Pollution resulting from the abandonment and subsequent flooding of Wheal Jane Mine in Cornwall, UK

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Abstract. The closure of Wheal Jane Mine in Cornwall and the withdrawal of dewatering pumps resulted in the flooding of mine workings extending over a large area. The mine drainage was historically very acidic and high in metals. In order to predict the impact of the mine discharge, the National Rivers Authority commissioned a programme of investigations and monitoring. This paper describes the monitoring and assessment work undertaken at Wheal Jane during mine flooding in order to predict the discharge, location, time, quantity and quality, and the potential impact on groundwater sources used for potable supply. It also describes the subsequent mine water discharge and actual monitored levels of flow and water quality.

Investigations and monitoring of the flooding mine system included a detailed mining survey, the recording of water levels at suitable shafts, the collection and analysis of mine water samples and water quality depth profile surveys in a number of shafts. Surveys and monitoring of groundwater sources were also undertaken. Measurement of water levels and the mining survey allowed accurate prediction of the location and time of discharge. An estimate of the mine water discharge of between 5000 $m^3 day^{-1}$ and 20 000 $m^3 day^{-1}$ was prepared from catchment water balance calculations. This compares with the seasonally fluctuating, actual discharge of between 5000 $m^3 day^{-1}$ and 40 000 $m^3 day^{-1}$. Mine water quality samples and water quality depth profiles taken from different shafts across the mine system identified large variations; in general, becoming more acidic with higher concentrations of metals with depth. Following flooding, the initial discharge quality was within the range predicted, with a pH of 2.8 and total metals of approximately 5000 $mg l^{-1}$, notably consisting of iron, zinc and cadmium. Surveys identified a number of groundwater wells and boreholes close to the mine system which required regular monitoring. None were identified to have been affected during the mine flooding or following discharge.

Wheal Jane is the collective name for a group of interconnected metalliferous mines situated in the Carnon Valley, near Truro in Cornwall (Fig. 1). Wheal Jane Mine itself was developed in the late 1960s using modern techniques to exploit the rich mineral lodes previously worked by shallow mines in the 17th, 18th and 19th centuries. In the 1970s, the mine extended beneath the Carnon Valley to connect with another working mine, Mount Wellington, and exploratory workings further to the west, connected into a large group of abandoned workings known as United Mines.

The workings associated with Wheal Jane are extensive, reaching to a depth of 450 m and for several kilometres laterally along a number of main mineral lodes. The mine was renowned for being very wet and substantial dewatering at up to 60 000 $m^3 day^{-1}$ was required in winter months. The pumped water was typically very acidic, with high concentrations of dissolved metals resulting from the sulphide mineral deposits. Approximately half of the pumped water was treated by the mining company prior to discharge to the Carnon River.

In March 1991, Wheal Jane was closed, and shortly afterwards, mine dewatering ceased and the pumps were removed. The National Rivers Authority (NRA) identified the potential for a substantial impact on the water environment and immediately commissioned an integrated investigation to characterize the mine water discharge and assess the probable impact.

Environmental setting

Wheal Jane was the last of more than 50 mines to operate in the Gwennap Mining District, an area with a rich mining history dating back to at least the 17th century (Dines 1956). These mines were developed to exploit minerals associated with quartz porphyry dykes intruded into the Killas mudstones, during a period of regional metamorphism associated with the emplacement of the Cornish granite batholiths. The main mineral lodes exploited by Wheal Jane trend approximately SW–NE and dip at approximately 45° to the northwest. They typically include the following minerals: cassiterite

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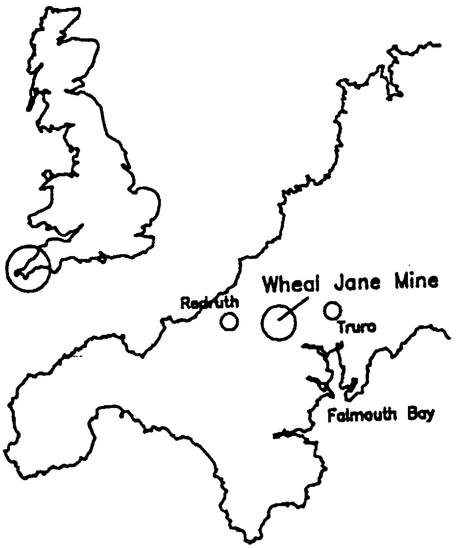

Fig. 1. Wheal Jane Mine location.

