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Dynamic behavior of fluid flow through a downscaled model of *Bissokotuwa* of ancient reservoirs in Sri Lanka

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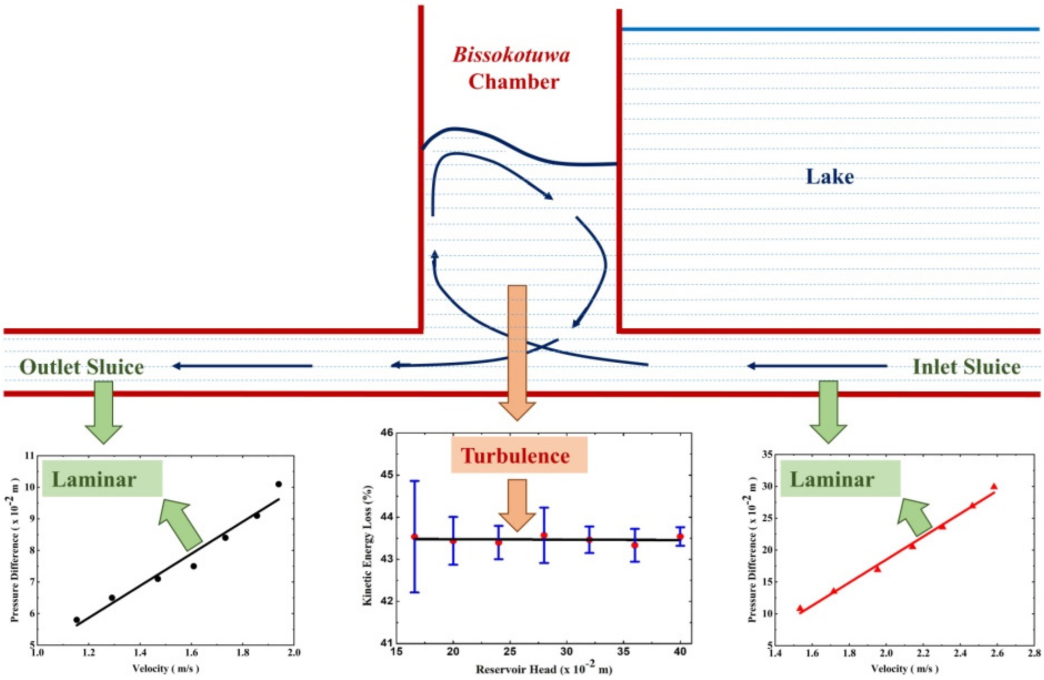

Highlights

- The prototype *Bissokotuwa* model showed a reservoir head independent kinetic energy loss of ~45%
- Laminar flows discharge through the inlet and outlet by the *Bissokotuwa* model
- High velocity gradient reduces the total head of inflow by forming shear stresses
- Laminar behavior of sluices in the model cannot be expected in reality

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Dynamic behavior of fluid flow through a downscaled model of *Bissokotuwa* of the ancient reservoirs in Sri Lanka

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Abstract: Artificial lakes were designed in Sri Lanka from ancient times to harvest rainwater and to detain floods. First, a network of smaller lakes was constructed, but with technological sophistication, later on medium to large lakes were reconstructed to cater the increasing human population. The *Bissokotuwa* technology was introduced to large lakes in order to channel water from the bottom of the lake, since techniques used for small and medium lakes are not sufficient to sustain the large static pressure of releasing flumes. The sluice gate of the *Bissokotuwa* is made of wood and outflow is regulated by a lever mechanism. This project investigated the kinetic energy (KE) losses inside *Bissokotuwa* and compared it with water channeling through a direct sluice with the aid of a scaled-down prototype model. The prototype model exhibited KE loss of ~43.5% due to *Bissokotuwa* and it was independent of the reservoir head. The motion of inflow confirmed subjecting to serve velocity gradient and turbulence inside the *Bissokotuwa*. This suggested forming shear stress within the water by reducing its pressure. *Poiseuille's* law supported justifying inflow and outflow are laminar for the prototype model; however, the same behavior cannot be expected for a real scenario according to terms in the Reynolds number formula.

