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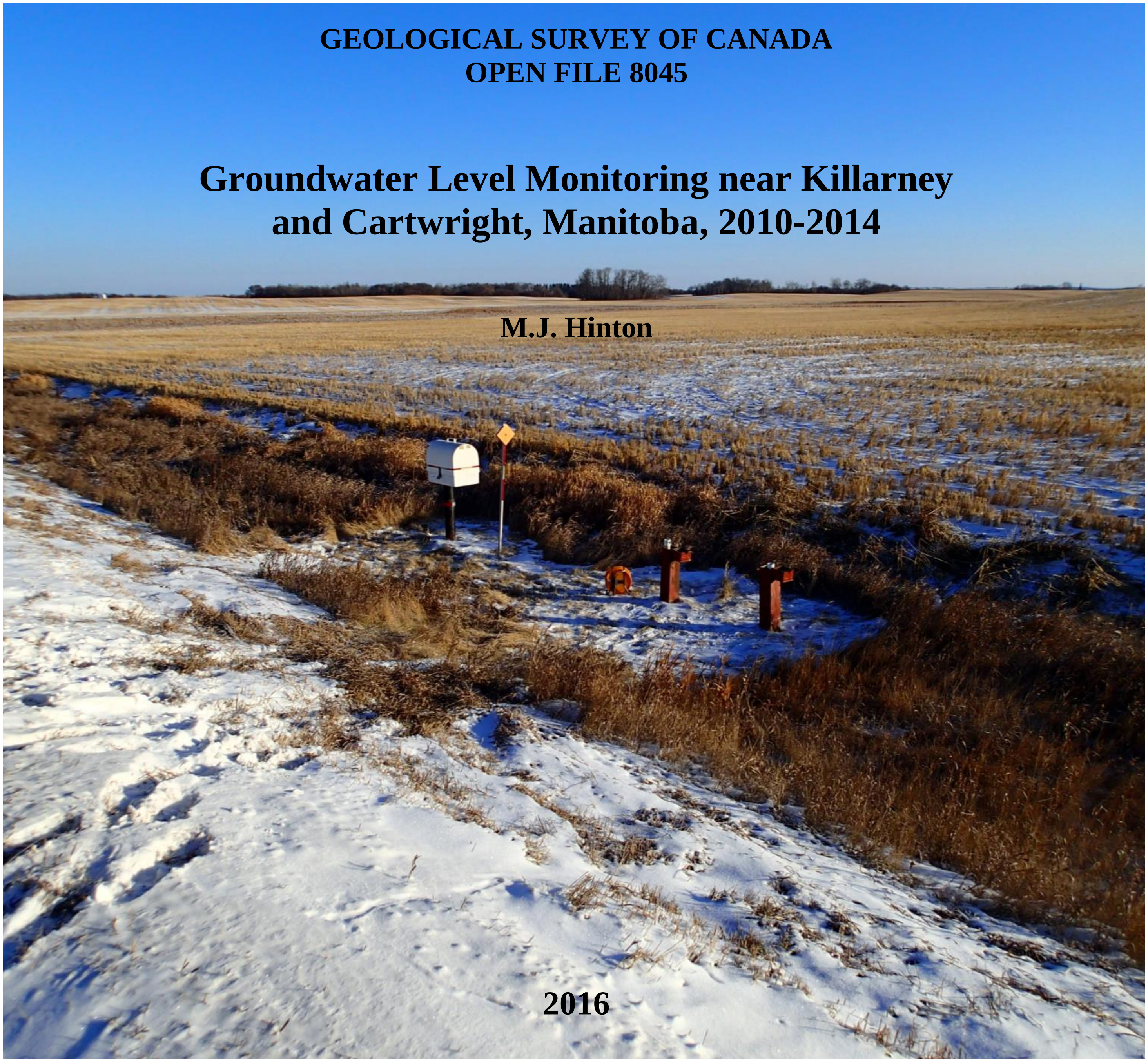

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8045

Groundwater Level Monitoring near Killarney and Cartwright, Manitoba, 2010-2014

M.J. Hinton

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Canada

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Cover photo: Site GSC-SW-02 showing Manitoba Conservation and Water Stewardship monitoring well G05OA010 (left) and GSC piezometers GSC-SW-02-p2 (center), and GSC-SW-02-p1 (right). Photo: Geological Survey of Canada, 26 November 2014, facing northeast.

Abstract

The Geological Survey of Canada (GSC) is investigating the hydrogeology of the Spiritwood buried valley aquifer in southwestern Manitoba as part of its Groundwater Geosciences Program. This Open File Report presents hourly groundwater level and temperature data collected between November 2010 and November 2014 from eight piezometers installed by the GSC at four sites located near Killarney and Cartwright, Manitoba.

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1. Introduction

The Geological Survey of Canada (GSC) is investigating the hydrogeology of the Spiritwood buried valley aquifer system in southwestern Manitoba as part of its Groundwater Geosciences Program. The Spiritwood buried valley aquifer is a cross-border aquifer extending from Manitoba, through North Dakota and into South Dakota (Figure 1). This aquifer has been studied extensively in North Dakota but is less known in Manitoba. The Water Resources Branch of Manitoba Natural Resources (currently Water Science and Management Branch of Manitoba Conservation and Water Stewardship, CWS) had previously drilled boreholes in the study area in 1974 and again in 2000-02. Eight of these monitoring wells along the Spiritwood buried valley aquifer between Margaret and the international border south of Cartwright, Manitoba, are currently being monitored by CWS (Figure 2). Most of these monitoring wells are screened at depth in confined units; interpretation of their water level fluctuations became problematic since there are no records of groundwater level response near the ground surface and at intermediate depths. A drilling program was undertaken in November 2010 to install six piezometers at three sites with active CWS monitoring wells along the Spiritwood buried valley aquifer system (Hinton and Sharpe, 2014). One shallow and one deep piezometer were also installed near the international border south of Cartwright, Manitoba, in March 2011 (Crow et al., 2012). The purpose of this GSC Open File is to present the methods and results of groundwater level monitoring in eight GSC piezometers up to November 2014. Results were compiled in Microsoft Excel spreadsheets, included as digital files in this Open File.

2. Methods

2.1 Piezometer locations

The GSC monitored eight piezometers at four sites (Figure 3). At the three sites with MCWS wells (GSC-SW-02, -03, and -04), the goal was to provide water level data from shallow to intermediate depths (Hinton and Sharpe, 2014) to complement data collected from Manitoba CWS monitoring wells and improve hydrogeological interpretations. At the fourth site, GSC-SW-07, a deep piezometer was installed in a cored borehole to monitor water levels in the Spiritwood buried valley aquifer along with a near-surface piezometer to monitor the water table at this site(Crow et al., 2012). Piezometer locations were initially determined in October 2011 using a Trimble Pathfinder ProXT GPS receiver with an integrated SBAS (Satellite Based Augmentation Systems) to provide approximately 2 to 5 meter horizontal accuracy. These locations were reported in Crow et al (2012) and Hinton and Sharpe (2014). Subsequent GPS surveying of the piezometers by Manitoba Conservation and Water Stewardship (CWS) measured vertical elevations relative to three stations from Manitoba's Primary Control network, which used the CGVD28 vertical datum and also provided new, yet similar, UTM coordinates (Table 1).

2.2 Piezometer installations

Complete descriptions of drilling and piezometer installations were presented in Crow et al (2012) and Hinton and Sharpe (2014). Piezometers at sites GSC-SW-02, -03 and -04 were installed in cased boreholes drilled by cable tool in November, 2010 (Hinton and Sharpe, 2014). Piezometers at site GSC-SW-07 were installed in Sonic (i.e. with vibration) drilled boreholes in March 2011 (Crow et al., 2012). Piezometer construction information is summarized in Table 2. Piezometers were developed by manual pumping with an inertial pump (i.e. a Waterra foot valve) fitted with a surge block. The exception was GSC-SW-07-p2, which was developed by air-lift pumping. Development was performed prior to pressure transducer installation with the exception of GSC-SW-07-p1, which was developed on October 15th, 2011 (Table 3). Piezometers have been slug and/or bail tested but the results have not yet been reported.