(tin), chalcopyrite (copper), pyrite (iron), wolframite (tungsten) and arsenopyrite (arsenic). Silver, galena (lead) and a number of alteration minerals also occur in lesser amounts.

The Killas rocks in the vicinity of Wheal Jane have low primary porosity. However, fractures, faults (cross courses) and weathered zones provide storage and allow limited groundwater flow. In general, the groundwater table away from the mined areas forms a subdued replica of the surface topography with locally steep hydraulic gradients. These rocks provide small yields and support a number of wells, boreholes and springs which supply cottages and small farms (British Geological Survey 1990) They are classified as a minor aquifer by the NRA.

In mined areas the low permeability of the Killas rocks contrasts with the high conduit flow permeability engineered by mine workings. The mine workings therefore provide a preferential flow route for groundwater. Dewatering of Wheal Jane occurred to 450 m depth, resulting in a cone of water-table depression. The precise extent of the cone has never been identified; however, the low permeability of the Killas rocks would have resulted in steep hydraulic gradients towards the dewatered mine workings, thus restricting its extent.

The mine workings underlie the Carnon Valley, extending at shallow depths beneath the Carnon River (Fig. 2). The river and a number of its tributaries are historically of poor water quality, with high metal concentrations resulting from discharges associated with previously abandoned mines and mine spoil.

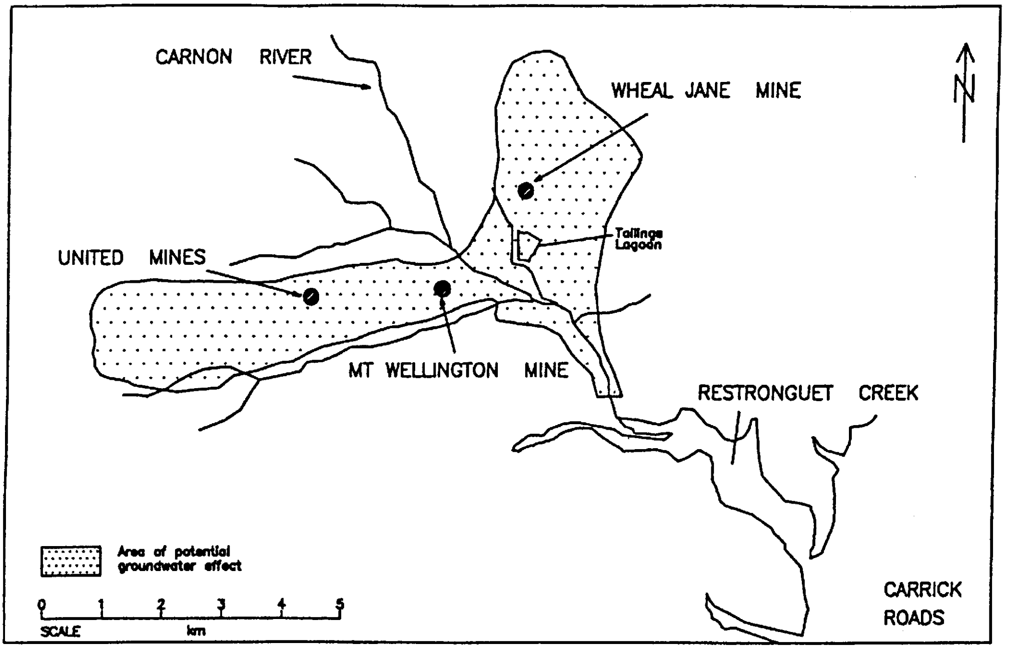

Fig. 2. The Carnon River mine locations and area of potential groundwater influence.

The Carnon River flows into Restronguet Creek, approximately 3 km downstream of Wheal Jane, and subsequently into Carrick Roads estuary. These tidal waters have shellfish and amenity value.

Mine flooding

Closure of the mine in March 1991 was effected rapidly, the mine dewatering ceased and the mine was stripped of equipment including all pumps. The extensive mine void began to fill, and a large surface area of mineral deposits exposed by mining was now exposed to groundwater leaching.

