Response to Increasing Rainfall and High Rainfall Events at Wheal Jane, Cornwall, UK

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ABSTRACT

After the closure of Wheal Jane mine in 1991, and the associated mine water rebound, highly contaminated acidic mine water overflowed from the mine and discharged at surface. This caused a major pollution incident affecting the Fal Estuary and resulted in emergency pumping being undertaken at Wheal Jane to prevent re-occurrence. Investigations by the Environment Agency into future options, resulted in the treatment plant being constructed, becoming operational in 2000.

Management of the Wheal Jane plant was transferred to the Coal Authority in 2011 as a result of its expertise in managing coal mine waters. Prior to 2011, the primary objective focused on operating and maintaining the plant in order to comply with the permitted discharge limits; with limited emphasis placed on other factors such as regional context. The approach undertaken by the Authority is to maintain compliance with the permit, whilst endeavoring to make efficiency savings. Part of this strategy includes the assessment of treatment methodology, the regional context and long-term water management.

Two high rainfall events have occurred since 2011, which have necessitated the requirement for additional emergency pumping; thus stressing the treatment plant. These events, although atypical, are part of an on-going trend of increased pumping requirements to control water levels, particularly during winter months. It is unclear if climate change causes these observed changes. To aid management and understanding of these events and identify any trends, the Authority has undertaken assessments of rainfall, water levels, abstraction rates and hydrochemistry. The results show variable time delays in response to rainfall, changes in key metal parameters, and different regional trends in groundwater levels. These results indicate that a number of different pathways for water entering Wheal Jane are present. A dynamic strategy is therefore required, to manage any future high rainfall events or increases in annual rainfall.

Keywords: mine water, treatment, operation, rainfall, metal mine

INTRODUCTION AND HISTORY

Wheal Jane mine is located within a complex of interconnected mines in Cornwall, southwest England (Figure 1) and is a former tin mine (that also includes other ores for copper and zinc), which was worked from at least the early 18th Century until 1991, when the mine was abandoned. After the mine closed, de-watering pumping ceased and the water levels rose in the workings. Contingency plans were implemented to control the foreseen rises in contaminated mine water, which could result in a pollution incident. Despite this however, in January 1992, the plan was suspended, which resulted in a build-up of mine water underground (Hamilton, 1993). Consequently, in the same month the contaminated mine water started discharging at surface, releasing approximately 40 000 m^3 of water in to the River Carnon (a tributary of the River Fal) over a few hours with an iron concentration of 1 800 mg/L (Hamilton, 1993).

