Flow Monitoring at Mine Water Discharges and Treatment Schemes in Wales – Challenges and Lessons Learnt

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Abstract

A key metric used in both the operational management of mine water treatment schemes, and the design of new schemes or other interventions, is flow. This paper considers the challenges of measuring mine water flows accurately, and the effect that these have on the uncertainty in the data. Through the Coal Authority's ongoing flow monitoring improvement programme, flow data uncertainty has been reduced by measures such as the installation of baffle plates, gauge boards, non-contact, low power, digital water level sensors and improved maintenance. New flow monitoring sites on the metal mine programme have also benefited from the revised 'best practice' approach.

Keywords: Mining, Uncertainty, Flow Data, Operations, Design

Introduction

The Coal Authority operate over 75 coal mine water treatment schemes (MWTS) managing water from historical coal mines across the UK, 15 of which are located in Wales. The Coal Authority is a partner in the Natural Resources Wales (NRW) joint Metal (Non-Coal) Mine Programme (MMP) investigating sources of pollution from metal mining activity and formulating solutions to mitigate these.

Flow is a key metric used in both the design of new schemes or other interventions, and effective management of existing treatment schemes. Operationally, the Coal Authority uses flow data for performance monitoring, including maintenance scheduling, dosing control and capacity assessment, as well as for permit and licence compliance monitoring. It is therefore clear that accurate flow data is essential to the efficient management of MWTS. In the first instance, flow data collected for the NRW MMP is used in the assessment of environmental impact from mine water discharges by calculating solute loads. Subsequently, the data will inform requirements for treatment solutions. As the MMP is in its relative infancy, this data will feed into longer term prioritisation of pollution mitigation measures.

Flow Monitoring Structures

The majority of flow data collected by the Coal Authority is via primary flow monitoring structures, which provide a volumetric flow rate. These predominantly consist of thin-plate weirs and flumes, though a variety of other methods are also used (broad-crested weirs, compound weirs, in-pipe sensors). Electromagnetic pipe flow meters also provide continuous flow data of the inflow to pumped MWTS. Thin-plate V-notch weirs have a triangular notch with an opening angle ranging from α=20-100°, installed perpendicular to the flow of water in a stream or channel (Achour & Amara 2021; Pospíšilík & Zachoval 2023). Water should spring clear of the weir plate through the notch, creating a fully aerated nappe. Rectangular thin plate weirs work in much the same way, but with a rectangular opening in the weir plate of a given size as opposed to a triangular one. By measuring the depth of water, or head *h*, upstream of these notches, and through knowledge of the approach channel and weir plate dimensions, flow rate can be accurately determined (Shen 1981). The requirement to have an aerated nappe, and the specific weir crest dimensions required, mean that thin-plate weirs are not best suited to measuring raw mine water, where iron levels will likely be high and the weir crest and approach channel will be subject to ochre accretion.

Flumes work to similar principles, with the discharge equations based upon boundary layer and hydraulic theory. They create a constriction in the channel via a narrowed throat section, with the upstream depth of water and flume geometry used to determine the rate of flow through the structure. They have the advantage that they do not cause a barrier to the flow, since the flume throat is usually set at the same level as the approach channel, and thus are better suited to measuring raw mine water as solids do not tend to accrete to the flume sides or in the approach channel. The Coal Authority has employed both rectangular and trapezoidal flumes, but a variety of flume geometries are available (Ribeiro et al. 2021).

A variety of hydrometric ISO standards detail how flow should be measured by primary structures (ISO 1438:2017; ISO 4359:2022; ISO 3846:2008; ISO 4377:2012). Since these standards are largely based on laboratory test conditions, the regulatory organisations in England and Wales have developed the Monitoring CERTification Scheme (MCERTS) which makes some concessions to the ISO standards, in order to allow the installation and maintenance of flow monitoring structures in often less than perfect real-world scenarios. MCERTS requires measurement at mean flow to an uncertainty of ±8%. The standard only legally applies in England and Wales, but the Coal Authority have adopted the principles to flow monitoring installations across the UK.

Flow Data Uncertainties

All measurements of a physical quantity are subject to uncertainties. The result of a measurement is only an estimate of the true value of the measured quantity, and therefore is only complete when accompanied by a statement of its uncertainty. In order to know the reliability of a flow record, it is necessary to identify the areas that give rise to errors in the process of estimating flow.