Keywords: Ancient irrigation, *Bissokotuwa*, Shear stress, Sri Lanka, Velocity gradient

INTRODUCTION

There are 103 different river basins, with sizes ranging from 10 to 10450 km^2 in Sri Lanka (Jayasena and John, 2004). The large river basins begin from the highlands while most of the dry zone basins initiate from the uplands. Sri Lanka receives rain from two monsoon seasons. The northeast monsoon (retreating monsoon) is usually effective in November and December and the southwest monsoon (or advancing monsoon) is effective between June and October (Samarakoon *et al*., 2021; Karunathilaka *et al*., 2017). Based on the rainfall pattern, the country can be divided into two major climatic zones, *viz;* the wet zone and the dry zone. The unique hydraulic and soil engineering practices in the dry zone of Sri Lanka are inherited after the 2nd century AD (Parker, 1909) which has been a back born to the development of the irrigation culture central to the present study.

Sri Lankan lakes are a variety of man-made structures used to collect and store water, mostly for agricultural use (Brohier, 1937). These are made up of man-made embankments that are placed in the way of gravity-fed waterways, such as rivers, streams, or even just slopes that might convey runoff after a monsoon downpour. Lakes are storage or storage/distribution systems created on a somewhat large scale and intended to contain water behind an embankment or dam, as opposed to within its main structure. They may or may not entail the excavation of a basin to contain this water (Bauer and Morrison, 2008).

According to historical records, ancient Sri Lanka is believed to have the most impressive irrigation systems in the world. The tank cascade system is a unique method of rainwater harvesting that can only be found in Sri Lanka and cannot be seen even in ancient prodigious irrigation cultures in the world (Jayasena, 2012; Gunasekara *et al*., 2022). This practice of irrigation culture is based on harmonizing the total environment, supported by advanced-technical development and properly maneuvering complex engineering, which still cannot be explained using the latest science and technology. Irrigation technology in Sri Lanka was developed under the subject of "culture-eco-based irrigation engineering" (Parker, 1909; Jayasena, 2012). Some places in the dry zone would have become deserts if such irrigation systems were not implemented. The temperature of the ecosphere in the dry zone is also dramatically decreased due to such irrigation practices (Balasooriya, 2004).

The outgoing water from small lakes was controlled using temporary cuts in the earthen banks. For medium-sized lakes "*Keta Sorowwa*" technique was used for flow controlling and releasing water (Parker, 1909; Jayasena, 2012). In *Keta Sorowwa* technique, there are a few clay rings kept atop one another to control the flow rate of the water leaving the lake. The outflow rate from the lakes is controlled by changing the number of clay rings. There was a requirement to build large lakes with a depth of ten to fifteen meters when the population increased. Water should be released from the bottom of these lakes as a large amount of water flow had to be released (Gunawardana, 1978; Peiris and Wijesinghe, 2008). However, releasing water directly from the bottom

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of the lake with high static pressure is damaging to the *Waa Kanda* (bund) due to the occurrence of a water hammering effect when closing sluice gates due to the generation of pressure waves (Fathi-Moghadam *et al*., 2013; Choon *et al*., 2012). In addition, pressure waves can propagate inside the sluice and, as a result, large noises and vibrations may occur. Then the bund may collapse from its weak points (Fathi-Moghadam *et al*., 2013; Bergant *et al*., 2006). The hydraulic jump occurs when water is discharged at high velocity into channels that have low velocity where the kinetic energy of water changes into potential energy (Hassanpour *et al*., 2017). The downstream turbulence can cause damage; hence, degradation and erosion of channel banks would result.

As a prevention mechanism, ancient engineers invented a marvelous structure called "*Bissokotuwa*" for larger lakes. A schematic diagram of a *Bissokotuwa* is shown in Figure 1 (Parker, 1909). This *Bissokotuwa* helped control the flow rate through the sluice without exerting high static pressure and flow velocities, which would affect the bund. The ancient *Bissokotuwa* chamber is a square-shaped structure built with bricks and properly polished gneiss slabs as walls (Peiris and Wijesinghe, 2008). Layers of clay are laid in between bricks wall and gneiss slabs to prevent water from leaking (Parker, 1909). The inlet and outlet sluices of the lake are made from gneiss slabs (Parker, 1909; Awusadahami, 1999).