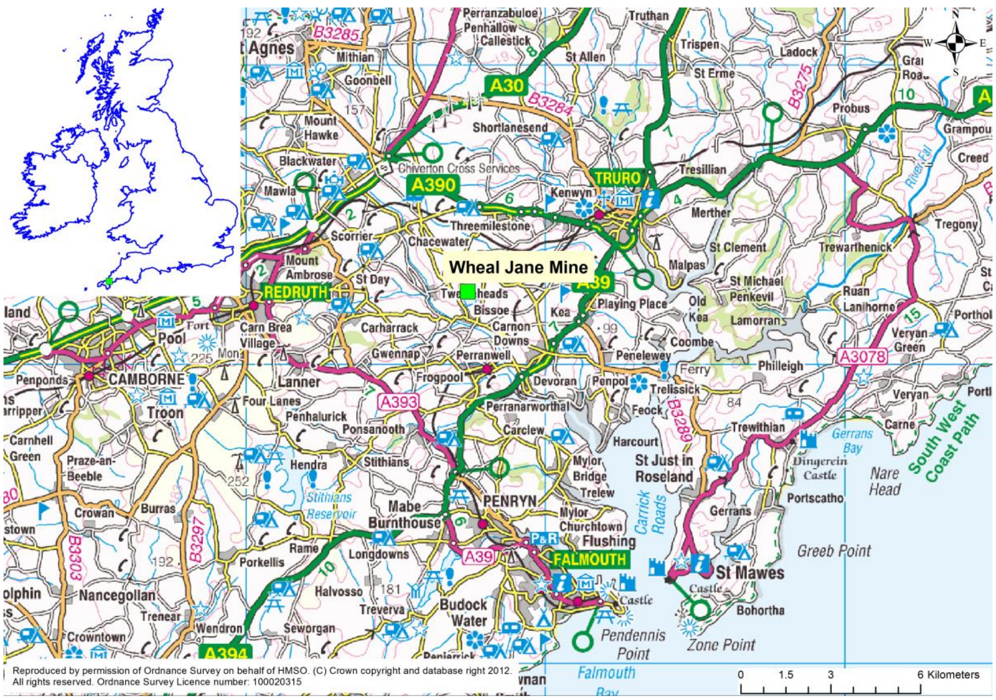

Figure 1 Location map for Wheal Jane mine and surrounding area

In the subsequent years, options for remediation of the mine water were considered, with a pilot passive treatment scheme being built in 1994, to undertake research in to long-term solutions. In 2000, the existing active (chemical treatment) plant was constructed and became operational. This plant remediates water pumped from Wheal Jane No.2 Shaft, using a high-density sludge approach, including aeration, pH adjustment (by lime dosing) and a clarifying (including polymer dosing) unit (Coulton *et al.,* 2003). Scheme capacity was originally designed for a flow of 440 L/s (Brown, Barley & Wood, 2000) with an environmental discharge consent of 350 L/s; this was later revised to the current discharge rate of 460 L/s. It should be noted that the discharge from the plant also includes a minor flow (*c.* 20 L/s) originating from the drain of the tailings lagoon.

GEOLOGY

Southwest England is dominated by late Carboniferous to early Permian Cornubian Granites, which intruded into predominantly Devonian-aged strata dominated by mudstones and siltstones, with occasional coarser-grained horizons; (Dines, 1956). A variety of different metal ores are found within the Cornish orefields including ores for tin, copper, lead, zinc and iron. These orebodies are typically zoned, following the order in which the minerals precipitated out of solution with increasing distance from the igneous intrusions. Typically tin-ores were the first to form, followed by copper-ore, zinc-ore, lead-ore and finally iron-rich minerals (Dines, 1956). At Wheal Jane the main mineralized lodes (or veins) occur in a ENE-WSW direction and recorded 19th Century returns are documented for tin, copper, lead, silver and zinc, with significant amounts of pyrite combined with smaller quantities of arsenic, ochre and iron-ore also being noted (Dines, 1956). These records suggest that a mineral assemblage containing ores such as cassiterite (tin-ore), chalcopyrite (copper-ore), arsenopyrite (source of arsenic contamination), sphalerite (zinc-ore), galena (lead-ore and also the source of silver) and pyrite (source of sulfur) are found at Wheal Jane. Assuming the ore deposit mined at Wheal Jane follows a similar zoning pattern to that found in other areas of the region, the cassiterite and chalcopyrite-rich sections of the mine will be concentrated in the deeper workings (i.e. nearer the emanative center, (Dines, 1956)), with the sphalerite-galena dominated assemblage situated in the shallower regions. Returns of ochre and iron-ore (situated in weathered gossans) (Dines, 1956), suggest that the ore body at Wheal Jane also contains a significant amount of pyrite. It is this mix of sulfide minerals which produces the acid mine drainage that occurs at Wheal Jane mine.

MINING CONTEXT

Wheal Jane Mine is located toward the southeast extent of a mining block including a series of interconnected abandoned mines, mine workings and drainage adits. Wheal Jane mine and its workings are connected to a number of other mines at depth and to at least three shallow drainage adits (Figure 2); including Janes Adit, Nangiles Adit and County Adit (or Great County Adit). The extent to which the river and streams in the area flow over shallow mine workings (lodes) and drainage adits, suggest that surface water ingress into the mine workings is common; in the catchment, this has been estimated at approximately 270 L/s (Wyatt *et al.*, 2013).

HIGH RAINFALL SETTING

In the southwest of England, the prevailing wind direction is from the southwest, resulting in Atlantic storms frequently buffeting the region, particularly over the autumn and winter months; although severe weather events can occur at any time of year. Some of these storm events can be localized in nature, being restricted to smaller individual catchment areas. For the purposes of this paper, rainfall data for the Wheal Jane area have been obtained from a number of locations within the catchment, spanning a variety of time periods.