2.3 Instrumentation

2.3.1 Pressure transducers and temperature sensors

Groundwater levels in each piezometer were monitored using Solinst Levelogger Gold (M10) pressure transducers. These are non-vented transducers measuring total pressure (i.e. including barometric pressure) up to 10 m. Solinst Gold Barologgers were used at each site to measure barometric pressure which was subtracted from Levelogger readings. Barologgers were deployed at each site above the water table within the PVC piezometer casing to minimize temperature variations that could affect pressure measurements. By factory default, 9.5 m equivalent of pressure is subtracted from Levelogger and Barologger readings, such that a true air pressure of 10.2 m water equivalent would be recorded as 0.7 m (10.2 – 9.5 m) at sea level. Since this offset is subtracted from both Levelogger and Barologger measurements, no correction is needed to calculate water levels. An additional pressure offset, calculated based on altitude, can be programmed into loggers. Leveloggers and Barologgers were programmed to the same altitude at each site to ensure that no altitudinal pressure corrections were required. Readings were measured and recorded hourly in Central Standard Time (i.e. Daylight Savings Time was not used). Leveloggers have a reported accuracy of 0.05% full scale (0.5 cm) and a resolution of 0.0006% full scale (0.006 cm) (Solinst Canada Ltd., 2011). Barologgers also have a reported accuracy of 0.05% full scale (0.1 cm) and a resolution of 0.02% full scale (0.003 cm) (Solinst Canada Ltd., 2011). In practice however, individual water level readings can be in error by several centimeters due to: i) a systematic difference in level (i.e. pressure) readings between the Levelogger and Barologger, ii) a gradual drift in sensor readings over time in some loggers, iii) possible errors in the logger measurement depth, and iv) possible surveying elevation errors (for groundwater elevations). These errors are either systematic (errors i, iii and iv) or generally change slowly with time (ii) so that the magnitudes of the short-term fluctuations are likely accurate, whereas the gradients calculated between two piezometers could be in error if the water level differences between them are small.

Leveloggers and Barologgers were deployed using 1/16″ stainless steel aircraft cable (Powerstrand 7×7 Type 304 aircraft cable by Wesco Industries Ltd.) secured by a loop at the end of the cable, fastened with two aluminum crimps. Unfortunately, some of the submerged aluminum crimps began to dissolve and, in one instance (GSC-SW-03-p1), they failed as the logger was being removed and the logger sank to the bottom of the piezometer. The Levelogger was recovered and aluminum crimps were subsequently replaced with stainless steel crimps. The top of the cable was secured either onto an eye bolt attached to the casing or through a hole drilled through the casing. For piezometer GSC-SW-07-p1, the upper end of the cable was secured onto the well cap. Levelogger depths were recorded *in situ* by temporarily taping the Levelogger to the weighted end of a stainless steel Solinst Tag Line (Model 103).

Leveloggers and Barologgers also included a platinum resistance temperature sensor for internal temperature compensation of the pressure measurements. Therefore, Leveloggers also recorded water temperature at the depth of deployment. Temperature measurements have a reported accuracy of 0.05°C and a resolution of 0.003°C (Solinst Canada Ltd., 2011).

2.3.2 Packer in GSC-SW-07-p2

When GSC-SW-07-p2 was initially drilled, the water level was near ground surface and there was some concern that freezing of the water in the well might occur and could damage the integrity of the PVC casing. Therefore, a 3.12 m long packer was custom built (Well Busters, Belleville, ON) for this monitoring well and was installed in October 2011 (photograph A6). The packer included a Solinst Direct Read cable (a cable connected directly to the Levelogger, allowing it to be read *in situ* from the surface) installed through the middle to allow a Levelogger to be deployed below the packer and controlled by computer from the cable connection above ground surface. The packer leaked slightly along the Direct Read cable during its first deployment and was re-caulked in October 2012 without any subsequent leaking.

2.4 Site visits

Pressure transducers were installed into piezometers as summarized in Table 3. Data was downloaded manually during site visits in October 2011, 2012, 2013, and November 2014. Data loggers remain deployed as of March 2016 and were last visited in November 2014. Water levels were also measured manually during site visits using Solinst Model 101 or Model 102 water level tapes (Tables 4-7). Site visits also included well development, slug/bail testing, water sampling and the deployment and downloading of soil moisture sensor data. These data are not reported in this Open File.

2.5 Data compilation

Data were retrieved using Levelogger Software (versions 3 or 4) and saved in both comma separated variable (*.CSV) and Solinst (*.XLE or *.lev) formats. Data were compiled and graphed in Microsoft Excel spreadsheets, which are included as part of this Open File. Each data logger download was imported into an Excel spreadsheet, in which barometric pressures were subtracted and water levels were calculated as: depth above the Levelogger; depth below the top of casing; depth below ground surface; and elevation above sea level. All data for each piezometer were compiled into a single spreadsheet and graphed. Spreadsheets also include manual data and information on each deployment of data loggers.

Piezometer GSC-SW-07-p2 showed a strong delayed response to barometric pressure fluctuations so they were corrected with Kansas Geological Survey barometric response function software (Bohling et al., 2011) based on the method discussed by Butler et al. (2011) and Stotler et al. (2011). Barometric response functions were calculated for 12 time lags (12 hours) with no earth tide corrections.

Manual water level data were only used to correct transducer water level data when there were significant errors in the resulting water level data, likely due to transducer drift. Transducer drift was apparent when both a Levelogger and Barologger at a site were both measuring air pressure simultaneously and there was a significant difference between them. This comparison was done when a Levelogger was removed from the piezometer for download or during testing or sampling of a piezometer. The value of comparing simultaneous Levelogger and Barologger measurements in air was demonstrated for Leveloggers in piezometers GSC-SW-02-p1 and GSC-SW-04-p1 when the water levels were drawn down below the Levelogger during bail testing in October 2012 and there was a significant difference between the Levelogger and Barologger readings. At these sites, Levelogger measurements were corrected to manual measurements and the corrections were interpolated between manual measurements.

The Barologger deployed within piezometer GSC-SW-07-p1 became flooded during spring melt in 2011 and, therefore, recorded both atmospheric pressure and an additional water pressure. The hourly station pressure at the Environment Canada Brandon weather station (Station ID 5010480) was highly correlated with the Barologger readings ($r^2 = 0.99$) and was, therefore, used for barometric correction of GSC-SW-07-p1 from 12 April to 30 June 2011.

3. Results and Discussion

3.1 Groundwater levels

3.1.1 GSC-SW-02

The monitoring record was longest (4 full years) at this site as it was the only site instrumented in November 2010. This site was located within a gentle ditch along an unpaved road (see photograph A1 in Appendix 1) and was probably subjected to temporary surface ponding as noted by above-ground water levels in GSC-SW-02-p1 during spring melt in 2011, 2013, and 2014 (Figure 4).

Piezometer GSC-SW-02-p1 took several months to recover after bail testing and water sampling in October 2012, in contrast to complete recovery within hours after development in October 2010 and slug testing in November 2014. It also responded relatively rapidly to individual storm or melt events (Figures 4 and 5). This delayed response could represent gradual aquifer recovery which followed localized dewatering rather than a slow well response due to low permeability.

Groundwater level fluctuations in GSC-SW-02-p1 showed a strongly seasonal pattern with the largest water level increases in response to spring melt and subsequent rainfall events. Water levels generally declined from late summer to spring, but were sometimes interrupted by a response to a large storm.

GSC-SW-02-p2 had a similar seasonal pattern although the response to spring melt was smaller and more delayed and there was seldom a response to late summer and autumn rainstorms (Figures 6 and 7). The initial water level rise in October 2011 was the recovery from well development.

The relative water elevations of the two piezometers indicated some reversals of hydraulic gradients (Figure 8). When water levels were highest during and following spring melt, groundwater was recharging and flow was downward. As the water table declined, it sometimes declined more rapidly in GSC-SW-02-p1 than in GSC-SW-02-p2 resulting in a reversal of vertical hydraulic gradients.

3.1.2 GSC-SW-03

Piezometer GSC-SW-03-p1 also showed a strongly seasonal pattern of water level fluctuations related to surface recharge with the largest increases following spring melt and large summer or autumn rainfall events (Figures 9 and 10). Water levels generally declined during winter. Following a relatively dry year in 2012, a very large increase in water levels was recorded in spring 2013.

