (Puttock et al. 2021, Graham et al. 2022). Furthermore, the increased water storage the dams provide can be particularly beneficial during drought (Karran et al. 2018, Westbrook et al. 2006, Hood and Bayley 2008) or wildfires (Fairfax and Whittle 2020).

In recognition of the positive effects of beaver activity, beavers have been translocated and reintroduced throughout much of their former range (Coz and Young 2020, Pettorelli et al. 2018, Halley et al. 2021). As beaver populations increase and their dams become increasingly commonplace in the landscape, it is vital to understand the hydraulic and hydrological implications of these structures for the watercourses and surrounding land on which they are built. An improved understanding of how the physical structure of the dam affects fundamental stream properties such as flow/pond depth and corresponding parameters such as pond size, inundation area and water storage are especially important if beaver dams are to be utilised as nature-based solutions.

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1.2. Beaver dams and flood attenuation

Several studies have demonstrated the positive effect beaver dams can have for flood-attenuation. Nyssen et al. (2011) conducted a comparative study on a site containing six beaver dams in series, both before and after the dams had been built. The results show clear evidence of flood peak attenuation due to the presence of the dams, with an increase of flood recurrence interval for major floods of more than 50 % and delaying flood peaks by up to one day. Puttock et al. (2017) and Puttock et al. (2021) also provide strong evidence that beaver dams can attenuate storm flows based on measuring flood discharges up- and downstream of beaver sites. Westbrook et al. (2020) demonstrated the potential of a series of beaver dams and ponds to delay downstream floodwater transmission, based on data collected for the largest recorded flood in the Canadian Rocky Mountains west of Calgary, Alberta.

However, despite it being generally recognized that beaver dams can aid in mitigating flooding, there has been some discussion regarding the extent to which this occurs, particularly for large flood events (Larsen et al. 2021). Neumayer et al. (2020) used a 2D hydrodynamic numerical model to show that beaver dams do not noticeably attenuate discharges or mitigate against flooding for events with return periods above 2 years (floods that have a 50 % chance of annual occurrence). Furthermore, Westbrook et al. (2020) provided evidence that the effectiveness of flood delay is determined by initial conditions, such as pond fullness. These contrasting findings highlight the complexity and variability in the hydrological response of beaver-dammed streams to high flows. To disentangle this discussion, there is a need to fully understand how a dam's physical characteristics can influence pond depths and dynamics under a wide range of flow conditions.

1.3. Beaver dam flow mechanisms

Beavers often strive to make the upstream face of their dams impermeable using compacted mud and sediment (Muller and Watling 2016, Nyssen et al. 2011). Although achieving full impermeability is unlikely, well-maintained beaver dams are often impermeable enough to block a significant portion of the stream discharge. Consequently, just as with a sluice-gate or spillway for a human-made dam, there must be a mechanism that allows flow to bypass the structure. Woo and Waddington (1990) categorised beaver dams into four main types in terms of flow mechanisms based on field observations: Overflow (water flows over the top of the dam – Fig. 1a), Gapflow (water flows through a gap at the top of the dam – Fig. 1b), Underflow (water flows through a hole at the base of the dam – Fig. 1c) and Throughflow (the dam is permeable, allowing water to flow through the entire dam face – Fig. 1d).

It is important to note that dam type is not a fixed property and can be related to the degree of beaver activity, with dams transitioning between dam types over time and throughout their lifecycle (Woo and Waddington 1990).

Ronnquist and Westbrook (2021) developed this work by conducting a survey of 162 dams over 19 sites in the Canadian Rocky Mountains, Alberta. Each dam was characterised in terms of its flow mechanism based on Woo and Waddington (1990), with two further dam types identified: Seep and Mixed. Seep is where there is no detectable surface flow mechanism through the dam, so it is assumed that downstream flow is maintained via groundwater. Mixed is where there is more than one main flow mechanism observed. A key part of this study involved measuring the breach area, defined as the total surface area in the dam face that allows water to flow through, for each dam type. This work emphasised that structural differences between dam types influenced hydrological effects and led us to use dam type as the template for the present experimental study.

1.4. Hydraulic equations for human-made flow-control structures

A useful starting point when evaluating the hydraulic response of beaver dams for different dam types is to consider standard hydraulic equations that are widely used to describe human-made flow-control structures. These could potentially serve as analogies for certain types of beaver dams. Several equations have been developed which provide the relationship between discharge and flow depth for such structures.

Flow over a rectangular weir can be described using the Weir Equation (Chadwick et al. 2013):

$$Q = \frac{2}{3} C_D \sqrt{2g} B H^{1.5} \tag{1}$$

where Q is discharge (m^3/s), C_D is the coefficient of discharge (−), g is acceleration due to gravity (m/s^2), B is the weir/channel width (m) and H is the height of the fluid above the weir crest (m).

The Orifice Equation can be used to describe discharge through a circular hole at the base of a tank or dam, where the hole is fully submerged (Chadwick et al. 2013):

$$Q = C_D A \sqrt{2gH} \tag{2}$$

where A is cross-sectional area (m^2) and H is the height of the fluid above the centre of the orifice (m).

Finally, Darcy's law can be used to describe the flow of water through porous medium or a porous dam (Darcy 1856):

$$Q = KA\left(\frac{\Delta H}{L}\right) \tag{3}$$

where K is hydraulic conductivity (m/s), L is length of the flow (m) and ΔH is the difference in hydraulic head (m) across the length of flow, L.

Using these equations as a starting point, the impact of different structural types of beaver dams on the relationship between pond depth and discharge can potentially be predicted.

1.5. Previous laboratory work on beaver dam hydraulics

McCullough et al. (2007) constructed a replica beaver dam in a laboratory flume with the dam's shell constructed out of smooth plywood, with branches from a real beaver dam attached to the downstream side. The dam was 2.85 m high and was installed in a flume that was 0.91 m wide. The dimensions were based on survey data of a real beaver dam and were full scale, except for the width, which was limited by the flume dimensions. Discharges were investigated in the range 0.014 to 0.11 m^3/s. Tests were conducted firstly with the plywood shell

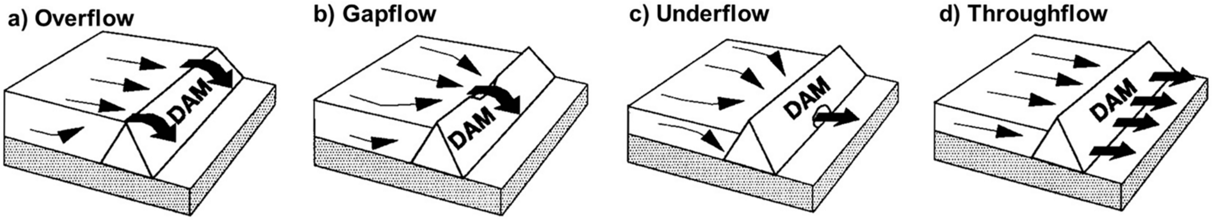


Fig. 1. Diagram representing the four main types of beaver dam.
Reproduced from Woo and Waddington (1990).

of the dam as a control, and then with the beaver dam branches attached. Results showed that the rating curves for both the replica dam and the control dam could be described by the Weir Equation (Eq. (1)), with a small but non-negligible decrease in the coefficient of discharge with the branches in place ($C_D = 0.572$ for the control and $C_D = 0.545$ for the replica beaver dam).

Muller and Watling (2016) tested two model beaver dams to assess the permeability and stability of dam structures. The first was formed from a collection of woody branches, sealed with clay to make the upstream dam face impermeable with a small hole at the base to allow water to pass through. The dam was 0.45 m high and was installed in a trapezoidal flume 2.5 m wide. Discharges investigated ranged from 0.031 to 0.129 m^3/s. It was found that the flow through the dam could be modelled using Darcy's law (Eq. (3)) and that the dam's hydraulic conductivity was $K = 0.67\,m/s$. The second test assessed a dam comprising a combination of rocks and branches, to investigate dam stability. The dam was 0.2 m high and installed in a 0.3 m wide flume. They found that a dam built of stones alone failed at a relative discharge of 0.06 m^3/s per meter width, but with the addition of wooded branches as internal reinforcement, the failure flow increased to 0.53 m^3/s per meter, whilst the addition of wooded branches as props on the downstream face of the dam stabilised it to 0.88 m^3/s per meter.

1.6. Research question

From the literature, a significant number of studies have observed beaver effects from a broad hydrological perspective. However, few studies have assessed the mechanisms supporting the hydrological changes i.e. how the physical structure, condition or specific dam type affects fundamental stream properties from a hydraulic perspective. Furthermore, despite previous flume studies, no previous work has systematically investigated the influence of the range of common dam types.

To address this gap, the objectives of this paper are to investigate if beaver dam type has a substantive effect on pond depth and if standard hydraulic equations can predict these effects. This will determine the degree to which dam type needs to be accounted for in future hydrological modelling.

To accomplish these objectives, a systematic experimental program was undertaken to test a range of beaver dams in a laboratory flume. We use pond depth as the primary response of the system to discharge, but more generally, this can be considered roughly analogous to pond size, inundated area, or water storage volume.

2. Methodology

2.1. Overview and concept of the test program

Our experiments were designed to compare how the four main dam types (Overflow, Gapflow, Underflow and Throughflow – Fig. 1) influenced pond depth for a range of breach areas and discharges. This paper focuses on these four primary dam types originally identified by Woo and Waddington (1990); Seep and Mixed types are beyond the scope of the study.

Typical beaver dams can be conceptually split into two main components: a 'structure', primarily made of woody branches for stability (Fig. 2a), and a 'dam face', consisting of compacted mud, vegetation, and sediment designed to make the dam impermeable (Fig. 2b).

The design of the model dams in this study were intended to recreate these two main components with an impermeable dam face on the upstream side that could be manipulated to conform to any of the four main dam types, and a structure on the downstream side to replicate the support branches of a real beaver dam. We acknowledge that natural beaver dam faces will never be completely impermeable. However, the conceptual framework of this study assumes the face to be impermeable, apart from the area of the face that is breached, to experimentally isolate the effect of the theoretical dam type.

2.2. Model dams

2.2.1. Dam design and overflow configuration

The model replica beaver dam (Figs. 3 and 4,) consisted of two main dam components: the dam face and the dam structure. The dam face was made of 10 mm thick impermeable polyester, with 2 mm thick supports running down the sides of the flume to maintain the correct angle (Fig. 4). The dam face was sealed to the side and base of the flume with rubber gaskets to ensure a watertight seal (Fig. 4). The seal was checked prior to each test to ensure it remained watertight. The dam crest was 152 mm high, with both the dam face and structure set at a 45^0 angle to the channel bed. The structure consisted of 10 mm diameter wooden dowels, with an off-set pattern where the gap between each dowel is equal to the dowel's diameter. The orientation of the dowels alternates between the longitudinal and transverse direction for every subsequent row to give the aggregated effect of branches at different orientations. Each dowel in the pattern was attached to the next row with a small plastic clip that was permanently fixed with high-viscosity adhesive (Fig. 4).

Based on the authors' field observations, the pattern and density selected for the structure was considered a reasonable approximation of a beaver dam, to investigate a simplified and easily quantifiable replica that provides a maximum effect scenario in terms of the regulatory influence of the structure on the pond depth.

