BLACK & VEATCH

Department of health
Committee Of Toxicity
Subgroup To Consider The Health Effects of the
Lowermoor Water Pollution Incident (LSG)

Lowermoor Water Quality
Modelling Report

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DEPARTMENT OF HEALTH

COMMITTEE OF TOXICITY – SUBGROUP TO CONSIDER THE HEALTH EFFECTS
OF THE LOWERMOOR WATER POLLUTION INCIDENT (LSG)

LOWERMOOR WATER QUALITY MODELLING REPORT

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LOWERMOOR WATER QUALITY MODELLING REPORT

1   Background

In January 2004, the Department of Health approached Black & Veatch Consulting Limited (BVCs) with the intention of BVCs undertaking a technical audit of reports prepared by Crowther Clayton Associates which summarized conclusions of two water quality models.

Following a brief review of the reports BVCs concluded that the reports did not fully address either the duration of the event or the implications of dispersion within the distribution system, both of which would impact on the exposure level to the public. BVCs was asked to address both points using water quality modelling tools and techniques.

A tanker load of aluminium sulphate was discharged into the last compartment of the contact tank at Lowermoor water treatment works. The aluminium sulphate mixed in that tank and the diluted contaminant transferred into the clear water tank on the site. Further mixing took place in this second tank prior to the water entering the distribution system. The area supplied, herein referred to as the "Lowermoor supply zone", includes; Tintagel, Boscastle, Marshgate and Otterham (to the north and east); Camelford, Slaughterbridge, Delabole, St Teath and Michaelstow (east of the works); and Port Isaac and St Endellion (to the west).

The purpose of the analysis was therefore to supplement the committee's understanding of the potential contaminant concentration and duration of exposure by modelling the two storage facilities at Lowermoor to quantify the time variable concentration of pollutant leaving the works and spread of the incident.

2   Modelling Approach

Any modelling of the incident needs to take into account the characteristics of the system (storage and pipework) and the demand (consumption) of water from the start of the incident. The normal consumer demand and the abnormal demands due to flushing the system will have a significant impact on the duration and spread on the incident. Furthermore, the hydraulic set-up of the model should reflect the actual operation of the water distribution network during and following the incident.

2.1   Sources of model information

Record drawings are available for the two tanks affected by the aluminium sulphate at Lowermoor water treatment works (Reference 1 and 2). The contact tank was converted from a reservoir to a contact tank in about 1972. Since it was not originally designed as a contact tank, its performance is unlikely to be as efficient as a purpose built contact tank. With the exception of the clarifications described below, the structure dimensions, top water levels and pipework arrangements at the time of the incident have been assumed to be as shown on the drawings for both tanks. South West Water (SWW) provided additional information in July 2004 relating directly to:

- *The construction of the baffle walls within the contact tank*: The baffles extend to the full depth of the tank. This will have a significant impact on the dispersion of the pollutant within the tank.
- *The contact tank outlet is at high level*: It is not at low level as previously reported.

▪   *The inlet pipe arrangement into the clear water tank*:   There was confusion and doubt about the inlet "structure" and its performance.   The tank inlet is a bellmouth discharging above the storage top water level as indicated on the drawing.

In 1993, BVCs created a computer hydraulic model (Stoner software) of the storage and trunk main distribution systems for the system supplying the Lowermoor supply zone and which included the Lowermoor water treatment works.   Although the hydraulic model represented a more recent operational supply scenario, it was a conversion from an earlier model (WATNET software) and included information that identified some of the changes made since 1988.   BVCs concluded that in the absence of any better information this model could be modified to produce a reasonable representation of conditions in July 1988.

2.2   Modelling the system components

The methodology used in this study was to analyse each component of the system in turn using the output of the upstream component as the input for the next component:

▪   Model of contact tank
▪   Model of clear water tank
▪   Model of network (trunk mains only)

The dilution effect within the pipe connecting the contact and clear water tanks was ignored because it was considered negligible compared with the dilution and dispersion taking place within the two tanks.

In 1988 water passed from the contact tank, into which the aluminium sulphate was discharged, into the clear water tank and thence into distribution.   The feed through the contact tank and into the clear water tank was dictated by the flow rate through the treatment works.   The discharge from the clear water tank was dictated by consumer demand.   The difference between the clear water tank inflow and outflow was accounted for by variation in water level in the tank.   Figure 1 illustrates the hourly flow profile and water level in the clear water tank between 6th July and 11th July 1988 (data source Reference 5 and 6).
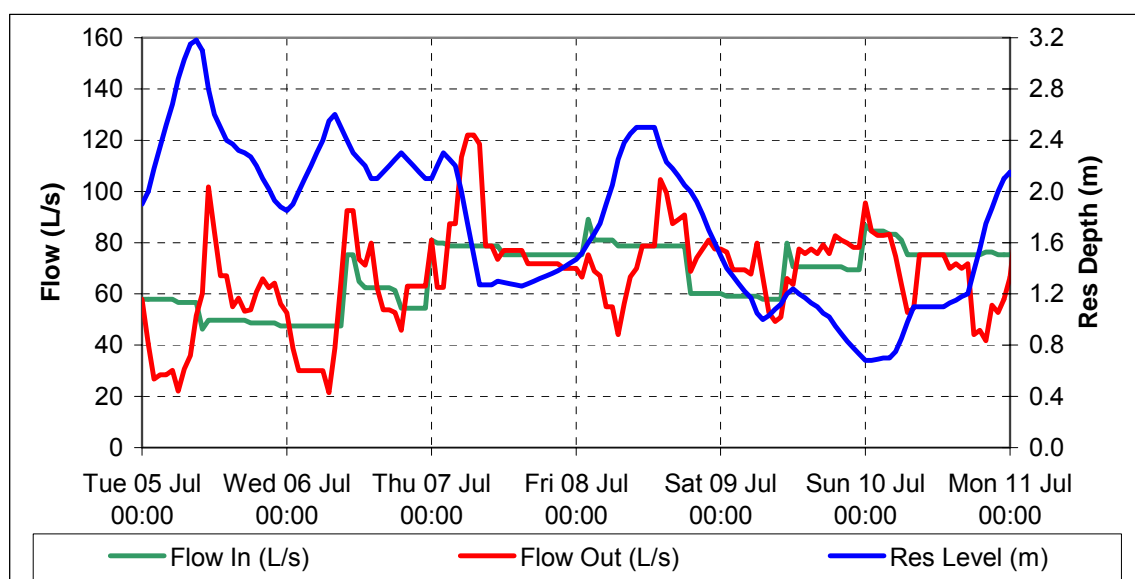

Figure 1   Flows and water level in clear water tank

In order to model the contact tank and reservoir, the flow into the treatment works was simplified as given below:

Model Time	Actual time	Flow	Reference
0 to 0.33 hr	17:00 – 17:20	63L/s	(Reference 5 & 10)
0.33 to 2hr	17:20 – 19:00	61L/s	(Reference 5 & 10)
2 to 7hr	19:00 – 00:00	54L/s	(Reference 5)
7 to 19hr	00:00 – 12:00	79L/s	(Reference 5)
19 to 24hr	12:00 – 17:00	76L/s	(Reference 5)

2.2.1 Contact Tank

The contact tank was analysed using computational fluid dynamics (CFD) software which simulated the three dimensional hydraulics and dispersion of aluminium sulphate. The model represents the full structural characteristics of the tank, the flow regime during the incident and the injection of the pollutant through the inspection cover at the upstream end of the final lane. Details of the model set up are given below:

- *Flow into tank*: As explained in Section 2.2 above
- *Pollutant details:*
    - 8% Aluminium Sulphate, equivalent to 56,000 mg/l Al
    - Density of 1.32 kg/L.
    - Discharge duration 37 min starting at 17:00hrs (time zero)
    - Discharge rate 6.82L/s (Reference DofH letter dated 14 April 2004).
- *Simulation details*:
    - Software: CFX version 5.7
    - Steady state analysis of hydraulics only at time zero to give start conditions.
    - Transient analysis 0 to 4.5hrs
    - Turbulence simulated using a *k-ε* model
    - Mesh size: 702,000 elements with an inflated boundary for more accurate modelling of the influence of walls.

This was a high detail model which took over one week for a high power (5.4Ghz) computer to simulate the first 4.5 hours of the incident.

A plan of the layout modelled is shown in Figure 2 with the basic flow path shown by the blue arrows. A 3D representation of the model is given in Figure 3.
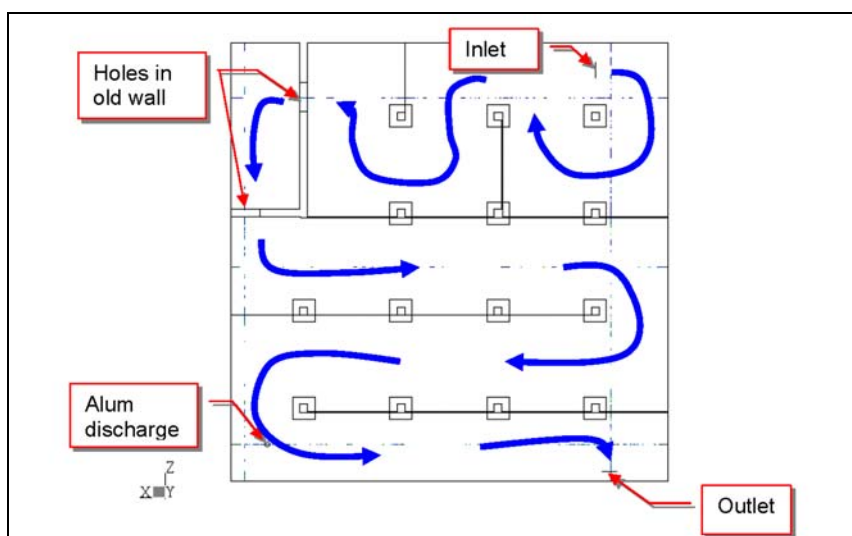

Figure 2 Plan of contact tank model

The mesh for the model is shown in Figure 4. This relatively fine mesh was specifically refined around the inlet, outlet and the hatch through which the aluminium sulphate was discharged since these are the regions of the model in which there is most hydraulic activity.
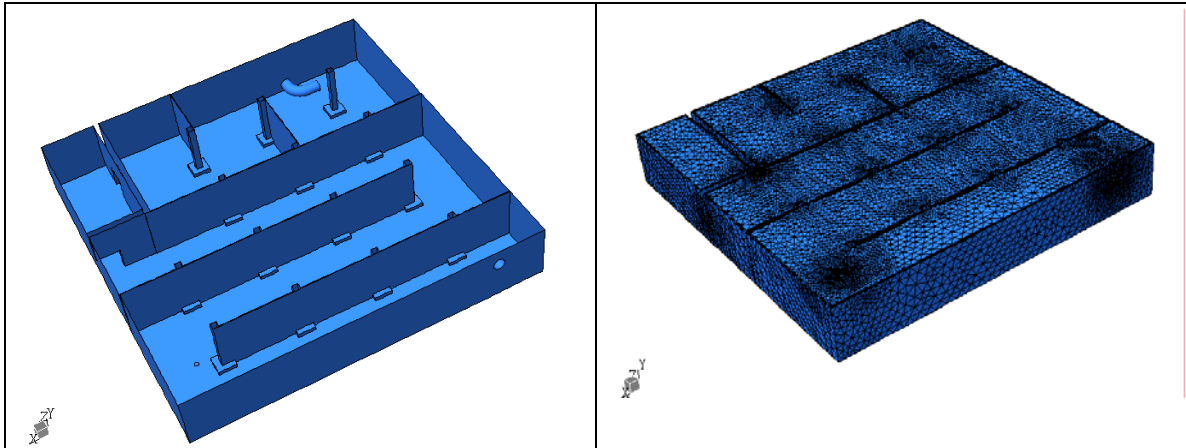

Figure 3 3D view of contact tank model   *Figure 4 3D view of contact tank mesh*

2.2.2   Reservoir

The reservoir was analysed using a CFD model which simulated the three dimensional hydraulics and dispersion of aluminium sulphate. In order to enable simulation of a full 24hr period, the level of detail in this model is lower than that used for the contact tank. However, this is a reasonable approach since:

▪ It is a simpler structure without baffles and internal constrictions
▪ The velocities are lower, so adjacent elements in the model tend to have similar values
▪ The concentrations are lower, so adjacent elements in the model tend to have similar values

Details of the model set up are given below:

▪ *Flow into tank*: As explained in Section 2.2 above
▪ *Water level*: The water level was simplified in the model as follows

Model Time	Actual time	Level
0 to 11hr	17:00 – 04:00	2.2m
11 to 15hr	04:00 – 08:00	2.2 falling to 1.3m (constant rate)
15 to 24hr	08:00 – 17:00	1.3m

▪ *Pollutant details:*
  – Properties as for contact tank
  – Concentration entering the tank as given by the preceding analysis of the contact tank
▪ Simulation details:
  – Software: CFX version 5.7
  – Steady state analysis of hydraulics only at time zero to give start conditions.
  – Turbulence simulated using a k-ε model
  – 0 to 11hr - Mesh size 393, 000 elements (medium quality)
  – 11 to 24hr: Mesh size 154,000 elements (coarse quality) with moving mesh to simulate change in reservoir level.

The duration of simulation (24hr) and the changing reservoir level resulted in a computationally intensive model which took over one week for a high power (5.4Ghz) computer to simulate.