Background rainfall

To undertake assessments of recent rainfall figures against the long-term background trends for the southwest of England, data from the rainfall gauge at Camborne (situated 14 km west of Wheal Jane Mine) was used to provide information commencing from 1979 to the present (Met Office, 2014). In addition to the rainfall gauge at Camborne, a separate gauge was installed in 2004 at Wheal Jane. A summary of these data are shown in Table 1.

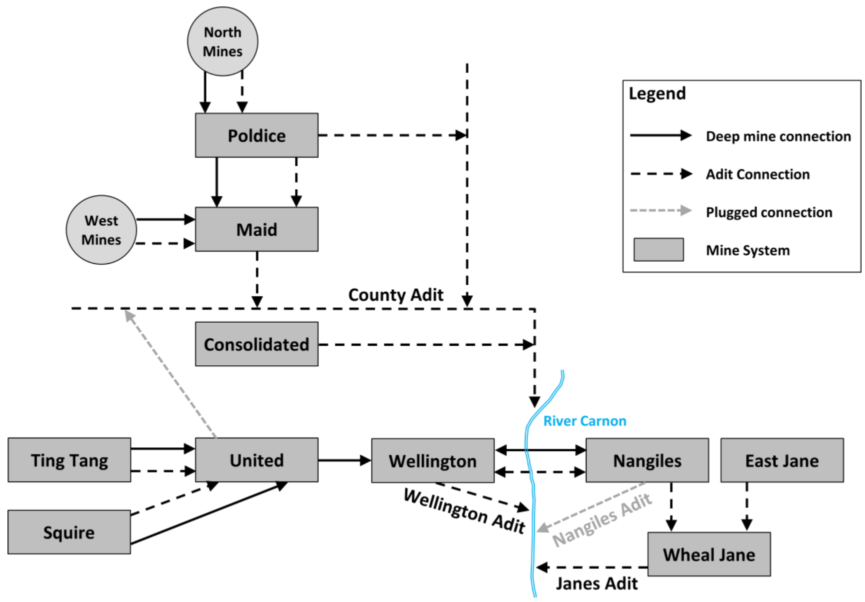

Figure 2 Conceptual diagram for Wheal Jane mine and connected mine (after Wyatt *et al.*, 2013)

Unprecedented high rainfall event in the UK

The time period between October 2013 and February 2014 resulted in exceptionally high rainfall throughout the UK, with the winter of 2014 (December 2013 to February 2014) being the wettest recorded (since 1766) in England and Wales (CEH, 2014a). Rainfall was especially high during the winter in southwest England with all months from December 2013 to February 2014 having higher than average rainfall. In December 2013, rainfall in the southwest of England was over 25% higher than the monthly average (CEH, 2013); in January 2014, the total rainfall was 63% (nearly two-thirds) higher than the monthly average (CEH, 2014b), whereas in February, double the monthly rainfall fell over the course of the month (CEH, 2014a).

Table 1 Summary table of rainfall for Camborne (C) and Wheal Jane (WJ) rainfall gauges (winter rainfall is 1st December to 28th February data)

Data set	Mean (mm)	Maximum (mm)	Period of Max Rainfall
C monthly rainfall 1979 to 2010	89	242	November 2002
C monthly rainfall 2010 to 2014	85	218	January 2014
WJ monthly rainfall 2004 to 2010	102	321	October 2005
WJ monthly rainfall 2010 to 2014	126	347	February 2014
C winter rainfall 1978 to 2010	348	561	1989/1990
C winter rainfall 2010 to 2014	345	584	2013/2014
WJ winter rainfall 2004 to 2010	305	501	2006/2007
WJ winter rainfall 2010 to 2014	467	876	February 2014

For the purpose of investigating the high rainfall events at Wheal Jane, comparisons of winter rainfall (*i.e.* 1st December to 28th February) have been assessed for both Camborne and Wheal Jane (see Table 1). Table 1 shows that the winter rainfall between 2010 and 2014, is higher than for the previous years; the winter of 2014 saw the highest volume of rainfall at Wheal Jane recorded. Furthermore, the weather patterns and uneven distribution of rainfall in the southwest of England (*i.e.* storm events) during this time period also resulted in the winter 2014 rainfall being significantly higher at Wheal Jane compared to that recorded at Camborne for the same time period (*i.e.* 876 mm at Wheal Jane compared to 584 mm at Camborne).