Flow data uncertainty is a measure of a number of parameters, all playing a part in determining the accuracy of flow data collected. In terms of V-notch (Q_t) and rectangular (Q_r) thin-plate weirs, the uncertainty calculation (u_c) comprises uncertainty in the discharge coefficient (C_d), uncertainty in the weir dimensions (b_e,α), and uncertainty in the head measurement (h_e) (Eq. 1).

Further errors may also be included, such as data treatment/ telemetry error, head to flow conversion error and others associated with non-conformance to ISO and MCERTS standards. Since the uncertainty in the discharge coefficient (C_d) and uncertainty in the weir dimensions (b_e,α) are typically small, it is clear from ***Equation 1*** that the uncertainty in head measurement has the greatest impact on data uncertainty, as this parameter has a 1.5 and 2.5 multiplier for rectangular and V-notch weirs respectively.

Equation 2 describes the uncertainty calculation for a flume (Q_f). Again, total uncertainty is a combination of uncertainty in head measurement (h), uncertainty in the flume dimensions (b, D, m), and uncertainty

$$u_c \times (Q)_r = \sqrt{u \times (C_d)^2 + u \times (b_e)^2 + [1{,}5u \times (h_e)]^2}$$

$$u_c \times (Q)_t = \sqrt{u \times (C_d)^2 + u \times \left[tan\left(\frac{\alpha}{2}\right)\right]^2 + [2{,}5u \times (h_e)]^2}$$

Equation 1 *Uncertainty equations for thin-plate weirs*

$$u \times (Q)_{flume} = \sqrt{u \times (C)^2 + \gamma^2 \cdot u \times (b)^2 + \varphi^2 \cdot u \times (h)^2 + \Psi^2 \cdot u \times (m)^2}$$

Equation 2 *Uncertainty equation for flumes* in the discharge coefficients (C_D, C_S, C_V). As with thin plate weirs, a multiplier is applied to the head uncertainty in the range 1.5 (rectangular flumes) to 2.5 (trapezoidal flumes). It can therefore be concluded that whilst there are other uncertainties involved, when combining all of the uncertainties the uncertainty in water level measurement has the largest effect (Burton & Willis 2005).

Challenges

The uncertainty in water level measurement itself comprises a number of factors, such as the zero head error, accuracy of manual readings, the implications of a clinging nappe, sensor selection and error. Each of these factors are discussed in turn below.

Zero head error is the accuracy with which the gauge board is zeroed to the crest or cease to flow level of the structure (e.g. the throat of a flume). Gauge boards must be installed using surveying equipment such as a dumpy or laser level to achieve tolerances of ±1 mm.

Accuracy of manual readings of the water level at a weir or flume are impacted by factors such as turbulence and reading location. Turbulent approach conditions can reduce the resolution at which manual readings can be taken, often from ±1 mm when laminar flow conditions persist to ±10-15 mm in turbulence. If a manual water level reading is taken within the notch of a thin-plate weir, or in the throat of a flume, then the drawdown effect will lead to an under-estimate of the water level (**Figure 1**). As the flow passes over a notch or into a flume, the water surface is pulled downwards (or 'drawn down'). On the other hand, if the water level measurement is taken further upstream away from any drawdown effects, it will not be under-estimated. Also, a lack of safe and easy access to sites may limit vital maintenance activities, meaning ochre and debris can build up on the weir crests and gauge boards, making manual readings difficult and imprecise. Ochre build up on the weir crest will cause an overestimation of the water level and thus flow.

A **clinging nappe** is where the flow is unable to freely spring clear of a weir plate. It can be caused by a lack of regular cleaning, the weir crest being too thick or the water level being below the minimum recommended in the standard. The effect of this is also to artificially drawdown the upstream head measurement, leading to an underestimation of the flow (Kay 1998).

