Evaluation of sinkhole data
Ausable Bayfield Maitland Valley Source Protection Region

Prepared for
Ausable Bayfield Maitland Valley Source Protection Region

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April 19, 2010

Executive summary

A review of information on the sinkholes and sinking streams in the Ausable Bayfield Maitland Valley Source Protection Region was carried out. It was found that probably the largest recharge of surface water to the bedrock aquifer is at a sinkpoint in the Ausable River (Upper Ausable Sink). Measurements of water levels at Chiselhurst and Tuckersmith sinkholes have shown that there are intermittent flooding episodes following heavy rainfall or snowmelt when the sinkholes become filled with water. These episodes typically last only a few days. Water quality measurements at wells close to the sinkholes have found no E. coli or total coliform bacteria, though high nitrate at two wells and large changes in major ions may be due to sinking stream recharge.

The sinkholes and sinking streams are drained by conduits that discharge at springs. Southwest of Hensall there is a broad area where water levels in the Lucas Formation are less than 3 m above the level of Lake Huron, even at a distance of 20 km from the lake. The exceptionally low hydraulic gradients in this area reflect the high permeability of the aquifer which is caused by karstification. Travel time along the conduits between the sinks and Lake Huron is likely to be only a matter of days, so bacteria from the sinking stream recharge could possibly be found over a very large area. The probability of any single well intersecting a conduit is low, but the large number of wells between the sinking streams and Lake Huron means that it is likely that some wells in the area may be impacted by poor-quality sinking stream water.

1. Introduction

There are a number of sinkholes and sinking streams in Perth and Huron counties. The direct recharge of surface water to the underlying bedrock aquifer at these locations has raised concerns over possible contamination of the aquifer. As a result a number of studies of the sinkholes have been carried out over the last thirty years.

The purpose of this report is to review and evaluate the information collected on these sinkholes. The information available comprises historical data in several reports as well as recent water level and water quality data collected over the last several years as part of an ongoing programme to evaluate the effect of sinkhole recharge on the aquifer. The goal is to identify any significant trends in the data and provide recommendations for any future data collection or studies which would be required to better evaluate the groundwater vulnerability in the area.

2. Review of historical studies

Karrow (1977) mapped the Quaternary geology of the St Marys area and identified more than 25 sinkholes in the Townships of Hibbert and Tuckersmith. Brown (1981) carried out a field investigation of seven sinkholes in these two townships and noted that sinkholes have been observed to be accepting more than 1000 litres per minute from the agricultural drains in the area (Brown, 1981, p. 1). Beukeboom (1995) investigated groundwater quality, including major ions, bacteria and herbicides at the sinkholes in Hibbert and Tuckersmith Townships as well as two in Ashfield Township.

International Water Consultants et al. (2003) carried out a groundwater assessment and municipal wellhead source protection study for Huron County. They noted the presence of sinkholes just east of Brussels in addition to the ones that had been reported previously. The map of groundwater elevations in the Lucas Formation showed that there is a broad area to the southwest of Hensall where water levels are less than 180 m (i.e. less than 3 m above the level of Lake Huron), even at a distance of 20 km from the lake. The hydraulic gradient in this area is as low as 0.00015, an exceptionally low value that implies very high permeability and demonstrates the well-developed karstic permeability in the bedrock.

WHI (2004) carried out a detailed investigation of the main area with sinkholes in Huron East and West Perth (in the former townships of Tuckersmith and Hibbert). They identified more than 50 sinkholes and measured water levels and water quality at selected sinkholes. A subsequent study by Hurley et al. (2008) carried out further studies in the same area, characterizing the bedrock using coreholes and geophysical logging, and extended the water level and water quality monitoring.

3. Drainage from sinkholes and sinking streams

Sinkholes are enclosed depressions that occur on the surface above karst aquifers. They are the result of a positive feedback process at locations where the underlying bedrock is slightly more permeable than elsewhere (e.g. where an open fracture occurs). More recharge can occur at such locations, resulting in more dissolution of the bedrock along the flow path downgradient of the open fracture. Once the flow path has been opened to an aperture of a few millimetres then soil and unconsolidated sediments can be carried along the open fractures through the aquifer. At this point a funnel-shaped depression starts to be created. This expands outwards and becomes deeper over time, thus capturing ever-increasing amounts of recharge.

In some instances sinkholes have sinking streams. Sinking streams are streams that lose all their flow to the underlying bedrock. If they lose part of their flow they are known as losing streams. Sinking streams and losing streams are very common in limestone and dolostone aquifers provided that two conditions are met. The first is that the water table must be lower than the bed of the stream. The second is the bedrock needs is be exposed along the bed of the stream or there needs to be minimal overburden (usually less than a few metres) between the bed of the stream and the bedrock.

A sinkhole, sinking stream or losing stream is not just a surface feature that represents point recharge to an aquifer. Instead, it represents the upstream end of a conduit (with an aperture of centimetres or more) that ends at a spring where the aquifer discharges to the surface. Thus sinkholes and sinking streams can be of great significance to aquifer permeability over broad areas. There is a large body of both theoretical and field evidence that shows that sinkholes are in all cases the upstream end of aquifer-scale conduits. The theoretical evidence comes from numerical models that simulate the development of karst aquifers (Dreybrodt et al., 2005; Worthington and Ford, 2009). The field evidence comes from many studies in caves and from many thousands of tracer tests from sinking streams. There is a long tradition of tracer testing from sinking streams and many thousands of tests have been carried out since the first well-documented test in 1860 (Worthington and Gunn, 2009). Figure 1 shows two compilations of tracer test results, one a global data set and the second from Ontario. Figure 1 shows that tracer tests from sinking streams have taken place over distances up to 75 km. Thus the distance of up to 27 km between the sinking streams in this study and springs (presumed to be in Lake Huron), though a substantial distance, is well within the known range of sink to spring conduit pathways in carbonate aquifers.

The permeability of conduits is typically several orders of magnitude higher than the surrounding bedrock. This means that hydraulic gradients along conduits are extremely low and that the conduits are associated with troughs in the water table (Worthington, 2009a and Figure 2a). Flow in conduits is usually in the turbulent rather than the laminar regime. This means that the hydraulic gradient increases by a factor of four when flow doubles. Meanwhile, in the surrounding bedrock with laminar flow, a doubling of flow results in a doubling of the hydraulic gradient. The result is that heads in the conduit will increase more than in the surrounding bedrock, resulting in a mound in the water table above the conduit (Figure 2, bottom). The mounding of water along conduits usually occurs only for a small fraction of the year; for most of the time water flows towards the conduit.

The high permeability of conduits results in very low hydraulic gradients, and this can result in a thick unsaturated zone where the karst aquifer is extensive. There is a broad area in southern Huron County where the water table has a very low gradient and there is a thick unsaturated zone, which can reach 100 m in some areas (Figure 3). The bedrock aquifers in this area are in limestones and dolostones of the Detroit River Group and Dundee Formation, and areas with these aquifers have been classified as "known karst" or "inferred karst" (Figure 4).

4. Analysis of data

4.1 Compilation and analysis of water-level data

Water level data were analyzed at two sinkholes (Tuckersmith Sinkhole and Chiselhurst Sinkhole) and at two wells (Hensall Road Well and the PGMN Sinkhole Well). The latter well is also referred to as 406-1 well, the Provincial Groundwater Monitoring Network Sinkhole Well, or the Chiselhurst Sinkhole Well.

The Tuckersmith Sinkhole data consists of water level measurements every 15 minutes since June 2003. The Chiselhurst Sinkhole data consist of water level measurements every ten minutes from January 2005 to October 2006 and measurements every 15 minutes since then. The Hensall Road Well data consist of measurement of water level every 10 minutes from January to February 2005 and measurements every 15 minutes since then. The PGMN Sinkhole Well data consist of measurements of water level every hour since February 2005. In addition, there are temperature measurements for most of the above records as well as some electrical conductivity measurements.

The water level data comprise a very large data set with more than half a million measurements of water level. The data were first imported into Microsoft Excel from their native (*.lev) format. The data were then inspected for spurious data points such as single data points that were several metres different from earlier and later water levels. Such measurements were removed and then hourly and daily averages were produced. These Excel files are on the attached CD.

4.2 Analysis of water quality data

The surface water quality data consist of more than five years of monthly measurement of 11 parameters at Chiselhurst Sinkhole and at Tuckersmith Sinkhole, with a total of 1332 measurements. The groundwater quality data consist of six years of monthly measurements of more than forty parameters at five or six wells, with a total of 9304 measurements. The data were sorted and inspected for low or high values that might represent mixing with water recharging at the sinkholes and a series of figures and tables showing significant trends were prepared.