Investigations and monitoring

The NRA was concerned that once the mine void was flooded a significant discharge of poor quality water would drain from the mine, impacting upon the Carnon River and tidal waters in Restronguet Creek and the Carrick Roads. It was also concerned that flooding mine waters would pollute groundwater sources close to Wheal Jane. They commissioned a programme of investigations and monitoring which included those described below.

Mine system and mine waters

- A detailed mining survey to identify all mine workings, interconnections, adits, mineral variations, underground structures, etc., relevant to the future drainage of the flooded mine.
- A water level survey of mine shafts throughout the Wheal Jane mine system and adjacent workings to identify hydraulic connections and appropriate monitoring points.
- Measurement of the rise of mine water levels in six appropriate shafts across the mine system.
- Collection of mine water samples from varying depths (bottom, middle and top waters), in three main shafts across the mine system.
- Continuous depth profile measurement of water quality in top waters at the three main shafts.

Groundwater sources

- Survey and measurement of groundwater levels in boreholes, wells and shafts (not interconnected with Wheal Jane) to identify the zone of groundwater depression from mine dewatering.
- Survey of private and licensed groundwater sources of supply.
- Baseline sampling of water supplies at risk from rizing mine waters.

Predictions of mine water discharge

The information obtained from investigations and monitoring was regularly reviewed during the period of mine flooding and the programme modified as appropriate. The main objective of the data collection was to enable the following assessments to be made to predict the mine water discharge:

- location and time
- quantity and water quality
- impact on private groundwater sources

Assessment of the mine water discharge location and time Monitoring of water levels across the mine system showed that the mine workings were hydraulically well connected, flooding at the same rate. The possible mine system decant points were identified from the mining survey and are shown in Fig. 3. The lowest decant is through Jane's Adit estimated at a level of 14–15 m AOD. However, the main mineral lode had been worked to within a few metres of the bed of the River Carnon at an elevation of 15–16 m AOD and there remained a potential for direct discharge to the river by diffuse seepages. The next decant point at Nangiles Mine was estimated to be at 16—17 m AOD elevation. A graph of the mine water rise at one of the main shafts monitored is shown in Fig. 4.

Early recovery was rapid but soon slowed and became irregular, presumably due to the varied filling time for voids at different levels. The flooding rate was considered to be related to the volume of workings and recharge from groundwater. As the mine flooded, the hydraulic gradient into the mine reduced and, therefore, the rate of filling from groundwater decreased. It was also known that at Wheal Jane, the volume of interconnected workings increased higher in the mine due to the number of extensive shallow old mines. Towards the end of mine flooding the recovery was slow, as expected, and discharge occurred on 17 November 1991 from Jane's Adit into the Carnon River.

Assessment of the mine water discharge quantity and quality Investigation and monitoring of the mine system identified a highly complex hydraulic system (Dussek 1992). Accurate prediction of mine discharge flow and water quality was not possible. However, a best estimate was required to allow prediction of the potential

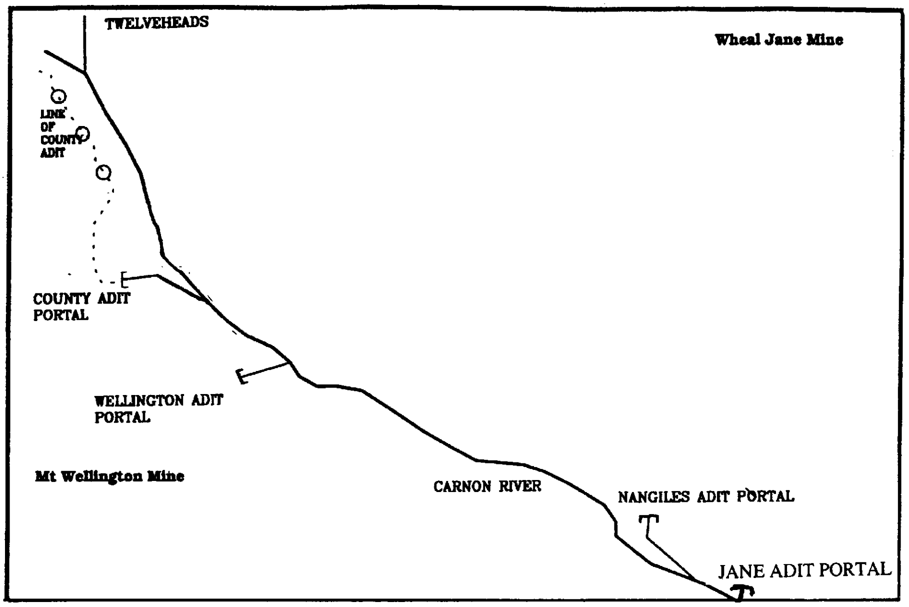

Fig. 3. Adit portal locations along the Carnon River.

impact on surface waters and also to enable appropriate treatment works to be designed and constructed.