The dam structure and dam face described in this section constitutes the Overflow dam type, where the entire dam face is impermeable and watertight, so water can only pass by flowing over the dam crest (i.e. it effectively functions as a weir – Fig. 4b). Modifications were then made to the dam face to model Gapflow, Underflow and Throughflow, which are described in Sections 2.2.2 to 2.2.4.

2.2.2. Gapflow configuration

Gapflow dam types were modelled by adding a square notch at the centre of the top of the dam face (Figs. 5 and 6). The notch was designed square as by making length equal to width, breach area could be set by a single dimensional variable.

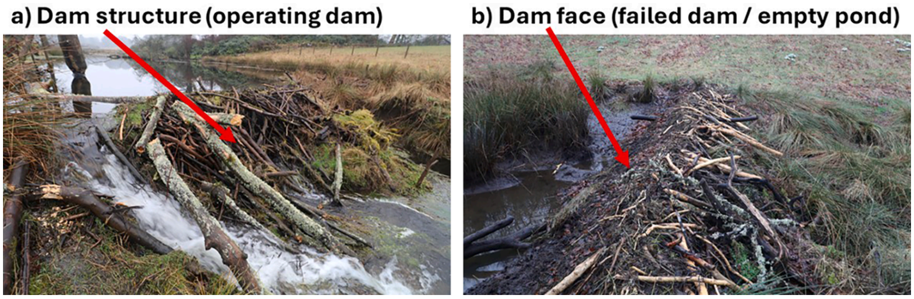


Fig. 2. Examples of beaver dams at Bamff Wildland, Scotland, UK, taken as part of preliminary work to inform the replica dam design for this paper © James Hart.

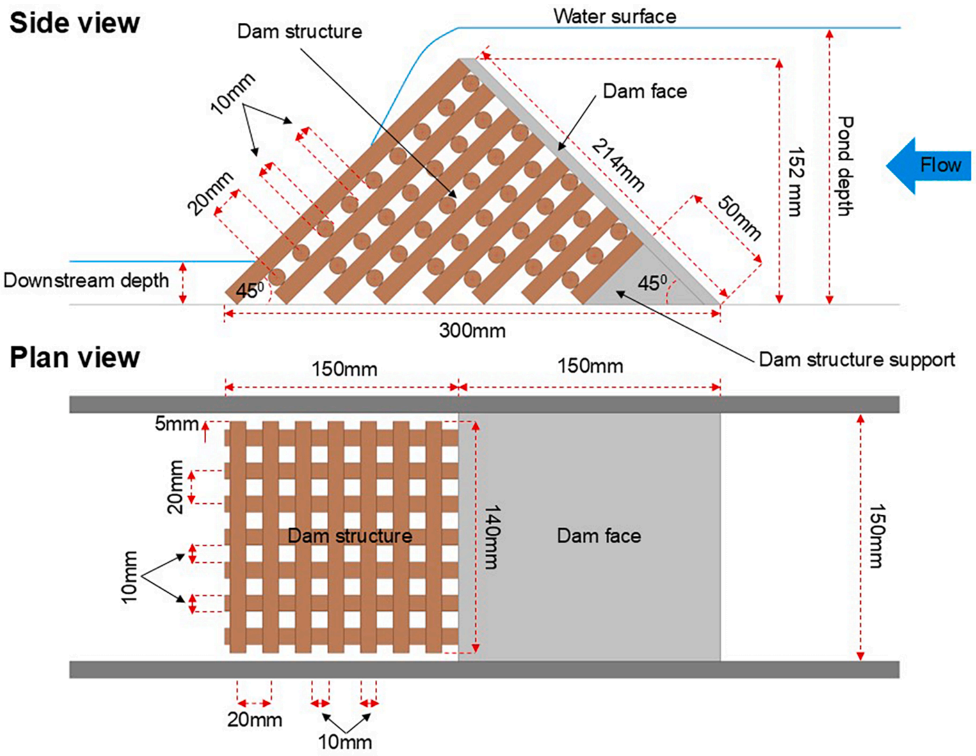


Fig. 3. Schematic of the model dam.

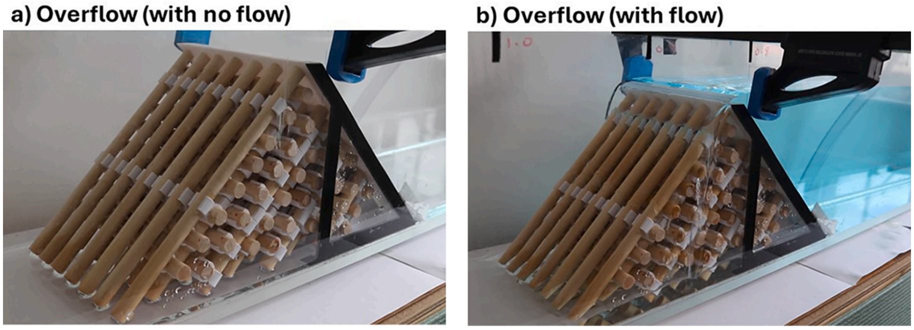


Fig. 4. Photos of the model replica beaver dam showing Overflow configuration. Water flows from right to left.

Three dam breach areas were considered for Gapflow that were intended to represent the minimum (0.25 %), maximum (20 %) and median (1 %) values observed in the field by Ronnquist and Westbrook (2021) (Figs. 5 and 6). These values are the closest to the minimum, median and maximum observed by Ronnquist and Westbrook (2021) that could be physically fabricated on the model dam.

In this study, breach area as a percentage of the dam face was calculated by defining dam height as the height of the dam crest relative to the stream bed (i.e. flume base). This contrasts with Ronnquist and Westbrook (2021), who reported breach areas as a percentage of effective dam height, i.e. the difference in up- and downstream flow depth. This divergence in definition only represents a subtle difference in the breach area calculation. However, this means for the current tests, breach area was a constant value independent of pond depth, which simplifies the presentation and comparison of results.

The different gap sizes could be set using an interchangeable panel (Fig. 6), meaning the dam could be left in place for all tests and the panel swapped without changing any other parts of the experimental set-up. The panel was watertight, so the only place water could pass was either through the notch or by overtopping the dam crest.

2.2.3. *Underflow configuration*

Underflow dam types were modelled with a hole in the centre of the dam face, positioned as close to the base as possible. Three diameters were used to investigate three breach areas (Figs. 7 and 8). Ronnquist and Westbrook (2021) found similar breach area distributions for Gapflow and Underflow, so the breach areas for Gapflow and Underflow were kept consistent for this study i.e. 0.25 %, 1 % and 20 % (Figs. 7 and 8).

The distance that the hole could be placed from the base of the dam face was limited by the dam structure support (shown in Figs. 3 and 7). Therefore, for Underflow, the minimum possible pond depth was 48 mm (Fig. 7). As with Gapflow, the different hole sizes could be changed via an interchangeable panel, that was watertight apart from the breach/hole.

2.2.4. *Throughflow*

Throughflow was modelled by replacing the largest possible area of the dam face with a porous material, where the only parts of the dam face left impermeable were those necessary for structural stability (Figs. 9 and 10).

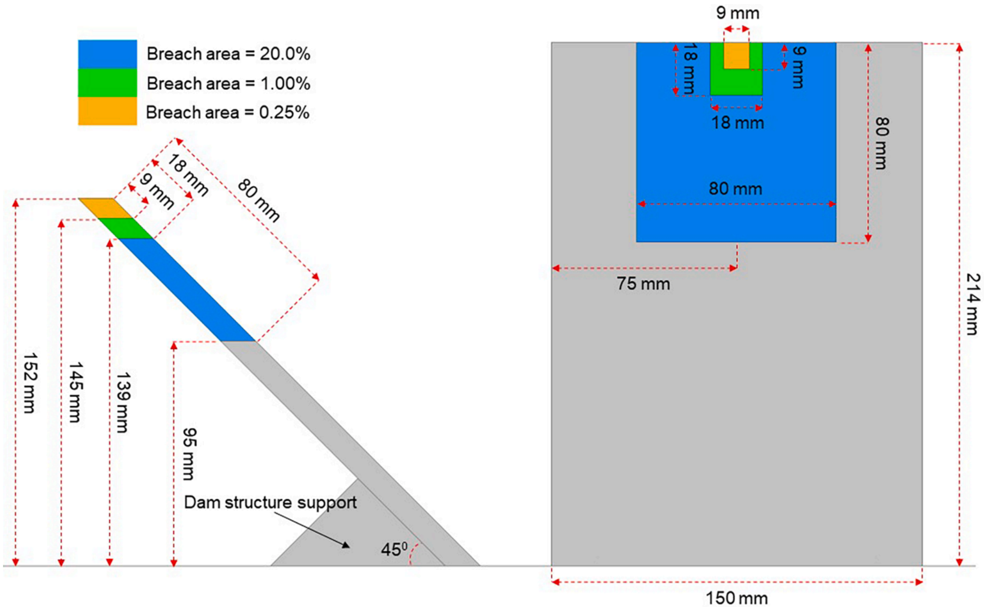


Fig. 5. Schematic of the Gapflow dam face.

a) Breach area = 0.25%

b) Breach area = 1%

c) Breach area = 20%

Fig. 6. Photos of the Gapflow Dam models. Water flows from right to left.

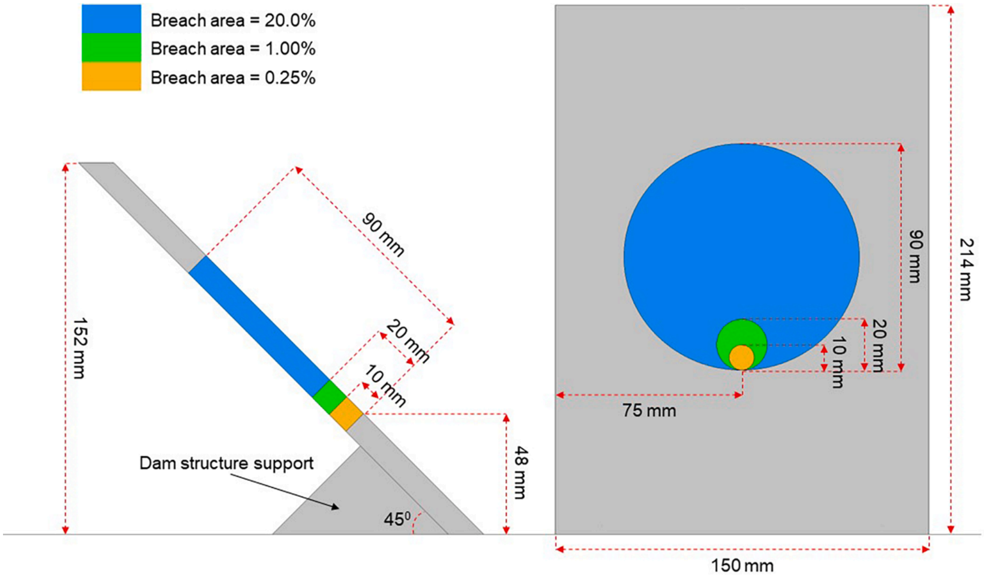


Fig. 7. Schematic of the Underflow dam face.