5 Results

5.1 Direct aquifer recharge at sinkholes and sinking streams

Waterloo Hydrogeologic (2003) identified more than fifty sinkholes in the study area and they grouped these into four groups. The total area drained by these four groups is 813 hectares. Subsequent investigations have focussed on Chiselhurst Sinkhole and at Tuckersmith Sinkhole. Both these sinkholes have sinking streams that recharge the bedrock aquifer.

In reviewing the literature, it became apparent that probably the largest aquifer recharge feature in the area is along the Ausable River at a location where bedrock outcrops in the bed of the river. The following details were recorded by Brown (1981):

> "At sinkhole location #3, in the bed of the McMillan Drain (Ausable River tributary) exposed fractured limestone accepts large flows in several locations where the water

> can be heard to echo from its initial drop" (Brown, 1981, p. 6).
>
> "Sinkhole number 3 in lot 19, concession XI receives the bulk of the flow of the McMillan Drain, a major headwater tributary of the Ausable River. This represents a drainage are of 1900 hectares (4800 acres) of which some 280 hectares (700 acres) appears to drain to sinkholes such as numbers 4 and 5. During periods of high flow, the McMillan Drain reportedly builds up and flows past sinkhole #3 (Brown, 1981, p. 7).

The observations by Brown (1981) suggest that all the flow of the river sinks where bedrock outcrops, except at high flow. However, the municipal drain was extended in approximately 1983 and this may have substantially reduced the amount of water sinking into the bedrock (Alec Scott, personal communication, February 2010).

The estimate by Brown (1981) that some 280 hectares appears to drain to sinkholes in what Waterloo Hydrogeologic (2004) named the Hibbert Cluster is rather different from the estimate of only 94 hectares in the latter report. These different estimates highlight the difficulty of making accurate estimates of drainage areas in the low-relief terrain in southern Ontario. Table 1 and Figure 5 show the area drained by the Upper Ausable Sink and by the sinkhole clusters.

The capture area of about 1620 hectares for the losing stream at Upper Ausable Sink is large, but it is not the largest in Ontario. There is a similar losing stream at Shallow Lake. An area of 13,200 hectares drains into the lake. In the winter months there is a creek that drains the lake, but in the summer and fall this creek is dry and all the surface flow into the lake recharges the underlying dolostone aquifer via sinkholes (Worthington, 2009b).

Table 1 Capture area for sinkhole clusters and the Upper Ausable Sink (after Brown, 1981 and Waterloo Hydrogeologic, 2003)

Area	Sinkhole capture area (hectares)	Reference
Watershed of Upper Ausable Sink	1620	Brown (1981)
Chiselhurst Cluster	389	Waterloo Hydrogeologic (1983)
Tuckersmith Cluster	258	Waterloo Hydrogeologic (1983)
Hibbert Cluster	94	Waterloo Hydrogeologic (1983)
Line 21 Cluster	72	Waterloo Hydrogeologic (1983)

5.2 Water level data

Water level results are shown in Figures 6 to 9. Figure 6 shows daily averages in the PGMN Sinkhole well from 2005 to 2009. There is a seasonal range in water level of more than 10 m. In the summer and fall of 2005 and 2006 it appears that the water level dropped below the level of the logger and subsequently the logger was installed four metres lower (D. Heinbuck, personal communication). The data for the last four years have higher maximums and minimums than the first two years. There may be an issue here with correction of the data from logger depth to height above mean sea level.

Figure 7 shows the results for the Hensall Road well. The data is very fragmentary and it appears that water levels drop below the base of the well (D. Heinbuck, personal communication). The record on February 12, 2005 shows a rise of 60 cm in eight hours, reflecting a major thaw and runoff event.

Figure 8 shows water levels at Chiselhurst Sinkhole. Since May 30, 2008, the probe has been located in the stream bed but the stream is shallow except during major flooding events when the water level rises up to 2.5 m. Consequently, the substantial short-term variation in apparent water level is largely a reflection of changing atmospheric pressure. The largest flooding event is shown in Figure 8b. The flooding event lasted 56 hours.

The situation at Tuckersmith Sinkhole is similar to Chiselhurst Sinkhole, except that flooding events are much more frequent (Figure 9). The probe at the site is situated about 2 m above the base of the sinkhole, and flooding events rise a further 7 m. Figure 9b shows that the nature of the events is similar to flooding events at Chiselhurst Sinkhole, with sharp rises and falls in water level.

5.3 Water quality data

Major anions for the six sampled wells are shown in Figures 10 and 11. The anions are easier to interpret that the cations because alkalinity concentrations reflect the dissolution of limestone and dolostone, sulphate concentrations reflect the dissolution of gypsum and anhydrite, and chloride represents the dissolution of salt (halite). Interpretation of cations is complicated by the fact that calcium ions are derived from both gypsum and carbonate minerals.   MW5 shows the largest variations in chloride and sulphate and Figure 12 shows a plot for all seven major ions at this well. These seven ions typically account for more than 95% of dissolved ions in natural groundwaters.

There are substantial variations in water quality in all wells. It is difficult to correlate the changes in well water chemistry with the chemistry of the sinking stream water for two reasons. First, the sampling interval at the wells is one month but major flooding episodes typically last only a few days. Consequently, it is difficult to establish whether changes at the wells reflect recharge from the sinking streams. Much more frequent sampling would be useful. Second, the sinking streams have been sampled for surface water parameters rather than groundwater parameters and so major ions have not been analyzed in sinking stream samples. Analysis of sinking stream water for these ions would facilitate comparisons with groundwater.

It would be expected that recharge water would be less mineralized than groundwater and so lower concentrations in the winter would be expected. Despite the substantial variations in alkalinity values, no well-defined seasonal trends are seen in any of the wells (Figure 10, top). High chloride values might be associated with runoff of road salt applied in winter. Such a trend is seen at MW5, with high values typically occurring in late winter and low values in the fall. MW1 also has high values of chloride but no seasonal trend is apparent (Figure 10, bottom). MW3, MW4, and MW5 have the highest concentrations of sulphate and all three wells show a seasonal trend, with a tendency for lowest concentrations in the winter and highest concentrations in the fall (Figure 11). This is probably because of dilution of groundwater by low-sulphate recharge water in winter and spring.

Figure 12 shows all major ions at MW5. There are positive correlations between magnesium and alkalinity, reflecting the dissolution of limestone and dolostone, and between sodium and chloride, reflecting the dissolution of salt (Figure 12).

Overall, there are substantial variations between the wells for all three anions (alkalinity, chloride, and sulphate; Figures 10 and 11). This reflects the heterogeneity of flow paths in the aquifer. MW4 is the furthest well from a sinking stream and this well has the highest total dissolved solids (TDS). MW2 and PGMN wells have the lowest TDS and are two of the three wells closest to Chiselhurst Sinkhole. However, the third close well is MW3 and that has substantially higher TDS. Consequently, the aquifer does not show a simple pattern of increasing dilution with increasing proximity to the sinking streams.

The longest flooding event documented is at Tuckersmith Sinkhole, from March 2 to March 18, 2004. The nearest monitoring well (MW-5) is 500 m away and this well does have decreases in sulphate and alkalinity values of about 30% and 10%, respectively, in the winter months. However, from the monthly sampling interval it is not possible to make direct correlations with flooding events that typically only last a few days or less.

Escherichia coli and fecal coliform were zero in all well samples. This contrasts with the elevated values found at the sinking streams. There are also substantial suspended sediment concentrations at the sinking streams (Table 2). The lack of bacteria in the sampled wells indicates a lack of open fractures that would provide fast pathways between the sinking streams and these wells.

Table 2 Bacteria and suspended sediment concentrations in the sinking streams at Chiselhurst and Tuckersmith Sinkholes

Location	**Parameter**	**n**	**Min.**	**Mean**	**Max.**
Chiselhurst Sinkhole	E. coli (cfu/100 mL)	19	1	327	2300
Chiselhurst Sinkhole	Fecal coliform (cfu/100 mL)	19	1	502	3800
Chiselhurst Sinkhole	Suspended sediment (mg/L)	32	1	54	710
Tuckersmith Sinkhole	E. coli (cfu/100 mL)	18	7	477	3100
Tuckersmith Sinkhole	Fecal coliform (cfu/100 mL)	18	30	1368	5600
Tuckersmith Sinkhole	Suspended sediment (mg/L)	29	1	73	1002

Table 3 Mean total nitrate concentrations in sinking streams and wells

Location	Nitrate (mg/L)	number of samples
Chiselhurst Sinkhole	7.62	60
Tuckersmith Sinkhole	6.42	53
MW1	0.38	37
MW2	7.26	39
MW3	2.25	39
MW4	0.86	18
MW5	0.97	31
PGMN well	8.55	30

Nitrate represents another water-quality concern. Concentrations in the sinking streams are high. Concentrations at MW2 and the PGMN well are much higher than at the four remaining wells sampled (Table 3). The major ion chemistry of MW2 and the PGMN well are very similar (Figures 10 and 11) and they are both close to Chiselhurst Sinkhole. The high nitrates in the two wells suggest that they are the wells most affected by the poor-quality water at the sinking stream at Chiselhurst Sinkhole.