At present, the mechanism of the *Bissokotuwa* is not used for releasing water from the large lakes as most of the bunds and the channel banks are strong as they are made with concrete. In the other case, energy dissipation of releasing water from modern artificial reservoirs is a disadvantage since it is used for electricity generation. The only functioning *Bissokotuwa* observed, during the project is at *Buduruwagala*, and is depicted in Figure 2. It had undergone renovations in the late 1900's so that water could be released utilizing *Bissokotuwa*.

This study demonstrates that adding the *Bissokotuwa* structure to a large lake lowers the inflow's pressure head by lowering both its static pressure and velocity. Water will experience high-velocity gradients upon entering *Bissokotuwa*. As a result of these high-velocity gradients, shear stresses will arise, and the pressure of the water will decrease. Through the outflow sluice from the *Bissokotuwa*,

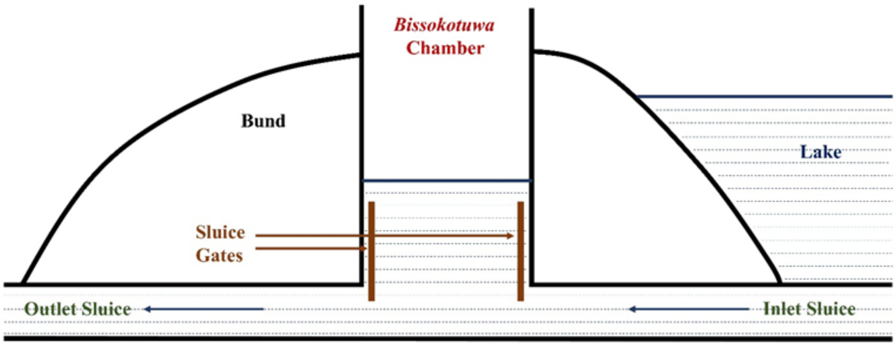

Figure 1: Position of the *Bissokotuwa* sluice in a large lake

Figure 2: *Bissokotuwa* of the *Buduruwagala* reservoir located in the *Moneragala* District in the *Uva* Province of Sri Lanka.

it is noted that water flows into the channel with reduced speed and energy, lessening degradation and erosion of channel banks.

METHODOLOGY

Several ancient *Bissokotuwa*s at *Minneriya, Polonnaruwa,* and *Buduruwagala* were initially observed and their locations on the Sri Lanka map are shown in Figure 3. After observing the physical model of *Bissokotuwa* in the national museum in *Colombo*, a prototype, scaled down (1:30) variation of *Buu Wewa* lake *Bissokotuwa* in *Polonnaruwa* was constructed with Perspex as shown in Figure 4 (a) and (b).

The prototype model is designed as a real reservoir head varied from 5.0 m to 12.0 m, which is equivalent to 16.6 to 40.0 cm, and can be used as a prototype model since it was originally designed to release water with a reservoir head from approximately 4.5 to 13.5 m in a real scenario.

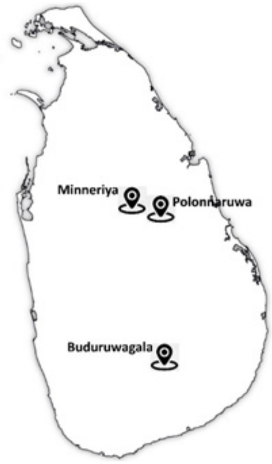

Figure 3: Study locations of the *Bissokotuwa* systems in the map of Sri Lanka.

Figure 4: (a) The prototype model of lake, *Bissokotuwa,* and sluices (b) releasing water by maintaining reservoir head at constant.

A square tube was introduced with the same scaled-down dimensions of inlet and outlet sluices of the *Buu Wewa* lake *Bissokotuwa* to the bottom of the lake. Another square tube was introduced to the bottom of the lake to measure the velocity of direct flow. Fixing an adjustable excess water emitting tube vertically, as indicated in Figure 4 (b), maintained a consistent head in the tank. Water was pumped into the tank using a water pump that had a flow regulator. A few transparent plastic tubes were connected to *Bissokotuwa* and the tank separately to measure the pressure head and they were vented to the atmosphere and behaved as piezometers.