This dam type is challenging to quantify in the field, as it may exhibit significant spatial and temporal variability at the scale of individual dams. Moreover, no field data on the porosity or permeability of dams is available, either from Ronnquist and Westbrook (2021) or in the broader literature. Consequently, Throughflow is the only case in this study where the scenarios tested were not directly matched to field measurements.

The porous material used was 20 mm thick sheets of Polyester filter/


a) Breach area = 0.25%
b) Breach area = 1%
c) Breach area = 20%

Fig. 8. Photos of the Underflow Dam models. Water flows from right to left.

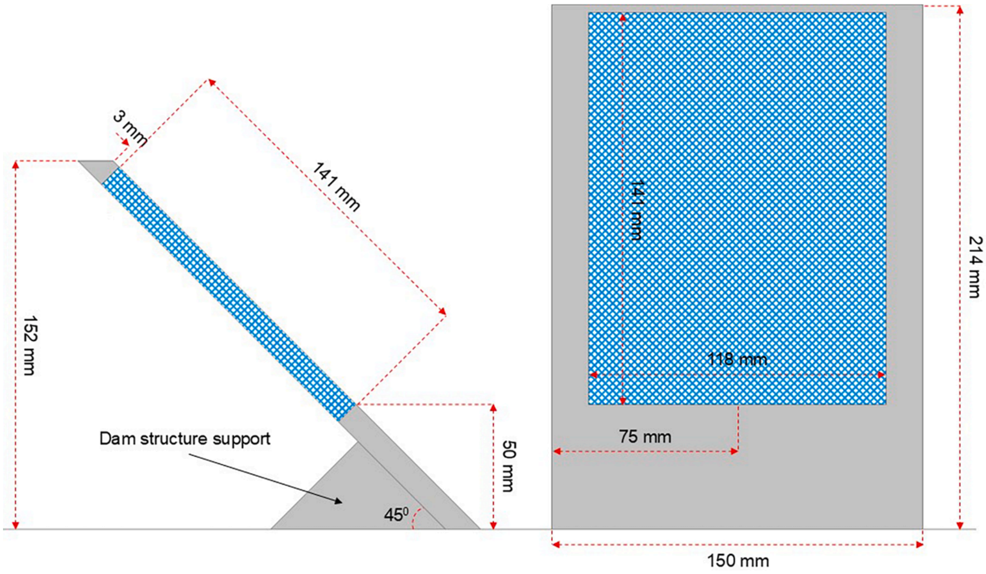


Fig. 9. Schematic of the Throughflow dam face.


a) Porosity = 85%
b) Porosity = 90%
c) Porosity = 95%

Fig. 10. Photos of the Throughflow Dam models. Water flows from right to left.

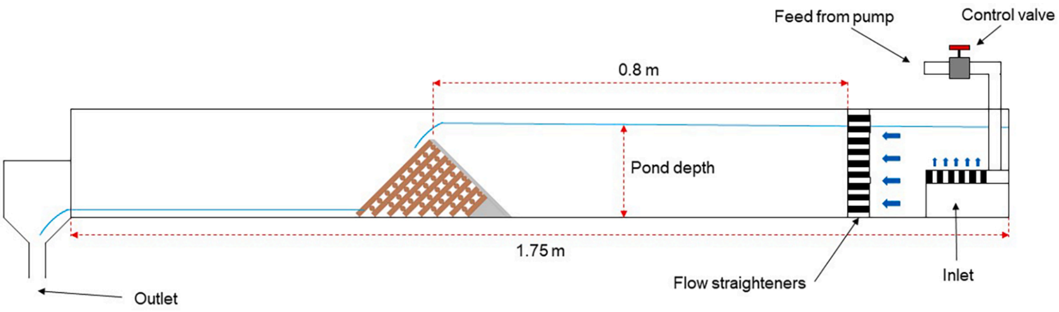


Fig. 11. Schematic of the flume set-up (side-view). Water flows from right to left.

sponge material (Figs. 9 and 10). The porosity (∅) of the three materials were estimated to be 85, 90 and 95 %. Porosity was estimated using the water displacement method, where the material was placed in a known volume of water, with the displaced water indicating the material's solid volume, and corresponding void volume. Porosity was then calculated as the ratio of the materials void volume to total volume. The porous material slotted into a compartment set in the dam face and was held in place with a plastic clip around the material's perimeter which ensured that flow could only occur through the interchangeable face.

2.3. Laboratory measurements and test program

Tests were conducted using a custom-built 1.75 m long, 0.15 m wide, 0.2 m high re-circulating flume (Fig. 11).

For the four dam types tested, a rating curve was produced by measuring the pond depth (flow depth upstream of the dam) at a minimum of five discharges. For some cases, additional discharges were added to ensure sufficient data was recorded in zones of interest. The range of discharges investigated for the model dam was approximately 0.03 to 0.27 l/s, however, limitations in the control valve adjustment resolution resulted in some variation at the range boundaries. The minimum and maximum discharge values have maximum deviations of 0.06 l/s and 0.02 l/s, respectively. Appendix A, Table A1 provides a full overview of the test series.

Discharge for each test was recorded volumetrically and was the average value from three repeat measurements. Flow depth measurements were made using a Vernier point depth gauge (accuracy ± 1 mm). For each test conducted, flow depth measurements were taken every 0.1 m along the flume, providing a full flow depth profile for every test. The dam was located 0.8 m from the flume's inlet. The flow depth was stable and uniform for all tests 0.2 m upstream of the dam, corresponding to a distance from inlet of 0.6 m. The pond depth was calculated as the average depth from readings taken at 0.6, 0.5, 0.4 and 0.3 m from the inlet: locations corresponding to stable flow upstream of the dam. All pond depths are quoted as a percentage of the main dam crest height.

3. Results

3.1. Overview of results

Figs. 12 and 13 demonstrate that dam type can significantly influence the magnitude and range of pond depths, with distinct responses observed for all four dam types. For both Gap and Underflow, the pond depth decreased as breach area increased, with high variability observed for Underflow. Increased discharge predominantly led to minor increases in pond depth (typically 1–5 %) regardless of dam type or breach area. Major increases in depth, as a function of discharge, was only observed for Underflow dam types with 0.25 % and 1 % breach areas, where pond depth more than doubled over the range of discharges tested (Fig. 13).

3.2. Proposed pond depth regulation mechanisms

From our experiments, several distinct mechanisms for regulating pond depth were observed. Based on our findings, we propose the following categories for pond depth regulation:

1. Crest-regulated: Pond depth is above the main dam crest but does not exceed + 10 % of the main dam crest height. In this scenario, the height of the main dam crest is the primary regulator of pond depth. Here, the mid-point of the crest-regulated zone (crest height + 5 %) can be used as a reliable prediction of pond depth, independent of any other parameter. In this scenario, pond depth is effectively independent of dam type.
2. Breach-regulated: Pond depth does not exceed + 10 % of the lowest point of the breach in the dam face (either the base of the notch for Gapflow, the hole for Underflow or the base of the porous section for Throughflow). In this scenario, the height of the lowest point of the breach is the primary regulator of pond depth. Here, the mid-point of the breach-regulated zone (breach height + 5 %) can be used as a reliable prediction of pond depth independent of any other parameter. In this scenario, dam type does influence pond depth, but the effect can be reliably accounted for based on the height of the breach.
3. Discharge-regulated: Pond depth either exceeds + 10 % of the main dam crest or is + 10 % above the lowest point of the breach but still below the main dam crest. This represents a case where discharge is

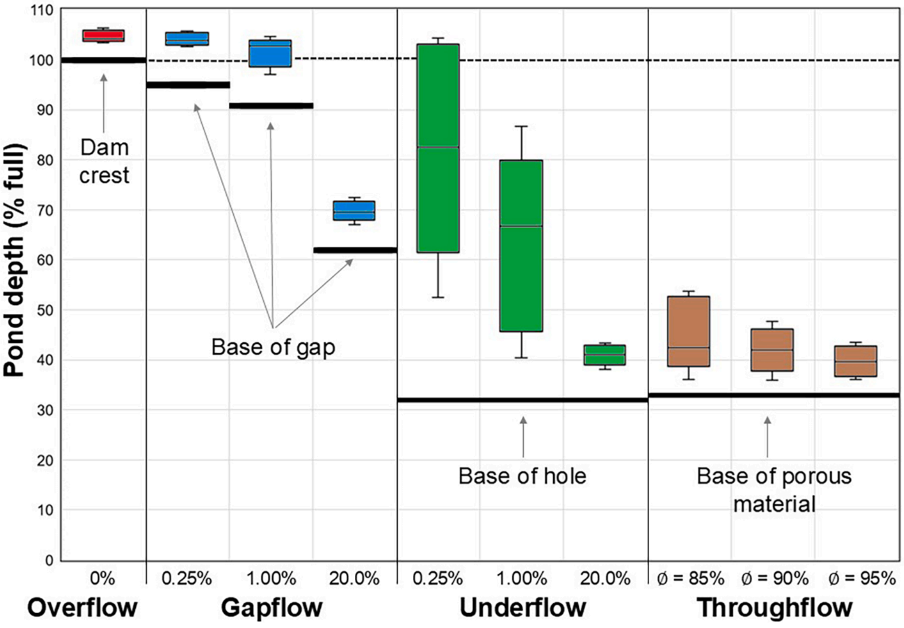
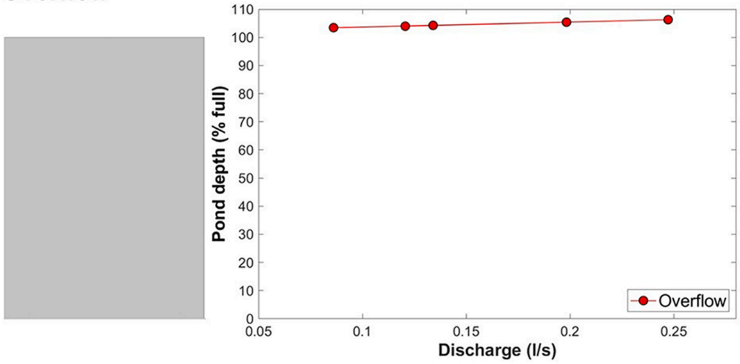
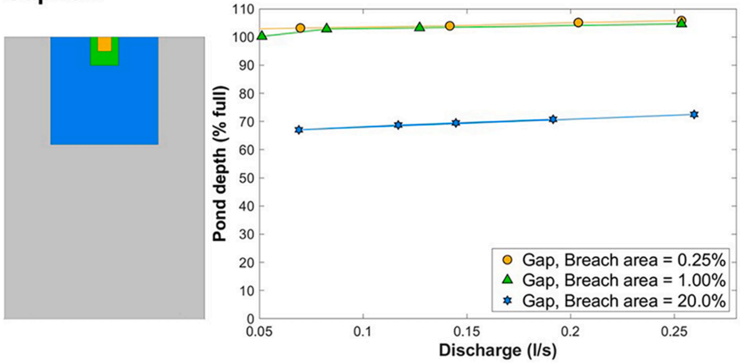


Fig. 12. Range of pond depths recorded for each dam type and breach area across the range of discharges tested.