RESULTS

To manage the treatment plant effectively at Wheal Jane, regular measurements of water level, abstraction rates and chemical analysis are collated at Wheal Jane mine site; more recently regional monitoring of water levels around Wheal Jane has also been undertaken. The results from this wider monitoring program, in conjunction with rainfall and river stage data, have been used to analyze the Wheal Jane mine system and its surrounding environment.

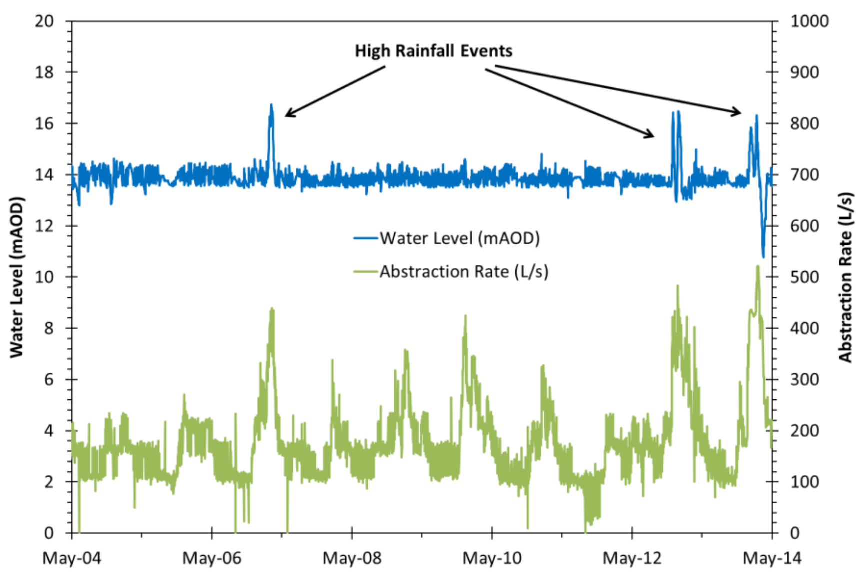

Figure 3 Plot of water level and abstraction rate at Wheal Jane

Water levels, abstraction rates and rainfall

Mine water levels have been measured on a daily basis concurrently with abstraction rates since the treatment plant became operational in 2000. A reasonably good correlation can be made between the data from the pumping shaft at Wheal Jane and the level of mine water in the shaft. Since 2011, datalogging systems have provided water level and pumping data at regular 15 minute intervals.

Results from the water level and abstraction rate data (Figure 3) show that under normal conditions, the pumping rate at Wheal Jane can be altered to maintain the water below an upper control level (i.e. 14.5 m above Ordnance Datum (AOD)); although on occasions the amount of water in the mine workings is too great for the pumps; hence there are peaks in water level. Since 2004, the volume pumped and the number of pumps installed has increased; the pumping rate has increased from c. 300 L/s (six pumps) to the current position of c. 400 L/s (eight pumps), with an additional two emergency pumps (additional c. 100 L/s) kept on standby. Since 2004, when the current control bands were implemented, there have been three instances where pumping has been insufficient to control the water level within this designated operational band due to high rainfall events.

Chemistry

Routine daily measurements of key parameters are taken of the pumped mine water and treated effluent. Throughout some of the high-rainfall / high-water level events there have been some changes in the mine water quality observed. The results of selected parameters are summarized in Table 2. Figure 4 shows selected mine water chemistry data against water level since 2004. The chemistry data for the pumped mine water shows a trend of decreasing concentrations for some of the parameters over time; this is part of the 'first-flush' trend which has been on-going since 1991 (Wyatt *et al*., 2013).

Iron, calcium, sulfate and arsenic

Figure 4 shows that prior to 2007, the variation in the iron concentration over any 12 month period was greater compared to the differences demonstrated post 2007, as concentrations of iron have decreased over time. The trends for arsenic and sulfate (not displayed on Figure 4) follow the same pattern as iron, as do the seasonal variations shown by the calcium concentrations. Figure 4 shows that there is a reduction in concentration of iron and calcium during high rainfall events, which is echoed by reductions in concentrations of sulfate and arsenic (Table 2).