OTT current meter was used to measure the velocity of the flume. Velocity measurements were taken for 7 different reservoir heads. A red dye solution was then applied from the interface between the inlet sluice and the lakeside to observe the motion through the inlet, *Bissokotuwa* chamber, and the outlet.

RESULTS AND DISCUSSION

The percentage of kinetic energy (KE) loss of the flow from the bottom of the lake due to the introduction of the *Bissokotuwa* chamber can be calculated using the average velocity of inflow (v_i) and average velocity of outflow (v_o) as given in Equation (1).

$$\text{Percentage KE loss} = \frac{v_i^2 - v_o^2}{v_i^2} \times 100\% \qquad (1)$$

Deviation of the percentage of KE loss of the inflow with 7 different reservoir heads of the lake is plotted as shown in Figure 5 and indicates that the percentage of KE loss is approximately constant for different reservoir heads. This concludes that the percentage of KE loss is independent of the reservoir head.

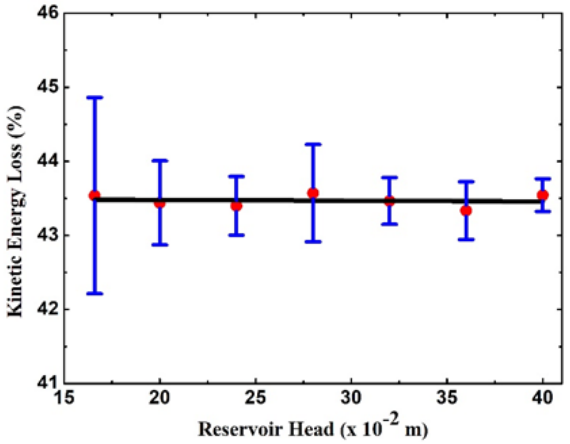

Figure 5: The graph of the percentage of KE loss of inflow vs. reservoir head of the lake for the prototype model.

In rheology, Poiseuille's formula for Newtonian liquids in laminar flow is often used and is given by the Equation (2), where ΔP is the total pressure loss or pressure difference between the ends of the pipe (in Pa), η is the Newtonian viscosity (in Pa s), l is the length of the pipe (in m), Q is the discharge rate (in m^3/s), and r is the radius of the pipe (in m) (Feys *et al.*, 2008). In order to apply Poiseuille's formula the following conditions are to be fulfilled; the flow must be isothermal and fully developed, the liquid must be incompressible, no radial or tangential flow component is allowed, the flow must be steady, there is no slip at the walls, and the flow is occurring in laminar condition (Feys *et al*., 2008; Modi and Seth, 1980).

$$Q = \frac{\pi r^4}{8\eta l}\Delta P \qquad (2)$$

According to the law of continuity, when the flow is steady and the pipe is uniform, *Q* can be derived as a multiple of the velocity of the flume (*v*), and the cross-section area (*A*), of the pipe as given by Equation (3) (Sianoudis and Drakaki, 2008).

$$Q = vA \qquad (3)$$

Equations (2) and, (3) imply that *v* is directly proportional to ΔP for a steady flow through a uniform pipe when the flow is occurring under laminar conditions.

Figure 6 (a) shows that ΔP of the inlet is directly proportional to v_i to the *Bissokotuwa*. This implies inflow of the *Bissokotuwa* obeys Poiseuille's law, proving it is laminar. Figure 6 (b) shows that ΔP of the outlet is directly proportional to v_o from the *Bissokotuwa*. The outflow from the *Bissokotuwa* is hence laminar in accordance with Poiseuille's law.

Figure 7 shows the motion of dye particles inside the *Bissokotuwa* chamber. Here, Figure 7 (a) shows the entering of dye particles into the chamber as a steady flow as proved by Figure 6 (a). Figure 7 (b) shows an upswing and mixing of dye particles. The mutation of steadily moved dye particles as shown in Figure 7 (b) is due to subjecting shear stress to water to serve velocity gradient. The path of the dye particles is schematically represented in Figures (a) and (b). This demonstrates that turbulence has occurred inside the *Bissokotuwa* chamber (Peiris and Wijesinghe, 2008; Buaria *et al*., 2019). When the *Bissokotuwa* was in operation, it was also observed that the inflow is partially filled. However, the outflow was observed to flow throughout the entire cross-section of the outlet sluice.