Wheal Jane is interconnected with a large number of unsurveyed 18th century workings (Hamilton Jenkin 1963) and it was not possible to predict the discharge flow from rate of rise and workings volume calculations. Therefore, a preliminary water balance was undertaken projecting the known workings to the surface to define a recharge catchment.

Water balance calculations using long-term average recharge data predicted a mine water discharge of between 5000 m^3 day^{-1} and

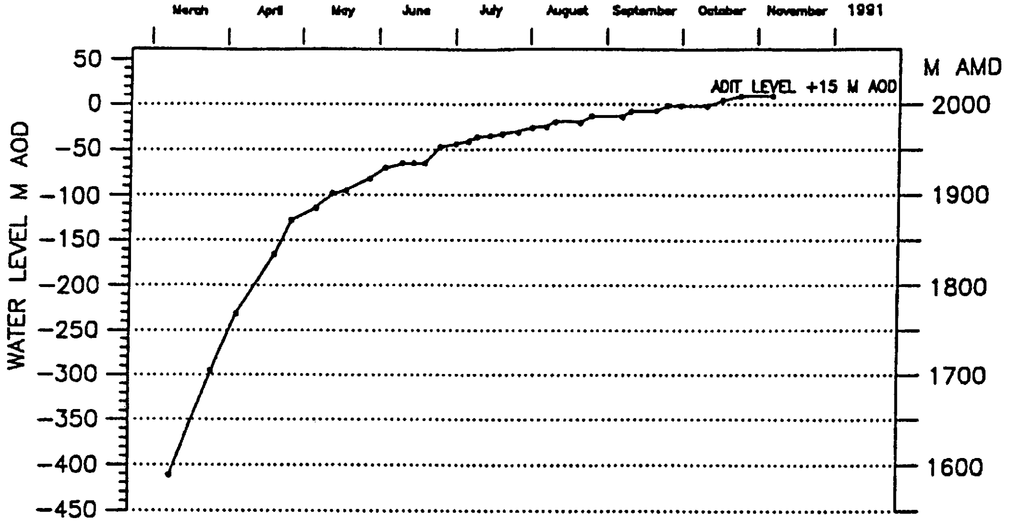

Fig. 4. Mine water level recovery – Wheal Jane No. 2 shaft.

Table 1. *Water quality in Wheal Jane No. 2 shaft when mine water was 45 m below adit level*

Sample depth (m bwl)	pH	Sp. Elec. Cond. ($\mu s\,cm^{-1}$)	Cadmium ($mg\,l^{-1}$)	Iron ($mg\,l^{-1}$)	Zinc ($mg\,l^{-1}$)	Copper ($mg\,l^{-1}$)
Shallow (10 m)	3.7	1640	0.13	94	98	4.5
Middle (90 m)	2.6	7390	2.6	1846	1379	40
Deep (180 m)	2.5	8440	4.8	2162	1541	44

20 000 $m^3\,day^{-1}$. The actual discharge since flooding has been recorded is between 5000 $m^3\,day^{-1}$ and 40 000 $m^3\,day^{-1}$. Surface samples collected regularly from the rising mine waters in six shafts across the mine system identified widely fluctuating levels of acidity and dissolved metal concentrations. These were considered to be due both to variations in mineral deposits and exposure, and to complex patterns of mine water flow.

To provide a better understanding of the variation in mine water quality, regular depth sampling and depth profile monitoring was also undertaken. Samples were taken using a flow-through bailer to a depth of up to 180 m below water level (bwl) at three main shafts across the mine system. A multi-probe water quality meter modified to allow monitoring to depths of up to 10 m was also used to identify water quality variations near surface. Table 1 identifies selected parameters indicative of the water quality at Wheal Jane No. 2 shaft on 5 July 1991 when mine waters were 45 m below adit level.