A pattern that was observed for all shallow piezometers, but was most noticeable for piezometer GSC-SW-03-p1, was that water levels were more responsive to individual events when water levels were close to ground surface. Water level responses to individual storms were either nil or very small in 2011 and 2012 when water levels were deeper than 1.6 m, whereas responses were large and rapid when water levels were above approximately 1.5 m depth in 2013 and 2014 (Figure 9).

The response of deeper piezometer GSC-SW-03-p2 was very different from that of overlying piezometer GSC-SW-03–p1. The annual peak water level was greatly delayed by almost a year and occurred around March prior to spring melt (Figures 11 and 12). Whereas water levels in GSC-SW-03-p1 were generally declining during 2011 and 2012 and increased greatly in 2013 and 2014 (Figures 8 and 9), the entire period of monitoring showed a decreasing trend in water levels in piezometer GSC-SW-03-p2 (Figures 11 and 12). These results suggest that there is a distinct hydrogeological barrier between 3 and 33 m depth and that the water levels in piezometer GSC-SW-03-p2 could have responded to water level fluctuations on a different time scale than GSC-SW-03-p1 and at a greater spatial scale than the GSC-SW-03 site (Figure 13).

The low water levels recorded in piezometer GSC-SW-03-p2 during October 2012 were the result of a bail test and water sampling (Figures 11 and 12). The rapid fluctuations in July 2013 and June and July 2014 could have resulted from sudden barometric changes, possibly combined with rainfall infiltration.

Water levels in GSC-SW-03-p1 were consistently above those in GSC-SW-03-p2, indicating that there was sustained downward groundwater flow at this site (Figure 13).

3.1.3 GSC-SW-04

As this site is located on a small hill, it had the deepest water table and deepest evidence of oxidation among the GSC sites. The water level fluctuations in GSC-SW-04-p1 (Figures 14 and 15) were similar to those in GSC-SW-03-p1 with large responses to spring melt and some storm events, suggesting that specific yields were low, possibly due to fracturing within the till as observed in the drill core (Hinton and Sharpe, 2014). Water level records included recovery from both well development in October 2011 and bail testing in October 2012 (Figures 14 and 15).

Water levels in GSC-SW-04-p2 (Figures 16 and 17) showed a similar seasonal pattern to those in GSC-SW-04-p1 with a delay on the order of a month (Figure 18). However, they did not show individual responses to storms, but rather a more gradual response, demonstrating the combined influence of several infiltration events. The water levels in GSC-SW-04-p1 were consistently above those in GSC-SW-04-p2 by more than 3 m, indicating that there was sustained downward groundwater flow at this site (Figure 18).

3.1.4 GSC-SW-07

Water levels in piezometer GSC-SW-07-p1 responded to both spring melt and autumn rain in each of the four years of monitoring with the spring melt showing the largest response (Figures 19 and 20). The site's position within the swale/ditch along the roadside could have led to enhanced recharge due to snow accumulation and runoff from the road (see Photographs A7-A10). The response during spring 2011 was particularly large and likely produced a temporary water table within the snow pack and standing water in the swale as water levels were up to 53 cm above ground surface (Figure 19). It is possible that drilling mud deposited within the swale could have contributed to these high water levels.

Short-term water level fluctuations, on the order of 5 cm magnitude, were observed in piezometer GSC-SW-07-p2 and were due to changes in barometric pressure since the piezometer was screened in a deep, confined aquifer and barometric pressure was not immediately transmitted through the packer (blue line, Figures 21 and 22). Correction of the barometric effects was performed with Kansas Geological Survey barometric response function software (Bohling et al., 2011). The average barometric response function value was -0.745. Barometric corrections averaged 1.5 cm and were no larger than 7.5 cm. The resulting corrected hydrograph shows more gradual changes in hydraulic head (red line, Figures 21 and 22).

The water-level recovery in GSC-SW-07-p2 after pumping in October 2012 is difficult to interpret. It apparently was not a slow hydraulic recovery from pumping, because bail testing of this piezometer repeatedly demonstrated > 97% recovery in 3 minutes. Rather, it may have been an indirect effect of pumping. Although the water pressure in GSC-SW-07-p2 is expected to have recovered within minutes after pumping, it is hypothesized that the observed water level decrease after pumping and its gradual recovery over months may have been caused by an increase in the water's density due to turbidity in the long water column between the screened interval of the piezometer and the Levelogger. This is demonstrated by the equation, $P = \rho g h$, where P is pressure, ρ is water density, g is the gravitational constant and h is the height of water. Therefore, even though P should rapidly return to its pre-pumping value, the increased density due to turbidity would result in a decrease in the height of water (i.e. water level). Because the Levelogger was deployed at a depth of only 2.4 m and most of the turbid or dense water was below this depth, the Levelogger should record a drop in water pressure and level. Then, the slow settling of fine sediment from the water column over about two to three months gradually lowered the water density and allowed water levels to recover. However, the difficulty with this hypothesis is that the observed 1.02 m drop in water level would require a turbid water density of 1.011 g/cm^3 which would require a high sediment concentration. A simple way to test this would be to deploy another pressure transducer within the screened interval and pump the piezometer again. If, following a short pumping recovery, the shallow pressure transducer records a decrease in water pressure (level) whereas the deeper one in the screened interval does not, then the density of the water within the casing would have increased. Similarly, measuring the change in pressure with depth in the turbid water column could also be used to test this hypothesis.

Except for the recovery following pumping, piezometer GSC-SW-07-p2 fluctuated over a small range of water levels (Figures 21 and 22). The large seasonal responses in shallow piezometer GSC-SW-07-p1 were not observed in deep piezometer GSC-SW-07-p2 where increases from spring melt were much smaller and delayed (Figure 23). Whereas winters were extended periods of steady water level decline in GSC-SW-07-p1, water levels in GSC-SW-07-p2 were stable or gradually increasing at these times. Although the two piezometers are screened too widely apart to interpret vertical gradients meaningfully, the water levels in GSC-SW-07-p2 are generally above those in GSC-SW-07-p1 except following significant recharge events such as spring melt (Figure 23).

3.2 Groundwater temperatures

Graphs of groundwater temperatures are presented for each piezometer in Figures 24 to 31 and plotted with groundwater depths in Figures 32 to 39. At shallow depths (2.5 - 4.4 m) in piezometers GSC-SW-02-p1, GSC-SW-03-p1, GSC-SW-07-p1 and GSC-SW-07-p2, temperature fluctuations were larger (6.2°C < ΔT <6.9°C) and showed a seasonal pattern with minimum temperatures after the start of spring melt (typically April-May) and maximum temperatures in late summer (typically September). At greater depths (8.2 – 8.3 m) in piezometers GSC-SW-02-p2 and GSC-SW-03-p2, the temperature fluctuations were smaller (ΔT <1.7°C) and delayed with minimum temperatures typically occurring in late July and maximum temperatures in December or January (Figures 25 and 27). Although temperatures in GSC-SW-04-p1 were recorded at a similar depth of 7.3 m and had a similar range (ΔT = 1.9°C), they showed distinct short term responses to the infiltration of spring melt, possibly as a result of lower water storage above the water table and more rapid infiltration through fractures (Figures 28 and 36). The deepest temperature record, at GSC-SW-04-p2 (13.2 m depth), had the smallest range of 0.32 °C and the greatest delay with minimum temperatures in September or October and maximum temperatures in April.

Average groundwater temperatures for each piezometer ranged from 5.5 to 7.4°C (Table 8). These values were considerably higher than the 1961-1990 air temperature normals of nearby weather stations, which range from 1.8°C in Brandon to 3.6°C in Morden. Warmer groundwater temperatures could have resulted from ground insulation provided by the snowpack during the coldest months.

4. Implications and Conclusions

Water table increases at each of the sites were greatest in response to spring melt, which was the main annual recharge event. Although the water table rose by approximately 0.5 to 3.5 m during spring melt, given the low runoff and estimated recharge values, it is likely that specific yields were low and flow in fractures may have been significant. Rapid and reasonably large water level responses to rainstorms also support the hypothesis that fracture flow was significant. These results were also consistent with observations of oxidation in cores to depths of approximately 3-8 m.