A plan of the layout modelled is shown in Figure 5. A 3D representation of the model and the mesh is given in Figure 6 and Figure 7.
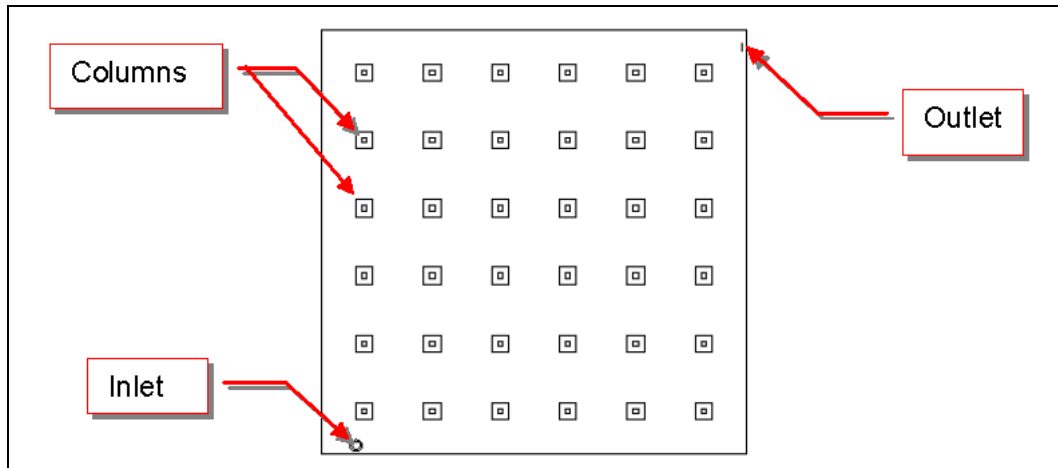
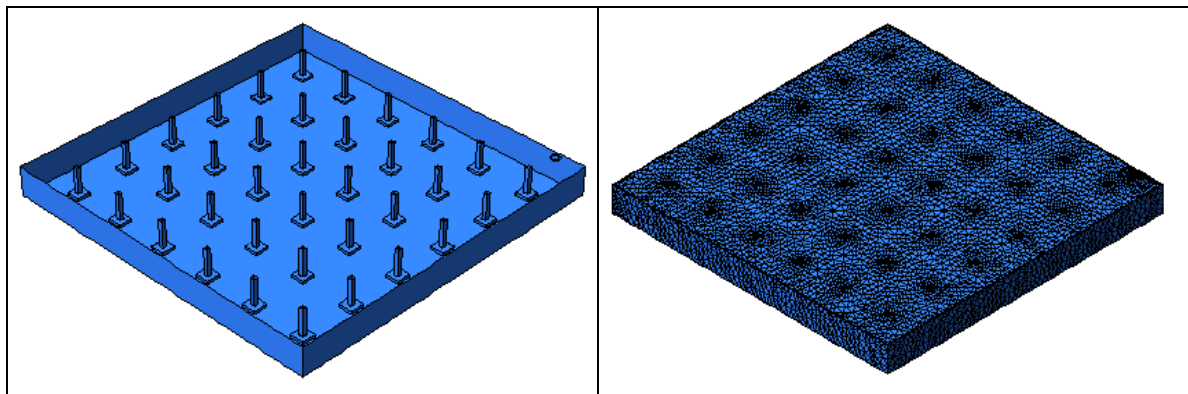

Figure 5 Plan of reservoir model

Figure 6 3D view of reservoir model   *Figure 7 3D view of reservoir mesh*

2.2.3   Network

A model of the Lowermoor supply zone has been created from the original spine main model by deleting all parts of the original model not connected with the Lowermoor supply zone. The extent of this revised hydraulic model, is shown in Figure 8. This model includes the Delabole and Rockhead service reservoirs, but does not include the storage facilities at Boscastle, Davidstow, Michaelstow and St Endellion which were omitted also from the original model.

The smaller distribution pipework feeding Camelford, St Teath and the areas supplied from Boscastle, Davidstow and Michaelstow reservoirs are not included in the model, nor were they in the previous model. The model results will therefore not take into account:

- Additional retention time in these smaller pipes
- Retention time, mixing and dilution in these storage facilities
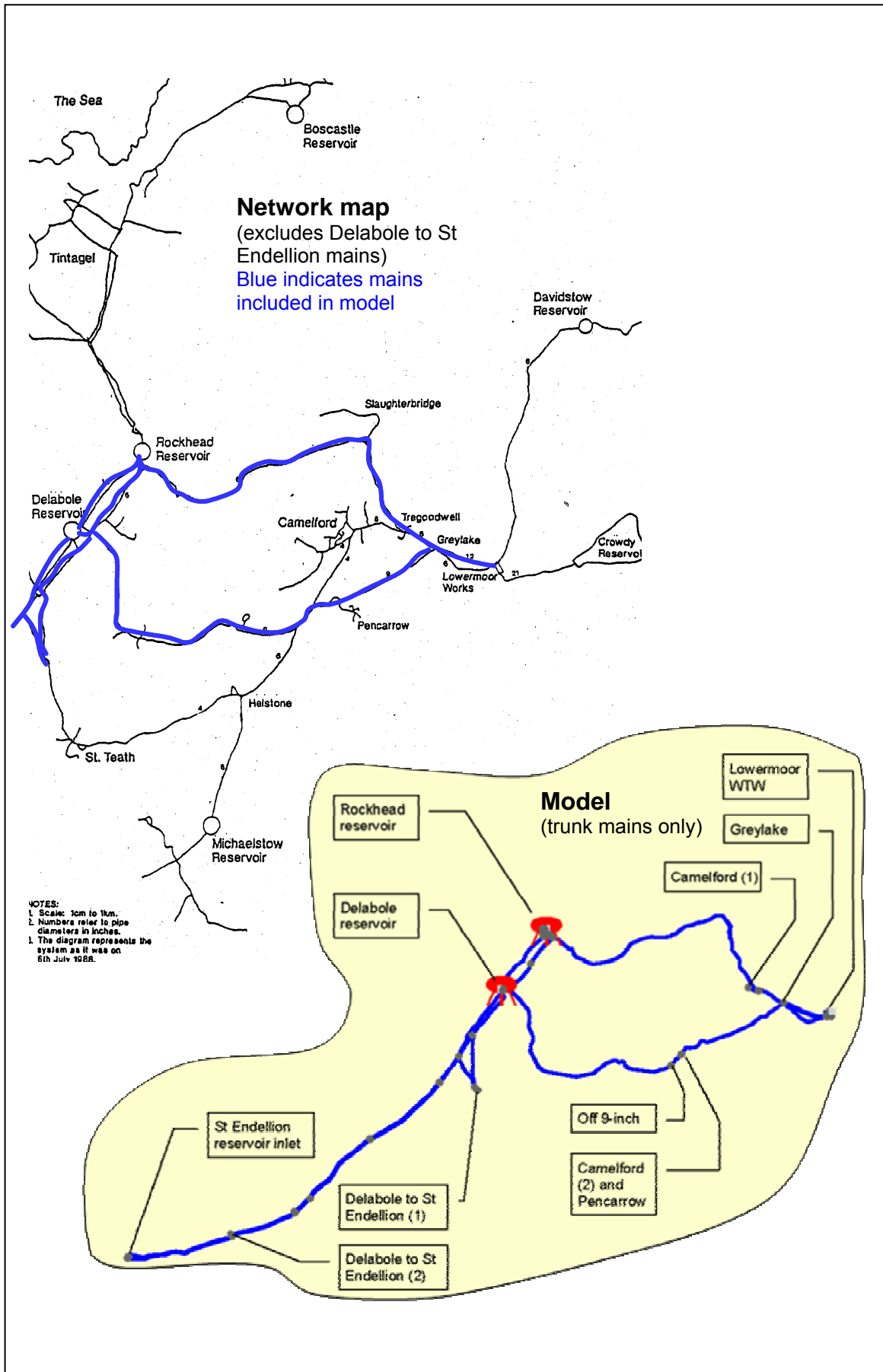- Local interconnections enabling local rerouting of supplies

Figure 8 Extent of Lowermoor network model

The supply arrangements for the St Endellion area are complicated by the ability to fill the service reservoir from an alternative source (the De Lank water treatment works). This alternative source enters the reservoir via a separate inlet pipe discharging above the storage top water level. Therefore there was no opportunity to back feed into the De Lank system from the Lowermoor supply zone. This alternative feed was used briefly during the period of the incident. This would have had the effect of increasing the retention time of the pollutant in the Camelford system.

The following information is known about the flushing of the network following the incident:

- In their letter dated 26 May 2004, SWW confirmed that there were no precise data of where and when the system was flushed
- Crowther Clayton reports "substantial flushing" during the night of 6th – 7th July 1988
- The analysis of flows and water levels at Lowermoor water treatment works indicate that there was significant abnormal additional demand from the system between the night of 6th through to about 10:00hrs on 10th July 1988.
- Verbal reports have confirmed that initially flushing was concentrated in and around the Camelford area. However as the incident continued flushing exercises were extended across the supply area.

In the light of this information, the demands in the Lowermoor hydraulic model have been derived from actual flow data recorded between 5 and 11 July 1988 as detailed below:

- The water consumed within the network was separated into two categories (1) consumer demand, and (2) flushing demand
- The consumer demand profile for the full period was assumed to equal the full flow profile into the network recorded on the day before the incident
- The spatial distribution of consumer demand is assumed to be as in the previous model of the area
- The flushing demand profile was calculated by subtracting the consumer demand from the overall flow into the network. Occasionally this returned a small negative value in which case zero flushing demand was assumed for that time-step.
- The flushing flow has been assigned to the Camelford area during the night of 6/7 July and into the morning of the 7th. Thereafter flushing has been assumed to be more widespread and has been distributed proportional to all demand centres in the model.

The pollutant concentration curve derived of the clear water tank outlet using CFD modelling (Section 2.2.2) was assigned to the outlet node of the clear water tank in the hydraulic model.

3   Analysis of results and discussion

3.1   Contact tank

Figure 9 shows the predicted streamlines for the flow through the tank immediately prior to the discharge of aluminium sulphate. Each blue line is the path taken by a small parcel of water entering at the inlet. The figure shows swirling flow around the inlet and the holes in the wall but on entering the last leg, the baffles have straightened out the flow path. This behaviour is as would be anticipated, giving confidence in the model predictions. The more swirling the flow the greater the mixing which will occur.

Figure 10 shows the predicted aluminium concentrations throughout the contact tank after 37 minutes of aluminium sulphate being discharged into the tank. This is just before the tanker completed discharging and so represents the peak quantity of aluminium sulphate within the tank.

The multicoloured planes in Figure 10 indicate the predicted concentration on cuts along the lanes in the tank. The colour coding is quantified by the legend adjacent to the figure:

- Dark blue: Regions of low concentration
- Green: 1,000 to 2,000mg/L Al
- Yellow / orange / red: 2,000 to 3,000mg/L Al
- Dark red: In excess of 3,000 mg/L Al

The model predicts that the aluminium sulphate did not mix rapidly with the water in the tank, and sank to the base. It then spread out along the base of the tank in all directions. Some of the aluminium sulphate spread against the principle flow direction until it reached the holes in the old wall. Here the velocity of flow is much higher causing the aluminium sulphate to be mixed up into the bulk flow (Figure 11). A small amount of aluminium sulphate spread through both the holes back to the tank inlet. It is this relatively small proportion of the aluminium sulphate which would have triggered the pH alarm.
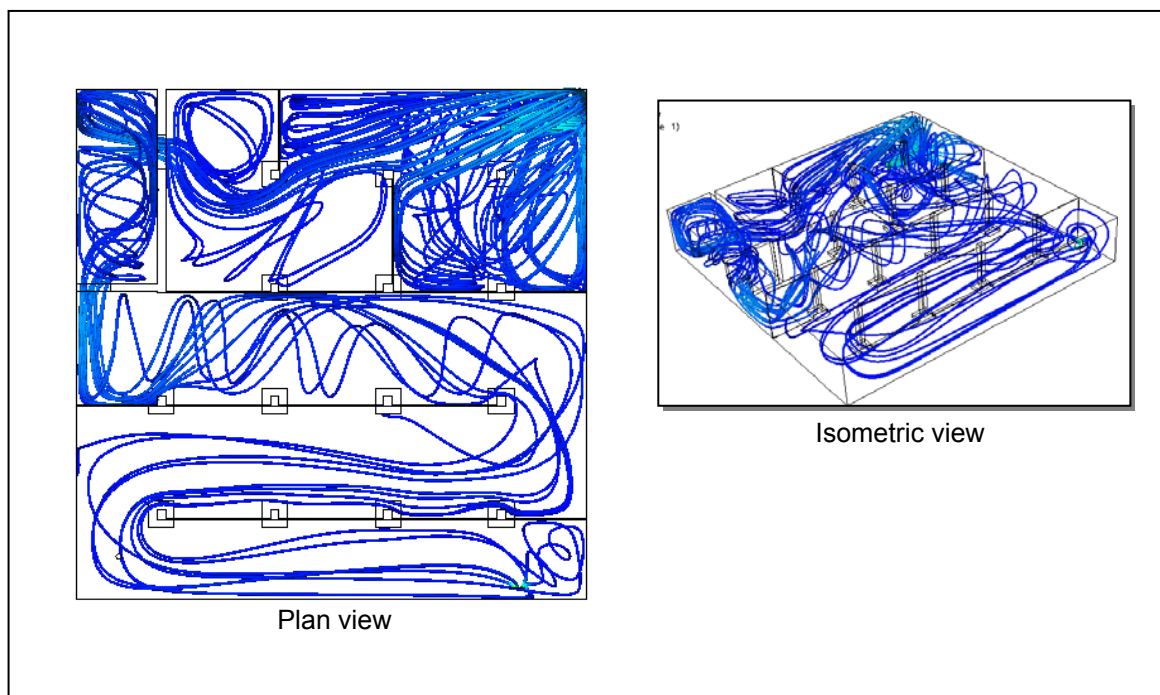