In general, water quality was found to deteriorate with depth within Wheal Jane, with samples from depth being very acidic with high concentrations of dissolved metals. Better water quality was observed close to the surface and waters sampled in United Mines were of much better quality. Mine water circulation was considered to be complex, possibly controlled by a combination of recharge, temperature gradient, density variation, and hydraulic mechanisms.

Accurate prediction of the discharge water quality was not possible, although a likely range was identified. The actual quality of the discharge was better than the worst water quality monitored, but it was still very acidic with high concentrations of dissolved metals.

Assessment of the impact of mine water discharge on private groundwater sources During mine flooding, groundwater drained into the dewatered zone, reducing the lateral extent of the zone. The groundwater gradient into the mine prevented sources of supply outside the dewatered area from becoming contaminated. However, on the boundary of this area, as groundwater recovered, it was possible that sources of supply could become affected. Groundwater sources identified to be within this boundary area were sampled and hydrogeological assessments undertaken to identify any impact by rising contaminated mine waters. None of the sources were considered to be directly at risk. However, seven sources were also identified adjacent to the Carnon River downstream of the discharge point. These were all shallow wells supported by alluvial deposits and therefore potentially at risk from a deterioration in river water quality. Following mine water discharge, these supplies were regularly monitored by Carrick District Council Environmental Health Department. Fortunately, none were identified as being contaminated by the river.

Mine water discharge

On 17 November 1991, the mine system flooded to 14.5 m AOD and mine water decanted through Jane's Adit into the Carnon River. A treatment lagoon constructed by the mine owners was rapidly overwhelmed by a flow of approximately 5000 $m^3\,day^{-1}$ of mine water with pH 2.8 and total dissolved metals of approximately 5000 $mg\,l^{-1}$.

The quality and quantity of the discharge was similar to that predicted. Back-up contingency treatment measures, funded by the NRA, were brought into operation immediately. These involved adding lime into the head of Jane's Adit to lower the acidity and precipitate metals, and pumping of mine water from behind a constructed plug near the adit portal into the Wheal Jane Tailings Dam.

In late December 1991, operational problems with the tailings dam halted pumping from the adit, which resulted in a gradual backup of water within the mine system. The mine water level increased by approximately 4 m resulting in seepages through the bed of the Carnon River and forcing a blockage within the second lowest known decant point, Nangiles Adit, to clear. Between 25 000 m^3 and 50 000 m^3 of poor quality mine water was suddenly released over