Shear stresses are caused by reducing the pressure of water. This implies that the deceleration of water entering and the energy dissipation inside the *Bissokotuwa* chamber is governed by those shear forces (Peiris and Wijesinghe, 2008). Total head is a measure of the potential of an incompressible fluid at the measurement point which can be used to determine a hydraulic gradient between two or more points (Farsirotou *et al*., 2014). This concept of head relates the energy in an incompressible fluid to the height of an equivalent static column of the fluid (Farsirotou *et al*., 2014). Units are in different forms of energy in Bernoulli's Equation and can be measured also in units of distance. Then, the total head is given as the sum of the pressure head, elevation head (z), and velocity head as shown in Equation (4) (Farsirotou *et al*., 2014). The total head can be written in terms of static pressure (*P*), flow velocity(*v*), and acceleration due to gravity (*g*) shown in Equation (5) (Farsirotou *et al*., 2014).

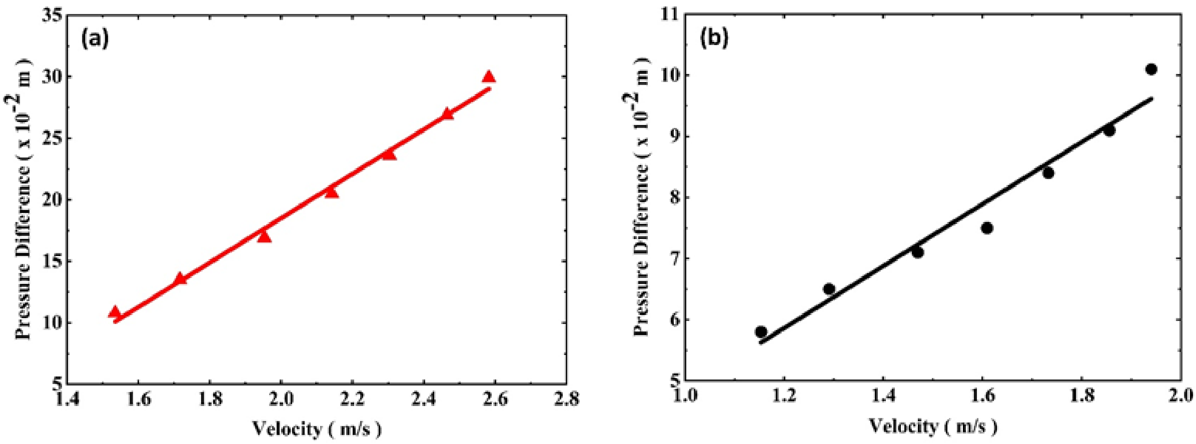

Figure 6: Plot of ΔP vs. *v* for (a) Inflow, and (b) Outflow.

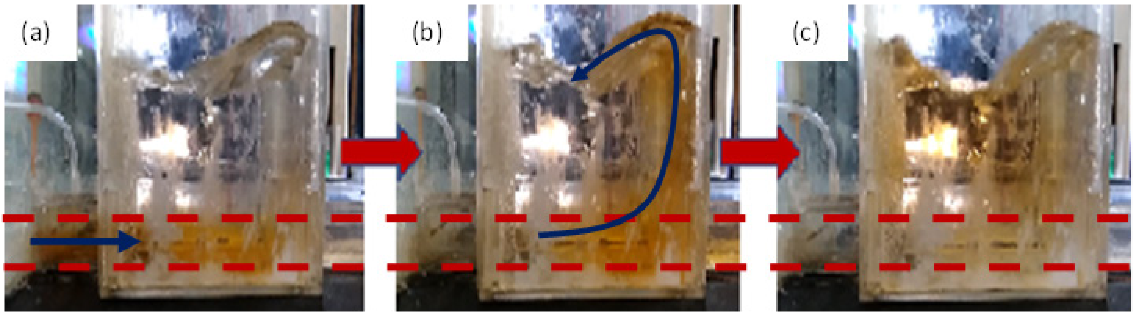

Figure 7: Motion of orange dye particles through the *Bissokotuwa* chamber (a) Entering dye particles into the chamber at a steady flow, (b) Shear stress acting on water inside the chamber, (c) Mixing of dye particles inside the chamber.