6. Synthesis

Sinking streams at Chiselhurst Sinkhole and Tuckersmith Sinkhole, and possibly at Upper Ausable Sink, deliver substantial quantities of surface water to the bedrock aquifer. This water will travel along conduits in a downgradient direction to springs. The general water table map of the area (Figure 3) and the water table map in the Lucas Formation (International Water Consultants, 2003, Figure 3.13) both indicate that the downgradient direction is westwards, towards Lake Huron. The distance from Upper Ausable Sink to Lake Huron is 27 km. Given expected velocities along the conduits to be in the kilometres per day range (Figure 1), it is likely that the travel time to springs below the surface of Lake Huron is just a few days. It is possible that the sinkholes and sinking streams are drained by single conduits, but it is equally possible that they are drained by anastomosing bands of a number of interconnected conduits.

The water level data at Chiselhurst and Tuckersmith Sinkholes show periodic flooding episodes where the water backs up in the sinkholes. The water-level record at the PGWM well, which is about 700 m northwest of the Chiselhurst Sinkhole, shows a seasonal variation of more than 10 m in water levels, with a maximum in March or April and a minimum in the fall between September (e.g. 2008) and December (e.g. 2007). This seasonal pattern reflects the seasonal water budget variation, where there is a water deficit in the growing season due to evapotranspiration and a water excess for the remainder of the year. In addition, some individual runoff events are reflected in water level changes at the PGMN well.

Table 4 shows the four largest recharge events at the Chiselhurst Sinkhole together with the response at the PGMN well. These four events had rises in water level of some 2 - 3 m at Chiselhurst Sinkhole (Figure 8) and the rise in water level took place over 15 - 23 hours (Table 4). At the PGMN well, there was a rise in water level of 2.69 m to 3.79 m and this occurred over a period of 101 hours to 165 hours. The large and rapid rise in aquifer water level reflects the dynamic nature of flow in the aquifer.

Table 4. Water level rises and time lags at the PGMN well for the four largest recharge events at the Chiselhurst Sinkhole

Chiselhurst Sinkhole			**PGMN well**			
	date / time	**time to peak**	**date/time**	**time of rise**	**water level**	**rise in water level**
start	10/03/2006 06 h		11/03/2006 10 h		204.02 m	
peak	10/03/2006 21 h	15 hours	15/03/2006 15 h	101 hours	207.17 m	3.15 m
start	01/04/2008 03 h		31/03/2008 08 h		208.10 m	
peak	01/04/2008 19 h	16 hours	05/04/2008 17 h	129 hours	211.03 m	2.93 m
start	27/12/2008 14 h		27/12/2008 15 h		210.68 m	
peak	28/12/2008 13 h	23 hours	01/01/2009 21 h	126 hours	213.37 m	2.69 m
start	11/02/2009 20 h		11/02/2009 19 h		207.77 m	
peak	12/02/2009 11 h	15 hours	18/02/2009 16 h	165 hours	211.48 m	3.79 m

The limited duration of flooding events at the sinkholes means that the radial outward spread of poor-quality sinking stream water is limited, probably to a distance of some hundreds of metres. On the other hand, this poor-quality water would move rapidly down the conduit(s) and probably reach springs in Lake Huron in a matter of days. Consequently, it is possible that wells many kilometres from the sinkholes could be affected by poor-quality water. The exact location of the conduits cannot be determined, but any wells in the Lucas Formation between the sinkholes and Lake Huron could be affected. However, the conduits and the aquifer close to them that is likely to be affected by poor-quality water probably only form a narrow band. Consequently, the probability of any single well being affected is very low. However, given the large distance between the sinkholes and Lake Huron, it is likely that there are some wells are affected by poor-quality sinking stream water.

7. Recommendations

A number of recommendations can be made, based on the data and above interpretation of flow in the aquifer.

1) The largest ingress of surface water to the bedrock aquifer may well be at the Upper Ausable Sink. The measurement of flow in the river upstream and downstream of the sink on a number of occasions including both low flow and high flow conditions would show the magnitude of water losses to the aquifer. Measurement of water quality would also be useful.

2) It would be useful to measure major ions (calcium, magnesium, sodium, potassium, sulphate, alkalinity, chloride) in the surface water entering Chiselhurst Sinkhole and Tuckersmith Sinkhole. Comparison could then be made with these parameters in groundwater samples. In addition, if there is found to be substantial recharge to the bedrock aquifer at Upper Ausable Sink, then this water should also be sampled for major ions.

3) There is a substantial set of water quality data from wells close to the sinkholes. Consideration should be given to modifying sites sampled, for instance by collecting data from Upper Ausable Sink if there is found to be substantial recharge at that location.

4) The water level record at Hensall Road well is intermittent because water level drops below the base of the well. It would be useful to deepen the well by at least several metres to ensure that continuous water level measurements can be made. Alternatively a new well could be drilled at this location..

5) It would be useful to measure electrical conductivity (EC) continuously at the PGMN well to better monitor short-term variations in aquifer water quality. Once the EC over several recharge events has been analyzed, it would be useful to collect water samples on a frequent basis (e.g. possibly daily for one week or twice weekly for one month) for one major recharge event at Chiselhurst Sinkhole. Analysis of the water quality in these samples would show how quickly and to how great an extent the poor-quality sinking stream water spreads to the PGMN well.

6) The installation of a vee - notch weir at Chiselhurst Sinkhole would give a continuous record of discharge into the sinkhole. This would facilitate calculations of the flux of poor-quality water into the aquifer.

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Appendices (on CD)

Excel files of the complete set of water level data
Excel files of hourly average of water level data
Excel files of the daily averages of water level data
Excel files of the complete set of surface water quality data
Excel files of the complete set of groundwater quality data
Corel Draw file of all figures

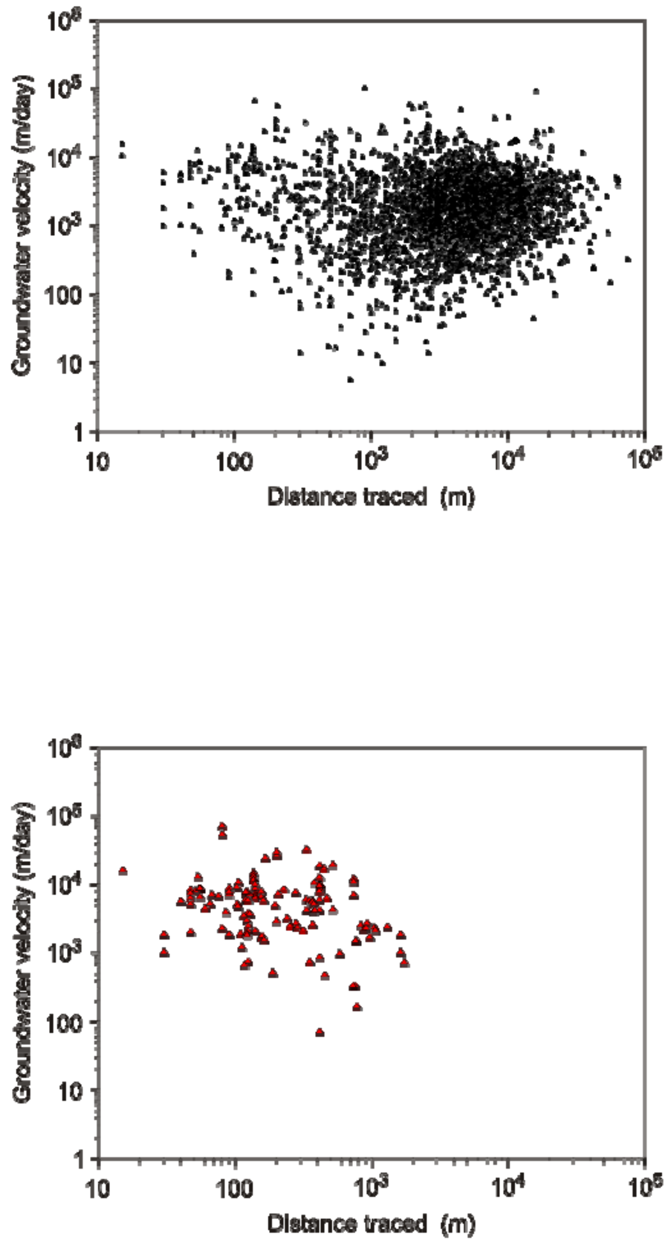


Figure 1 Groundwater velocities from tracer tests between sinking streams and springs in carbonate aquifers.
(a, top) data for 3015 tracer tests from 31 countries (after Worthington and Ford, 2009)
(b, bottom) data from 129 traces in southern Ontario carried out by S. Worthington