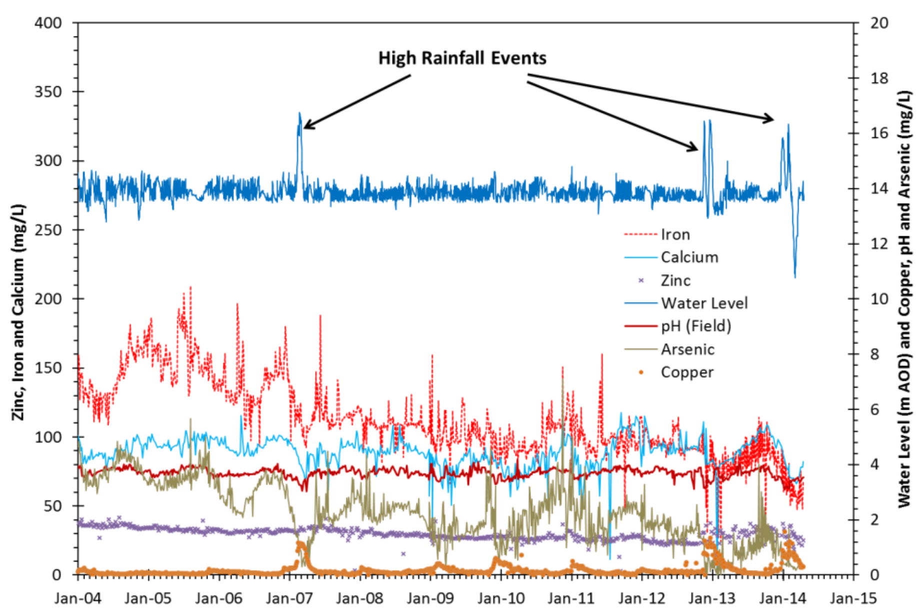

Figure 4 Plot of water level and selected chemistry parameters for the pumped water at Wheal Jane

Copper, pH and cadmium

Copper, pH and cadmium all show similar trends with respect to high rainfall and seasonal variations; with higher concentrations (decrease in pH) corresponding with high water levels and winter periods. However, the high water level peaks in cadmium are not as pronounced as copper.

Zinc, aluminum, manganese and nickel

Trends in zinc, aluminum, manganese and nickel concentrations do not appear to show any direct correlation with high rainfall or high water level events, and variations in concentrations throughout a season or during these events is very minimal or not present.

Table 2 Summary table of selected chemistry data for peak of each event and typical winter values

Parameter	Typical winter	2007 event	2012/2013 event	2014 event
Iron (Fe)	107 mg/L	118 mg/L	76 mg/L	70 mg/L
Zinc (Zn)	28 mg/L	32 mg/L	30 mg/L	31 mg/L
Sulfate (SO_4) *	624 mg/L / 457 mg/L	499 mg/L	401 mg/L	357 mg/L
Aluminum (Al)	10.6 mg/L	12.1 mg/L	9.6 mg/L	8.7 mg/L
Manganese (Mn)	3.7 mg/L	3.5 mg/L	3.3 mg/L	3.0 mg/L
Calcium (Ca)	91 mg/L	82 mg/L	87 mg/L	82 mg/L
Copper (Cu)	135 µg/L	1 044 µg/L	1 026 µg/L	863 µg/L
Nickel (Ni)	249 µg/L	267 µg/L	169 µg/L	177 µg/L
Cadmium (Cd)	15 µg/L	33 µg/L	41 µg/L	26 µg/L
Arsenic (As)	2,155 µg/L	932 µg/L	283 µg/L	443 µg/L
pH (in-situ)	3.7	3.3	3.3	3.2

* typical sulfate winter values are pre / post 2007 concentrations

DATA ANALYSIS

Analysis of the results presented above indicate a number of patterns and trends, these may represent different scenarios of the mine system during high rainfall events and high water levels.