$$\text{Total Head} = \text{Pressure Head} + \text{Elevation Head} + \text{Velocity Head} \tag{4}$$

$$\text{Total Head} = \frac{P}{\rho g} + z + \frac{v^2}{2g} \tag{5}$$

Since fluid flows through the inlet and the outlet of the *Bissokotuwa* system at the same horizontal level, the total head of inflow and outflow can be compared by neglecting the term z as given in Equation (6). Hence, the total head of the inflow and the outflow can be written in the terms of P, ρ, g, and v as shown in Equation (7).

$$\text{Total Head} = \text{Pressure Head} + \text{Velocity Head} \tag{6}$$

$$\text{Total Head} = \frac{P}{\rho g} + \frac{v^2}{2g} \tag{7}$$

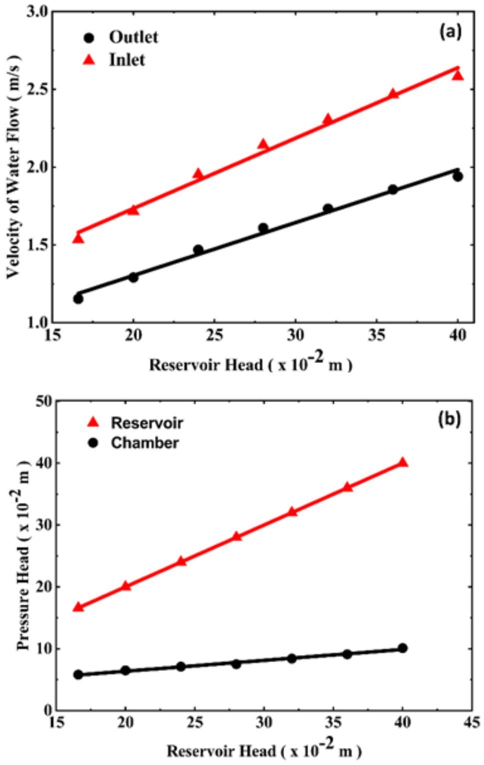

Figure 8: Comparison of (a) velocity of flow through the inlet and outlet for different reservoir heads and (b) pressure head of water flow, through the reservoir and the *Bissokotuwa* chamber for different reservoir heads.

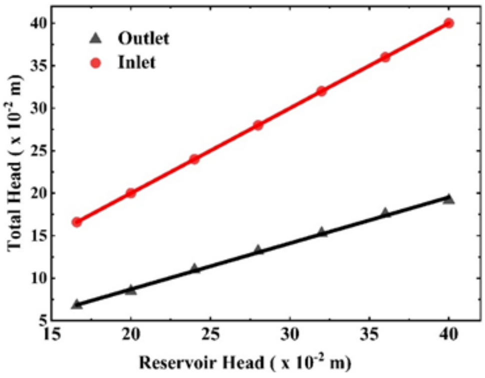

Figure 9: Variation of the total head of inflow and outflow for different reservoir heads.

Inflow velocity is higher than the velocity of outflow for different reservoir heads as shown in Figure 8 (a). The pressure head inside the reservoir is higher than the pressure head inside the *Bissokotuwa* chamber as shown in Figure 8 (b). According to Equation (7), the total head of the outflow should be less than the total head of the inflow and is shown graphically in Figure 9 as observed in the experiment.

The dropping of the velocity head and the pressure head of the outflow happened due to the intervention of the *Bissokotuwa* chamber to the sluice. This can be concluded due to the occurrence of turbulence only inside the *Bissokotuwa* chamber as observed in Figure 7, and due to inflow and outflow being laminar as proven by Figures 6 (a) and (b). Then, less turbulent water is released to the channel through the outlet, which would reduce the erosion, and degradation of channel banks. Since the water flowing out has lower pressure head, the static pressure of the outflow is not harmful to the bund of the lake.