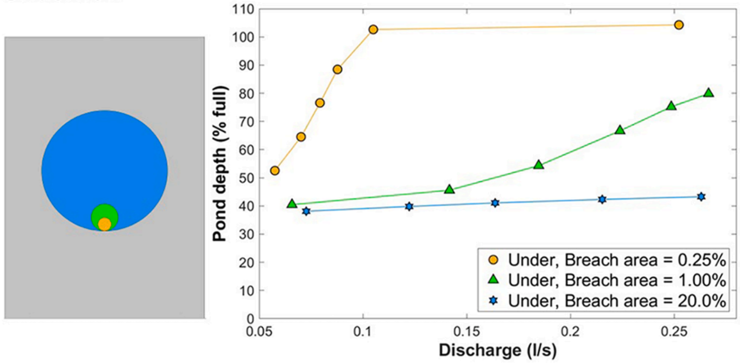
a) Overflow



b) Gapflow



c) Underflow



d) Throughflow

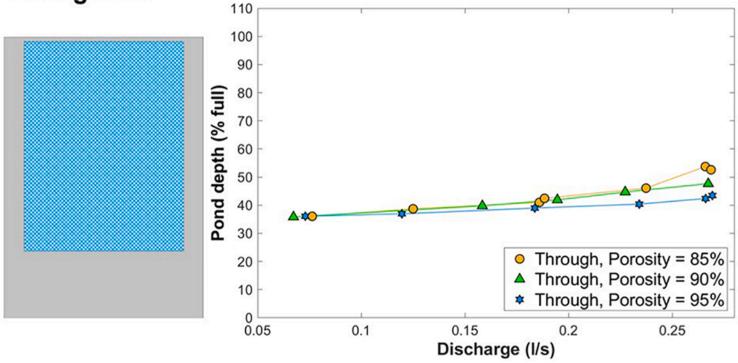


Fig. 13. Rating curves for all dam types and breach areas, with dam height diagrams to scale along the y-axis. Presentation of each individual rating curve including error bars is provided in Figs. 14–23.

the primary regulator of pond depth. Here, as neither the height of the main dam crest or the lowest point of the breach provides reliable indicators of pond depth, the relationship between discharge and pond depth is critical to accurately predicting pond depth. In this scenario, dam type has a significant influence on pond depth, and predicting pond depth now requires an estimation of the discharge-pond depth relationship for the specific system.

Dams exhibit one or a combination of these mechanisms based on dam type, breach area and discharge. Sections 3.3 to 3.6 will consider each mechanism in turn, and conditions under which they were observed. When investigating possible frameworks to predict pond depth, we consider any that predicts pond depth within 5 % as 'good' and within 10 % as 'reasonable'.

3.3. Crest-regulated dams

The Overflow configuration represents a base-case where for the idealized, impermeable model dam face used for testing, all flow must overtop the main dam crest. The degree to which other dam types influence pond depth can be considered in terms of the degree to which they deviate from this. Overflow tests show that for the range of discharges investigated, pond depth has a small range from approximately 103 % to 106 % (Fig. 14a). Thus, Overflow is crest-regulated for the entire range of discharges considered. Assuming pond depth as the mid-point in the crest-regulated zone (crest + 5 %) provides a good prediction of pond depth (error $<$ 2 % across all tests, see Fig. 14b).

Gapflow dams with breach areas of 0.25 % and 1 % both exhibited a similar response to Overflow. For Gapflow (0.25 %), the breach was saturated for all discharges, resulting in the dam being consistently overtopped. Here, there was almost no distinction between the rating curve of Overflow and Gapflow (0.25 %). For this case, assuming the pond depth as crest + 5 % provides a good prediction of pond depth (error $<$ 3 % for all tests, see Fig. 15b).

For Gapflow (1 %), the dam was crest-regulated for all discharges investigated, except for the lowest discharge tested (Fig. 16a). Thus, assuming the pond depth as crest + 5 % provides a good prediction of pond depth (error $<$ 5 % for tests in the crest-regulated range, see Fig. 16b). Despite the lowest discharge being outside of the crest-regulated zone, the prediction of pond depth as crest + 5 % still provided a reasonable estimate (error $<$ 10 %, see Fig. 16b).

The data suggests that for the conditions investigated, Gapflow with breaches $\leq$1 % are likely to be crest-regulated and can effectively be treated as Overflow dams. Here, dam type is having only a minor impact on pond depth. However, the data also suggests that as breach area increases beyond 1 %, this assumption becomes less valid.

The simple framework proposed here, assuming pond depth as crest +5 %, provides a good fit for Overflow, Gapflow (0.25 %), and for Gapflow (1 %). However, it is important to note that above the centre of the crest-regulated zone (pond depths $>$ 105 %), the accuracy of the prediction reduces as discharge increases. This is because even though a good prediction of pond depth can be made in this zone independent of discharge, there is still a positive relationship between pond depth and discharge, meaning eventually pond depth will exceed the threshold for the crest-regulated zone. At this point, the dam can be considered 'discharge-regulated'. In this region, discharge would be the primary regulator of pond depth, and it would be necessary to obtain the relationship between discharge and pond depth to make accurate predictions.

We propose applying the Weir Equation (Eq. (1)) for crest-regulated dams. For the Overflow case, this simply requires a regression analysis using Eq. (1) to obtain the coefficient of discharge. For Gapflow dams that overtop the main dam crest, the prediction is more complex as water is both overtopping the main dam crest but also passing through the gap in the dam face. Therefore, to apply the Weir Equation in a physically valid manner, the flow passing through the gap first needs to be estimated and then separated from the calculation for the main dam crest (Weir Equation (crest), Q adjusted). This was achieved by using a modified version of the Weir Equation, as shown in Appendix B, Eq. B (1).

Whilst Eq. B(1) provides a physically appropriate version of the Weir Equation for the conditions investigated, the disadvantage of this method is that there may be practical limitations to separating the discharges in this way. For example, for uncontrolled settings, such as complex field sites, obtaining the exact measurements needed for this procedure may be challenging. Therefore, a simpler method was also considered where the Weir Equation was applied to the data with no correction (Weir Equation (crest)) which is also shown in Figs. 15a and 16a.

Predictions using the Weir Equation models (Eqs. (1) and B(1)) for all crest-regulated dams are shown in Figs. 14a–16a and the coefficients of discharge and regression parameters are provided in Appendix C, Table C1.

For Overflow, the Weir Equation model provides a good prediction of pond depth (error $<$ 1 % for all tests, see Fig. 14b). For Gapflow (0.25 %) and (1 %), the adjusted Weir Equation (Eq. B(1)) and standard Weir Equation (Eq. (1)) offers similar levels of predictive power (error $<$ 2 % across all tests, see Figs. 15b and 16b). The only meaningful difference between the two methods is the coefficient of discharge, which is larger than would normally be expected for the non-adjusted Weir Equation, as here the coefficient of discharge is essentially compensating for the flow passing through the gap (see Section 4.3 for further discussion on this

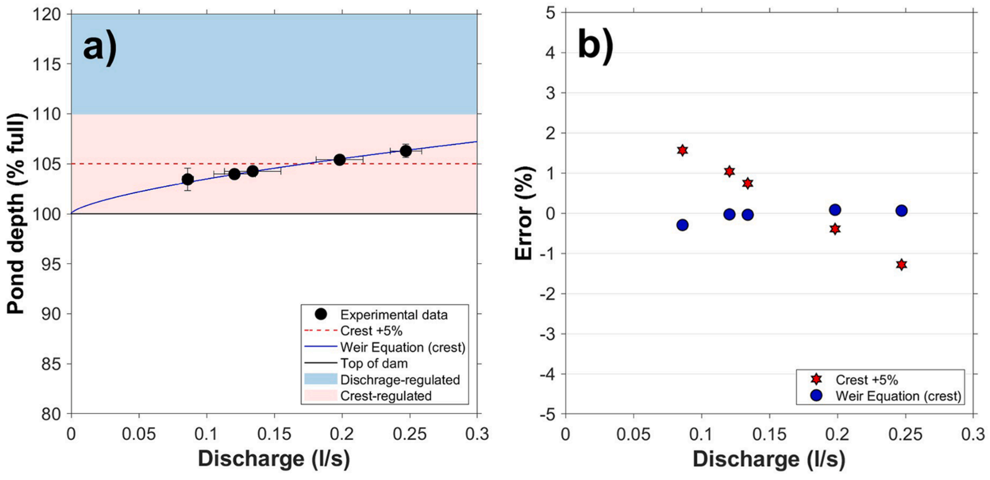


Fig. 14. Overflow results: (a) Rating curve experimental data vs predictions. Error bars = 10σ. (b) Error in predicted pond depth compared to data.