Isometric view

Plan view

Figure 9 Streamlines for flow through tank at time zero

Figure 10 Predicted aluminium concentrations in contact tank at 37 minutes

See Figure 10 for legend to colour coding

Figure 11 Cut showing mixing at hole in old wall at 37 minutes

The progressive build up and release with time of aluminium sulphate in the tank is shown by Figure 12 and Figure 13. Time zero is the start of the discharge (approximately 17:00).
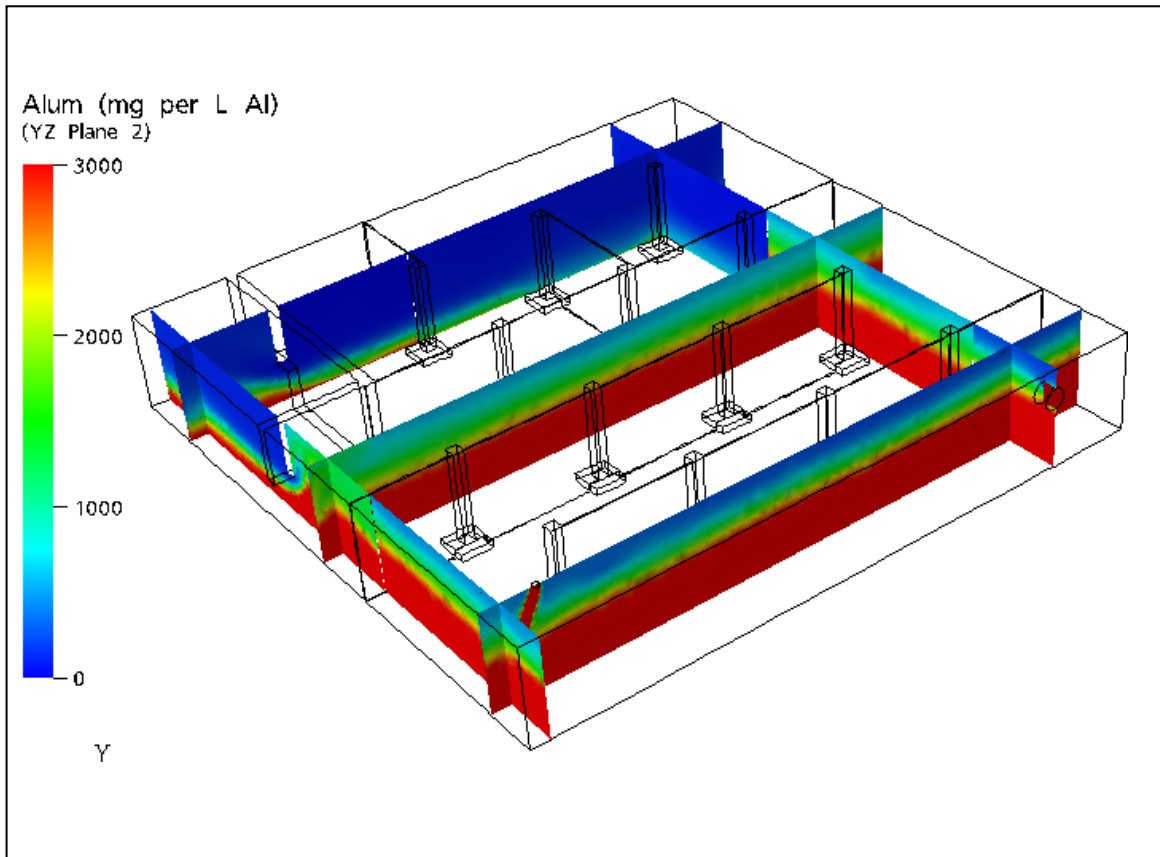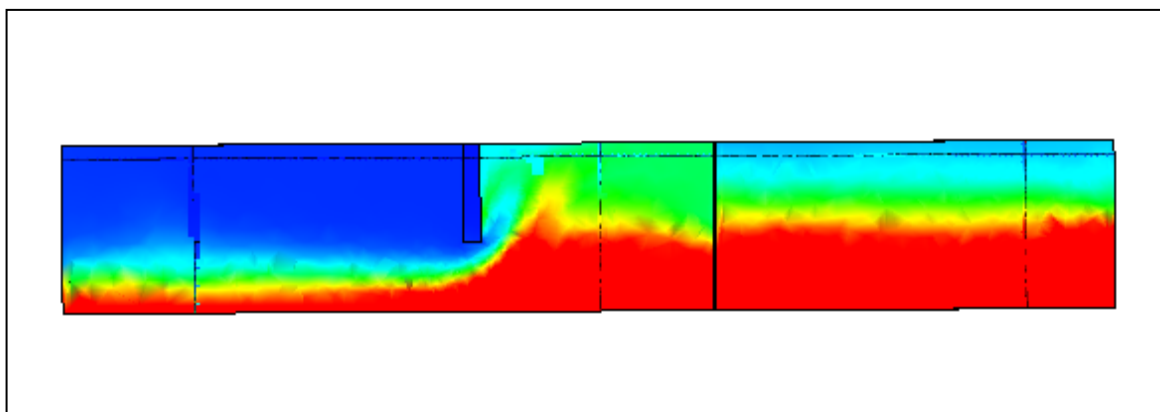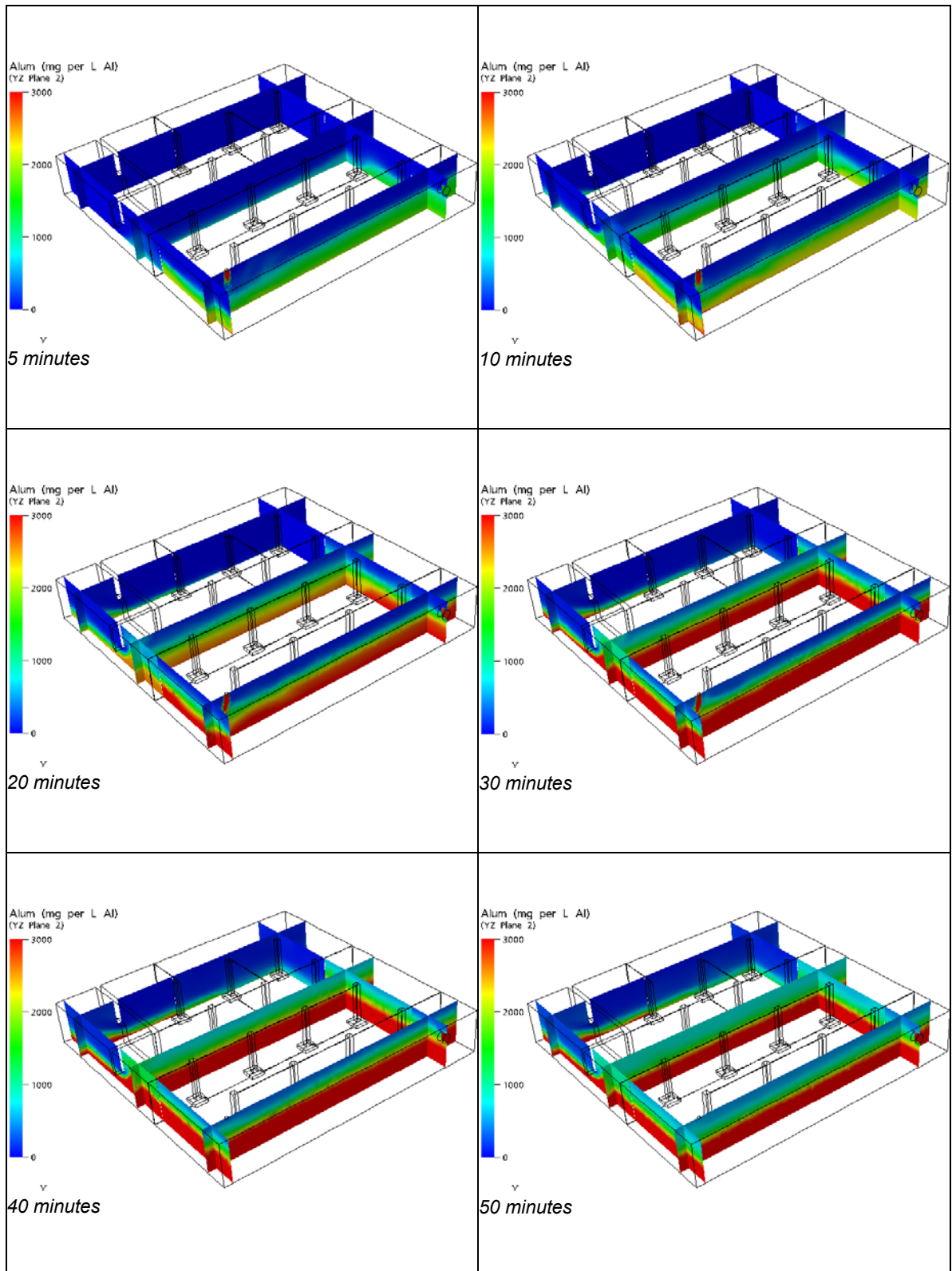

See Figure 10 for legend to colour coding

Figure 12 Predicted aluminium concentrations in contact tank 5 to 50 minutes
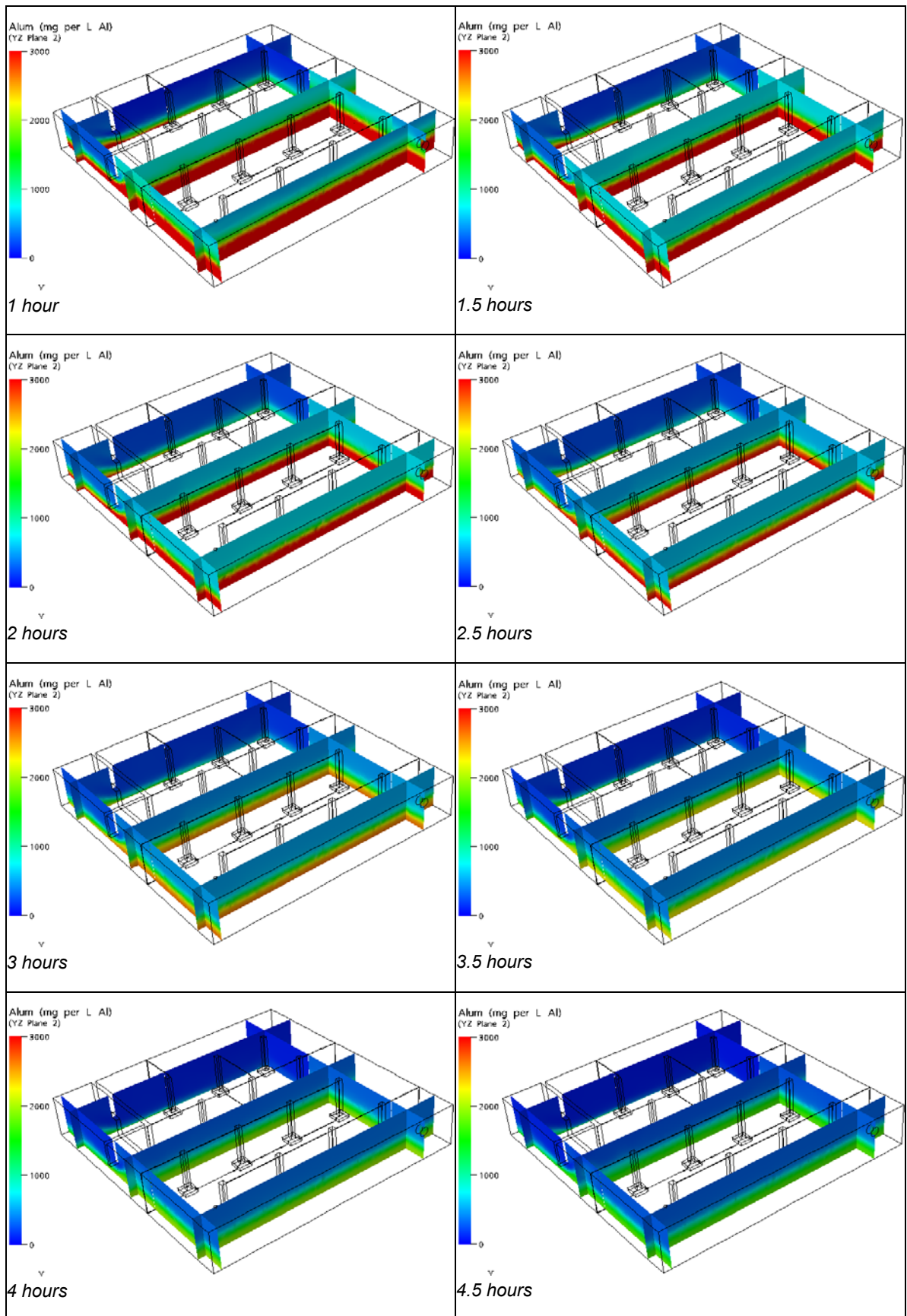
See Figure 10 for legend to colour coding

Figure 13 Predicted aluminium concentrations in contact tank 1 to 4.5 hours

Figure 14 shows the predicted concentrations along the final lane of the contact tank. The outlet is shown by the circle on the top right of each cut. For times 10 to 37 minutes, the discharge of aluminium sulphate is clearly visible as a red plume entering from top left. The colour coding is the same as in Figure 10.

0 minutes	10 minutes
20 minutes	30 minutes
37 minutes (peak quantity in tank)	50 minutes
1 hour	1.5 hours
2 hours	2.5 hours
3 hours	3.5 hours
4 hours	4.5 hours
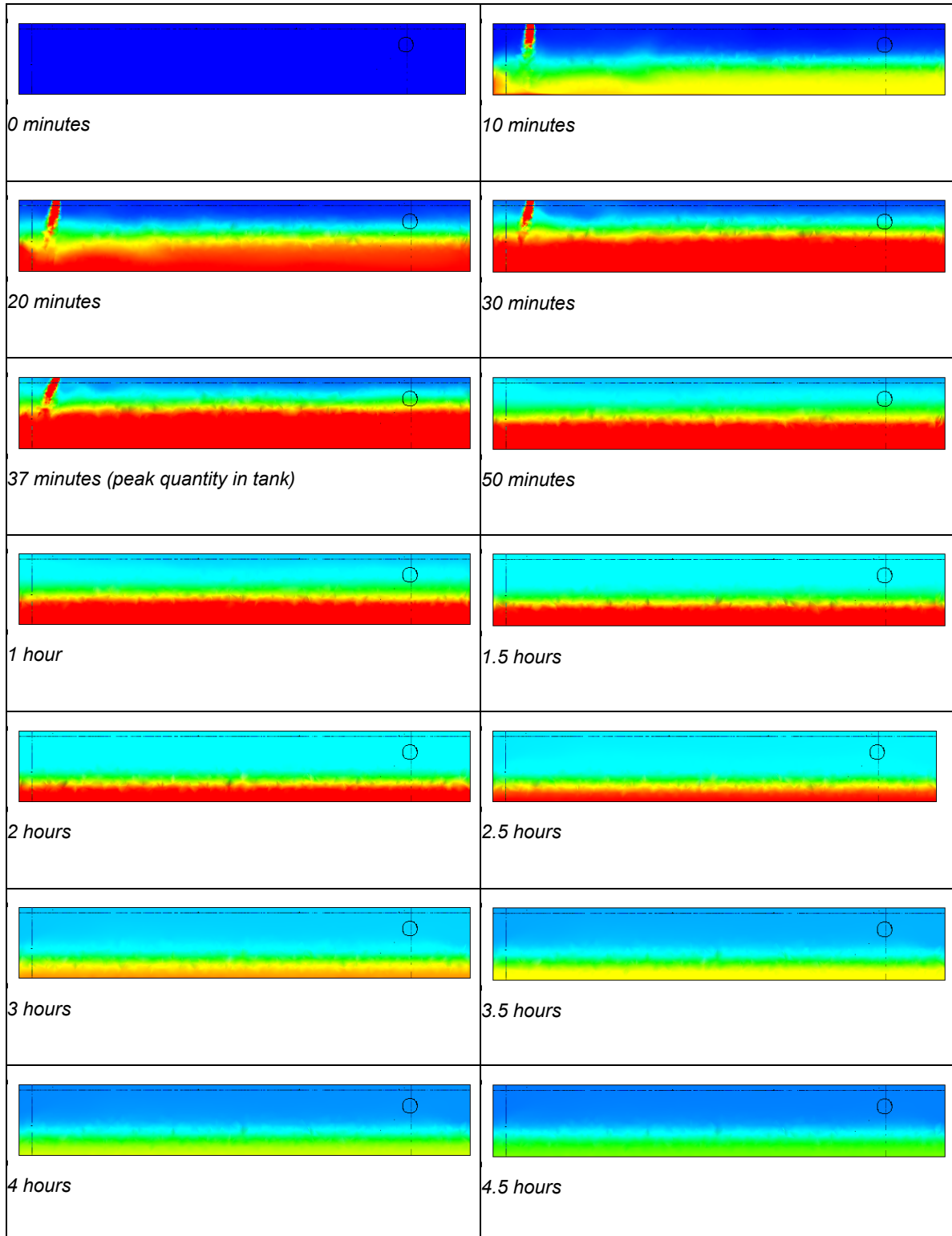
See Figure 10 for legend to colour coding