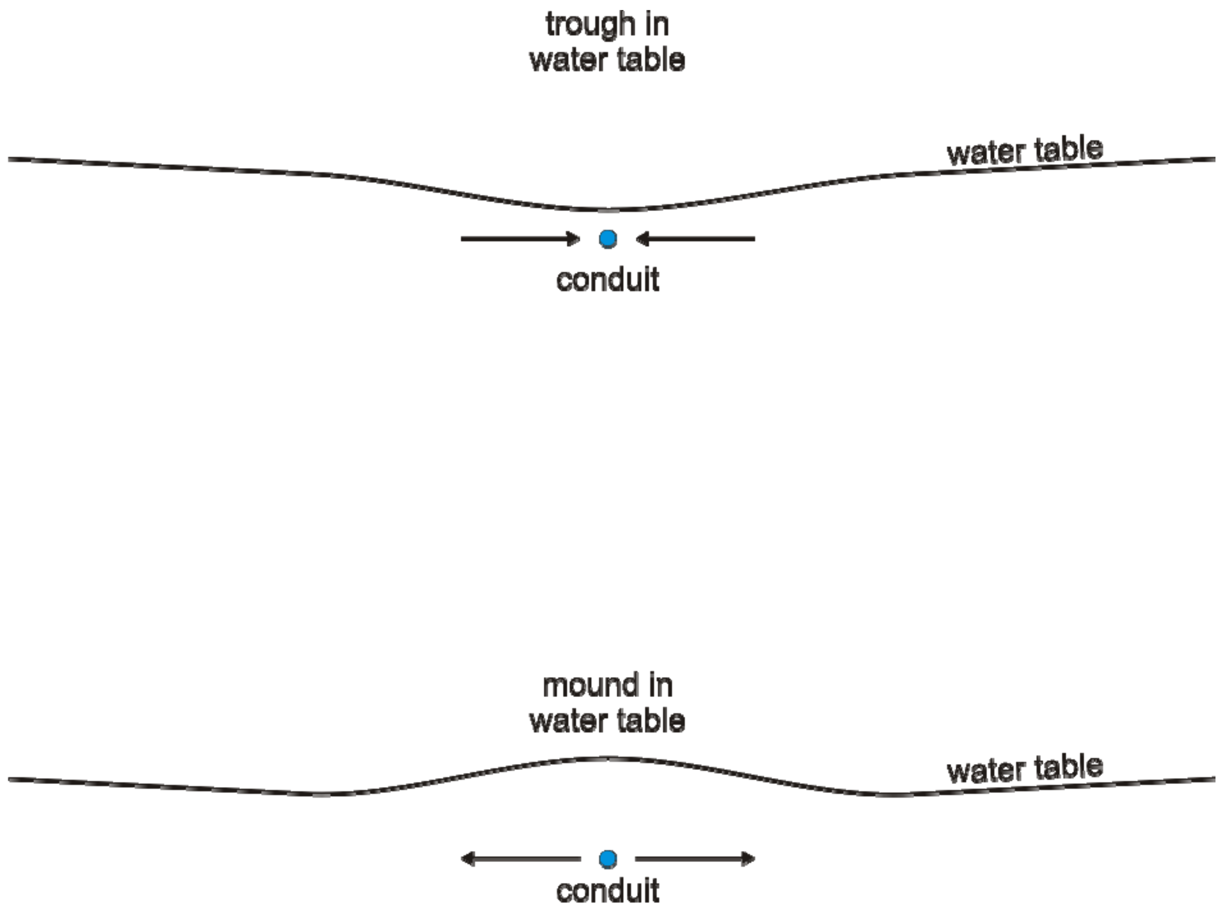
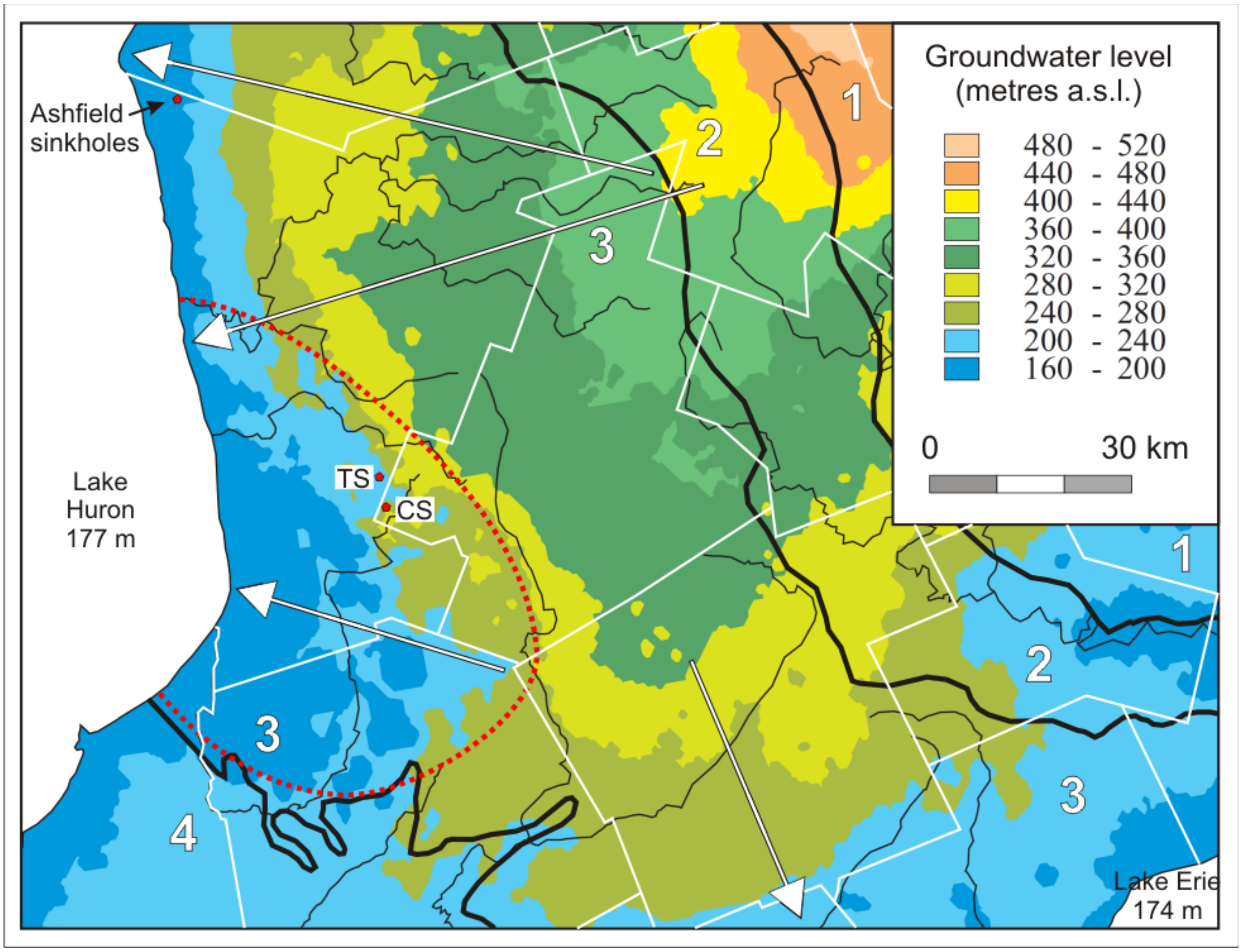


Figure 2 Water table conditions close to a conduit in a karst aquifer. In low-flow conditions (top), the head in the conduit is lower than in the surrounding aquifer. This results in flow towards the conduit and a trough in the water table coinciding with the location of the conduit. In high-flow conditions (bottom), there may be substantial rises in the head in the conduit so that water may flow outwards from the conduit into the surrounding bedrock.