Groundwater recharge in the study area was considered to be low as Water Survey of Canada stream gauging stations indicated total runoff (i.e. surface runoff and groundwater discharge) to range between 22-68 mm/year (note that 10 of 12 stations only operated from March to October as they go dry in the autumn-winter) with most of the flow occurring as surface runoff during spring melt. The two stations with annual records had winter baseflow values averaging 1 mm/year. This low baseflow appeared to contradict the water table responses that suggested higher recharge rates even if specific yields were low. However, it is possible that groundwater recharge was greater than suggested by winter baseflow if recharge from spring melt were rapidly discharged through shallow fracture systems in localized flow systems. Similarly, some groundwater recharge may have been discharged from the subsurface as evapotranspiration and would not have been reported as stream runoff. Furthermore, the position of the GSC piezometers within the roadside ditches or swales could have resulted in higher localized recharge rates due to the redistribution of snow and overland flow into the ditches.

Deeper groundwater level responses were considerably delayed and muted, indicating that there were barriers to vertical groundwater flow, even within the upper 33 m of till. Shallow and intermediate GSC piezometer data will allow for better interpretation of groundwater level responses in the deeper Manitoba CWS monitoring wells and, along with data from piezometer GSC-SW-07-p2, will contribute to improved understanding of groundwater dynamics in the Spiritwood buried valley aquifer system in southwestern Manitoba.

5. Acknowledgments

This work was conducted within the Groundwater Geoscience Program of Natural Resources Canada (NRCan). Charles Logan and Angus Calderhead are thanked for their assistance in the field. Charles Logan also produced Figure 1. Useful review comments of this Open File by Nicolas Benoit and Sam Alpay are greatly appreciated. Manitoba Conservation and Water Stewardship are gratefully acknowledged for providing in-kind support by surveying the GSC piezometers.

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Figures

Figure 1. Regional map of the approximate extent of the Spiritwood buried valley aquifer system.

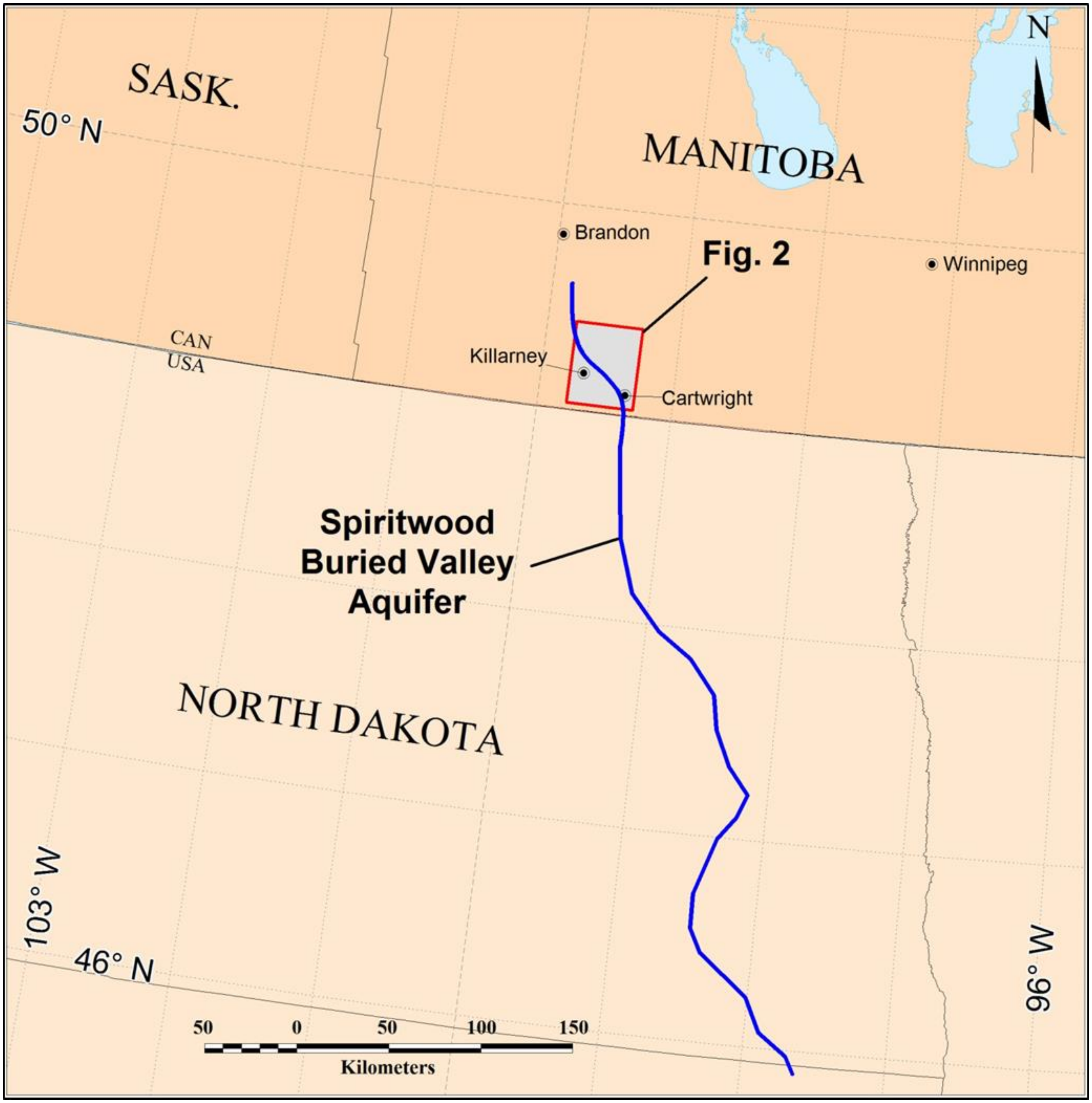


Figure 2. Satellite image (source: Google Earth, accessed 12 April 2016) showing the locations of the nine active MCWS monitoring wells in the study area. Monitoring well G05OA007 is constructed in shale bedrock and is located outside the Spiritwood buried valley.