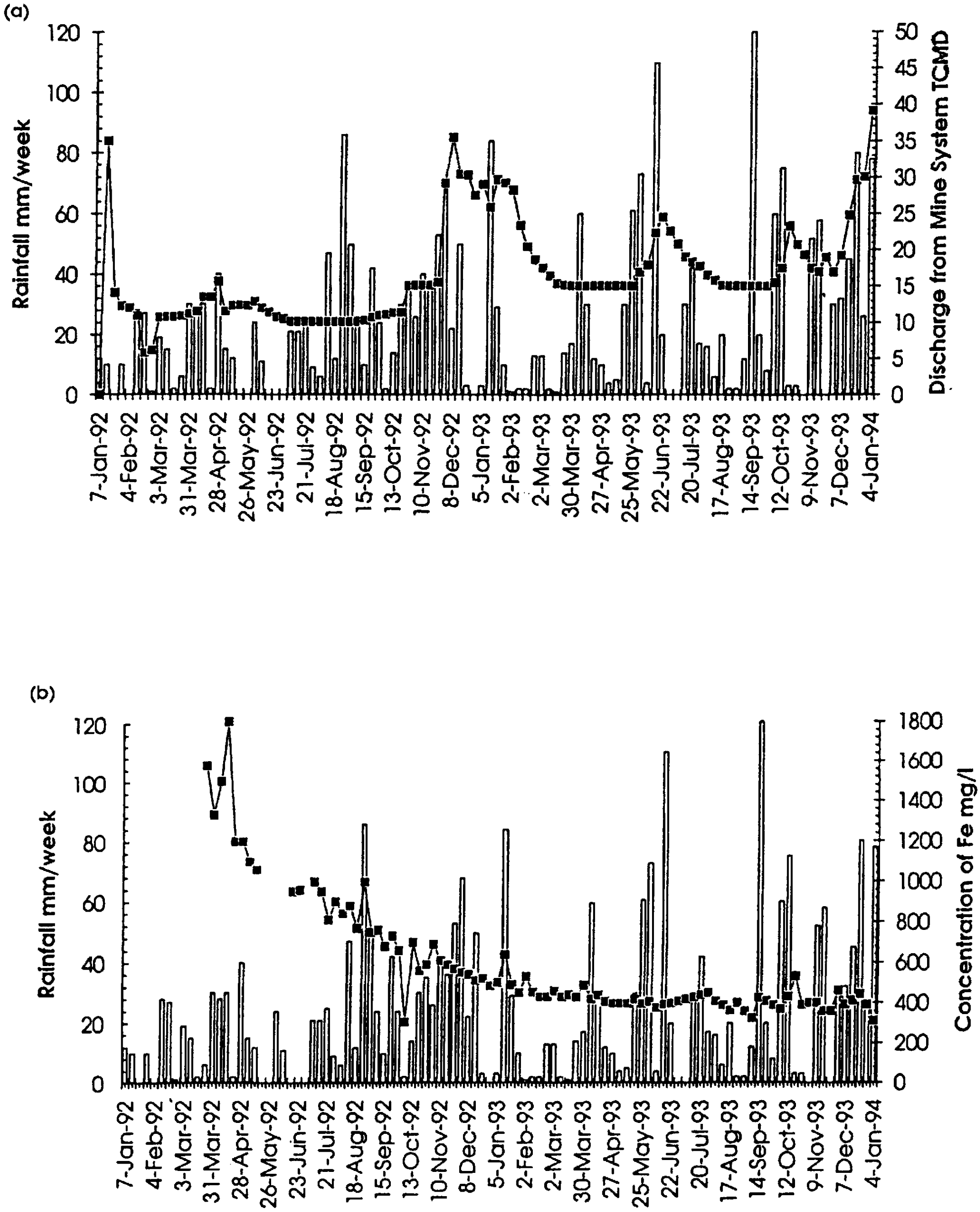

Fig. 5. (**a**) Mine water discharge flow and rainfall January 1992 to January 1994. (**b**) Mine water discharge quality monitored at No. 2 Shaft and rainfall January 1992 to January 1994.

a period of 24 h. The resultant pollution extended down the Carnon River into Restronguet Creek, the Carrick Roads and the ochre plume of contamination was visible into Falmouth Bay.

Following this incident, additional treatment measures were implemented. Pumps were installed into one of the main shafts at Wheal Jane and the treatment process control was optimized to improve metal precipitation within the tailings dam.

Intensive surface water and tidal water monitoring and assessment work was undertaken following the uncontrolled mine water discharge. In addition, monitoring of the mine system and mine water discharge was continued. This information was used to construct simple models to predict future mine water discharge quality and quantity.

Figure 5 graphically shows the discharge flow and water quality (Fe concentration only) compared with rainfall (bar chart) between January 1992 and January 1994. The flow is closely related to rainfall events although a lag exists of up to one month between a rainfall event and corresponding peak flow. The quality of the discharge in terms of metal concentrations has greatly improved, but the levels are still substantial and the water remains very acidic.

Long-term mine water discharge

The monitoring and investigations undertaken during the flooding of the mine and since the mine waters overflowed have provided information essential in mitigating the short-term pollution of the aquatic environment. However, the pollution of groundwater from metalliferous mining at Wheal Jane will continue for many tens of years or even centuries. Mines abandoned for more than a century close to Wheal Jane are still discharging acidic groundwaters, high in metals concentrations which impact upon streams and rivers.

The majority of drainage from Wheal Jane is currently being treated by an expensive short-term operation. Investigations are under way to identify a long-term, low-cost treatment system that will mitigate the pollution. In order to design such a treatment system effectively it is essential to characterize fully the future mine water discharge flow and water quality. The investigations and monitoring undertaken to date have provided a good understanding of the characteristics, and this will be developed by further monitoring over the next few years.

Conclusions

Metaliferous mining at Wheal Jane resulted in an extensive void, exposing metaliferous minerals to oxidation and weathering. Following the cessation of dewatering and with a knowledge of the mine system, it was possible to monitor the mine water rebound rate and water quality to accurately predict the location, quantity and quality of the discharge.

The eventual discharge required a substantial treatment operation involving co-operation between the National Rivers Authority and the mining company. This treatment operation is continuing and will need to be continued for many tens of years into the future if the water quality and aquatic environment of the region is to be protected.

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