Figure 14 Predicted aluminium concentrations along final lane of contact tank

Figure 15 shows a similar series of plots at 37 minutes (just before tanker completed discharging) for various heights above base level.
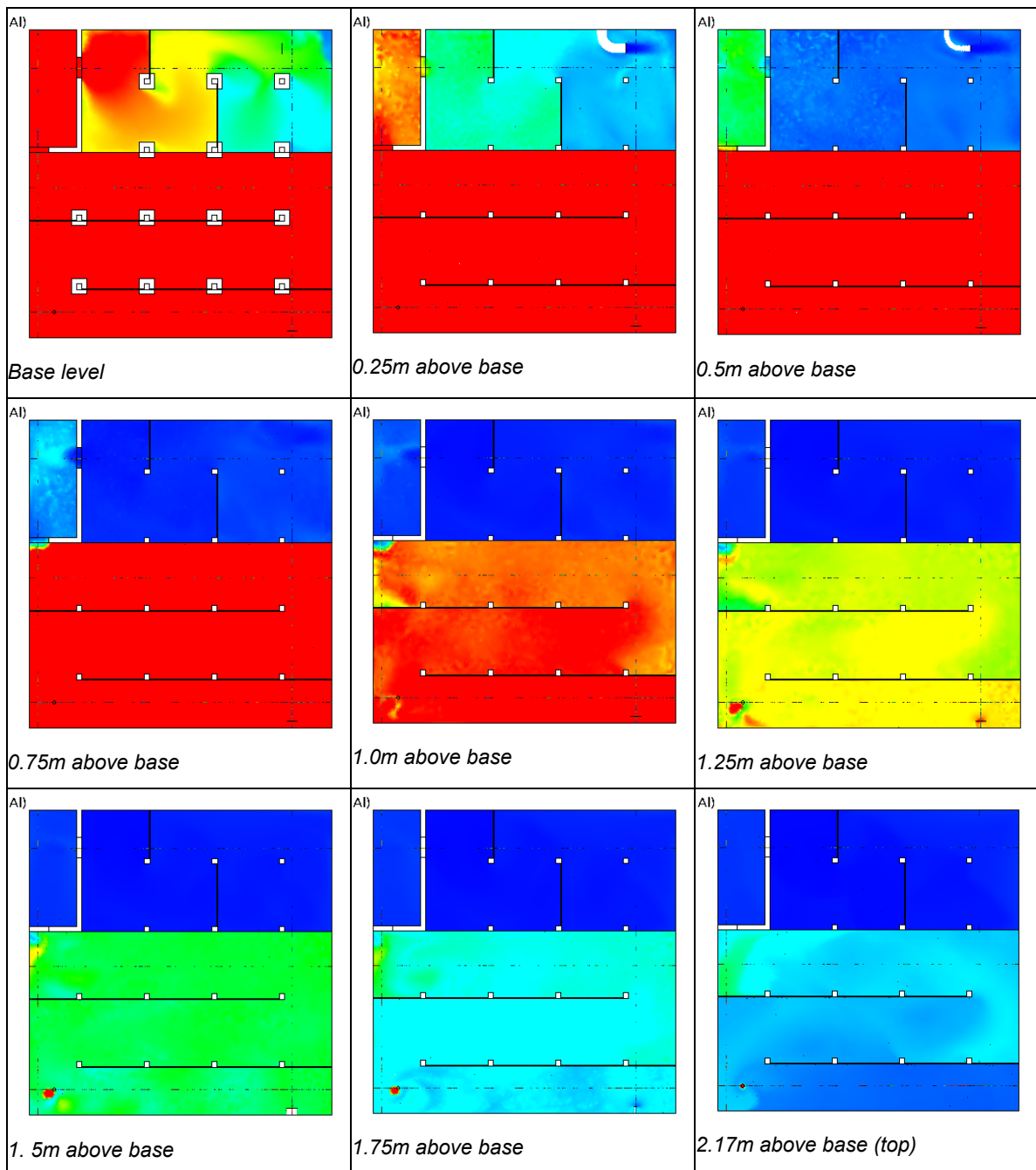
See Figure 10 for legend to colour coding

Figure 15 Predicted Al concentrations after 37minutes at various heights above base

The overall concentration for the water exiting the tank versus time is shown in Figure 16. The red line shows the model predictions covering the first 4.5 hours since the start of the discharge. The peak concentration is 1470mg/L Al at 37 minutes (when the tanker was fully discharged). After 4.5 hours 82% (by mass) of the aluminium sulphate which was discharged into the tank has exited the contact tank. The blue crosses show extrapolated data fitted using an exponential decay curve.
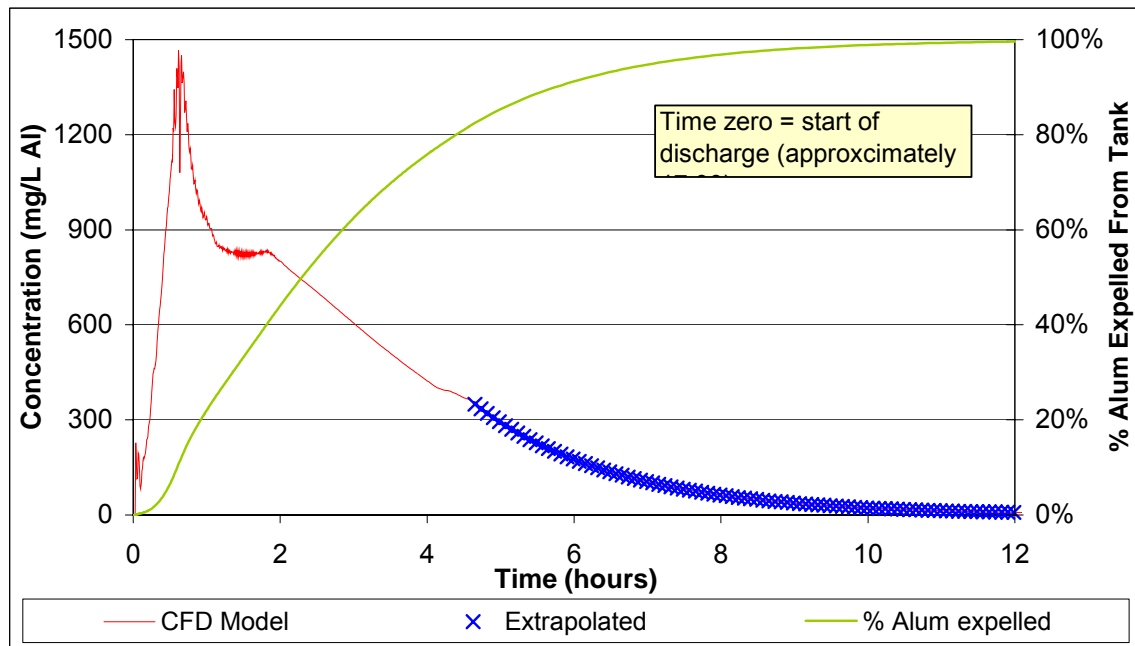
Figure 16 Predicted aluminium concentration in water exiting tank

The results from the CFD analysis are dependant on some modelling assumptions in particular the coefficients associated with turbulence and the diffusivity of the aluminium sulphate. If alternative values were used then the predicted rate of mixing could be increased. However, we have reasonable confidence in the current predictions because:

▪ We have used accepted 'default' values for these parameters
▪ The conditions being modelled are not highly stressed and similar to those for which CFD simulations have been validated
▪ If the rate of mixing was significantly higher then the aluminium sulphate would not have been predicted to migrate upstream along the base against the main flow stream. The fact that it did migrate upstream is validated by the triggering of the pH alarm at the inlet to the tank.

Nevertheless, in order to determine a maximum theoretical limit for the aluminium exiting the contact tank, two spreadsheet calculations have been performed:

▪ *Fully mixed in last section of contact tank*: This represents an upper limit for a fully mixed solution, but is unrealistic because it does not replicate the migration of the Aluminium Sulphate back towards the contact tank inlet as confirmed by the pH probe at the inlet. This calculation predicts a maximum aluminium concentration of 4800mg/L Al exiting the tank with there still being a trace concentration in the tank after 3.5 hours (20:30).
▪ *Direct injection into outlet pipe*: i.e. dilution proportional to outlet flow only. This is also not realistic because it is known that the pollutant injection point was at the upstream end of the last leg and not at the outlet. This calculation predicts a peak concentration of 5660mg/L Al exiting the contact tank with it being clear within minutes of the completion of the tanker discharge.

Figure 17 presents the concentration curves for the CFD analysis and the comparative spreadsheet calculations. This figure defines the extremes for the range of aluminium concentration at the contact tank outlet and entering the clear water tank.
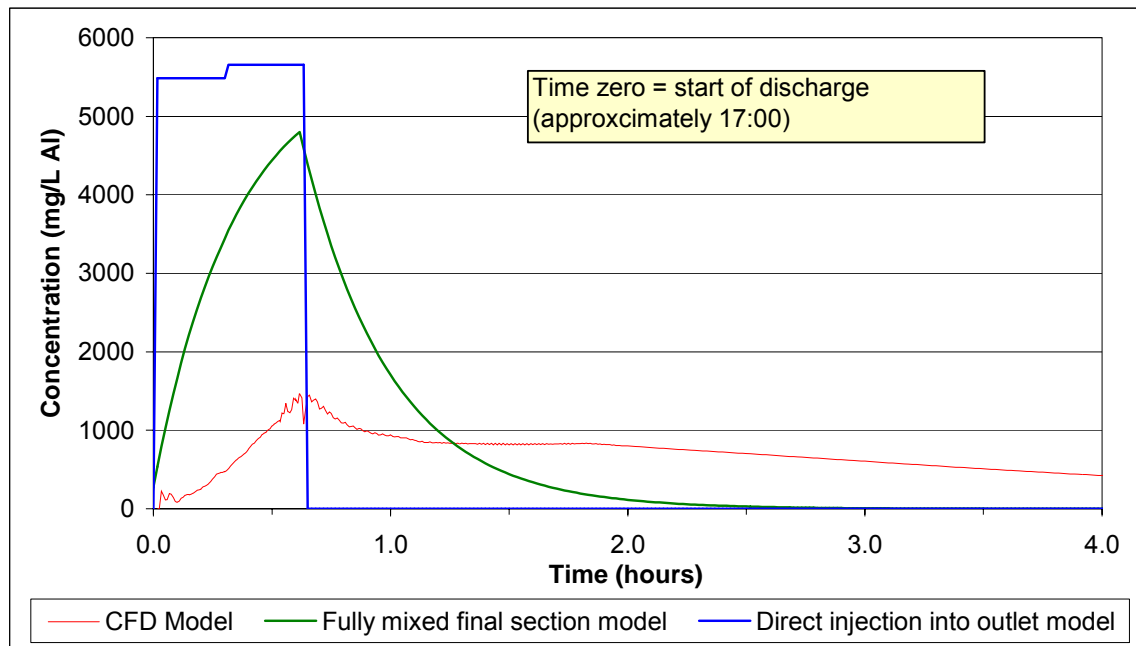
Figure 17 Comparison of CFD prediction with simple spreadsheet models

3.2 Clear water tank

Figure 18 shows the predicted streamlines for the flow through the tank. Each blue line is the path taken by a small parcel of water entering at the inlet. The figure shows that there is a tendency for water to short circuit directly from the inlet to the outlet. The implications of this are:

▪   The contaminant will pass relatively rapidly from the inlet to the outlet and will not be diluted by the full volume of water contained in the tank.
▪   Some contaminant will migrate into the low flow regions and once there it will take time before it is purged from the tank
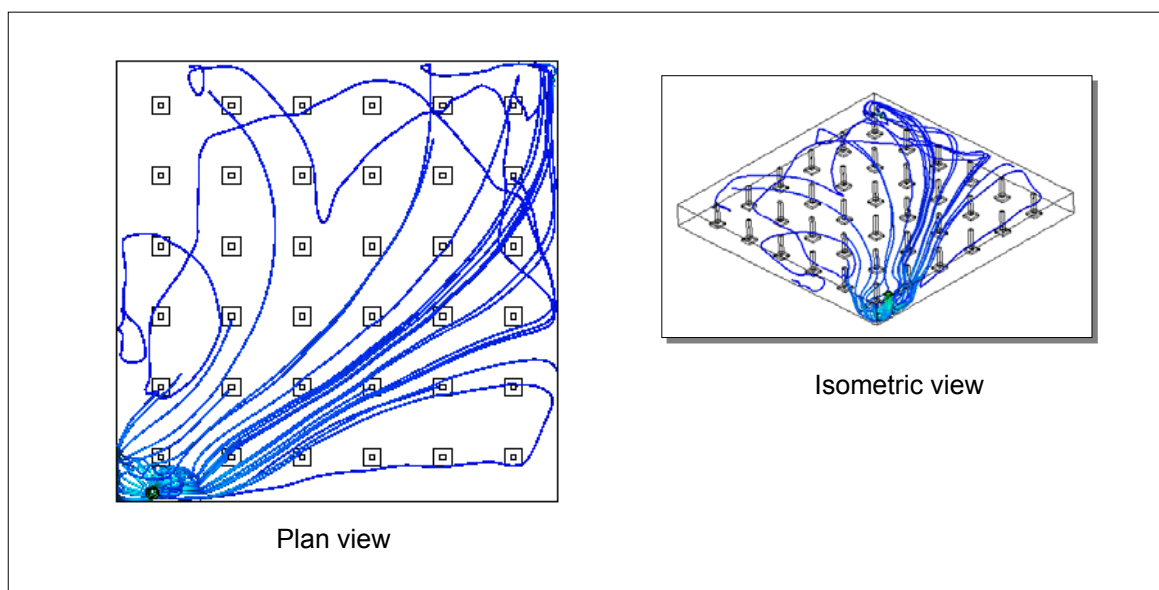
Figure 18 Streamlines for flow through tank