Large flow through a real-world scenario

The laminar or turbulent nature of the flow in a pipe can be determined by calculating the Reynolds number, "*Re*". *Re* is directly proportional to the effective hydraulic diameter of the pipe (D), velocity (u), of the fluid flow, and the density of the fluid (ρ), while it is inversely proportional to the dynamic viscosity of the fluid (μ), as represented in Equation (8) (Gnielinski, 2013; Rott, 1990; Kim *et al.*, 2008).

$$Re = \frac{uD\rho}{\mu} \tag{8}$$

When $Re < 2300$, the flow is laminar, and when $Re > 4000$, the flow is turbulent (Gnielinski, 2013; Rott, 1990; Kim *et al.*, 2008).

Compared to the actual situation, the inflow and outflow behavior of the prototype model is different. First, because of the bigger reservoir head in the real scenario than the prototype model, the inflow and outflow velocities are substantially higher. Second, compared to the prototype model, sluices have a much greater diameter in the real-world scenario. Third, because the sluice walls in the real scenario are constructed from rock slabs and cubes, they are substantially rougher than in the prototype model. The smoothness of sluice walls in the prototype model is due to its construction with Perspex.

This implies that the observed laminar behavior for the inflow and the outflow can't be expected as the pressure head and sluice diameters are larger in the real scenario as shown in figure 10. A much larger pressure head results in high flow speeds. High flow speeds and larger sluice diameter can increase *Re* as they are the directly proportional terms, u, and D in Equation (8). This suggests there is a gap between the behavior of flows through sluices in the prototype model and in the real scenario. However, the energy dissipation mechanism inside a real *Bissokotuwa* chamber can be expected to be the same for already observed phenomena in the case reported.

Figure 10: Behavior of outflow in a real scenario (Photo Credit: H.A.H. Jayasena - *Kala Wewa* ancient sluice gate).

CONCLUSION

With the help of a prototype model, it has been found that the creation of the *Bissokotuwa* to a lake causes the total head of inflow to be reduced by lowering inflow velocity and static pressure before outflow. The average KE loss of the prototype model of the *Bissokotuwa* is about 43.5% and is unaffected by the reservoir head. This concludes that the percentage of KE loss is independent of the reservoir head. Water will experience high-velocity gradients upon entering *Bissokotuwa*. These high-velocity gradients will cause shear stresses, and in turn decrease the total head of the water. According to Poiseuille's formula and the continuity Equation applied for the prototype model, the inflow and the outflow were observed to follow laminar behavior; however, laminar behavior of flows through the sluices cannot be expected for the real-world scenario. The energy dissipation of inflow is only found inside the *Bissokotuwa*. But in reality, the energy dissipation process inside the chamber can be expected to be similar to the energy dissipation process of the prototype model.

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DECLARATION OF CONFLICT OF INTEREST

The authors have no conflicts of interest regarding the publication of this paper.

REFERENCES

Awusadahami, U. B. (1999). *Wewa.* Boralasgamuwa: Prachi Publishers.

Baalasooriya, J. (2004). *Polonnaruwe Purana Warimarga* . Polonnaruwa : Sooriya Printers.

Bauer, A. M. and Morrison, K. D. (2008). Water management and reservoirs in India and Sri Lanka. *Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures*, 4376-4385.

Bergant, A., Angus, R. S. and Arris, S. T. (2006). Water hammer with column separation: A historical review. *Journal of fluids and structures,* **22**(2), 135-171. doi:10.1016/j.jfluidstructs.2005.08.008

Brohier, R. L. (1937). The inter-relation of groups of ancient reservoirs and channels in Ceylon. *The Journal of the Ceylon Branch of the Royal Asiatic Society of Great Britain & Ireland,* **34**(90), 64-85.