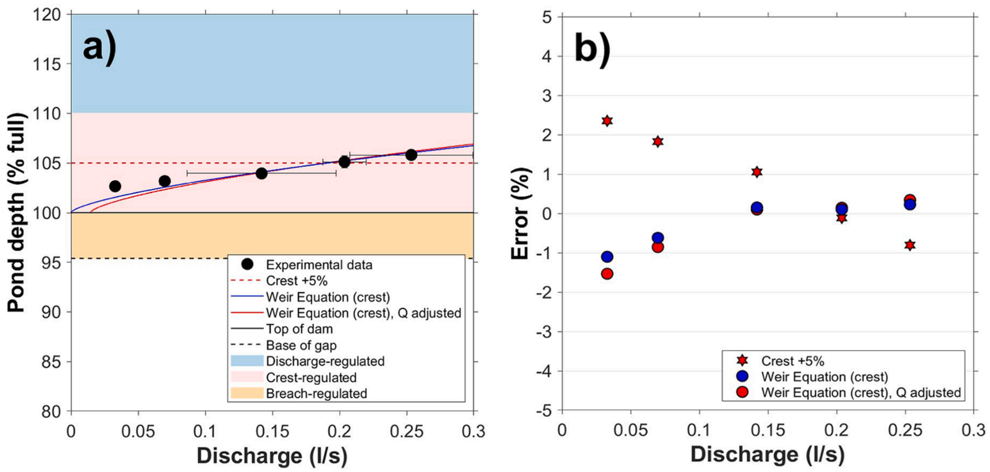


Fig. 15. Gapflow (0.25 %) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

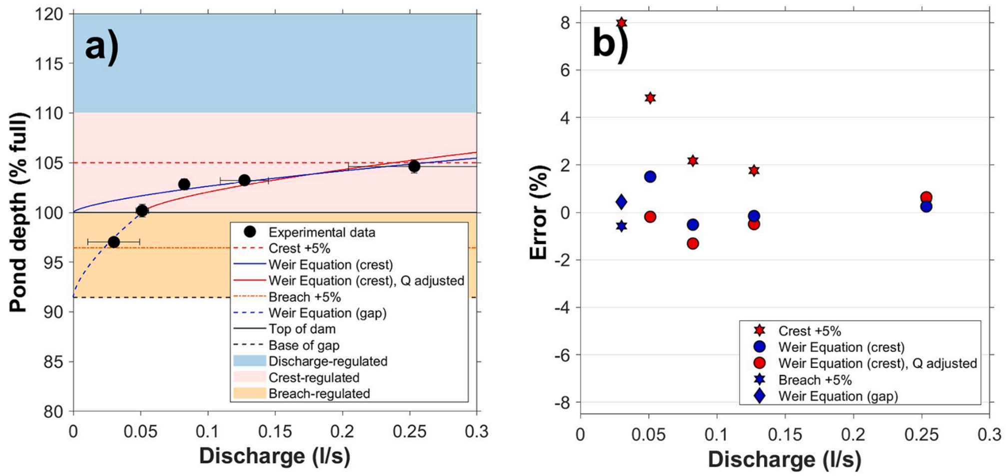


Fig. 16. Gapflow (1 %) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

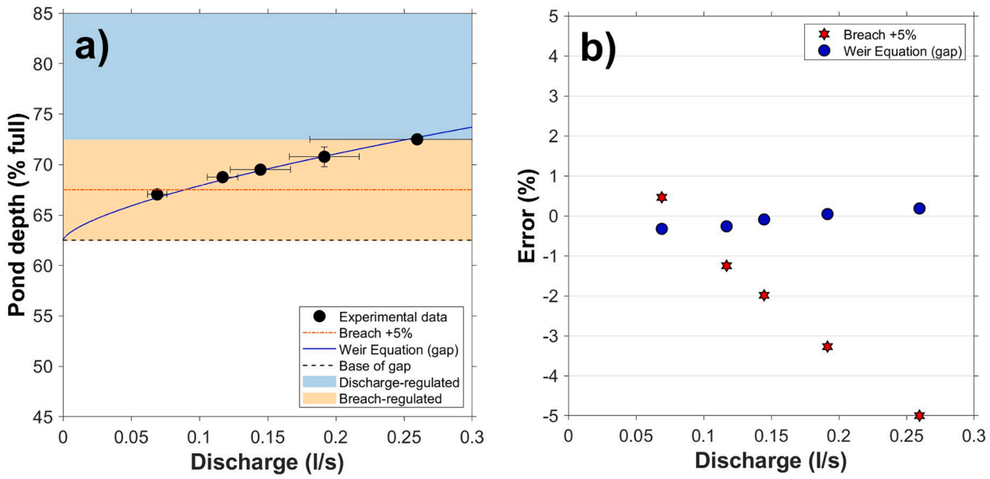


Fig. 17. Gapflow (20 %) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

topic).

3.4. *Breach-regulated dams*

Gapflow (20 %) is breach-regulated for the entire range of conditions tested, with pond depth never exceeding + 10 % of the base of the breach (Fig. 17a). Underflow (20 %) is breach-regulated for most discharges considered, with only the two highest discharges exceeding the breach-regulated threshold (exceeded for Q > 0.2 l/s), but still within 2 % of the breach-regulated zone (Fig. 18a).

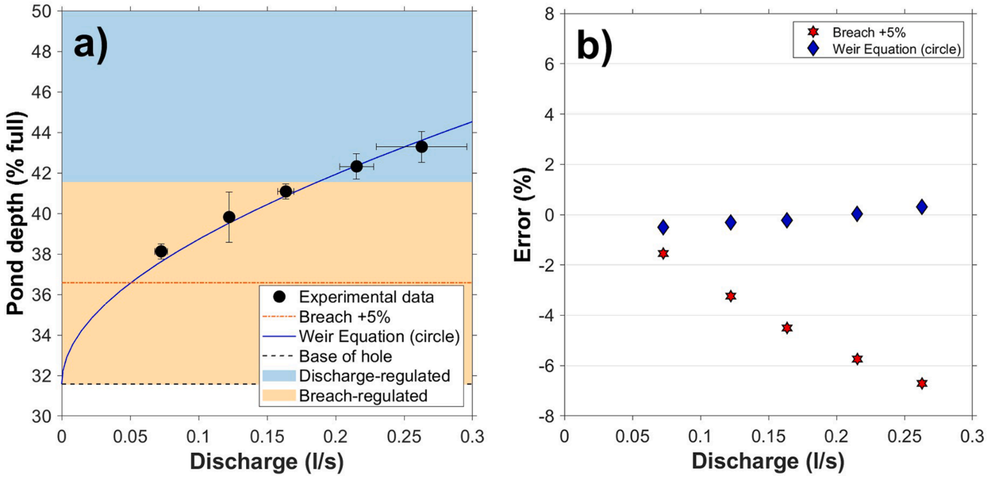


Fig. 18. Underflow (20 %) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

For both cases, the range of pond depths was similar to Overflow, indicating that the breach is effectively acting as a dam crest. However, the actual pond depths recorded are notably lower in magnitude: the maximum pond depth is 73 % for Gapflow (20 %) and 43 % for Underflow (20 %), compared to 106 % for Overflow. This demonstrates that for both Gapflow and Underflow cases with a breach area ≥ 20 %, dam type can have a significant influence on the magnitude of pond depth depending on the hight of the base of the breach.

As Gapflow (20 %) and Underflow (20 %) are breach-regulated for most of the tests, pond depth was initially estimated as the mid-point of the breach-regulated zone (breach + 5 %). This framework provides a good prediction of pond depth for both cases within the crest-regulated zone (error < 5 %, see Fig. 17b and 18b). Furthermore, despite the highest two discharges of Underflow (20 %) being outside the crest-regulated zone, the breach + 5 % assumption still predicts pond depth reasonably within this region (error < 8 %, Fig. 18b).

However, it is worth noting that the error for all tests for Gapflow (20 %) and Underflow (20 %) are larger than was observed using crest +5 % for crest-regulated dams. This is because the width of the breach is narrower for Gapflow and Underflow compared to Overflow, which increases the dependence of pond depth on discharge. Here, both cases are either on the boundary of the crest-regulated zone or exceed it, showing that the threshold for the transition to a discharge regulated system will be lower for Gapflow and Underflow compared to Overflow dams, and will primarily be a function of the width of the gap.

For Gapflow (20 %), the square geometry of the breach means the gap acts as a rectangular weir with a reduced width compared to the main dam crest. As such, the discharge pond depth relationship was established using the Weir Equation (Eq. (1)) using dimensions for the gap (Weir Equation (gap)), see Fig. 17a.

For the Underflow (20 %), the breach is as a partially filled circle. In this case, the breach is also modelled as a weir, using the Weir Equation (Eq. (1)), with the weir geometry adjusted to match the geometry of the partially filled circle rather than a rectangle (Weir equation (circle)). The predictions made by both models do not exceed 2 % error for either model (Figs. 17 and 18). The coefficients of discharge and regression parameters are provided in Appendix C, Table C2.

3.5. Discharge-regulated

For Underflow (1 %), the breach area is fully saturated for all discharges considered, and all but one of the recorded pond depths are within the discharge-regulated zone (Fig. 19a). Underflow (0.25 %) shows a similar response, except for the highest two discharges ($Q > 0.1$ l/s), which overtop the main dam and are crest-regulated (Fig. 20a). It is also important to note that the region where pond depth is above the breach but below the main dam crest represents freeboard, where excess water volumes in periods of time-varying flow could potentially be stored. The steady-state nature of the current tests means storage cannot be fully investigated, but the potential for storage in this zone is evident here and is considered in more detail in the Discussion (Section 4.2).

Both Underflow (0.25 %) and (1 %) show the largest dependence on

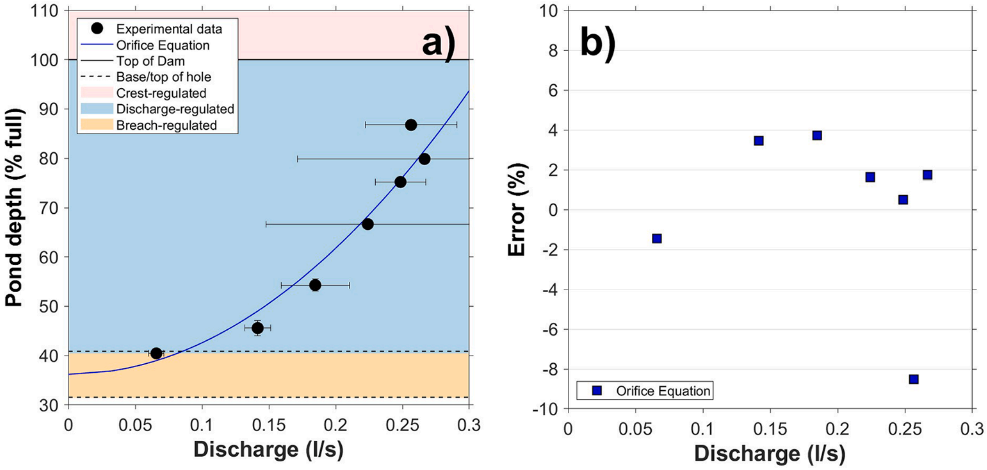


Fig. 19. Underflow (1 %) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

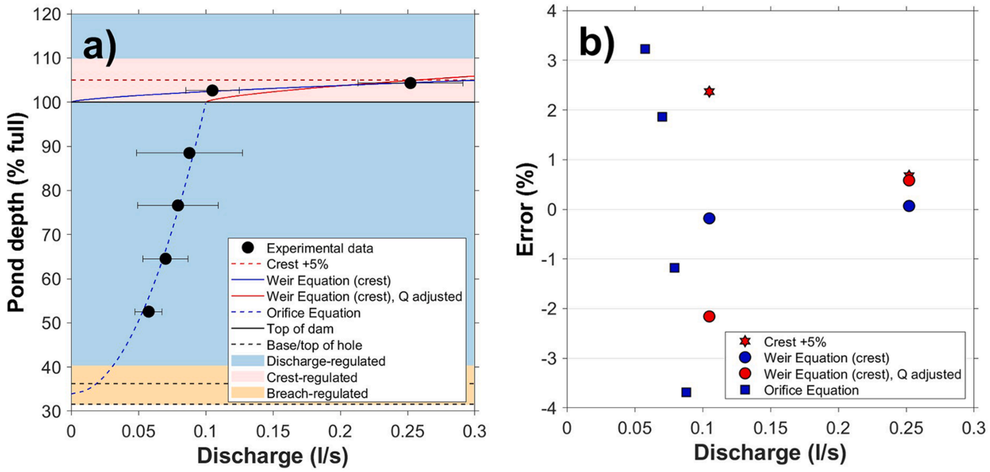


Fig. 20. Underflow (0.25 %) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

dam type across the whole dataset (Figs. 12, 13, 19 and 20), with both dams having a range of pond depths of the order of 50 % of the main dam height. Here, pond depth is not simply regulated by the constant heights of either the base of the breach or the main dam crest, but is set by discharge, leading to higher variability in pond depth and a greater challenge in making accurate estimations.

In cases that are discharge-regulated, it is crucial to establish the relationship between discharge and pond depth, as neither the dam crest nor the base of the breach provides a reasonable estimate of pond depth. For both Underflow (0.25 %) and (1 %), the discharge-pond depth relationship was established using the Orifice Equation (Eq. (2)), essentially treating the dam as a tank and the breach as an orifice. The coefficients of discharge and regression parameters are provided in Appendix C, Table C3. The Orifice Equation provides a good prediction of pond depth for both cases (Figs. 19a and 20a), with the error < 5 % for all tests, except for the second-highest discharge in the Underflow case (1 %), in the discharge-regulated zone (Figs. 19b and 20b).