Finally, the **choice of water level sensor** is important to ensure accurate flow data, at sites where continuous data collection via a data logger is required. At many Coal Authority sites there is no mains power, and thus battery powered solutions are required. Until recent years, this limited the choice of sensors to pressure transducers which have to be installed below the water surface, and therefore can be compromised by ochre

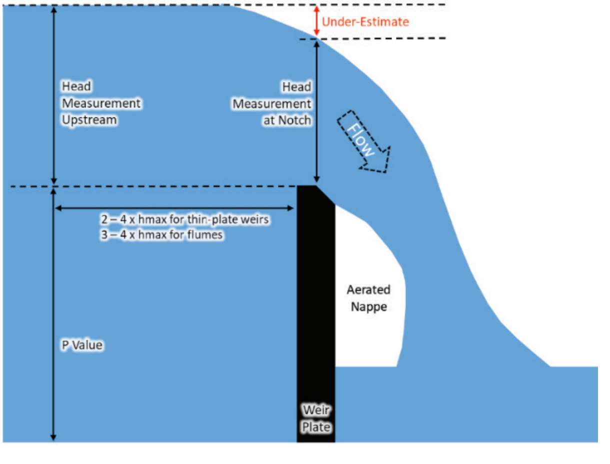

Figure 1 *Drawdown effect over a thin-plate weir*

accretion. However, low powered non-contact radar sensors, which can be mounted above the water surface, are now available. These are therefore preferred, except at sites where there is surface turbulence or the treatment process results in foam on the water surface. Digital, rather than analogue sensors are also preferred.

Given the numerous potential sources of error in water level measurement, and the fact that many of them cause compounding errors, it is worth considering the sensitivity to a ±10 mm water level measurement error in the estimation of flow (**Table 1**), bearing in mind the MCERTS requirement of uncertainty at mean flow of better than +/- 8%.

Solutions

The Coal Authority has been working to reduce uncertainty in our flow data, both from operational MWTS and the NRW MMP. Through this work, the Coal Authority has developed a new 'best practice' approach when upgrading existing flow monitoring structures, as well as when designing and installing new structures.

To lower manual reading error, the Coal Authority has retrofitted baffle plates at various sites, reducing turbulence in the approach channel to weirs (**Figure 2a**). Furthermore, improved weir maintenance training to site operators has been initiated to ensure weir plates, approach, downstream channels and gauge boards are regularly cleaned and cleared. This minimises the build-up of debris and ochre on and around primary monitoring structures (**Figure 2b**).

Non-contact battery operated MCERTS approved digital radar sensors have been deployed at a number of sites, where conditions are appropriate and no mains power is available (**Figure 2c**). The non-contact sensors have also been fitted with vandal resistant covers, to reduce the risk of damage where sites are publicly accessible (**Figure 2c**). Weir plates that were damaged, corroded or non compliant with MCERTS standards have also been replaced (**Figure 2d**). Not only has this returned many sites to compliance, but the use of carrier plates has also improved the durability and flexibility of these sites. Damaged, corroded or incorrectly sized weir plates can be easily replaced in isolation in the future, without the need to replace the entire structure (**Figure 2e**). The example in **Figure 2e** shows a compound weir structure, which has a small low level notch with a wider high level notch. Such structures are useful when the anticipated flow range is great, but there is a low base flow, as they can accommodate both low and high flows.

Implementation of additional access and health and safety measures at sites improves worker safety allowing easier maintenance, and more accurate manual readings (**Figure 2f**). The Coal Authority has routinely installed fixed gauge boards where possible, so that accurate manual readings can be taken to a resolution of ±1 mm, and the effects of the drawdown zone do not influence data. The Coal Authority is also now trialling aluminium gauge boards, intended to withstand more frequent and vigorous cleaning activities required at our schemes. Upgrading sites so that data may be transferred via telemetry has also progressed, allowing for better remote monitoring and interpretation of flow data, in turn improving ability to pro-actively manage sites.

***Table 1** Percentage difference in flow estimate caused by a ±10 mm error in the Head reading*

	Head (*h*) Flowing Over Weir		
	200 mm	100 mm	Minimum Head*
V-Notch	± 13%	± 26%	± 45%
Rectangular Notch	± 7.5%	± 15%	± 52%

Note: *60 mm for a V-notch weir, 30 mm for a rectangular weir.