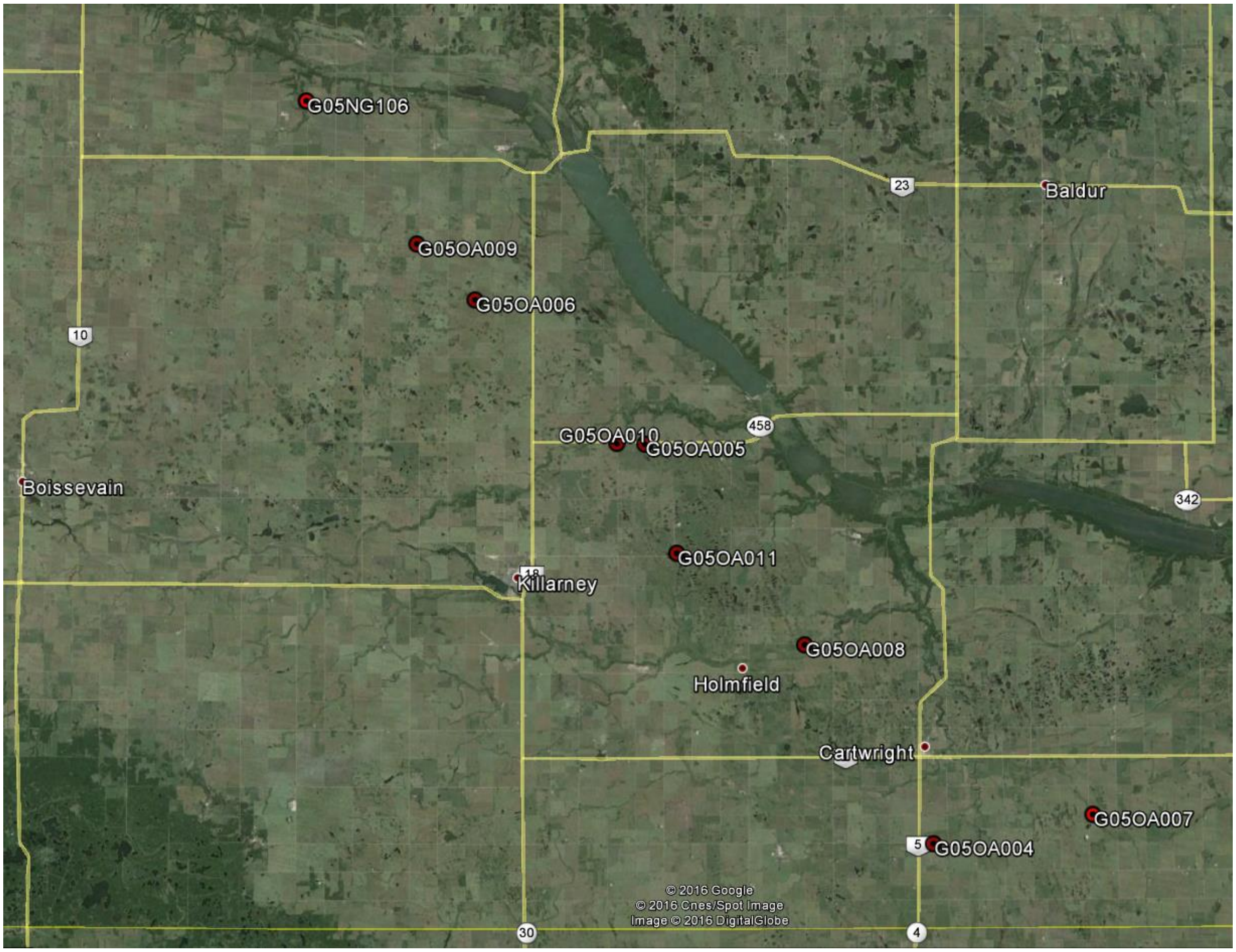


Figure 3. Satellite image (source: Google Earth, accessed 23 February 2016) of the four piezometer sites. There were two piezometers (-p1 and –p2) at each site.

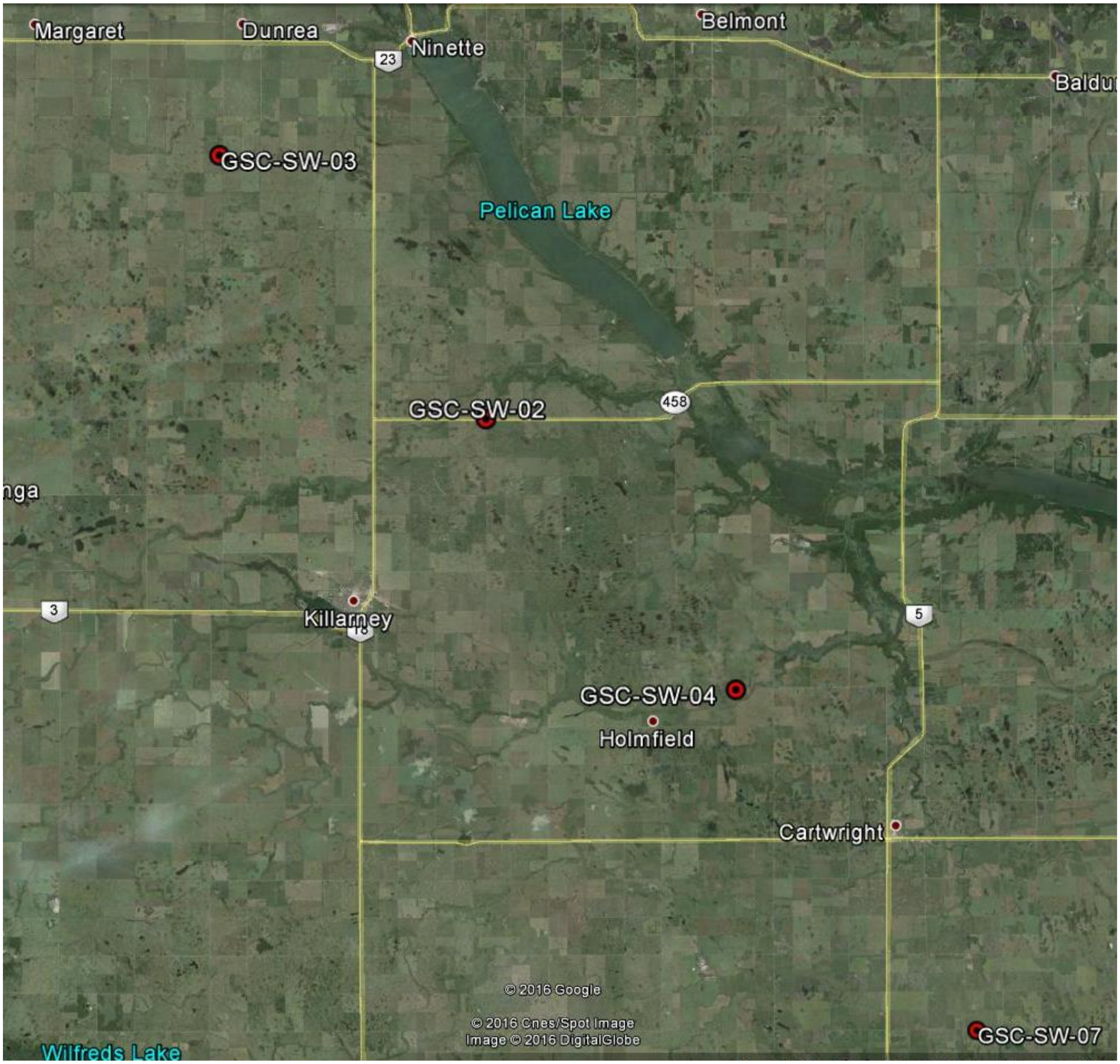


Figure 4. Water depth, GSC-SW-02-p1. Black diamonds represent manual water level measurements.

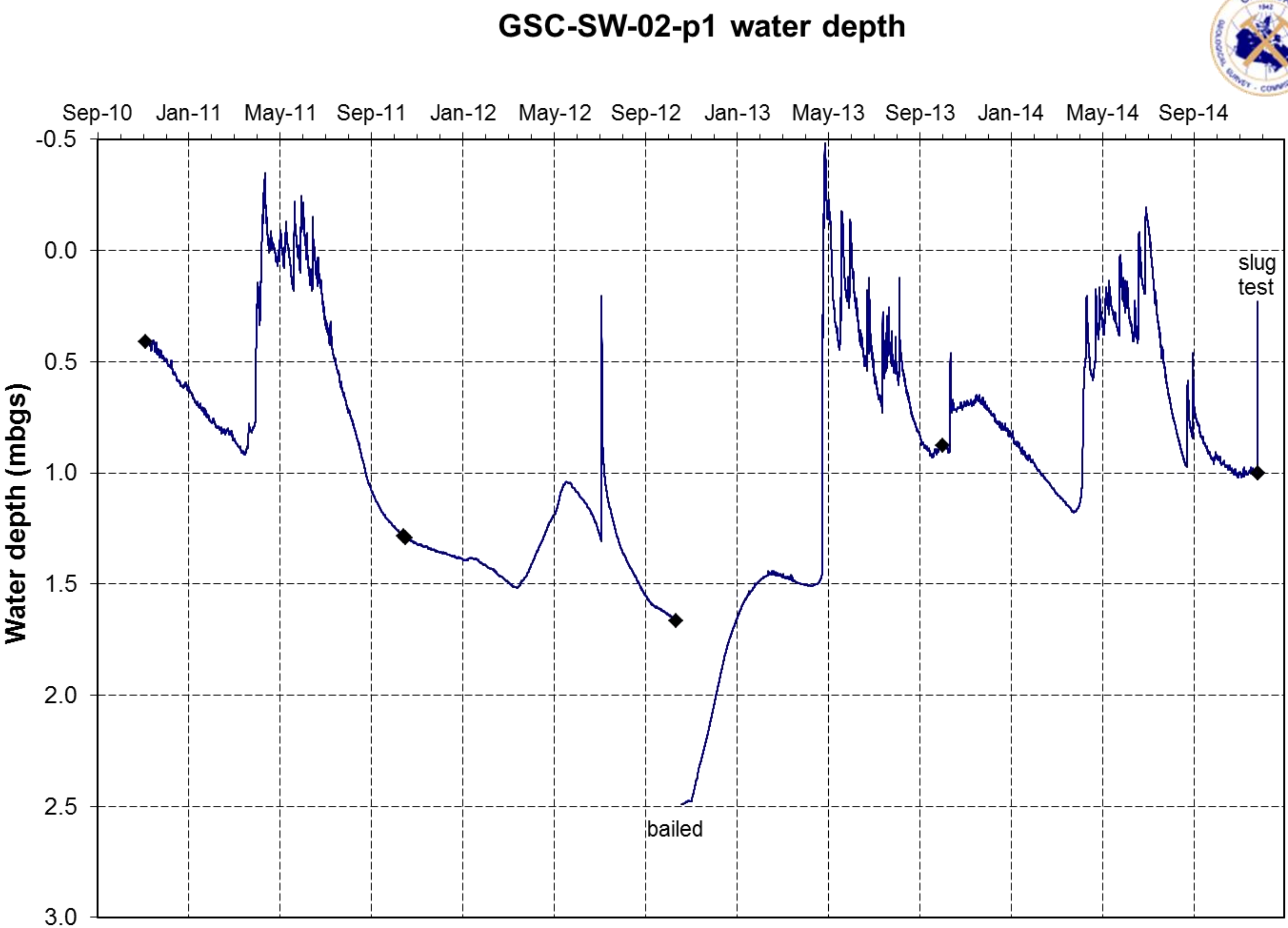


Figure 5. Groundwater elevation, GSC-SW-02-p1.