Analysis of the rainfall data against water level (Figure 5) show that although the high water levels do correspond with high monthly rainfall, there are similar high monthly rainfall periods, which have not resulted in elevated water level. However, based on a seven day cumulative total rainfall (Figure 5) the peaks in water level do correspond more closely with the highest rainfall peaks (*e.g.* 5th to 6th February 2014). More detailed analysis of the rainfall data and water level data indicates that there is often a delay in response to rainfall, with the water level peaking approximately five to 10 days after a high rainfall event; although towards the end of the 2014 extreme event, this delay was only a few hours.

These data show that the Wheal Jane system is sensitive to rainfall; although the differences in water level responses suggest that there may be a variety of situations which affect the water flow paths and / or the residence of water in the mine workings. Given the complexity between the underground mine workings, available storage, rainfall volume, extent of saturated strata, surface conditions, river water levels and possible connections between surface and near-surface water to the mine workings; the exact reasons for the different responses is complex and poorly understood. However, during the extreme rainfall event in 2014, which included a prolonged period of high rainfall, it could be seen that under fully saturated conditions, any rainfall impacted Wheal Jane almost instantaneously. Furthermore, evidence from previous high rainfall events indicate that as the ground becomes more saturated, the response time between rainfall and water make (*i.e.* water level and abstraction rate) generally becomes less.

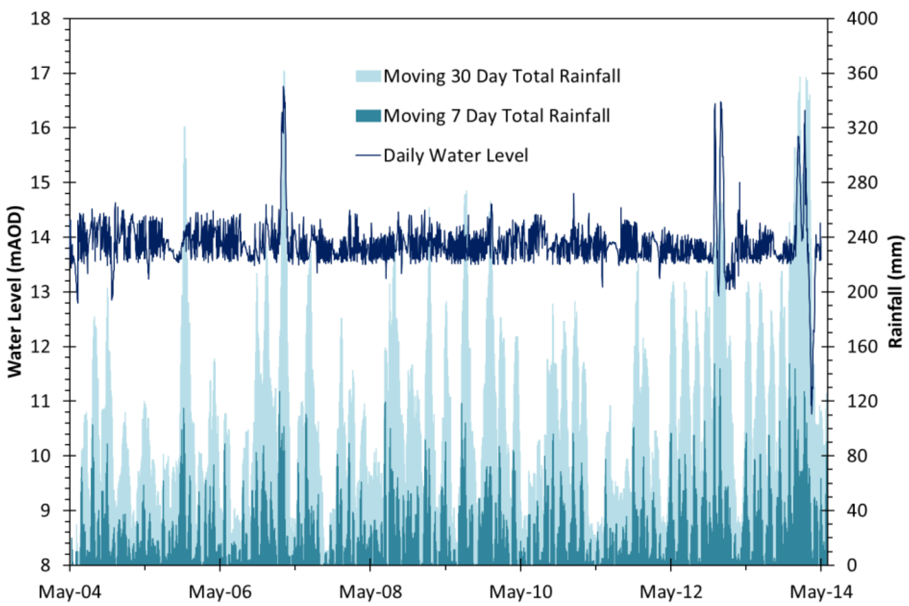

Figure 5 Plot of water level and rainfall as 30 day moving total

Chemistry

Throughout high rainfall events and high water level scenarios, there are changes in the mine water chemistry. Concentrations of some key metals and other parameters rise (*i.e.* Cu and Cd), some fall (*i.e.* As, Ca, SO_4, pH and Fe), whilst others remain steady (*i.e.* Ni, Zn, Al and Mn). These patterns in chemistry, although complex, suggest a different source of water during periods of high water level. Increases in certain metals, indicate that this water may not be all 'clean' shallow groundwater or surface water; moreover the results imply that water is passing through shallower mine workings (which are usually dry). However, from the geology and mineralization of the area, the copper ore (chalcopyrite) is often present in deeper workings, whereas the zinc ore (sphalerite) is commonly found in shallower workings; this trend is the opposite of those observed in the high water level scenarios. A possible explanation for this would be that secondary mineralization rich in Cu and Cd, potentially found in usually dry mine workings, tailing ponds and ore processing waste areas contribute a larger proportion of flow to the mine workings during these 'wet' periods.