Figure 19 shows the predicted aluminium concentrations throughout the contact tank after 3 hours. This is close to the time of the peak concentration in the outflow from the tank.
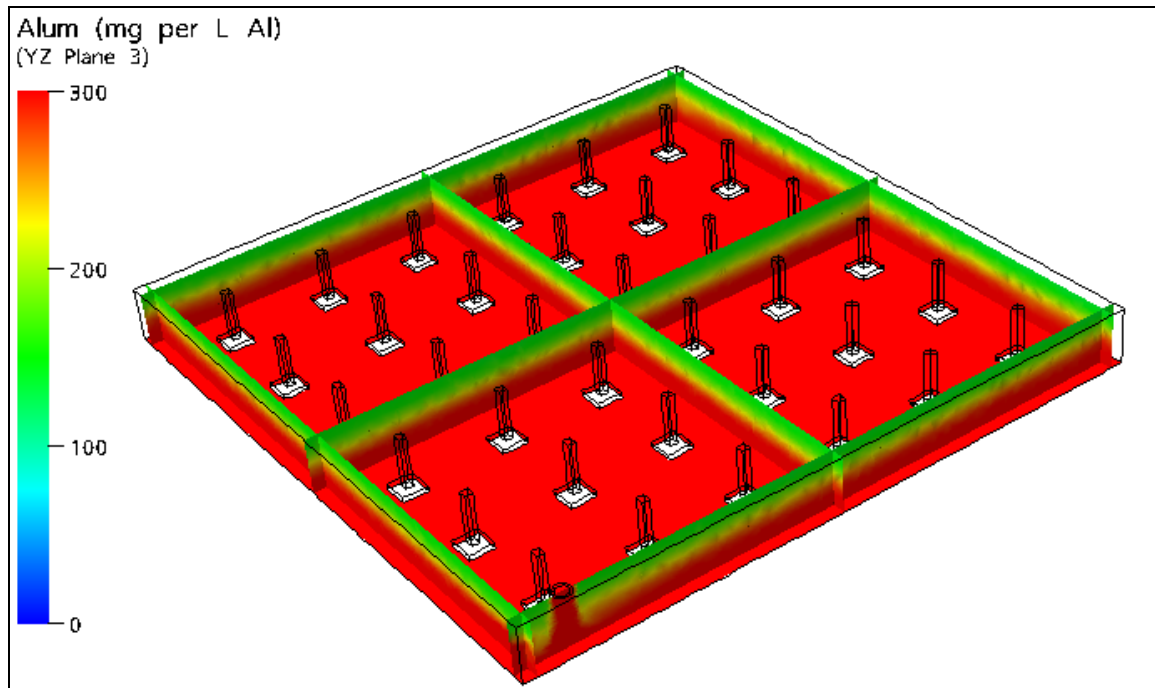
Figure 19 Predicted aluminium concentrations in reservoir at 3hours

The multicoloured planes in Figure 19 indicate the predicted concentration on cuts within the tank. The colour coding is quantified by the legend adjacent to the figure. It should be noted that due to the dilution in the clear water tank, this scale is a factor of ten lower than the colour coding scale shown for the contact tank:

- Dark blue: Regions of low concentration
- Green: 100 to 200mg/L Al
- Yellow / orange / red: 200 to 300mg/L Al
- Dark red: In excess of 300 mg/L Al

The model predicts that the concentration at the base of the tank is higher than the concentration at the top of the tank, but the extent of stratification is much less severe than that predicted in the contact tank.

The progressive build up and release with time of aluminium sulphate in the clear water tank is shown by Figure 20. Time zero is the start of the discharge (approximately 17:00).
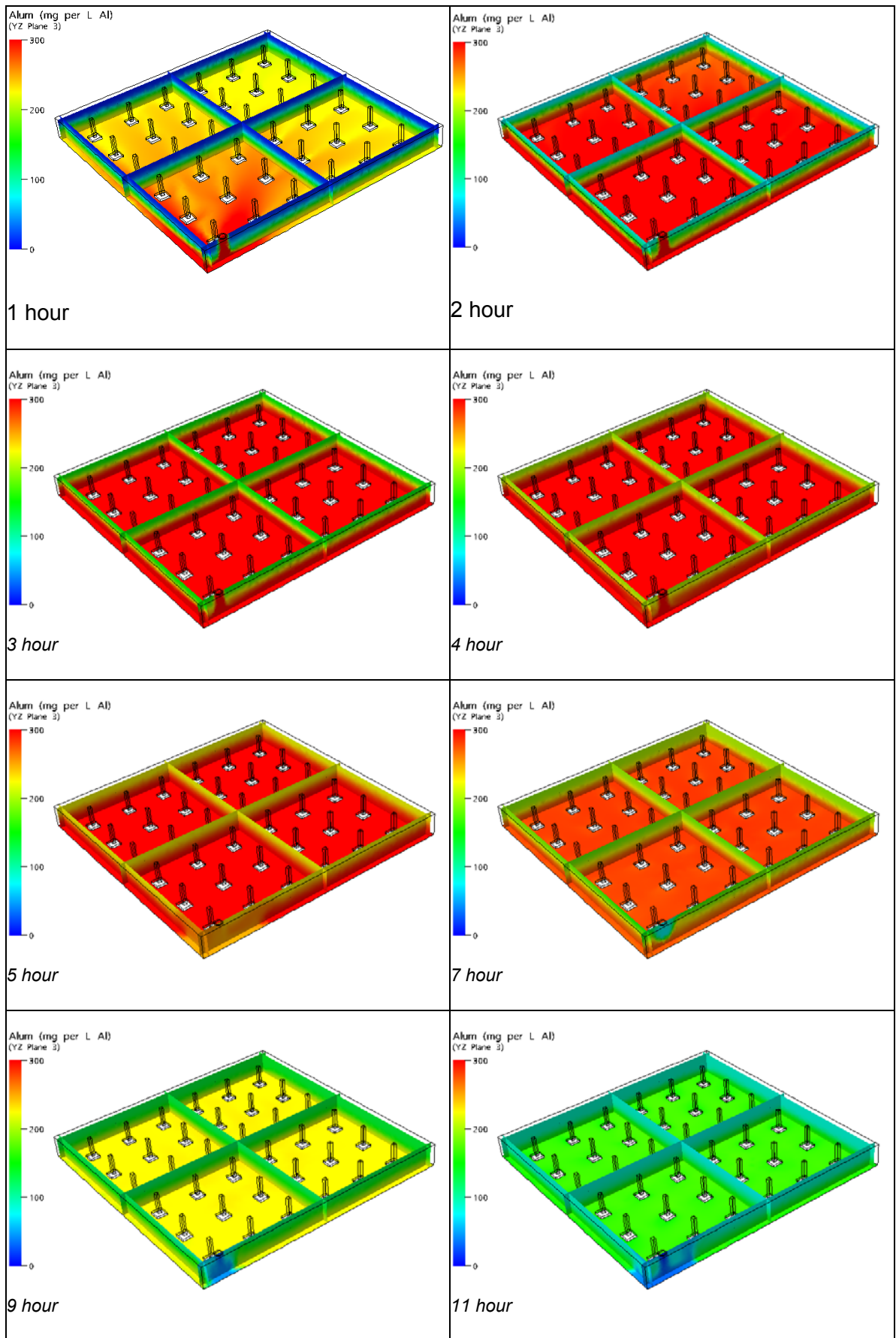
See Figure 19 for legend to colour coding

Figure 20 Predicted aluminium concentrations in clear water tank 1 to 11 hours

The overall concentration for the water exiting the clear water tank versus time is shown in Figure 21. The red line shows the model predictions covering the first 12 hours since the start of the discharge. The peak concentration is 325mg/L Al after 3.7 hours. After 24 hours 92% (by mass) of the aluminium sulphate which was discharged into the tank has exited the clear water tank. The blue crosses show extrapolated data fitted using an exponential decay curve.
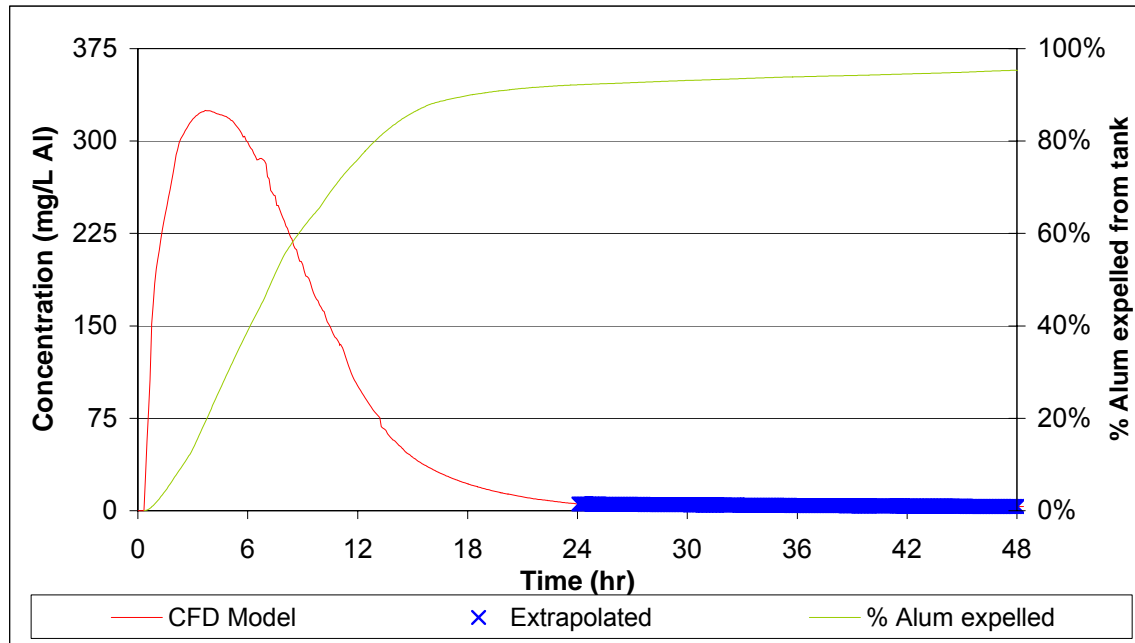
Figure 21 Predicted aluminium concentration in water exiting clear water tank

3.3   Distribution system

Network models can predict the age of water and propagation and mixing of contaminants as they pass through a system. However, before reviewing the results, it is important to understand several limitations of the Lowermoor model.

- The model only includes trunk mains, omitting small local pipework and some service reservoirs (see Section 2.2.3 for full details). The effect of this is to underestimate the time of travel to consumers and ignore the dilution affect of the reservoirs omitted.
- Since no data is available for the water level at Rockhead and Delabole reservoir, they have been simulated as being 50% full throughout the incident. In reality the water level would probably have fallen during the flushing. In addition, these reservoirs have been modelled as fully mixed. The combined affect of these assumptions is that the model probably underestimates the rate at which aluminium sulphate was drawn through these reservoirs reducing the accuracy of model predictions downstream of these reservoirs.
- As previously discussed the information about the location of flushing details is limited.

Within the relatively simple trunk main system, the predicted travel times are predominantly dictated by the assumed demands (consumer and flushing). Whilst there are limitations in how these have been assigned, the following gives confidence in the results:

- The demand allocation in the network is based on recorded flow data – we know we have assigned the right quantity of water at each timestep, the only uncertainty is where that water was consumed.
- Since the population had not changed significantly between 1988 and 1993, It is reasonable to assume that the spatial distribution of consumer demand was as in the 1993 model.
- The model can show that it would be hydraulically infeasible for significantly higher flows to be imposed on the network when flushing was underway

Hence, the model is capable of giving a reasonable indication of the way that the contaminated water propagated through the network.

Table 1 summarizes the time of travel to/age of water at different points in the network for the 5th July 1988, the day before the incident; assumed to be a typical day demand for that time of year, and on 7th July 1988, the day after the incident when flushing flows and volumes were at their greatest.

Table 1 Predicted age of water before incident (5th) and when flushing system (7th)

Node Name	Location	Predicted water age (hr)				Related location	Comment
		5th July Max	5th July Min	7th July Max	7th July Min.		
LOWERMOOR	Lowermoor WTW	0.0	0.0	0.0	0.0		Res outlet = 0 hrs
1A0004F	Lowermoor	0.5	0.1	0.2	0.1	Davidstow	
1A0006C	Greylake	1.6	0.4	0.8	0.4		
1A0010F	Camelford (1)	2.3	0.6	2.1	0.4	Slaughterbridge	
1A0034F	Camelford (2) & Pencarrow	3.7	1.2	2.0	0.6		
1A0038C	Off 9inch	3.6	1.1	2.0	0.9	St Teath (1), Helstone, Michaelstow	
N03	Delabole res inlet	6.3	2.5	4.1	2.1		
DELABRES	Delabole res. Outlet	18.3	14.8	18.0	12.7		
1A0044F	Delabole to St Endellion	22.2	18.3	22.6	16.0	St Teath (2)	
1A0068C	Delabole to St Endellion	28.9	25.8	35.7	23.6	Port Isaac	
STEN1 / STEN4	St Endellion res. Inlet	50.9 47.8	35.8 34.7	59.7 53.9	42.6 38.3	St Endellion	2 supply points
ROCKTF	Rockhead res. Inlet	7.4	4.5	11.4	3.3		
ROCKRES	Rockhead res. Outlet	13.7	10.3	14.2	8.7	Tintagel Boscastle Marshgate Otterham	

Table 2 summarizes the maximum contaminant concentration estimated at the same locations as in Table 1 . The table includes the maximum concentration value with the time it occurred and summarizes the highest concentration in subsequent days. Where the peak has passed the model node, the daily peak value occurs at 00:00hrs.