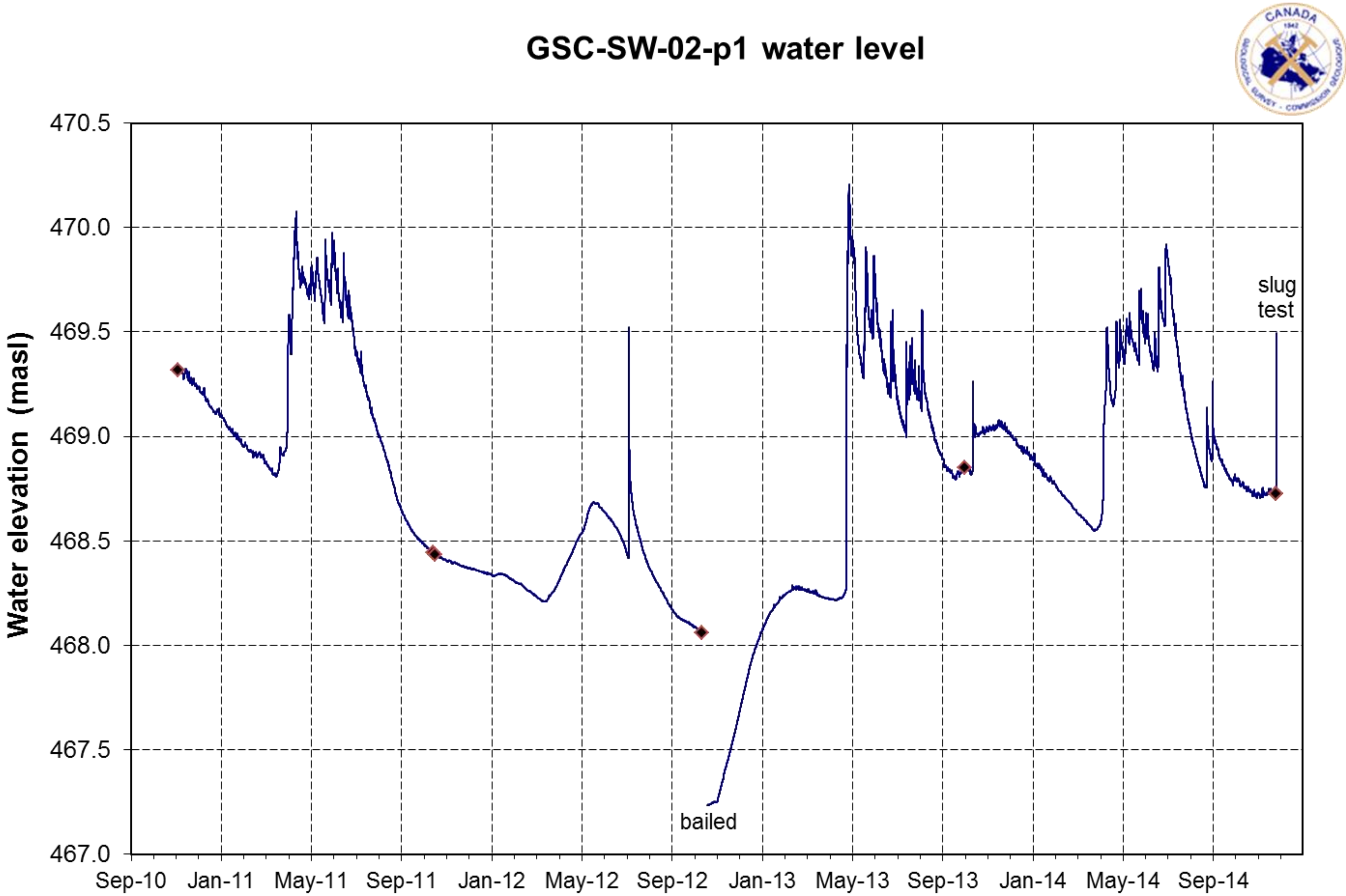


Figure 6. Water depth, GSC-SW-02-p2.

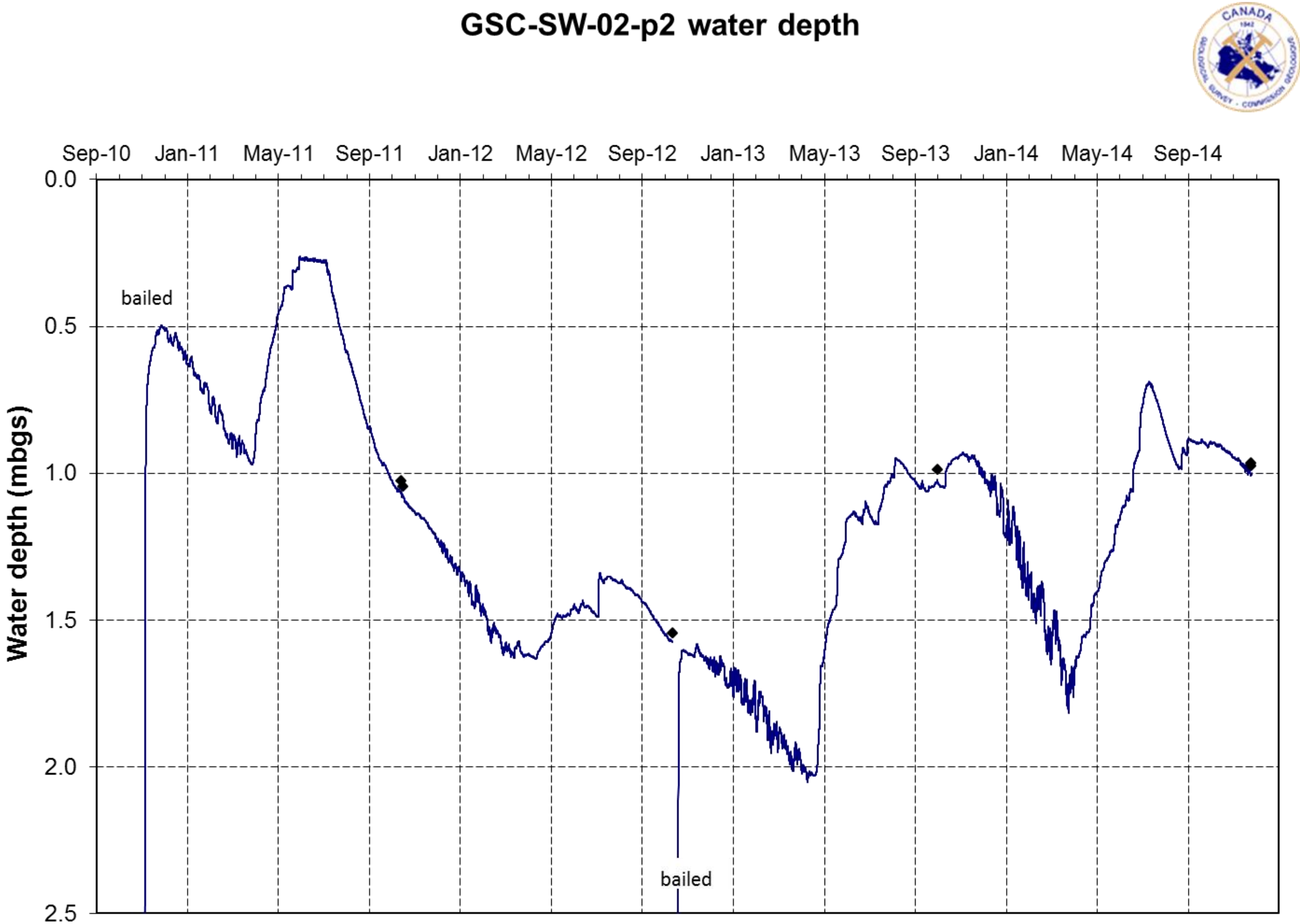


Figure 7. Groundwater elevation, GSC-SW-02-p2.