Regional groundwater flow

Area with deep unsaturated zone

3 Hydrostratigraphic unit

TS Tuckersmith sinking stream

CS Chistlehurst sinking stream

Key to hydrostratigraphic units:
1: Decew to Guelph (carbonates)
2: Salina (evaporites, carbonates, shales)
3: Bass Islands to Dundee (carbonates)
4: Marcellus to Kettle Point (shales)

Figure 3. Water table map of Huron County and surrounding areas, showing hydrostratigraphic units, regional flow patterns, and the locations of the principal sinkhole areas (water table map after Singer et al., 2003)

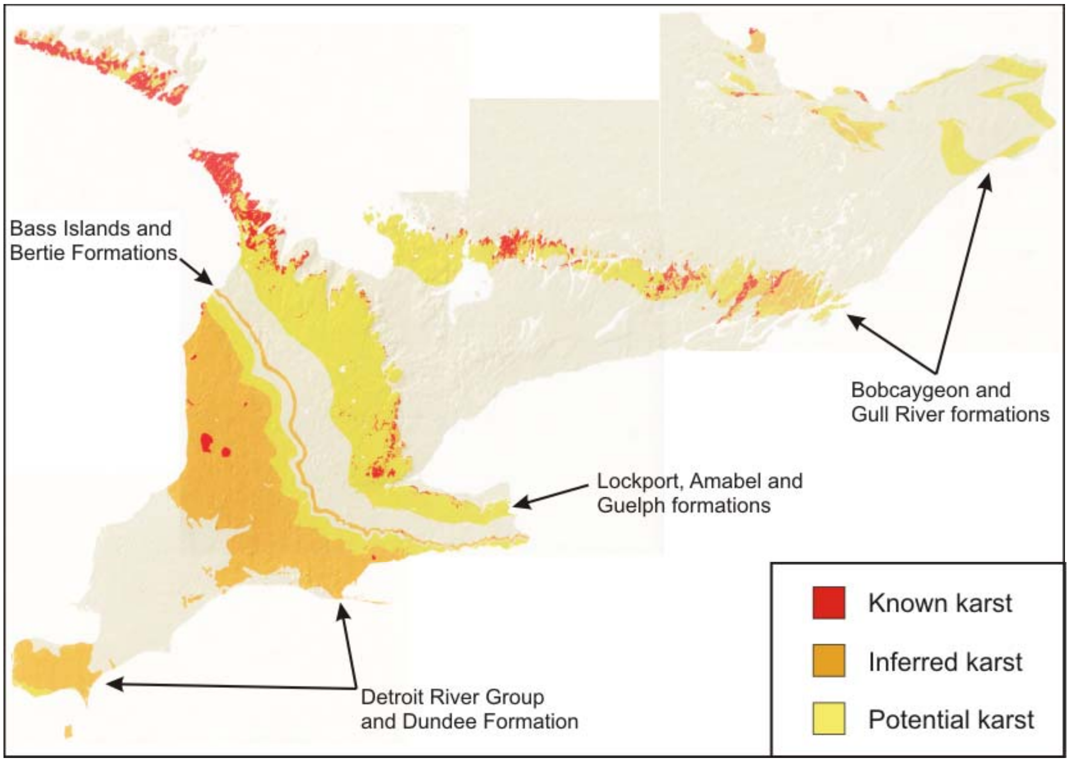
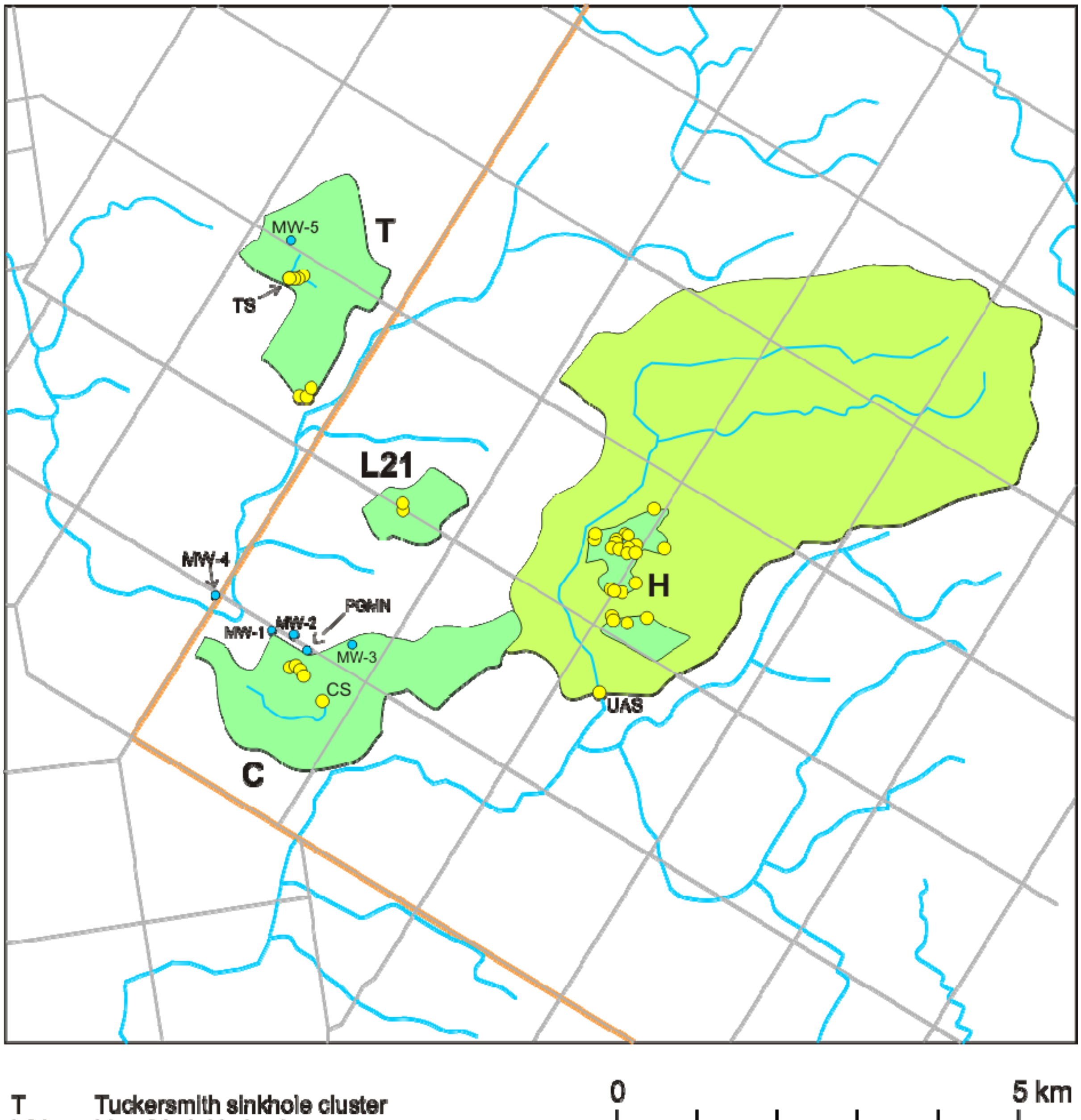


Figure 4. Karstified Paleozoic rocks in southern Ontario (after Brunton and Dodge, 2008)



T	Tuckersmith sinkhole cluster
L21	Line 21 sinkhole cluster
H	Hibbert sinkhole cluster
C	Chiselhurst sinkhole cluster
CS	Chisolhurst sinkholo
TS	Tuckersmith sinkhole
UAS	Upper Ausable Sink
PGMN	Provincial Groundwater Monitoring Network borehole