Table 2 Predicted maximum contaminant concentration (mg/L Al)

Location	Related location	Max. Conc	Day	Time	Maximum concentration on day				
					7th	8th	9th	10th	11th
Lowermoor WTW	Davidstow	325	6th	20:30	281	5	3	2	1
Lowermoor		325	6th	20:30	281	5	3	2	1
Greylake		325	6th	21:00	285	5	3	2	1
Camelford (1)	Slaughterbridge	325	6th	21:30	287	5	3	2	1
Camelford (2) & Pencarrow		325	6th	22:15	303	5	3	2	1
Off 9inch	St Teath (1), Helstone, Michaelstow	325	6th	22:15	309	5	3	2	1
Delabole res inlet		324	7th	00:00	324	5	3	2	1
Delabole res. Outlet		130	7th	07:25	130	32	5	3	2
Delabole to St Endellion	St Teath (2)	129	7th	11:15	129	43	6	3	2
Delabole to St Endellion	Port Isaac	123	7th	16:45	123	78	9	5	2
St Endellion res. Inlet	St Endellion	123 129	8th	06:15 02:45	0 0	123 129	24 18	4 2	2 2
Rockhead res. Inlet		322	7th	03:45	322	5	3	2	1
Rockhead res. Outlet	Tintagel Boscastle Marshgate Otterham	193	7th	12:00	193	21	4	2	1

The hydraulic model represents the trunk main system only. It does not include the following local distribution pipework and dead ends. Figure 8 shows the extent of the network modelled.

- Davidstow reservoir and supply area downstream. The supply into this area is 21% of the total system demand (about 11l/s on 5 July 1988). The area is represented by a demand node downstream of the Lowermoor clear water tank. The average age of water at Davidstow reservoir inlet is about 3.5 hours. However there are no other details available to assess the retention time in Davidstow reservoir or the age profile in the network downstream.
- Camelford. The area is represented by demand off two nodes in the model. The trunk main model will slightly underestimate the age of water in the town and therefore reduce the duration of the contaminant concentrations.

- Tintagel, Boscastle reservoir, Mashgate and Otterham. These areas are supplied from pipework downstream of Rockhead reservoir. The age of water and concentrations will reflect the results at the Rockhead reservoir outlet. The distribution system is complex downstream and any assessment would require the whole area to be modelled in detail. However results at the outlet will reflect the likely concentration profile as far as Boscastle reservoir. The concentration profile and age downsteam of Boscastle reservoir will relate directly to the retention time and hydraulic performance of the storage.

- Helstone and Michaelstow reservoir are supplied through a 6inch main off the trunk main model near Camelford. As for the Davidstow reservoir area, there are no other details available to assess the retention time in the storage, the effect of dilution within the tank or the age profile in the network downstream.

- St Teath is supplied from two directions, one from the 6-inch main feeding Helstone and Michaelstow reservoir and the second off the mains between Delabole reservoir and St Endellion. Although the 4-inch connecting pipe is not modelled, the analysis results for the two modelled nodes either side of St Teath will reasonably represent the range of ages and concentrations at that location.

- Port Isaac is supplied off the mains between Delabole reservoir and St Endellion. The local supply pipes are relatively short and therefore the trunk main model will reflect reasonably the ages and contaminant concentrations in the local pipework, albeit that peak concentrations and durations are likely to be delayed and extended by local hydraulic conditions.

- The results for St Endellion will reflect the conditions at the inlet to the St Endellion reservoir and any properties supplied upstream of the inlet. The hydraulics of the supply downstream are complicated by the following:
  - Mixing and retention time of the two sources within the reservoir; Lowermoor and De Lank. This will be directly related to the relative proportions of the two supplies and the retention time/ hydraulic conditions in the tank.
  - Mixing and retention time with the reservoir of the contaminant with the stored water
  - The timing of the use of the alternative water supply. It is known that the inlet from the Lowermoor system was shut at some time soon after the contamination was discovered and prior to the arrival of the contaminated water at the reservoir (ie the reservoir was fed only from the De Lank system), but that the valve was reopened at some later time when there was still aluminium sulphate in the Lowermoor system.

  The implication of the above is that it is likely that concentrations of the contaminant within the stored water and entering the network downstream will be less that the predicted concentrations at the reservoir inlet.

4   Discussion

4.1   Assessment of sample data and hydraulic model results

The following assessment is based on the SWW Distribution System Sample Data for pH, Al and SO_4 7 July to 4 August 1988 (Reference 7). The analysis is restricted to samples dated between 6th July and 11th July 1988. However data after the period has been reviewed where the local distribution network extends significantly beyond the modelled pipes. The assessment takes into account the analysis results for samples taken from four private water supplies (Reference 8). BVCs has been unable to locate the fifth private supply, that titled "Mount Camel".

Figure 22 shows the predicted propagation of contaminant through the network. Further details for each site is given in Sections 4.1.1 to 4.1.7.
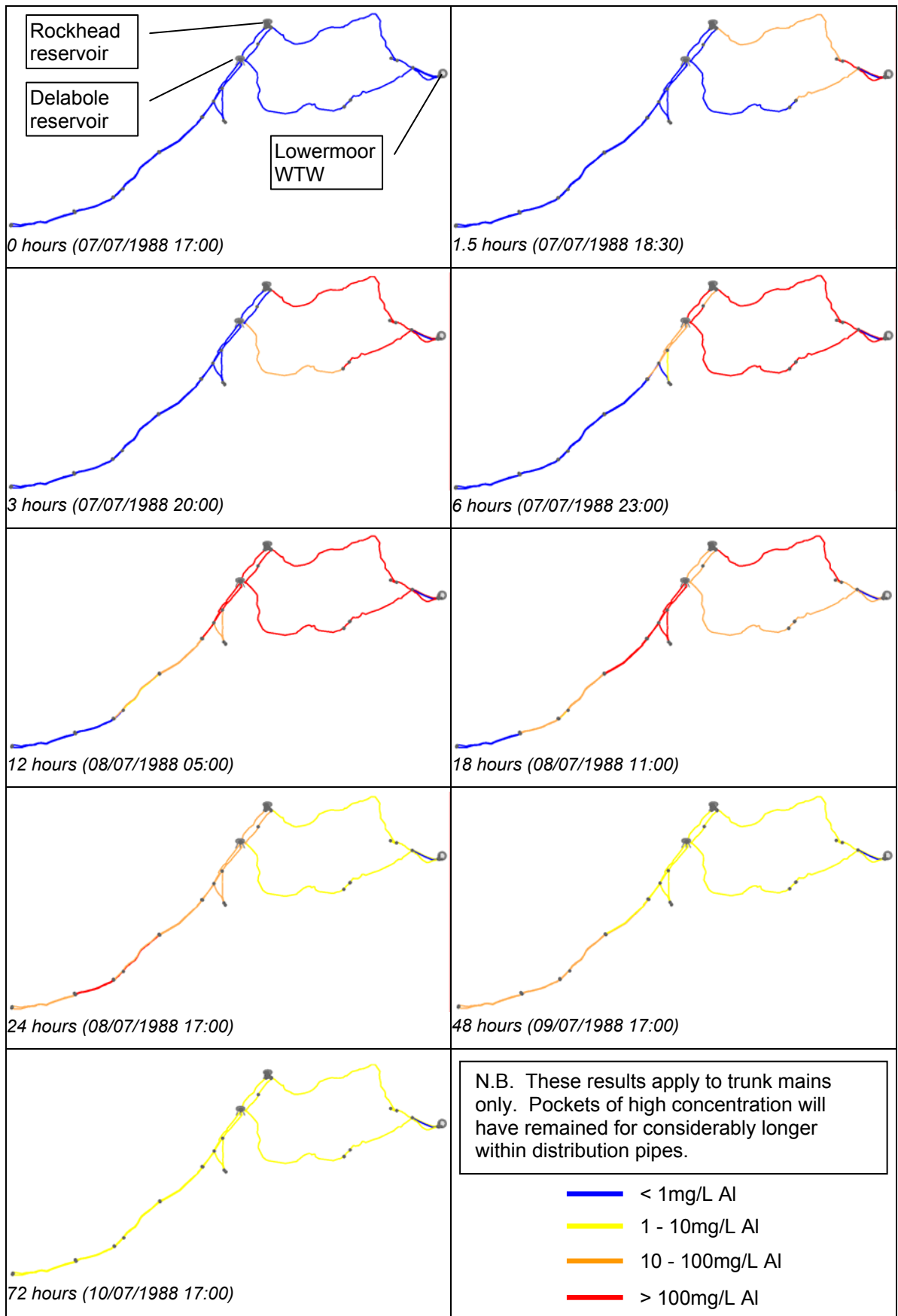
Figure 22 Predicted propagation of aluminium through trunk mains

4.1.1 Camelford

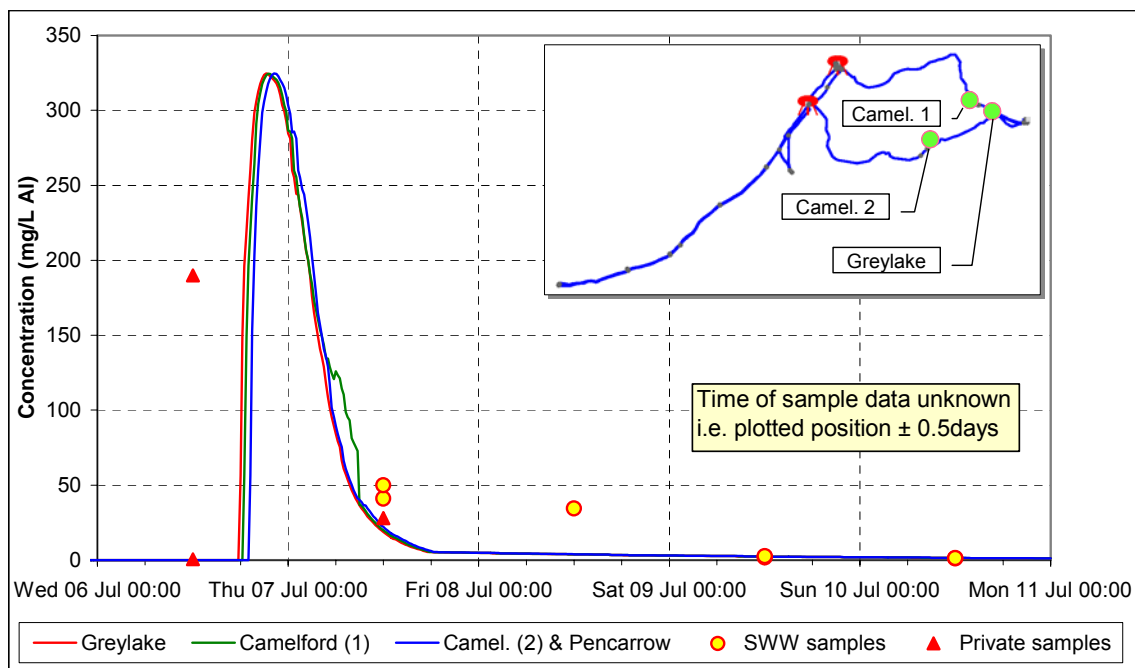The model predictions for the Camelford area are shown in Figure 23 below.

Figure 23 Predicted aluminium concentration on trunk mains in Camelford area

The first complaint was received at 19:55hrs on 6th July 1988. This is consistent with the model predicting the contaminant reaching Camelford at about 19:00hrs.

The following summarizes the available sample data for the Camelford area.

Date	Place	Sample (mg/L Al)	Model (mg/L Al)	
			Max	Min
07/07/88	Camelford	41.00	303	5
07/07/88	Slaughterbridge	50.00	287	5
08/07/88	Camelford	34.50	5	3
09/07/88	8 Roughtor Drive, Camelford	1.87	3	3
09/07/88	5 Longfield Road, Camelford	2.71	3	3
10/07/88	5 Longfield Drive, Camelford	1.07	2	2
10/07/88	8 Rough Tor Drive, Camelford	1.37	2	2

The bulk of the high aluminium concentration had passed the two supplies to Camelford by about midday on the 7th July. The sample, taken on 8th July, exhibits concentrations typical of the day before. This suggests that the sample could have been taken at a point not flushed on the previous day, possibly a dead end, at a consumers tap or from a consumer's storage tank. Otherwise the model is consistent with the sample data.

Two private samples taken on the night of 6th July were analysed by the Laboratory of the Government Chemist, Taunton in August and December 1988. The respective result of >0.5 mg/l and 190 mg/l are consistent with the modelled results.

Two private samples taken on the 11th July were analysed by the Laboratory of the Government Chemist, Taunton in August and December 1988. The sampling technique, location of sample point, the time the sample was taken, preceding hydraulic conditions

time and hydraulic characteristics of the private pipework can all impact on the sample. Both these samples were taken from the hot water tank filled on 7th July, where the contaminated water would have mixed with previously stored water.   The respective result of >0.5 mg/l and 3.1 mg/l are consistent with the modelled results.

4.1.2   St Teath

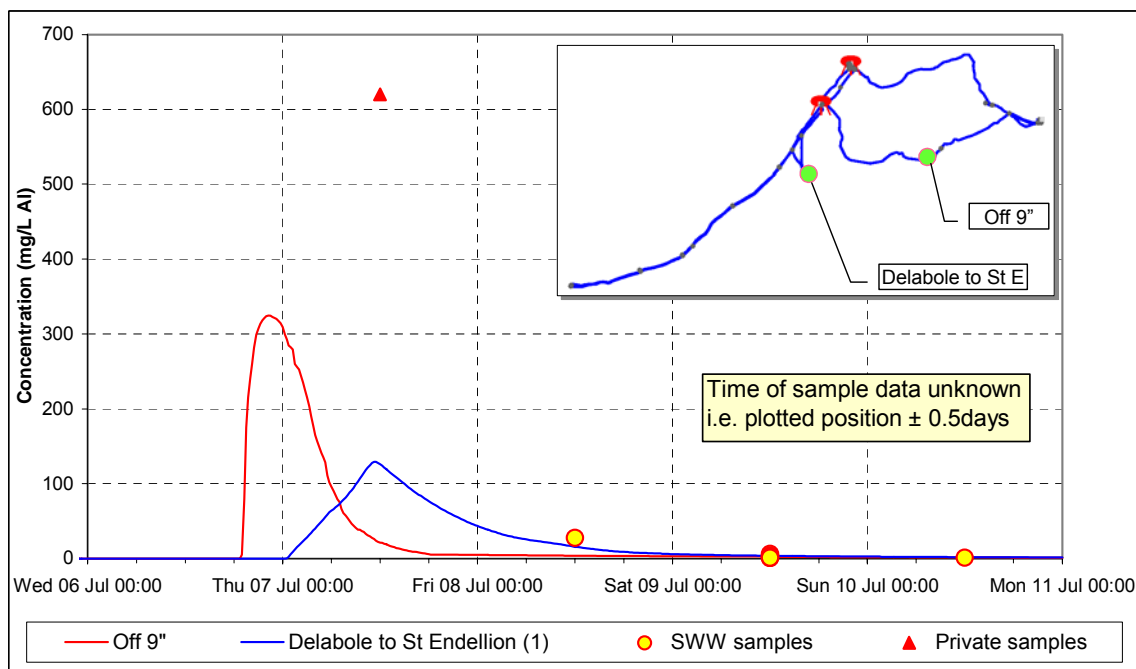The model predictions for the St Teath area are shown in Figure 24 below.