Underflow (0.25 %) overtops the main dam for the highest two discharges investigated ($Q > 0.1$ l/s), at which point the flow is crest-regulated. Here, crest + 5 % can be used as a reliable predictor of pond depth (error < 3 % for all discharges overtopping the main dam, see Fig. 20b). It is worth noting that despite having the same breach area, Gapflow (1 %) overtops the main dam at approximately half the discharge for Underflow (1 %), highlighting the difference in hydraulics of the two dam types.

The Weir Equation was used to establish the discharge-pond depth relationship for the crest-regulated zone. As for previous tests, this was achieved firstly by using a modified version of the Weir Equation (Weir Equation (crest), Q adjusted) which in this case, adjusts for flow passing through the hole, provided in Appendix B, Eq. B(2). The second method applies the Weir Equation (Eq. (1)) with no correction. The coefficient of discharge for the two methods are presented in Appendix C, Table C3 and predictions are shown in Fig. 20a. The errors for both methods of the Weir Equation are comparable, and never exceed 2 % (Fig. 20b). The only notable difference between the two methods is the discharge coefficient, which is larger for the non-corrected Weir Equation (see Section 4.3 for further discussion).

3.6. *Throughflow*

Throughflow is addressed in a separate subsection because flow through porous media is theoretically more complex, and the observations presented here align less well with the theoretical framework compared to the other three dam types. Furthermore, Throughflow is the only dam type not parameterized based on existing field observation. Additionally, the porosity of the three Throughflow dams is not directly comparable in terms of the percentage of the dam face breached, relative to the range of breach areas selected for Gapflow and Underflow.

All Throughflow cases have consistently low pond depths, with the maximum depth for all cases never exceeding 55 % of the main dam crest. This demonstrates that Throughflow is a case where dam type potentially has a significant impact on pond depth for the range of porosities tested.

All three Throughflow cases are breach-regulated for a large portion of the range of discharges considered ($Q < 0.2$ l/s), see Figs. 21a–23a. The discharge threshold where the dam transitions from breach-regulated to discharge-regulated decreases as porosity decreases. For Throughflow ($\varnothing = 95\%$ and $\varnothing = 90\%$), assuming pond depth as breach + 5 % provides a reasonable prediction for the whole range of flow conditions (error < 10 % for all tests, see Figs. 21b and 22b).

For Throughflow ($\varnothing = 85\%$), the dam is breach-regulated for the first four discharges measured, and then is discharge-regulated for the final three, where there is then considerable deviation from the breach-regulated zone for larger discharges. Here, assuming pond depth as breach + 5 % still provides a reasonable prediction (error < 10 %, see Fig. 23b), except for the highest two discharges.

The results show that despite the clear relationship between discharge and pond depth, and that many of the depths observed for Throughflow are discharge-regulated, a reasonable prediction of pond depth can still be made using the breach + 5 % estimation. This assumption provides a reasonable prediction to within 10 % error for the majority of Throughflow tests, with the error never exceeding 20 % for all tests. This suggests that for the range of flow conditions considered, pond depth can still be reasonably estimated using the breach-base alone for $\varnothing \geq 85\%$). However, it is also clear from the data that all Throughflow tests are near the threshold of the breach-regulated/discharge-regulated zone, and that any further increase in discharge or decrease in porosity would mean that the dam-specific relationship between discharge and pond depth would become crucial and need to be established. This is important to note, as beaver dams that have only recently been abandoned may be classified as Throughflow, but with a far lower porosity than the range tested here.

Flow through porous media is traditionally modelled using Darcy's law (Eq. (3)), which was applied to all three Throughflow cases. Hydraulic conductivities for the three sets of materials used for Throughflow are presented in Appendix C, Table C4. In terms of error, the framework makes a reasonable prediction of pond depth for the range of discharges considered, with the error in prediction being below 10 % for most cases. However, it can be clearly observed that Darcy's Equation does not accurately model the trend in pond depth (Figs. 21–23). These results demonstrate that a different framework is required to predict the discharge-pond depth relationship in the discharge-regulated zone for

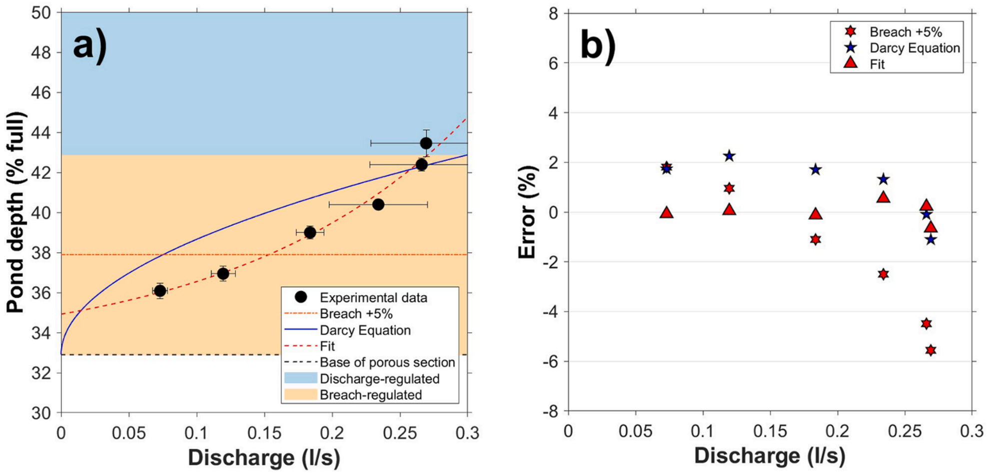


Fig. 21. Throughflow ($\varnothing = 95\%$) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

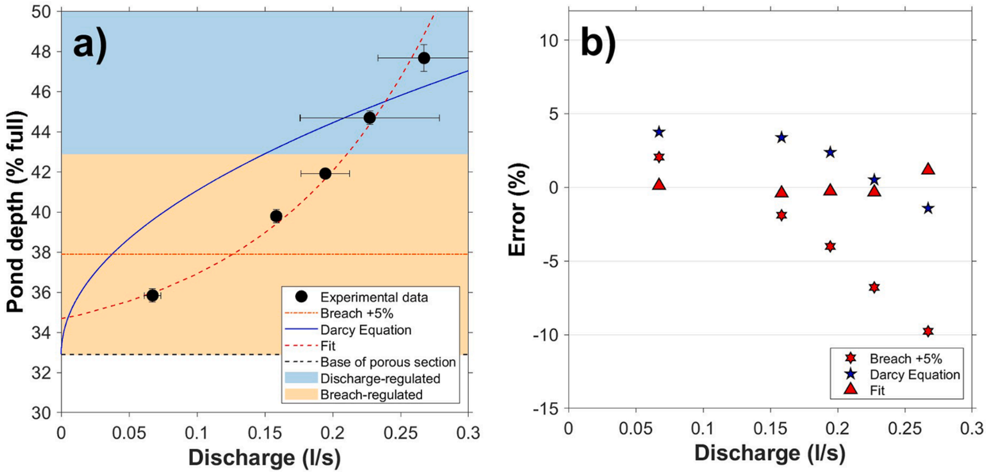


Fig. 22. Throughflow ($\varnothing = 90\%$) results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

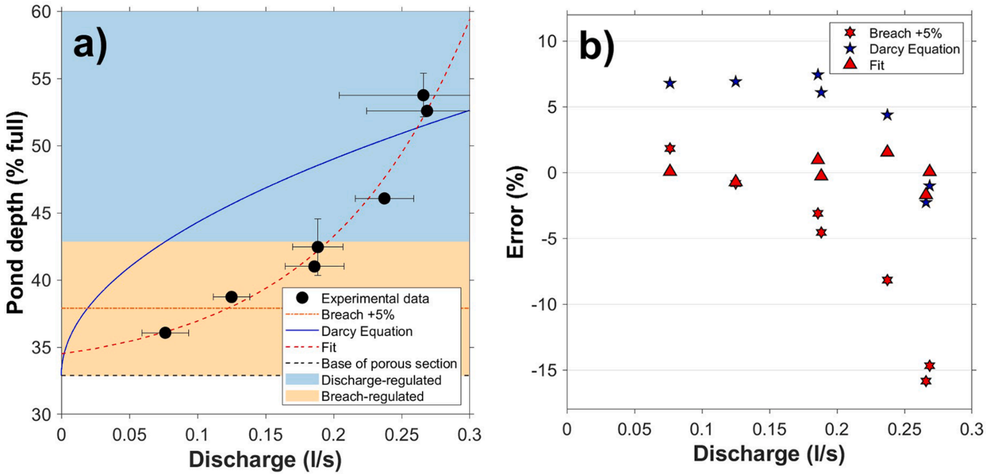


Fig. 23. Throughflow ($\varnothing = 85\%$). Results: (a) Rating curve experimental data vs predictions. Error bars $= 10\sigma$. (b) Error in predicted pond depth compared to data.

the material tested. However, establishing this relationship theoretically was beyond the scope of the current project.

In the absence of a theoretical model for the discharge-regulated zone for Throughflow, several types of data-fitting were considered to provide the discharge-pond depth relationship. It was found that the data can be well-described by the following simple logarithmic function:

$$Q = Aln(H) + B \tag{4}$$

where H is the height of flow above the base of the porous section (m), A

and and B are constants.

Values for the constants A and B are provided in Appendix C, Table C4. Eq. (4) provides a good prediction of pond depth for all three cases (Error $<$ 2 %, see Figs. 21b–23b).

4. Discussion

4.1. Summary of results

Based on the results from the test-series, three categories of pond depth regulation were proposed: crest-regulated, breach-regulated and discharge-regulated (Section 3.2). The overall picture demonstrated by the results is that dam type does have an influence on pond depth and ultimately needs to be accounted for to accurately predict pond depth across a large range of flow conditions. However, the results also highlight that the extent to which dam type influences pond depth varies greatly depending on breach area and discharge (Table 1).

Overflow can be considered the base-case, and the results show that Gapflow has the smallest influence on pond depth, where both Gapflow (0.25 %) and Gapflow (1 %) effectively behave as Overflow dams, with Gapflow (20 %) being the only Gapflow case for which dam type is significant. In contrast, both Underflow and Throughflow show considerable deviation from Overflow behavior and dependency of pond depth on dam type.

The dependence of pond depth on dam type increases with breach area. The results suggest that any breach area $\geq$ 20 % will lead to a breach-regulated system, whereas any breach area $<$ 0.25 % (at moderate discharges) will lead to a crest-regulated system that is independent of dam type. The results also indicate that as discharge increases, the influence of dam type on pond depth decreases, with all dams tending towards being crest-regulated, and thus dam type independent, at high discharges. This threshold is observed within the discharge range tested for Gapflow (0.25 % and 1 %) and Underflow (0.25 %) and can be inferred from the data for all other cases. Underflow shows the greatest dependency on dam type, with all three of the proposed pond depth regulation mechanisms being observed for Underflow.