Buaria, D., Pumir, A., Bodenschatz, E. and Yeung, P. K. (2019). Extreme velocity gradients in turbulent flows. *New Journal of Physics,* **21**(4), 043004. doi:10.1088/1367-2630/ab0756

Choon, T. W., Lim , K. A., Lim , E. A. and Teoh , T. H. (2012). Investigation of water hammer effect through pipeline system. *International Journal on Advanced Science, Engineering and Information Technology,* **2**(3), 246-251. doi:10.18517/ijaseit.2.3.196

Farsirotou, E., Kasiteropoulou, D. and Stamatopoulou, D. (2014). Experimental investigation of fluid flow in horizontal pipes system of various cross-section geometries. *EPJ Web of Conferences,* **67**, 02026. doi:10.1051/epjconf/20146702026

Fathi-Moghadam, M., Haghighipour, S. and Mohammad Vali Samani, H. (2013). Design-Variable Optimization of Hydropower Tunnels and Surge Tanks Using a Genetic Algorithm. *Journal of Water Resources Planning and Management,* **139**(2), 200-208. doi:10.1061/(ASCE) WR.1943-5452.0000243

Feys, D., Ronny , V. and Geert , S. D. (2008). Extension of the Poiseuille formula for shear-thickening materials and application to Self-Compacting Concrete. *Applied Rheology,* **18**(6), 62705-1. doi:10.1515/arh-2008-0021

Gnielinski, V. (2013). On heat transfer in tubes. *International Journal of Heat and Mass Transfer, 63*, 134-140. doi:10.1016/j.ijheatmasstransfer.2013.04.015

Gunasekara, K. A., Nandalal, K. D. and Imbulana, U. S. (2022). A Model for Management of Sivalakulama Tank Cascade System. In *Lecture Notes in Civil Engineering* (pp. 521-532). Singapore: Springer. doi:10.1007/978-981-16-4412-2_40

Gunawardana, R. A. (1978). Hydraulic engineering in ancient Sri Lanka: the cistern sluices. *Studies in South Asian Culture,* **7**, 61-74.

Hassanpour, N., Dalir, A. H., Farsadizadeh, D. and Gualtieri, C. (2017). An Experimental Study of Hydraulic Jump in a Gradually Expanding Rectangular Stilling Basin with Roughened Bed. *Water,* **9**(12), 945. doi:10.3390/w9120945

Jayasena, H. A. (2012). Socio-technical Aspects of Water Management in Sri Lanka: The Past and the Present. *Ceylon Journal of Science (Physical Sciences) Earth*

Sciences, **16**(1), 19-30.

Jayasena, H. A. and John, S. S. (2004). Thousand Years of Hydraulic Civilization Some Sociotechnical Aspects of Water Management. *Water and Politics*, pp. 225-236.

Karunathilaka, K. L., Dabare, H. K. and Nandalal, K. D. (2017). Changes in rainfall in Sri Lanka during 1966–2015. *Engineer: Journal of the Institution of Engineers, Sri Lanka,* **50**(2), 39-48. doi:10.4038/engineer.v50i2.7251

Kim, C., Mansoo , L. and Cheolheui , H. (2008). Hydraulic transport of sand-water mixtures in pipelines Part I. Experiment. *ournal of mechanical science and technology,* **22**(12), 2534-2541. doi:10.1007/s12206-008-0811-0

Modi, P. N. and Seth, S. M. (1980). *Hydraulics and fluid mechanics.* Delhi : Standard Book House.

Parker, H. (1909). *Ancient Ceylon.* Asian Educational Service .

Peiris, K. and Wijesinghe , S. (2008). Introduction to the function of Bisokotuwa in ancient Vewa. *Engineer: Journal of the Institution of Engineers, Sri Lanka,* **41**(3), 24-28.

Rott, N. (1990). Note on the history of the Reynolds number. *Annual review of fluid mechanics,* **22**(1), 1-12. doi:10.1146/annurev.fl.22.010190.000245

Samarakoon, E. B., Mendis, M. M. and Yapage, N. (2021). Analysis of rainfall distribution and variation during the Southwest monsoon in the wet zone of Sri Lanka. *Ceylon Journal of Science,* **50**(4), 459-465. doi:10.4038/cjs.v50i4.7944

Sianoudis, I. A. and Drakaki, E. (2008). An approach to Poiseuille's law in an undergraduate laboratory experiment. *European journal of physics,* **29**(3), 489. DOI:10.1088/0143-0807/29/3/009

Wong, M. K., Sheng, L. C., Nor Azwadi, C. S. and Hashim, G. A. (2015). Numerical Study of Turbulent Flow in Pipe with Sudden Expansion. *Journal of Advanced Research in Fluid Mechanics,* **6**(1), 34-48.