Figure 24 Predicted aluminium concentration on trunk mains in St Teath area

The following summarizes the available sample data for the St Teath area.   As discussed above St Teath can be supplied from two directions.   The village of Pendogget is supplied off the trunk main between Delabole reservoir and St Endellion close to the take off for St Teath.

Date	Place	Sample (mg/L Al)	Model (mg/L Al)	
			Max	Min
08/07/88	St. Teath .	27.50	5/43	3/6
09/07/88	Pengavne, Pendogget	6.20	6	3
09-10/07/88	Bruallan Nursery, St. Teath	3.98	3/6	2/3
09-10/07/88	Vale View, Trewannan Lane, St. Teath	2.96	3/6	2/3
09-10/07/88	Bruallan Nursery, St. Teath	0.58	3/6	2/3
09-10/07/88	Vale View Bungalow Trewennan, St. Teath	0.97	3/6	2/3
10/07/88	Pengawne Bungalow, Pendoggett	0.96	3	2
11/07/88	Mr. Sutton 2 Chapel Cane, Treveigan, St. Teath Hot Water	0.31	1/2	1/2
11/07/88	Mr. Sutton 2 Chapel Cane, Treveigan, St. Teath Cold Water	0.45	1/2	1/2

The model results are consistent with the sample data.

One private sample taken at 05:00hrs on 7th July was analysed by the Laboratory of the Government Chemist, Taunton in December 1988. The result of 620 mg/l is anomalous with the modelled results. The model predicts that contaminated water would have entered the village from the south east after about 19:00hrs on 6th July, with the peak

contamination of about 325 mg/l occurring after about 22:30 hrs that day. There is a second supply into the area, from the north west via the Delabole to St Endellion trunk main. The peak concentration from this main was about 130 mg/l and occurred at mid day on the 7th July. It would appear that the private sample was taken from the former supply into St Teath, but the measured concentration is significantly higher than any other analysed sample in the whole system and is inconsistent with the predicted aluminium concentrations at any time during the incident.

4.1.3   Helstone and Michaelstow reservoir

The model predictions for the Helstone and Michaelstow reservoir area are shown in Figure 25 below
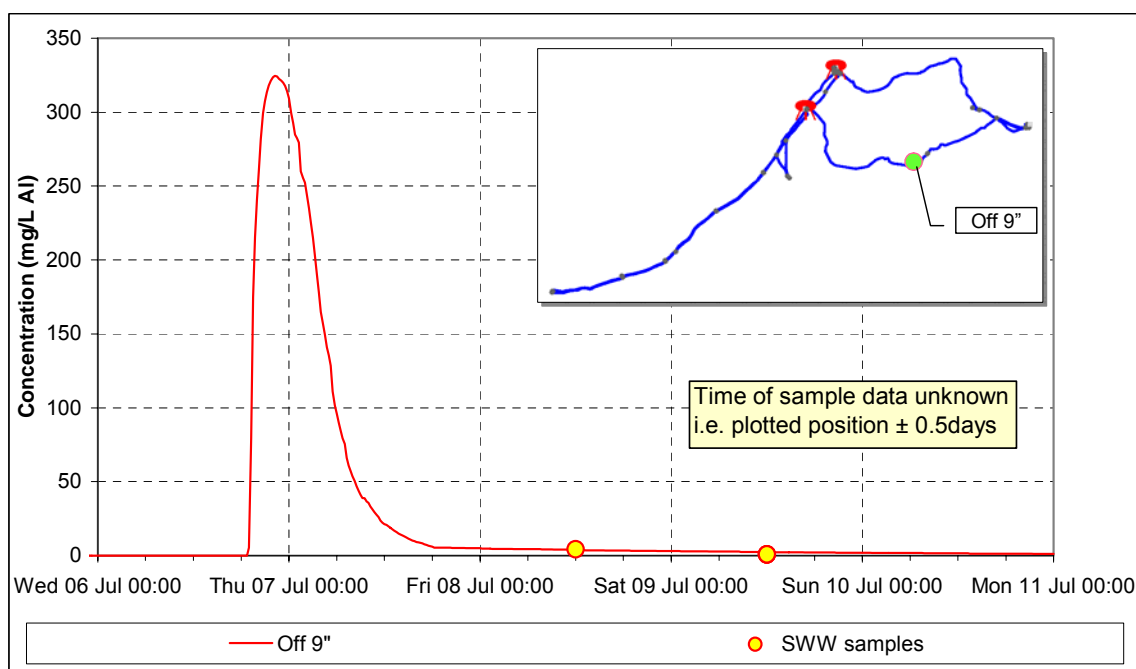
Figure 25 Predicted aluminium concentration on trunk mains in Helstone and Michaelstow reservoir area

The following summarizes the available sample data for the area supplied from the trunk main at Helstone into the Michaelstow area and its service reservoir.

Date	Place	Sample (mg/L Al)	Model (mg/L Al)	
			Max	Min
08/07/88	Michaelstow	4.39	5	3
09/07/88	5 Woodbine Cottage, Miehelston	0.81	3	2
09-10/07/88	Glebe View Bungalow, Michaelstow	0.98	3	2
09-10/07/88	Woodbine Cottage, Michaelstow	1.00	3	2

The model results are consistent with the sample data.

4.1.4   Port Isaac and St Endellion

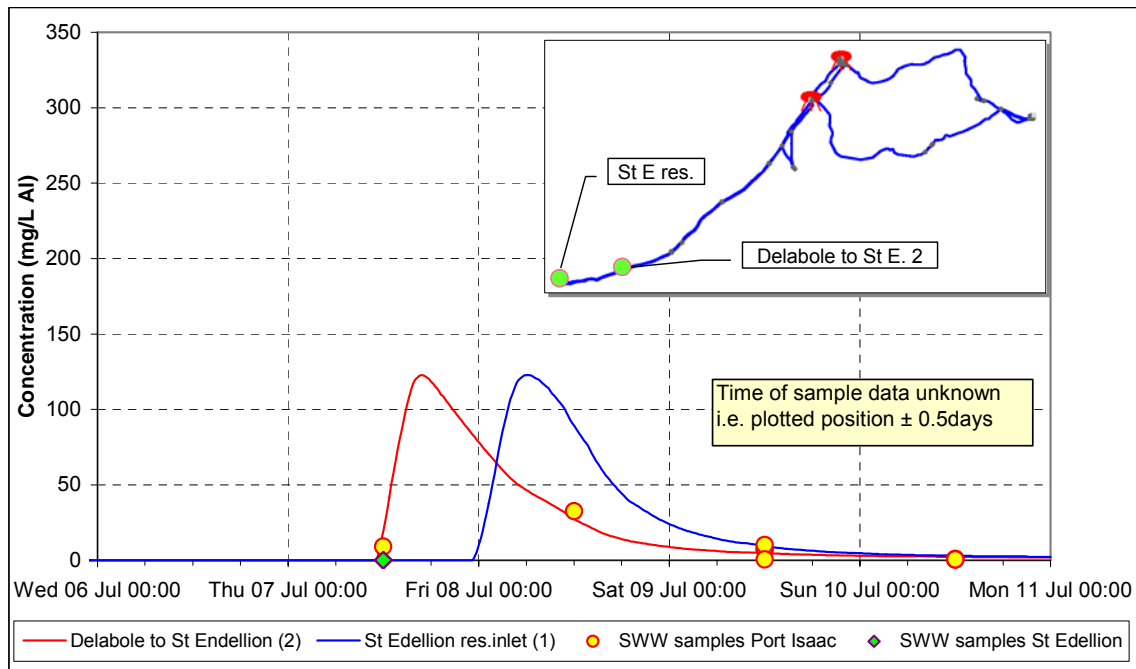The model predictions for the Port Isaac and St Endellion reservoir areas are shown in Figure 26 below

Figure 26 Predicted aluminium concentration on trunk mains in Port Isaac and St Endellion areas

The following summarizes the available sample data for Port Isaac and St Endellion. However as discussed above the St Endellion system is complex, is also supplied by a second source, De Lank water treatment works, the split between flows from the two sources is not recorded and the bulk of the local distribution pipework is not included in the hydraulic model. Accordingly the confidence in the model results for this area is low.

Date	Place	Sample (mg/L Al)	Model (mg/L Al)	
			Max	Min
Port Isaac				
07/07/88	2 Mayfield Drive, Port Isaac (West)	9.00	123	80
08/07/88	26 St. Verse Road, Port Isaac	32.50	78	9
09/07/88	Trewetha Cottage, Trewetha.	6.93	9	3
09/07/88	Trewetha Farm, Trewetha.	7.70	9	3
09/07/88	Spar Shop, Port Isaac	10.08	9	3
09/07/88	Port Isaac Fishemen Ltd	0.60	9	3
10/07/88	Trewetha Cottage, Nr. Port Isaac	1.00	5	2
10/07/88	Trewetha Farm, Trewetha, Nr. Port Isaac	0.80	5	2
10/07/88	The Spar Shop, Port Isaac	0.43	5	2
10/07/88	84 Fore Street, Port Isaac (Opposite Fishermen Ltd)	0.60	5	2
11/07/88	Mayfield Drive, Port Isaac	0.69	2	2
St Endellion				
07/07/88	Sycamoire Avenue Rock	0.10	0	0
07/07/88	Blue Hills, Higher Triscon, Polzeath	0.06	0	0
07/07/88	St. Endellion Service Reservoir	0.19	0	0

Lower sample concentrations are likely to result from one or more of a number of reasons including the time, location and method of sampling and the time the peak concentration arrived at Port Isaac (about mid day on 7th). The model results are consistent with the sample data. It is worth noting that no samples were taken in the St Endellion system between 8th and 11th July, the period when aluminium concentrations peaked (see Table 1).

4.1.5 Delabole reservoir

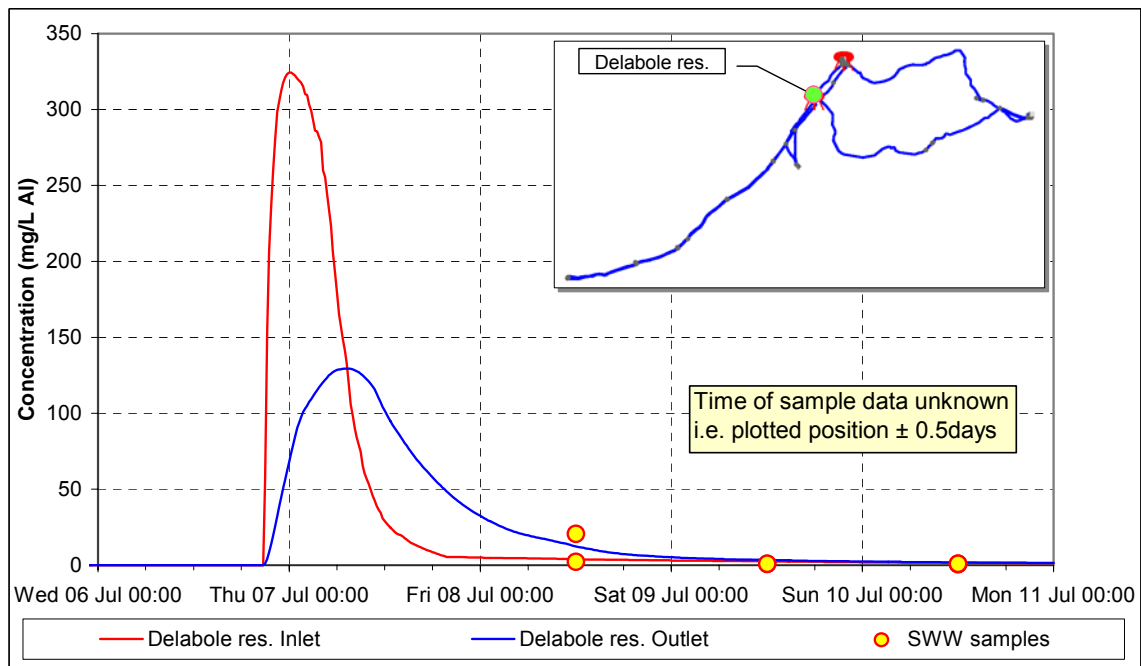The model predictions for the Delabole reservoir area are shown in Figure 27 below

Figure 27 Predicted aluminium concentration on trunk mains in Delabole reservoir area

The following summarizes the available sample data for area supplied immediately around the Delabole reservoir.

Date	Place	Sample (mg/L Al)	Model (mg/L Al)	
			Max	Min
08/07/88	Delabole Inlet	20.50	5	3
08/07/88	Delabole S.R. Outlet	2.26	32	5
09/07/88	34 Rock Road, Delabole	0.75	5	2
09-10/07/88	Rockmead Rock Road, Delabole	0.99	5	2
10/07/88	142 High Street, Delabole	0.47	3	2
10/07/88	33 Roch Head Road, Delabole	1.02	3	2
10/07/88	Rochead Rock Head Street, Delabole	1.00	3	2

The bulk of the high contamination concentration had passed the through the reservoir by 08:00 hrs on 7th July. Therefore the sample data for the inlet is higher than would be expected. However the predicted results for the water into supply are consistent with the sample data.