Areas of internal drainage in the sinkhole clusters

Area that drains to Upper Ausab e Sink

Figure 5 Area of sinkholes in southern Huron and western Perth counties

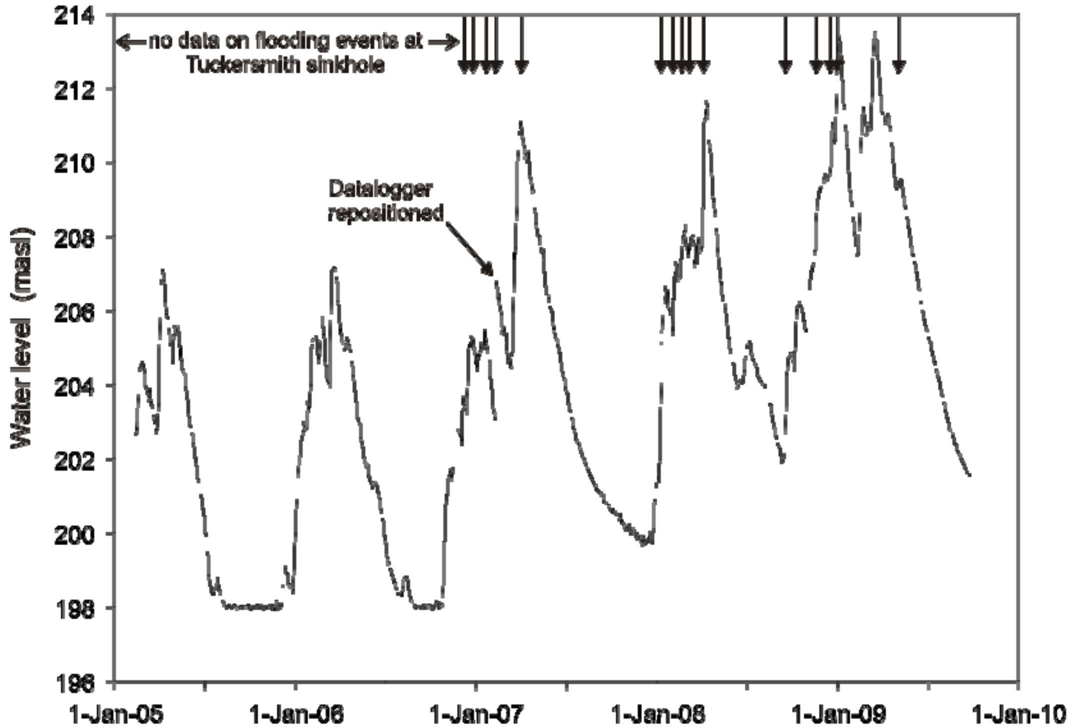


Figure 6 Average daily water levels at the PGMN Sinkhole Well. The vertical arrows indicate the peak of flooding events at Tuckersmith sinkhole where the water level rose at least 4 m above the transducer.

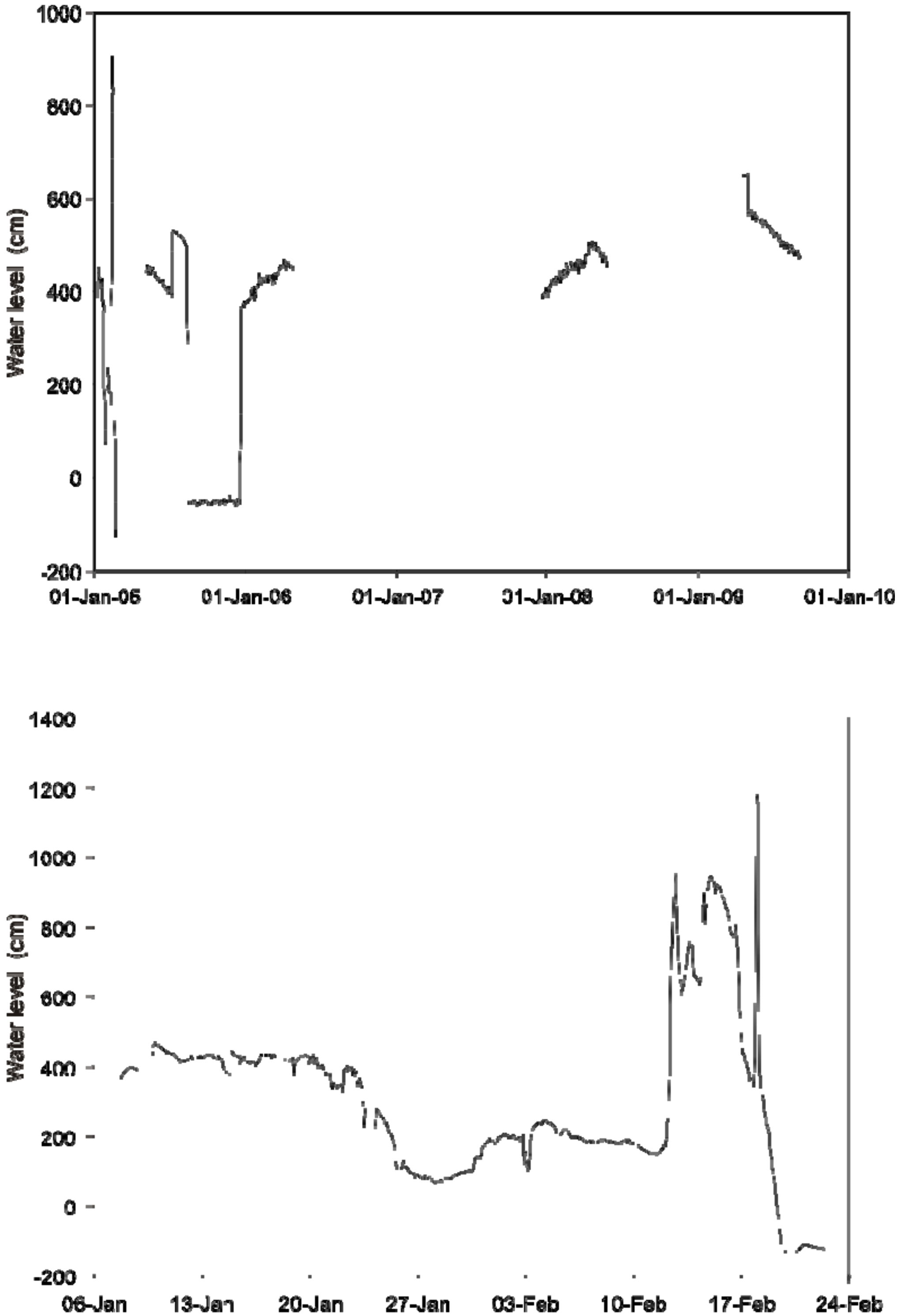
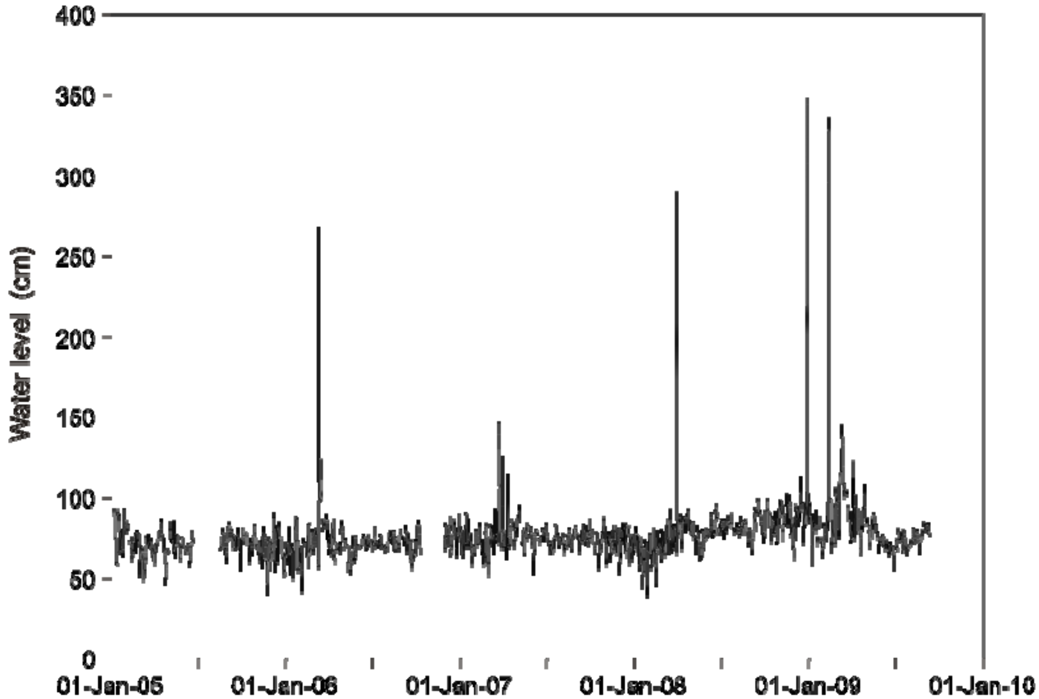


Figure 7 Water levels at the Hensall Road Well.
(a) average daily levels
(b) average hourly values in early 2005