4.2. Implications of the results

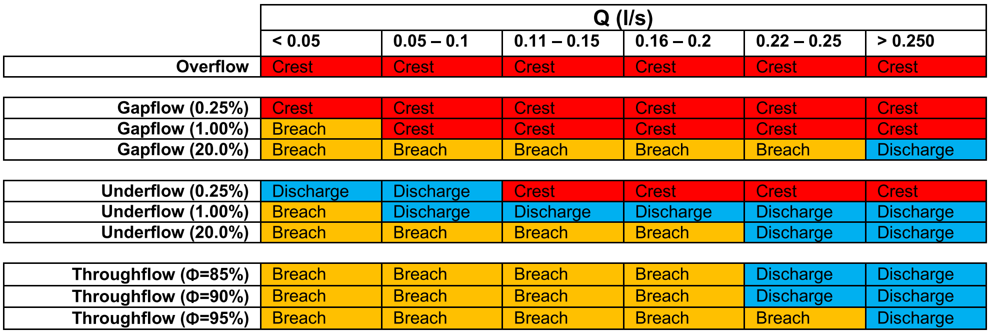
The results presented in this paper consider the influence of dam type on steady-state pond depth and highlight the large variability in pond depth as a function of dam type, breach area and discharge. Whereas the data in this study are limited to steady-state testing, the results provide insights into how beaver dams may perform under dynamic conditions.

Crest-regulated and breach-regulated systems are, by definition, always overflowing and as such offer no excess flow-storage capacity. The results presented indicate that both Overflow and Gapflow dams would have little impact on flood attenuation if a pond were already full, as are both Crest-regulated or Breach-regulated for almost all conditions tested. This confirms the findings of Woo and Waddington (1990) and Westbrook et al. (2020), who presented field data to suggest that both Overflow and Gapflow dams do little to delay or attenuate storm peaks. Woo and Waddington (1990) also suggested that Throughflow dams have little effect on flood attenuation as “the highly porous nature of the dam allows water to pass through readily”. Results presented in this paper generally align with this, as all Throughflow dams investigated operate under breach-regulated conditions for most discharges tested. This implies that for the three porosities investigated, Throughflow dams would not offer significant flow-storage or lead to significant ponding. The rating curves for Throughflow do, however, suggest that as both porosity decreases and discharge increases, the dams have some potential to fill and pond, implying that Throughflow dams have potential to attenuate flood peaks under certain conditions, especially where beavers achieve porosities lower than those tested, which is plausible for actively maintained or recently abandoned Throughflow dams.

The above findings initially appear to be in contrast with many studies that have demonstrated the ability of beaver dams to attenuate peak flows and mitigate against flooding (Nyssen et al., 2011; Law et al., 2016; Puttock et al., 2017; Puttock et al., 2021) but in fact simply highlight the dependency and sensitivity of potential flood mitigation on dam type. Underflow (0.25 % and 1 %) both provide significant freeboard in the discharge-regulated zone, demonstrating the potential to attenuate and delay excess discharges. Further investigation under dynamic conditions, potentially with multiple dams, would be required to fully establish how these systems would respond to unsteady flows, but our work does provide evidence that there is significant potential for Underflow dams with breach areas up to 1 % to store and attenuate excess flow, and this likely extends to dams of lower porosity than those we tested. This finding confirms initial field observations by Woo and Waddington (1990), whose data show flood peak attenuation and delay by Underflow dams. The contrast in the potential response to flood peaks between Underflow dams and all other dam types highlights the need to consider dam type when discussing beaver dams in relation to extreme flows. It is also worth noting that beaver dams rarely occur singly and therefore even individually small attenuation benefits of one structure may become significant when compounded across a series of multiple dams.

In addition, Underflow dams that do have the potential to offer flood peak attenuation and delay will eventually become crest-regulated at a certain discharge threshold. This suggests that there is a limit to the degree of attenuation that an Underflow dam can provide, i.e. the point the main dam is overtopped and becomes crest-regulated. Neumayer et al. (2020) suggests that beaver dams do not appreciably attenuate discharges or mitigate against flooding for flood events with return periods above 2 years, implying that there is a limit to the flood

Table 1
Summary of pond depth regulation mechanisms per dam type and discharge. Categories are color-coded as: discharge-regulated (blue), breach-regulated (orange), and crest-regulated (red).



	Q (l/s)					
	< 0.05	0.05 – 0.1	0.11 – 0.15	0.16 – 0.2	0.22 – 0.25	> 0.250
Overflow	Crest	Crest	Crest	Crest	Crest	Crest
Gapflow (0.25%)	Crest	Crest	Crest	Crest	Crest	Crest
Gapflow (1.00%)	Breach	Crest	Crest	Crest	Crest	Crest
Gapflow (20.0%)	Breach	Breach	Breach	Breach	Breach	Discharge
Underflow (0.25%)	Discharge	Discharge	Crest	Crest	Crest	Crest
Underflow (1.00%)	Breach	Discharge	Discharge	Discharge	Discharge	Discharge
Underflow (20.0%)	Breach	Breach	Breach	Breach	Discharge	Discharge
Throughflow (Φ=85%)	Breach	Breach	Breach	Breach	Discharge	Discharge
Throughflow (Φ=90%)	Breach	Breach	Breach	Breach	Discharge	Discharge
Throughflow (Φ=95%)	Breach	Breach	Breach	Breach	Breach	Discharge

mitigation potential of beaver dams at high discharges. This finding is supported by our results for both Overflow and Gapflow dams at all discharges investigated and Underflow dams at high discharges, where the dam is being overtopped and therefore no longer offering freeboard.

The systematic testing in our work highlights the crucial dependency of beaver dam flood-mitigation potential on dam type, breach area and discharge. The three mechanisms suggested in this paper to describe pond depth regulation (crest-, breach- or discharge-regulated) offers a coherent system of classification that integrates these variables.

4.3. Considerations when applying the proposed frameworks to real beaver dams

We suggest two frameworks to predict steady-state pond depth. The first is proposed for crest-regulated or breach-regulated dams where pond depth is assumed independent of discharge and equal to either the crest-height $+5\,\%$ or the lowest point of the breach $+5\,\%$. This method is simple to apply, requiring only the height of either the main dam or the base of the breach. This method is also shown to be predictively powerful; for the crest-regulated or breach-regulated dams investigated in this test series, this assumption provides an estimate of pond depth with an error $< 10\,\%$ for all conditions tested. Crest-regulated and breach-regulated dams also make up the majority of the scenarios considered, so this method offers a simple and effective tool to approximate pond depth in the absence of the data required to apply more sophisticated theoretical models.

However, there are limitations to this method. Firstly, while the proposed framework assumes that pond depth is independent of discharge within the crest-regulated zone due to the minimal effects of discharge in this region, it is important to note that pond depth is still a function of discharge and still exhibits a positive relationship with discharge in the results presented. This implies there will eventually be a discharge threshold where the framework becomes invalid, meaning the applicability to extreme flows may be questionable. Secondly, without having established the relationship between discharge and pond depth, it is not clear at what discharge this threshold occurs. Finally, this method is not applicable to any discharge-regulated systems, where the discharge pond depth relationship must be established.

The alternative proposal involves establishing the relationship between discharge and pond depth using pre-existing hydraulic equations. For Overflow, Gapflow, and Underflow the equations that are proposed are extremely robust and allow for an accurate estimation of pond depth within the range of discharges measured. This method also allows for extrapolation, which can be used to estimate pond depth for extreme discharges as well as for estimating the transition point between the crest-regulated, breach-regulated and discharge-regulated zones.

The main disadvantage of the second framework is that it requires an estimation of the coefficient of discharge, which, to be estimated with confidence, requires a pre-measured rating curve for the specific system. This may pose significant practical challenges for practitioners wishing to make quick predictions of pond depth.

The alternative is to estimate the coefficient of discharge for the system in question. McCullough et al. (2007) estimated this coefficient for a replica beaver dam, designed based on survey data and built using real beaver dam material, as $C_D = 0.5452$, which is notably similar to the value obtained in this study for Overflow of $C_D = 0.5896$. The repeatability of the results between the two replica dams suggests that values in this region may be a reasonable starting point for estimating C_D in the absence of any other data. However, estimating the coefficient is more challenging when considering dams which are both discharging through a breach in the dam face (such as Gapflow and Underflow) and simultaneously overtopping the main dam. This would make estimating the coefficient from literature without pre-measuring the rating curve challenging, as the effect would be system specific.

For Throughflow, Darcy's law (Eq. (3)), which is traditionally used to model flow through porous media, inadequately predicts the trend in pond depth for moderate discharges. Consequently, the trend observed in the rating curve for Throughflow results necessitated further investigation. It remains unclear whether this discrepancy arises from limitations in the experimental design, the selected material or factors pertinent to real-world beaver dams. One possible explanation for the deviation from Darcy's law is that the flow within the dam may be turbulent, leading to 'non-Darcy' flow (Zeng and Grigg, 2006; Pang et al., 2021). Several methods have been proposed to correct for non-Darcy flow in porous media (Pang et al., 2021); however, a comprehensive evaluation of these methods was beyond the scope of this study. Instead, we employed regression analysis to fit the data, offering a straightforward alternative for predicting the functional relationship between pond depth and discharge for real dams, assuming sufficient data points are available. These findings contrast with those of Muller and Watling (2016), who demonstrated that their replica beaver dam adhered to Darcy's law across a broad range of discharges, with a permeability of $K = 0.67\,m/s$. The non-Darcy flow observed in the present study may be attributable to the material used, which could create complex flow dynamics that may or may not be analogous to flow types occurring in real beaver dams. Nevertheless, the analysis of Throughflow dams in this study primarily highlights the need for further work to investigate this case more fully and theoretically.

The mechanisms whereby beaver dams attenuate floods still need further research to incorporate potential for movement of water outside the channel (flow diversion both lateral and vertical) at a range of flood magnitudes and topographies (Larsen et al., 2021). This implies that for real sites, considerations such as topography, water table depths and valley shape may make the discharge-depth relationship more complicated compared to the idealised physical model used for our analysis. Furthermore, real beaver dams are often found in series. This not only increases the complexity of modelling but also raises the possibility of emergent processes resulting from the combined effects of multiple dams. While this topic was beyond the scope of the present study, it represents an interesting avenue for future research. It is also important to recognise that beaver dams are one example of a broader class of channel-spanning wood structures, including natural logjams formed by fallen trees, branches, and debris, as well as engineered features such as leaky barriers used in flood management. Further work could extend the analysis presented here to encompass these broader categories of structures.

The flow conditions and dam dimensions in this paper could potentially be scaled for full size systems using standard frameworks such as Froud similitude. However, the hydraulic response of such complex systems to different flow conditions will most likely be highly system specific. It is not intended that the discharge thresholds suggested in this paper should be scalable to any specific system, but rather that the general mechanisms and responses observed across the range of dam types can act as a blueprint and conceptualization framework for how real systems may respond to a large range of flow conditions. However, the specific thresholds of transition from each mechanism would most likely need to be established for each specific system in question. The fact that the Overflow, Gapflow, and Underflow tests conform to established hydraulic frameworks (i.e., the weir and orifice equations) demonstrates that, despite the use of scaled-down models, the systems behave consistently with standard hydraulic theory, with no significant deviations from expected behaviour observed. Moreover, the weir and orifice equations used to generate rating curves in this study are themselves scalable. These equations could therefore be used to estimate the thresholds for each pond depth regulation mechanism in a full-size system, based simply on the dimensions of the dam (and dam face breaches) and an approximate estimation of the relevant coefficients.