4.1.6   Area supplied from Rockhead reservoir

The model predictions for the Rockhead reservoir area are shown in Figure 28 below.
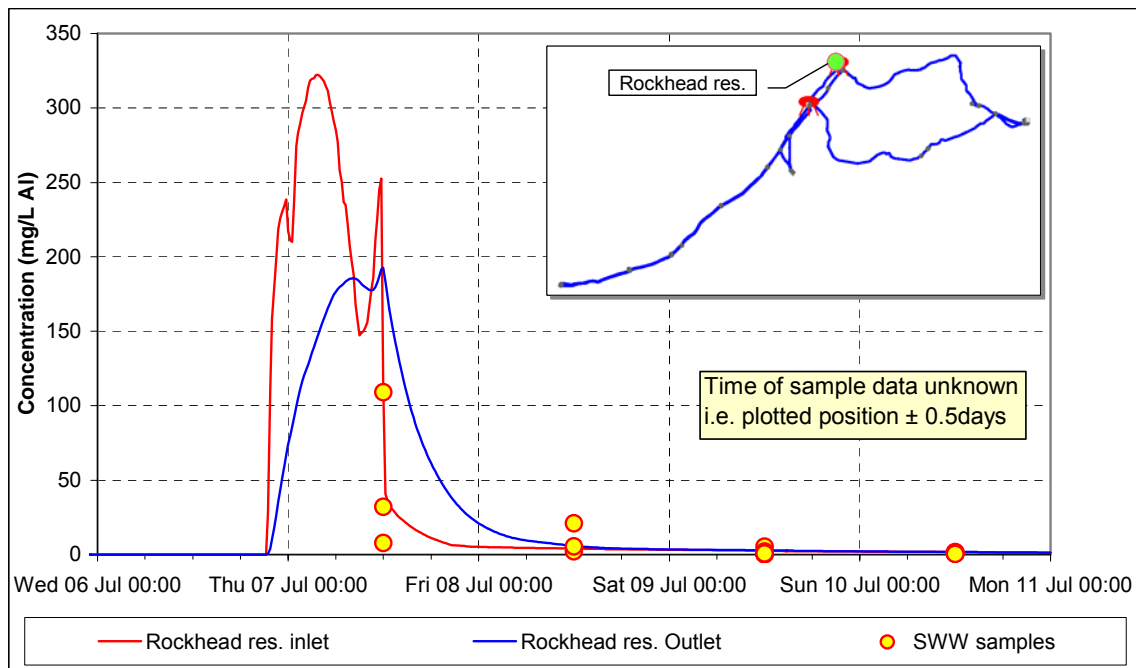

Figure 28 Predicted concentration on trunk mains in Rockhead reservoir area

The following summarizes the available sample data for the area supplied from the Rockhead reservoir including the Tintagel and Boscastle reservoir supply areas.

Date	Place	Sample (mg/L Al)	Model (mg/L Al)	
			Max	Min
07/07/88	Bocastle Service Reservoir	109.00	193	22
07/07/88	Bocastle Service Reservoir	7.90	193	22
07/07/88	Rockhead Service Reservoir	32.00	322	5
08/07/88	Bocastle Inlet	2.17	21	4
08/07/88	Rockhead Inlet	21.00	5	3
08/07/88	Rockhead Inlet	5.58	5	3
09/07/88	Vine Cottage, Boscastle	5.29	4	2
09/07/88	Hillside Cottage, High Street, Boscastle	1.95	4	2
09/07/88	Cottage High Street, Boscastle	1.93	4	2
09/07/88	Hillside Bocastle Hot Water	0.23	4	2
09/07/88	Polkerr, Tintagel	0.49	4	2
10/07/88	Vine Cottage, Boscastle	0.82	2	1
10/07/88	Orchard House, Boscastle Cold Water	1.68	2	1
10/07/88	Fairfield Fore Street, Boscastle Cold Water	0.90	2	1
10/07/88	Hillside Bocastle Cold Water	0.90	2	1
10/07/88	Grange Cottage Bossiney	0.80	2	1
10/07/88	Tintagel Cold Water	0.39	2	1
11/07/88	Orchard House, Boscastle	0.46	1	1
11/07/88	Heigh-Ho Boscastle Hillside	0.61	1	1
09-10/07/88	Vine Cottage, Boscastle Hot Water	0.33	4	2
09-10/07/88	Orchard House, Boscastle Hot Water	0.18	4	2
09-10/07/88	Fairfield Fore Street, Boscastle Hot Water	0.58	4	2
09-10/07/88	Grange Cottage, Bossinor	0.91	4	2
09-10/07/88	Grange Cottage, Bossiney Hot Water	1.32	4	2
09-10/07/88	Tintagel Hot Water	0.68	4	2

The modelled node is the outlet to Rockhead reservoir which supplies the Boscastle area and its service reservoir. Since there will be a time of travel lag between the two reservoirs and the peak concentration passed through Rockhead reservoir about mid day on 7th July, the peak will have occurred later in the day in the Boscastle supply area. Depending on the dilution effect and retention time in Boscastle reservoir, the peak could have been delayed until into 9th July 1988. For reference the Rockhead service reservoir inlet pipe sample data are included. One inlet sample records a higher concentration than the model predicts. However generally the modelled results are consistent with the sample data.

4.1.7   Area supplied from Davidstow reservoir

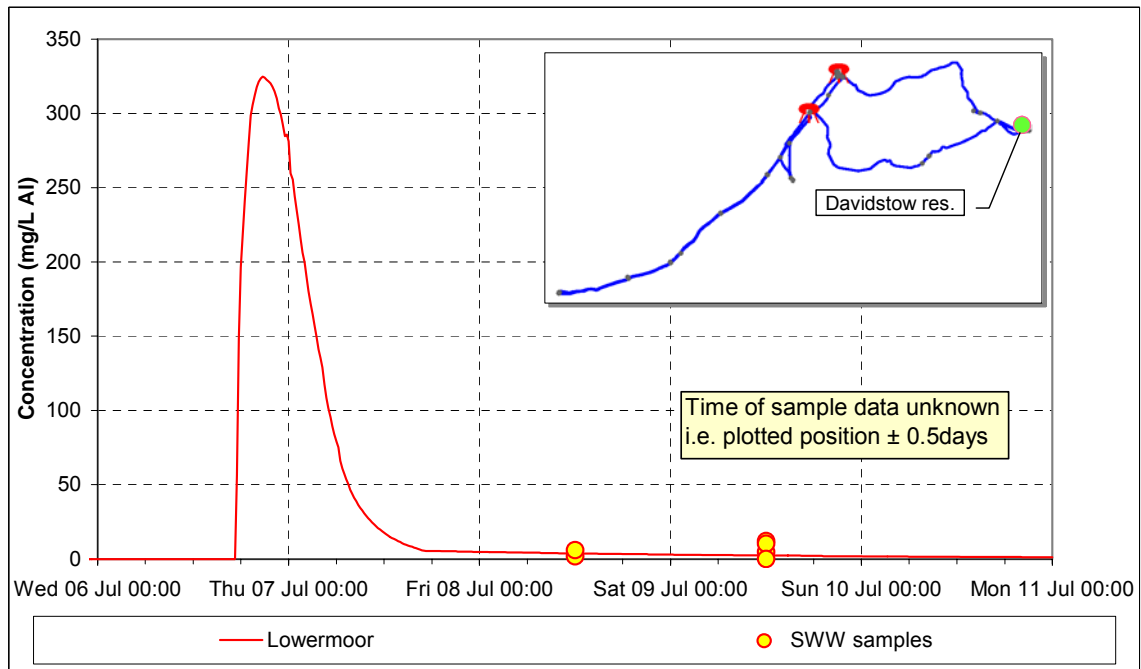The model predictions for the Davidstow reservoir area are shown in Figure 29 below

Figure 29 Predicted aluminium concentration on trunk mains in Davidstow reservoir area

The following summarizes the available sample data for the area supplied from Davidstow reservoir, which is assumed to include the Marshgate and Otterham supply area.

Date	Place	Sample (mg/L Al)	Model (mg/L Al) Max	Min
08/07/88	Davidstow Inlet .	1.80	5	3
08/07/88	Davidstow Outlet	6.00	5	3
09/07/88	Treven "A" Marshgate Hot Water	4.86	3	2
09-10/07/88	Treven, Marshgate	11.97	3	2
09-10/07/88	ESSO Garage, Otterham Station	10.26	2	2
09-10/07/88	2 Westwinds, Otterham Station Hot Water	0.07	2	2

There is poor correlation between the sample data and model results for this supply area which is not covered by the model. However the following points should be taken into account when considering the relevance for the sample data:

- The time of travel to and dilution and retention time in the Davidstow reservoir can not been modelled. However the peak concentration will have occurred at least 3 hours later than the model predicts the peak at Lowermoor water treatment works.

- Similarly the extent of the distribution pipework downstream of Davidstow reservoir and the demand in the area are unknown, both of which could have a significant impact on the age of water and hence concentration at a particular point in the network at a particular time.

- If either or both Marshgate and Otterham were supplied from Boscastle, the recorded concentrations could be feasible.

- The age of the water of samples taken from a hot water system is unknown. Therefore two of the samples are likely to be for water delivered earlier than the sampling date.

More data collection and modelling would be required to be able to compare model and field sample data for this part of the system.

4.2   Specific questions to be answered

In the DofH letter dated 14 April, the committee requested answers to the following questions;

1a. *What would have been the effect on the water level within and the flow through the contact tank and into the outfall pipe of relatively dense liquid entering the vertical outfall pipe?* SWW have confirmed that the outlet pipe is at high level in which case this is not relevant. If this were not correct, the worst conceivable case would be for there to be undiluted alum (density 1.32kg/L) in a vertical outlet pipe and pure water throughout the contact tank (density 0.998kg/L). The static pressure in a column of water is proportional to the density and so a 30% increase in the water level of the contact tank would be required to overcome the increased pressure in the outlet and allow flow to continue. This does not appear to have happened since there are no records of the tank overflowing and the level of the clear water tank remained fairly stable indicating that the flow out of the contact tank remained fairly constant. The CFD model predicts a peak concentration on the base of the tank of approximately 4,000mg/L Al (14 fold dilution) giving a peak density of approximately 1.02kg/L. This would require a 2% increase in water level. In reality, the density of the whole water body in the tank has increased and so the level increase would be even less than this.

1b. *If the outfall was delayed because of the higher density of water in the vertical pipe how soon would normal flows have resumed once the greater part of the high density liquid has passed through the outfall pipe?* Not relevant. See answer to 1a above. However it is worth noting that in a gravity system any forced or uncontrolled change to the hydraulic gradient will be compensated for relatively quickly within the flow and level control points, with overflow discharges taking place if necessary. There are no reports of overflows occurring within the works or at either of the tanks on the site, although both tanks include overflow structures.

2. *What concentration of aluminium is likely to have been present in the outflow from the outlet pipe over the time period needed to have extracted most of the contaminated water from the contact tank?* See the curves for the individual tanks above.

3. *What would have been the likely effect of dilution on this outflow in the small basin in the treated water tank upstream of the weir that contained the outlet pipe from the contact tank?* SWW has confirmed that there is no inlet weir on the inlet pipe to the clear water tank. The top of the pipe comprises a bellmouth as shown on the original reservoir drawing (Reference 01).

4. *If the solution in this small basin is relatively concentrated how would the denser liquid overflowing from the chamber into the main treated water tank have behaved in its passage through the treated water tank? Would there still have been plug flow through the treated water tank or would a sheet flow across the base of the treated water tank to its final outlet have been possible?. In either*

case what would have been the estimated concentration ot the outlet of the treated water tank and over what period? As stated in 3 above there is no separate inlet chamber. The plots of the performance of the tank illustrate the short circuiting in the tank combined with the stratification by concentration. Note also that the bottom water level outlet mitigates the effect of stratification.

5. *The likelihood of compacted sludge in the base on the contact tank.* From our experience and knowledge of the water chemistry of the Lowermoor source, our treatment works specialist does not believe that the "sediment" reported to have settled in the floor of the contact tank would have been hard. Possible chemical sediments resulting from treatment process carry over are more likely to have been soft and because of the hydraulic characteristics and induced turbulent flows at changes of flow direction in the tank (see Figure 9), significant quantities of sediment are unlikely to have settled out in the contact tank. They are more likely to have settled out in the clear water tank where the flow velocities will be significantly lower. One possible explanation of the "so firm that a man could walk on it" would be the benching on the tank floor which with time would become discoloured. I tend to conclude with the SWW denial. However if there was a sludge blanket on the bottom of the tank, the answer to the question would depend on the relative densities of the sludge and pollutant. At worst the contaminant concentration would be no greater than the CFD modelling predicts. If the density of the sludge blanket was greater than the contaminant, the latter would be a layer above the sludge blanket and therefore dilution and dispersion would have been accelerated.

6. *Distribution system dead ends*. Dead ends and through pipes with very low flows may happen to draw off a large slug of contaminated water due to a localized short term period of high demand. Once the dead end had been "filled" with water of a particular concentration, it would remain in the section of pipe until it had been used or leaked away. There would however be a dilution effect from lower concentration water "topping up" the dead end as water is used, but again the rate of dilution will depend on the local demand patterns. However once fully mixed, the concentration of the contaminant will not increase due to extended retention in a pipe or storage.

7. *Elevation of pipes.* The elevation of the pipe will have no effect on the pollution levels.

8. *Plug flow and flushing.* The distribution network is a CLOSED (or pressurized) pipe system operating effectively as plug flow with dispersion taking place at leading and trailing edges. Demands from the system, be they domestic, commercial, or a flushing exercise do not alter the basic hydraulics of closed pipe systems. Even when the system is being flushed it is still a closed system. There has been no mention of the network being drained down completely and then refilled, a condition which would be more akin to being analysed as a sewer, eg open channel.

5   Conclusions

1. The CFD modelling supports the belief that the aluminium sulphate sank to the bottom of the contact tank and migrated throughout the floor of the tank. This is validated by the pH meter readings which indicated that the pH increased near the inlet, probably due to the presence of aluminium sulphate which had migrated upstream against the main flow in the tank.

2.   The sample data indicates that low level contamination concentrations persisted for at least a month after the incident. This is consistent with the model conclusions for the decay curve for the aluminium sulphate out of the Lowermoor clear water tank, the subsequent retention in service reservoirs and the distribution system downstream.

3.   The models of the tanks only cover the first 24 hour period, beyond this time, water company sample data will be a more reliable indication of concentrations than the models.

4.   A concentration against time profile has been predicted for the water exiting the clear water tank (Figure 21). The implications for this in the network have also been modelled at trunk main level only. The peak values predicted within the network are given in Table 2. The values are reasonably consistent with the majority of the SWW sample data.

5.   One private sample is anomalous with the modelling results. This is the sample from Mayrose Farm St Teath taken on 7th July 1988 (but not analysed until December). Given that this is the only major anomaly with the modelling results, it raises serious doubt about the validity of the sample.

References / Information sources

1.   Lowermoor reservoir, General Details, April 1971
2.   Drawing 16/805/A – Conversion of ex. Reservoir to Contact Tank, June 1972
3.   1:25,000 map showing DMAs (returned to DofH)
4.   A4 Copy of Item 3
5.   Lowermoor Raw Water Flow Chart, 4th – 11th July 1988
6.   Lowermoor Clear Water Tank Water Level Chart, 4th – 11th July 1988
7.   SWW Distribution System Sample data for pH, Al and SO_4 7/7 to 4/8 1988
8.   Private Samples Analysis data for samples taken 6 – 11 July 1988
9.   Crowther Clayton Report dated 12 June 2003
10. Crowther Clayton Report dated 21 November 2003
11. Crowther Clayton Report dated 11 December 1993
12. Works schematics – Fax dated 27/03/02