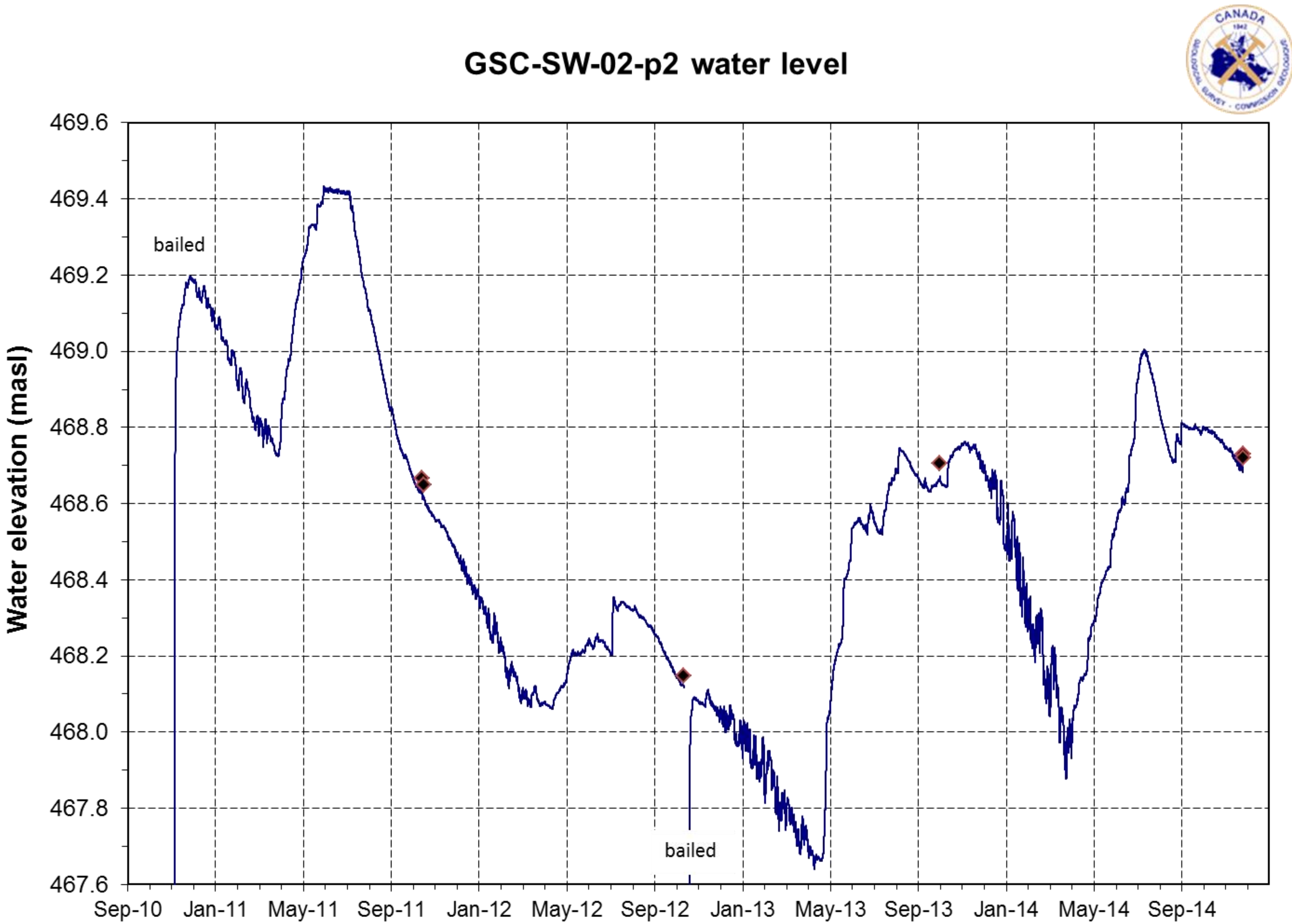


Figure 8. Groundwater elevations, GSC-SW-02-p1 and GSC-SW-02-p2

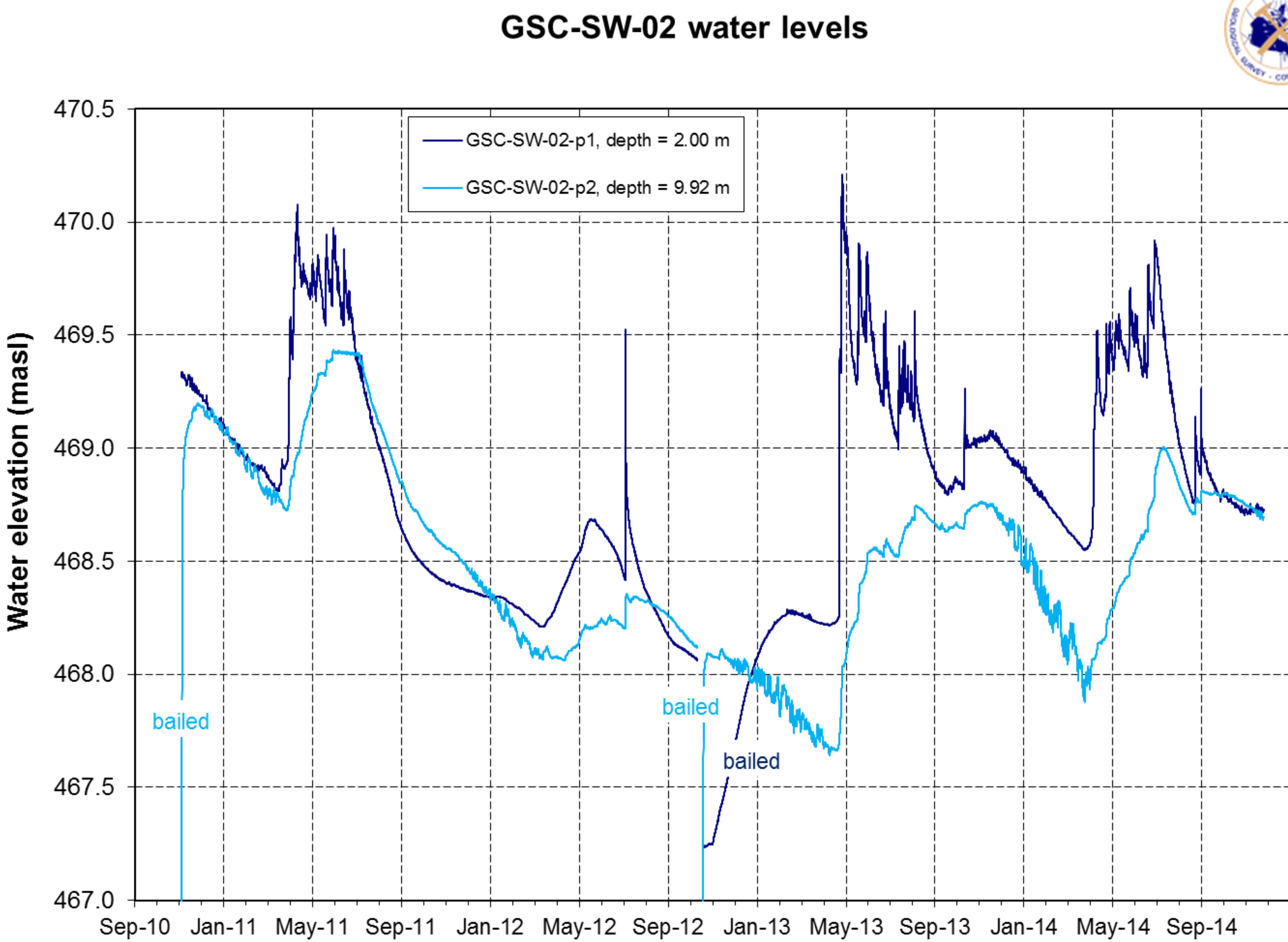


Figure 9. Water depth, GSC-SW-03-p1.