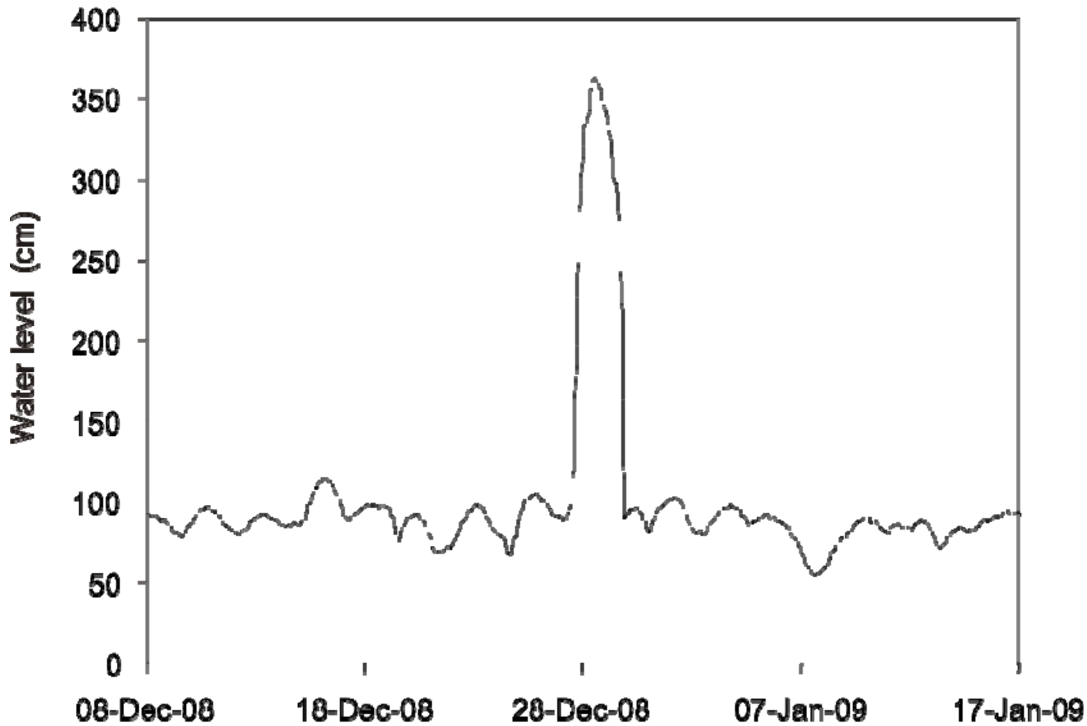


Figure 8 Water levels at Chiselhurst Sinkhole:
(a) average daily levels
(b) average hourly levels during a flooding events when the water level rose 2.5 m above the monitor

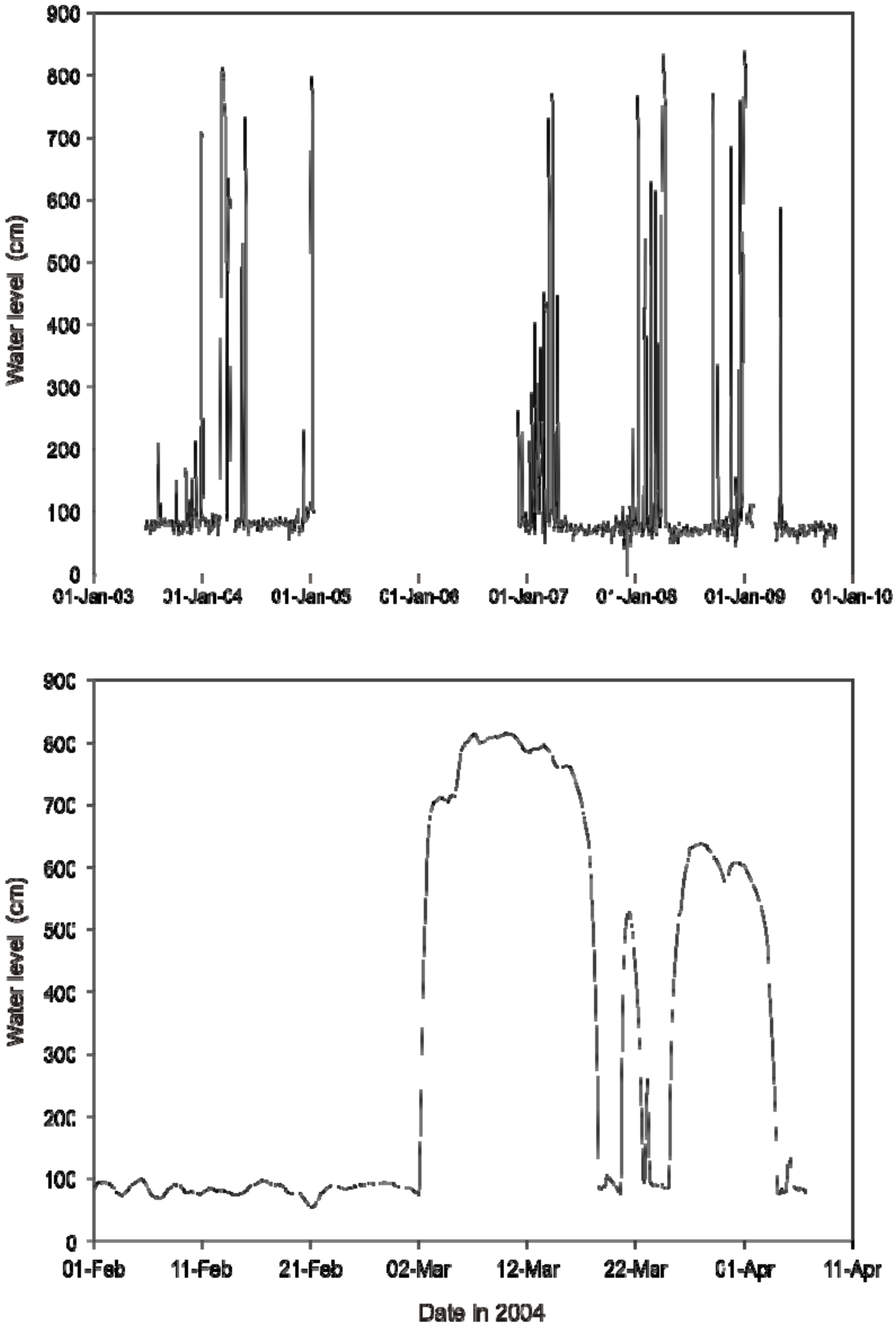


Figure 9 Water levels at Tuckersmith Sinkhole
(a) daily averages
(b) hourly averages during a series of flooding events when water levels rose up to 7 m above the monitor

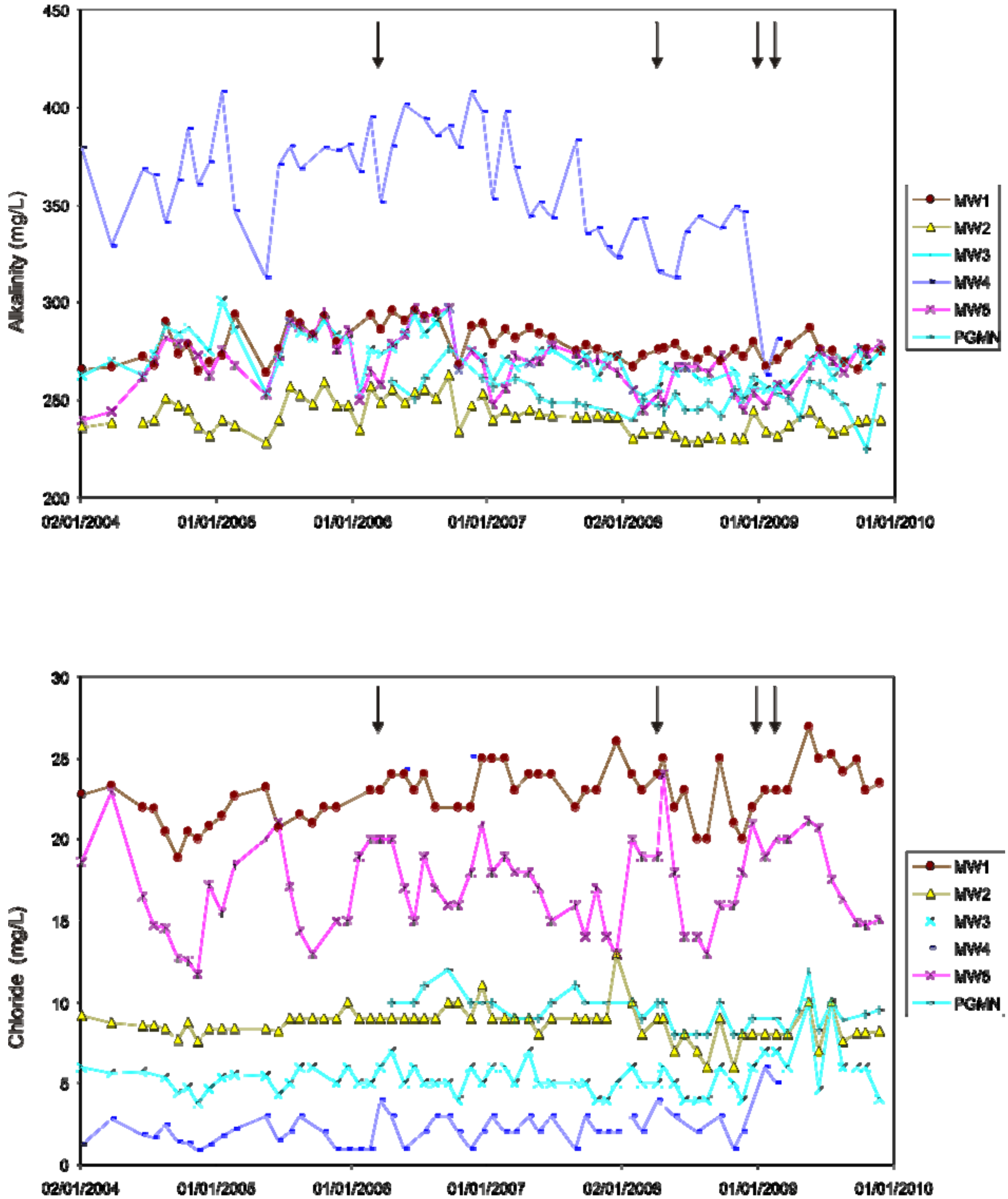


Figure 10 Major anion concentrations at the six sampled boreholes: alkalinity (top) and chloride (bottom). The vertical arrows indicate the peak of flooding events at Chiselhurst sinkhole where the water level rose at least 1 m above the transducer.