All dam breaches used for testing (apart from Throughflow) are modelled with a single breach. This is unlikely to be the case for real beaver dams, where multiple breaches are more common. This is particularly true for larger breach areas, such as 20 %. Further work is needed to examine more complex patterns of multiple breaches. However, the modelling in this paper is also relevant for human-implemented beaver dam mitigation, such as pond levelling devices, which may utilize a single breach point.

Quoting pond depths as a percentage of the main dam crest provides a useful fixed reference point for pond depth comparison. However, it is important to note that the height of flow above the dam crest is primarily a function of discharge. This means that a particularly short or tall dam structure could artificially increase or decrease the definition of the crest-regulated or breach-regulated zone. Further work is required to investigate the extent to which this has a significant effect on the pond depth model proposed in this paper for a range of real beaver dam geometries. Similarly, the width of a given dam will influence the rating curve. The model dam in this study has an aspect ratio of approximately 1:1, whereas real beaver dams are often much wider than they are tall, as can be seen in the datasets of Woo and Waddington (1990) and Ronnquist and Westbrook (2021). The most significant hydraulic implications of a wider dam for steady-state flows would be to flatten the rating curve. Therefore, the dam used in this study represents a conservative model, where real beaver dams would likely remain crest-regulated or breach-regulated at higher discharge thresholds than observed for this test series; but as previously noted, this only emphasises the need to obtain these thresholds for the system in question.

Finally, a central consideration when applying the modelling framework proposed in this study is the dynamic nature of real beaver dams. Woo and Waddington (1990), Ronnquist and Westbrook (2021) and Aguirre et al. (2024) highlight the time-dependence of dam type based on its lifecycle stage, with Ronnquist and Westbrook (2021) arguing that dam type should more appropriately be referred to as dam ‘state’, as dams transition between the four dam types depending on level of beaver activity. This means that when making predictions of pond depth for a given system based on dam type, practitioners and modellers need to be aware of the potential change in dam type with time and beaver activity.

4.4. *Further limitations of experimental conceptualization*

The experimental work presented in this study is, to the authors’ knowledge, the first systematic series of flume tests to comparatively investigate beaver dam type, breach area, and discharge in combination. We view this work as a preliminary exploration and pilot investigation that lays the groundwork for more detailed studies of the physical flow mechanisms through beaver dams. To this end, the conceptual framework employed was intentionally simplified to isolate the key parameters under investigation. However, this simplified physical modelling has its limitations. Real beaver dams exhibit considerable diversity and variability in composition and structure (Ronnquist and Westbrook 2021), leading to a broad range of porosities and permeabilities. There is also significant temporal variability depending on the age and condition of the dam, as well as the level of beaver activity (Woo and Waddington 1990). The challenge of modelling beaver dams is compounded by the scarcity of field data on porosity and permeability. In this study, overflow was modelled as an idealized case in which the dam is entirely impermeable. While this scenario is unlikely to be fully realized in nature, it serves as a control within the test series. Gapflow and Underflow dams were modelled with a range of breach areas that covers much of the range observed in an extensive cross-site survey (162 dams across 19 sites; Ronnquist and Westbrook 2021). Due to a lack of available data for parameterizing Throughflow, a range of porosities was investigated using available materials. The Throughflow damns are likely representative of the high end of the porosity spectrum, possibly reflecting either new beaver dam construction (Woo and Waddington 1990) or abandoned sites. Further field-based research is needed to explore the full range of possible Throughflow porosities.

In the model dam conceptualizations for this test series, the dam face was considered the primary flow impediment. Given that the dam face material in the model is 100 % impermeable, it likely represents more of a real dam’s cross-section than just the sealing layer, as in reality, it will most likely require both the sealing layer and sediment in the main body of the dam in combination to achieve the same level of impermeability. Therefore, breaches in the model dam face can reasonably be interpreted as breaches through the entire dam cross-section, except for the branches, which have only a minor effect on permeability and pond depth. A downstream wooden structure was included to account for secondary resistance to flow, which may have a minor additional effect on pond depth (McCullough et al. 2007). This is why breaches were applied only to the dam face and not to the structure. Additionally, this explains why no attempt was made to forensically match the structure density with a real-world dam, beyond using the expertise of the authors to establish a reasonable, high-density case in terms of the wood pattern. Further research is needed to systematically investigate how structure density and pattern, including more complex wood/sediment combinations for the structure, influence pond dynamics.

Beavers will often attempt to repair significant, unintended breaches, so larger breach areas may only be temporary. However, the breach repair process is not fully understood (Gurnell, 1998). Sometimes the sound of running water prompts immediate repair behavior, while other times, beavers may delay repairs. Beavers may also abandon a site after a breach, especially if local food resources are depleted (Żurowski, 1992). This suggests that breaches may persist for extended periods, especially if the site is abandoned. Additionally, beaver dams with mechanisms to allow flow through the dam —- Gapflow, Underflow, or Throughflow —- are likely to be more structurally stable than Overflow dams. Despite uncertainties regarding the duration of breach persistence, it is evident that dams can experience a wide range of breach areas throughout their life cycle, even if only temporarily. Thus, the systematic testing presented in this paper offers valuable insights into the steady-state behavior of dams across a spectrum of possible conditions and life cycle states.

5. Conclusions

This study presents results from a systematic set of laboratory tests investigating the influence of four primary types of beaver dam (Overflow, Underflow, Gapflow and Throughflow) on pond depth. Based on the experimental observations, we propose three categories of pond depth regulation: crest-regulated, breach-regulated, and discharge-regulated.

1) Crest-regulated systems maintain consistent pond depths that are proportional to the height of the main dam crest and largely independent of discharge variations. These systems show little evidence of storage potential.
2) Breach-regulated systems regulate pond depth primarily through the size and position of the breach, with pond depths being proportional to the height of the lowest point of the breach. These systems show little evidence of storage potential.
3) Discharge-regulated systems exhibit a strong relationship between discharge and pond depth, with flow conditions becoming the primary regulatory factor. These systems show evidence of storage and thus potential for flood mitigation.

The analysis further demonstrates that standard hydraulic equations can effectively estimate rating curves for Overflow, Gapflow, and Underflow dams. However, a comprehensive theoretical framework for Throughflow dams remains to be established.

The diverse range of responses identified in this study highlights the complexity of beaver dam behavior in response to extreme hydrological events, particularly in terms of flood attenuation and water storage. The results indicate that beaver dams have the potential to mitigate flooding, though this potential is highly dependent on dam type, breach area and discharge, with Underflow being the only type investigated showing clear evidence of storage and thus flow attenuation potential. Additionally, our findings suggest that all dam types tend towards becoming crest-regulated as discharge increases, meaning all dams will have an upper limit to their storage and attenuation potential.

CRediT authorship contribution statement

James Hart: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alan Law:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Cherie Westbrook:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Matteo Rubinato:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Nigel Willby:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1

Appendix A:. Summary of test series

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Table A1
Summary of test series.

Dam type	Breach area (%)	Discharges tested (l/s)
Overflow	0.00	0.09, 0.12, 0.13, 0.20, 0.25
Gapflow	0.25	0.03, 0.07, 0.14, 0.20, 0.25
	1.00	0.03, 0.05, 0.08 0.13, 0.25
	20.0	0.07, 0.12, 0.14, 0.19, 0.26
Underflow	0.25	0.06, 0.07, 0.08, 0.09, 0.10, 0.25
	1.00	0.07, 0.14, 0.18, 0.22, 0.25, 0.26, 0.27
	20.0	0.07, 0.12, 0.16, 0.22, 0.26
Throughflow	Porosity, $\varnothing$(%)	
	85.0	0.08, 0.12, 0.19, 0.19, 0.24, 0.27, 0.27
	90.0	0.07, 0.16, 0.19, 0.23, 0.27
	95.0	0.07, 0.12, 0.18, 0.23, 0.27, 0.27

Appendix B:. Corrected hydraulic equations for breached dam

For a Gapflow dam that is overtopping the main dam and discharging through a gap in the dam face:

$$Q = \frac{2}{3} C_D \sqrt{2g} B H^{1.5} + Q_G \tag{B1}$$

Where Q_G is discharge through the gap (m^3/s), which can be estimated using the Weir Equation for the gap.

For a Underflow dam that is overtopping main the dam and discharging through a hole in the dam face:

$$Q = \frac{2}{3} C_D \sqrt{2g} B H^{1.5} + Q_O \tag{B2}$$

where Q_O is the discharge through the hole (m^3/s), which can be estimated using the Orifice Equation for the hole.

Appendix C:. Regression analysis for hydraulic equations used for discharge-pond depth relationship

Crest-regulated dams:

Table C1
Model parameters for crest-regulated dams.

Dam type	Model	Zone	Equation	Coefficient of discharge,C_D	Goodness of fit,R^2
Overflow	Weir Equation (crest)	Crest-regulated	1	0.5896	0.99
Gapflow (0.25 %)	Weir Equation (crest), Q adjusted	Crest-regulated	B2	0.5976	0.88
Gapflow (0.25 %)	Weir Equation (crest)	Crest-regulated	1	0.6516	0.92
Gapflow (1 %)	Weir Equation (crest), Q adjusted	Crest-regulated	B2	0.6359	0.83
Gapflow (1 %)	Weir Equation (crest)	Crest-regulated	1	0.8939	0.84

Breach-regulated dams:

Table C2
Model parameters for breach-regulated dams.

Dam type	Model	Zone	Equation	Coefficient of discharge, C_D	Goodness of fit, R^2
Gapflow (20 %)	Weir Equation (gap)	Breach-regulated	1	0.5707	0.99
Underflow (20 %)	Weir Equation (circle)	Breach-regulated	1	0.8121	0.98

Discharge-regulated dams:

Table C3
Model parameters for discharge-regulated dams.

Dam type	Model	Zone	Equation	Coefficient of discharge, C_D	Goodness of fit, R^2
Underflow (0.25 %)	Orifice Equation	Discharge-regulated	2	0.9082	0.93
Underflow (0.25 %)	Weir Equation (crest), Q adjusted	Crest-regulated	B2	0.5319	0.66
Underflow (0.25 %)	Weir Equation (crest)	Crest-regulated	1	1.0436	0.98
Underflow (1 %)	Orifice Equation	Discharge-regulated	2	0.7294	0.95

Throughflow dams:

Table C4
Regression fit parameters for Throughflow.

Dam type	Model	Equation	Hydraulic conductivity, K (m/s)		Goodness of fit, R^2
Throughflow ($\varnothing = 85\%$)	Darcy's law	3	0.0400		–
Throughflow ($\varnothing = 90\%$)	Darcy's law	3	0.0778		0.15
Throughflow ($\varnothing = 95\%$)	Darcy's law	3	0.1562		0.37
			A	**B**	
Throughflow ($\varnothing = 85\%$)	Logarithmic fit	4	0.0001063	0.0006415	0.98
Throughflow ($\varnothing = 90\%$)	Logarithmic fit	4	0.0001213	0.0007186	0.99
Throughflow ($\varnothing = 95\%$)	Logarithmic fit	4	0.0001697	0.0009812	0.99

Data availability

Data will be made available on request.

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