To assess which mineral phases are saturated under normal and high flow conditions, the geochemical model PHREEQCi has been used. During normal flow conditions, iron and aluminum-rich phases such as gibbsite (SI=0.34), goethite (SI=1.82), alunite (SI=4.66) and hematite (SI=5.65) are supersaturated. In contrast, during high flow conditions the mineral phases are all under-saturated. This geochemical difference necessitates an increased level of treatment during high flow conditions; i.e. extra alkali dosing to counter a lower initial pH. This increased operational demand is exacerbated by the increased flows occurring concurrently with worse water quality.

OPERATIONAL MANAGEMENT

At Wheal Jane, the primary purpose of the pumping and treatment is to prevent uncontrolled discharges of polluted mine water. Typically this is achieved through altering the pumping rate to maintain the water level within a control band (*i.e.* 13.5 mAOD to 14.5 mAOD). However, since the CA was awarded the management of Wheal Jane in 2011, key drivers have been to make efficiency savings whilst investigating alternative operational strategies (Wyatt *et al*., 2013).

The two most recent events have resulted in additional emergency pumping being required to prevent outbreak of mine water to the river; the latest event being in 2014 also resulted in the requirement to purchase additional pumps. However, this method of using emergency pumps (provided by the fire service) resulted in undesirable increases to the costs of managing Wheal Jane. These high rainfall events, in conjunction with the current conceptual model of the mining hydrogeology system, has led to some changes and recommended alterations to the management of Wheal Jane, especially during high rainfall / high water level events, which include:

- Purchase of additional pumps (in 2013) plus emergency pump and second back-up pump (in 2014) to give a total pumping capacity of *c.* 550 L/s; some 150 L/s greater than the rate in 2012.
- Drawdown test undertaken to assess the possibility of lowering the water level and acquire additional storage capacity in the mine workings ahead of predicted high rainfall events. This test also allowed assessments of any chemistry changes to be understood and specifically to confirm any improvements in water quality.
- Analysis of Wheal Jane mining and hydrogeological context to assess the impacts from pumping and to assess the influence on the surrounding environment on Wheal Jane. Required to confirm if changing the pumping control level will impact the surrounding area.
- Development of a high water level management strategy, including determination of any thresholds and triggers to develop a simple pragmatic system to manage the water level.

Investigation in to utilizing a controlled overflow (*i.e.* via Janes Adit) during high rainfall events; anticipated to be <50 L/s for <1 % of the time.

High water level management

A simple pragmatic system to manage the proposed water level is summarized below:

- Use up to six pumps to hold water level below 14.5 mAOD in normal conditions
- If water level rises, use all available pumps to lower water level to 11 mAOD
- Pump sufficient quantities of water to hold the level between 11 mAOD and 11.5 mAOD
- Continue to hold the water level at this band until only four pumps are required

Based on historical pumping data, this trigger level approach described above would only be implemented for up to 5 % of the time. Hence, such a trigger approach should not result in unwarranted extra pumping costs for an unacceptable number of false alarms.

SUMMARY AND CONCLUSIONS

Following work and investigations undertaken by the CA since 2011 in to various hydrogeological features of the Wheal Jane system, a variety of aspects have been observed, which include:

- Relatively quick response at Wheal Jane to high rainfall events suggests inputs from shallow groundwater and / or surface water. Thus, likely implying direct mining connections to the shallow drainage systems (*i.e.* County Adit) or to the surface (*i.e.* open stope workings)
- A quick response to rainfall suggests little available storage within the Wheal Jane mine system; especially in winter months when the ground storage is lower. To prevent risks of uncontrolled discharges to surface during high rainfall events, a lower water level could be maintained in drier periods for a lesser costs than at certain times in the winter
- High rainfall events which have high water levels, lead to a different hydrochemistry of the pumped mine water. This could reflect the influence of shallow water inputs, and / or different mineralogy in shallower mine workings
- A different approach in the management of high water levels could be implemented to create additional storage ahead of anticipated wet periods, this could also significantly reduce or remove the need for costly emergency pumping

The option of a controlled overflow reduces the current risks, however further investigations regarding flow and chemistry are required. In the medium to long-term and based on natural improvements to hydrochemistry of the mine water, this option (possibly with passive treatment) would be highly beneficial

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