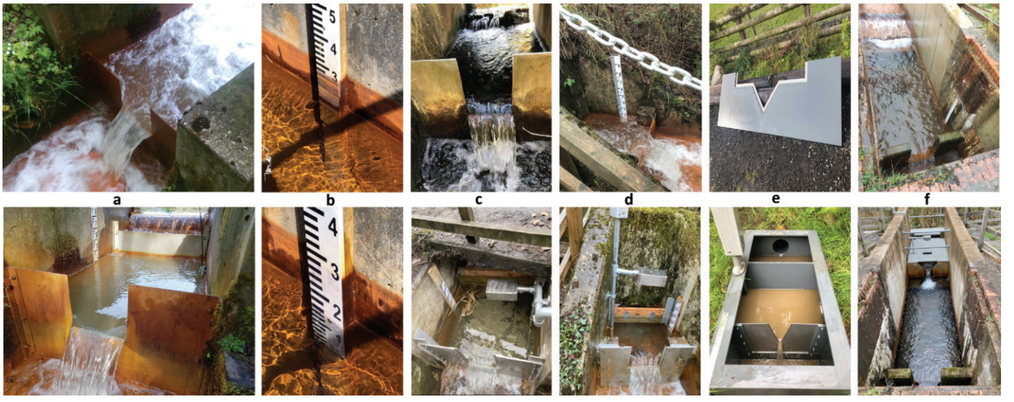

Figure 2 *Improvements to primary flow monitoring structures*

Figure 3 *Glyncorrwg MWTS flow monitoring upgrades*

Case Study: Glyncorrwg

Glyncorrwg MWTS is located in the Afan Valley, South Wales, 13 km northeast of Port Talbot. The scheme provides passive treatment to mine water discharging from both the East and West bank of the Afon Corrwg, comprising 11 reed beds in series. Flow monitoring at the scheme is undertaken at three locations via primary flow monitoring structures (**Figure 3**):

a. Thin plate V-notch weir at Reed Bed 4 (East Bank) Discharge
b. Thin plate rectangular weir Final Consented Discharge
c. Thin plate rectangular flume West Bank Discharge

These structures suffered from a variety of issues, including incorrect sizing, weir crests being too thick and not chamfered, turbulent approach conditions, no gauge boards upstream and ochre build-up. In 2023, the Coal Authority undertook a weir improvement project at the site, with the three locations upgraded as a result (**Figure 3**).

***Figure 4** Parc Mine flow monitoring structures*

The flow structures were re-designed to accommodate a greater flow range with, increased peak capacity. The thick, coated plywood weir plates were replaced with stainless steel plates chamfered to 1-2 mm thickness. Non-contact battery powered water level sensors were installed at each location, to mitigate ochre-build up. Solar panels were also installed to provide battery recharging for each logger and sensor, thus reducing the need for frequent battery replacements. Aluminium gauge boards were installed at an appropriate distance upstream of each structure, providing a durable and maintainable water level measurement point. The West Bank discharge was re-configured as a flume rather than a thin-plate weir, due to the limited upstream head. This location was also prone to ochre accumulation which would have quickly built up behind a replacement weir plate.

Case Study: Parc Mine

Parc Mine is located approximately 1.6 km south-west of the town of Llanrwst, North Wales. The Coal Authority, in conjunction with NRW, have an ongoing project to monitor the discharge of mine water from Parc Mine, with a view to potential remediation measures in the future. As part of this project, flow monitoring data is required to understand the magnitude and composition of mine water discharging at surface. To meet this requirement, the Coal Authority commissioned the design of seven flow monitoring sites for the Parc Mine in 2021. Construction and installation began in 2022 and was completed in April 2023 (**Figure 4**).

The prefabricated Glass Reinforced Plastic (GRP) weir tank used at Cutting Level is a good example of where preformed units can provide accurate measurement of smaller flows, with baffle plates, carrier plate, weir plate, gauge board and instrumentation all contained within a covered unit. A level base and an appropriately levelled inlet and outlet channel are required, but no further civils work is needed. Pre-fabricated twin trapezoidal GRP flumes were deployed elsewhere on the site. These require more civils work to adequately secure in place. Non-contact sensors were used to measure flows of highly ochreous water discharging from historical tailings.

Conclusions

As shown above, the factor with the greatest impact of flow measurement uncertainty at weirs and flumes is the water level measurement, and there are numerous sources of error which can compound to create large uncertainties in the data. The approach taken by the Coal Authority to tackle these challenges and reduce measurement uncertainty includes the installation of gauge boards and baffle plates, the use of non-contact digital water level sensors with battery power connected to solar, training provision, replacement weir plate and flume upgrades and the use of carrier plates.

The flow monitoring challenges experienced by the Coal Authority are not unique to mine water or to specific locations in Wales or the UK. The learnings and approach described here could therefore be applied elsewhere to improve monitoring of existing or future mine water and reduce uncertainty in flow data around the world.

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