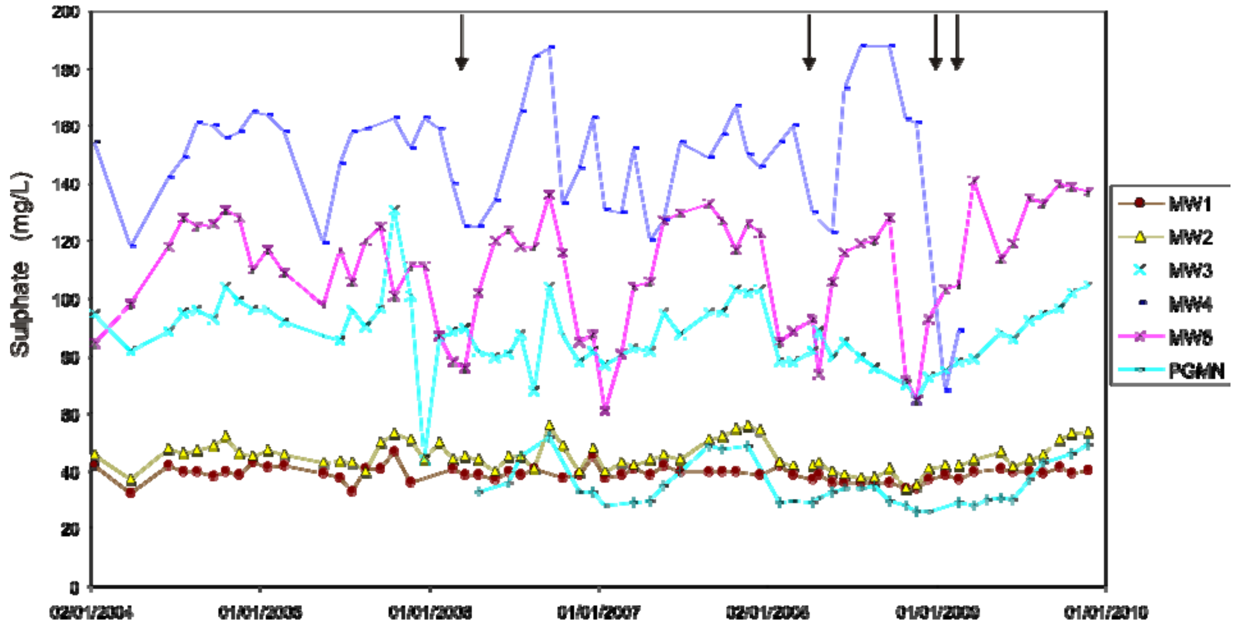
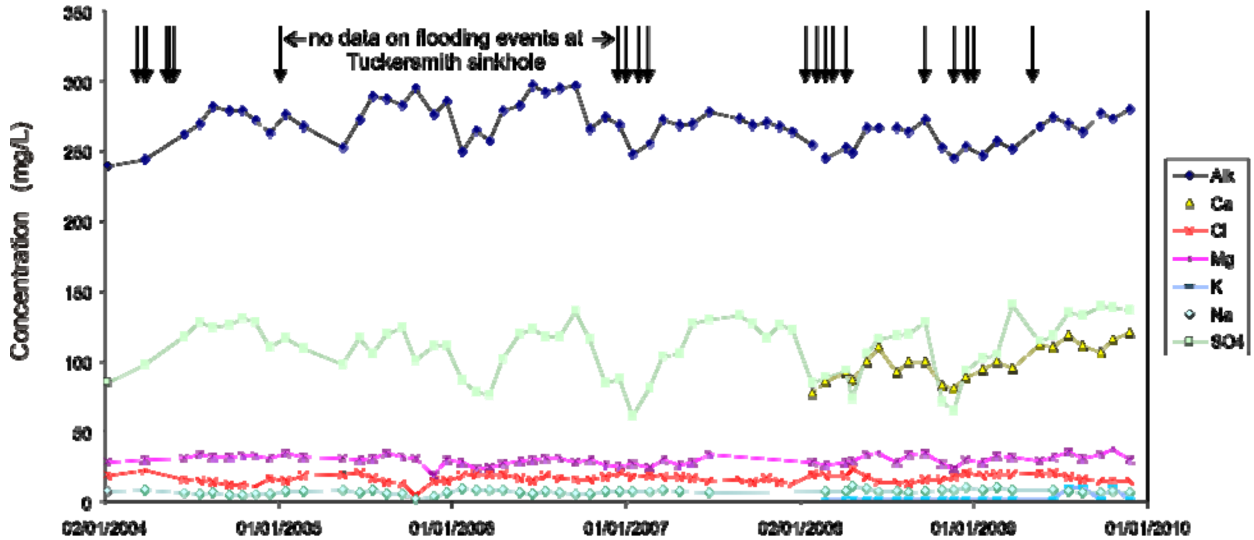


Figure 11 Major anion concentrations at the six sampled boreholes: sulphate. The vertical arrows indicate the peak of flooding events at Chiselhurst sinkhole where the water level rose at least 1 m above the transducer.



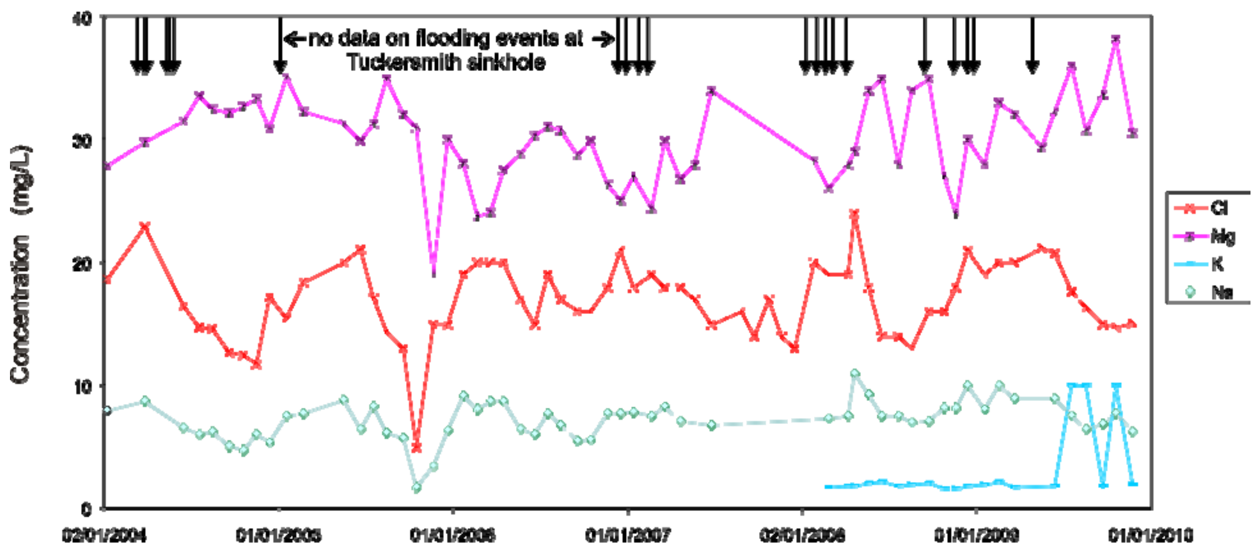


Figure 12 Major ions at MW5 between 2004 and 2009. The lower figure has an expanded scale to show the four ions with lowest concentrations. The vertical arrows indicate the peak of flooding events at Tuckersmith sinkhole where the water level rose at least 4 m above the transducer.