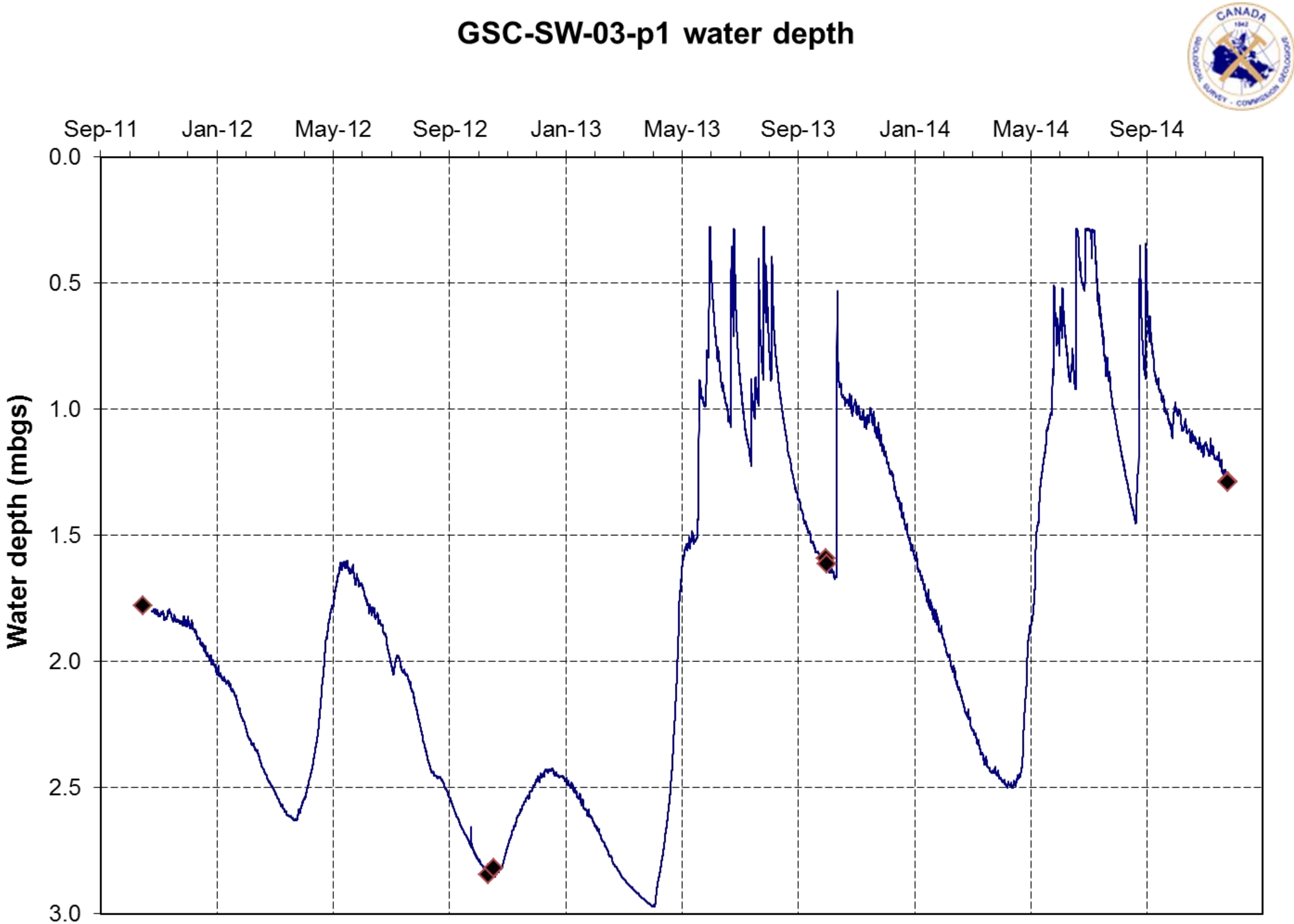


Figure 10. Groundwater elevation, GSC-SW-03-p1.

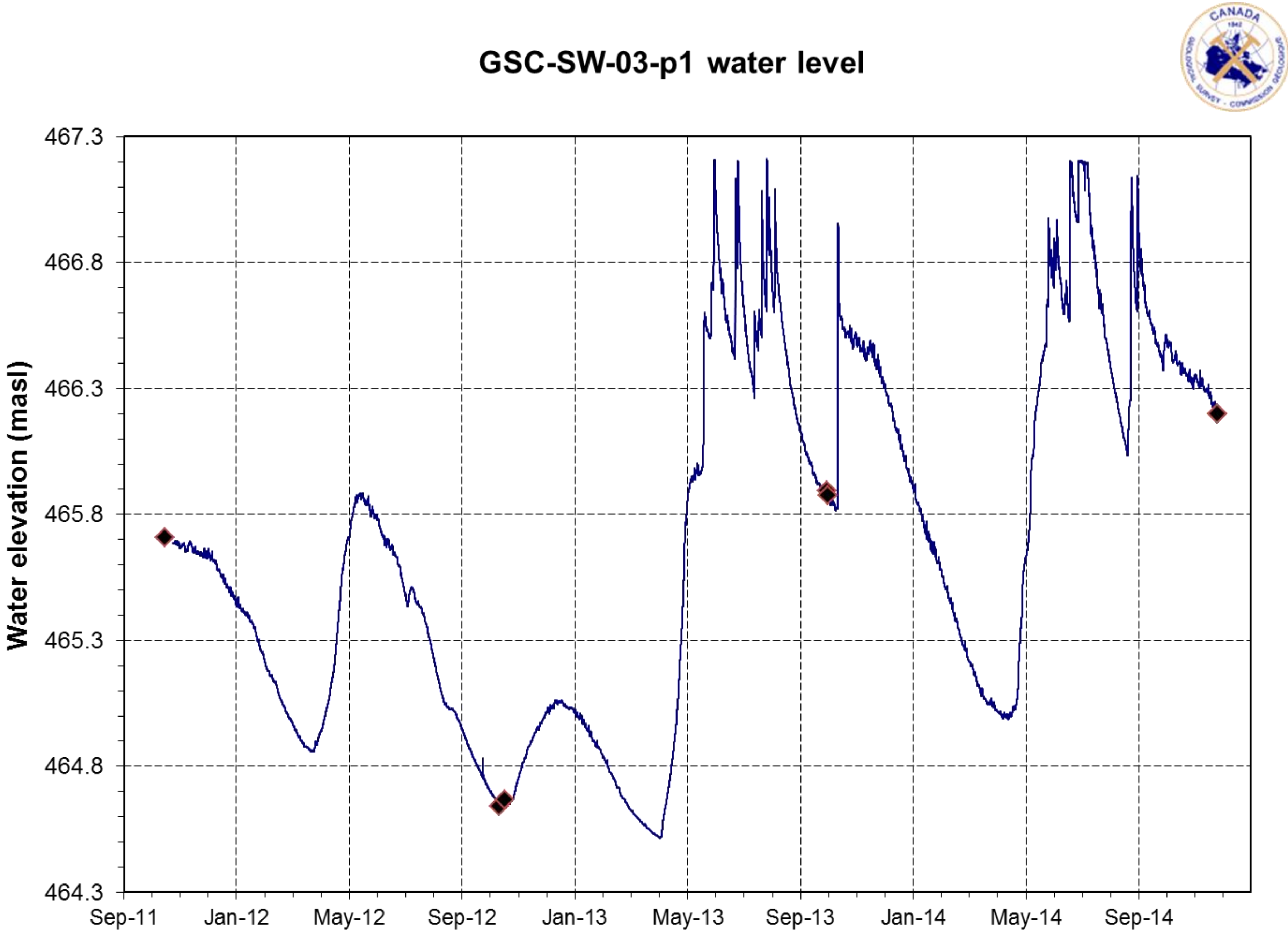


Figure 11. Water depth, GSC-SW-03-p2.

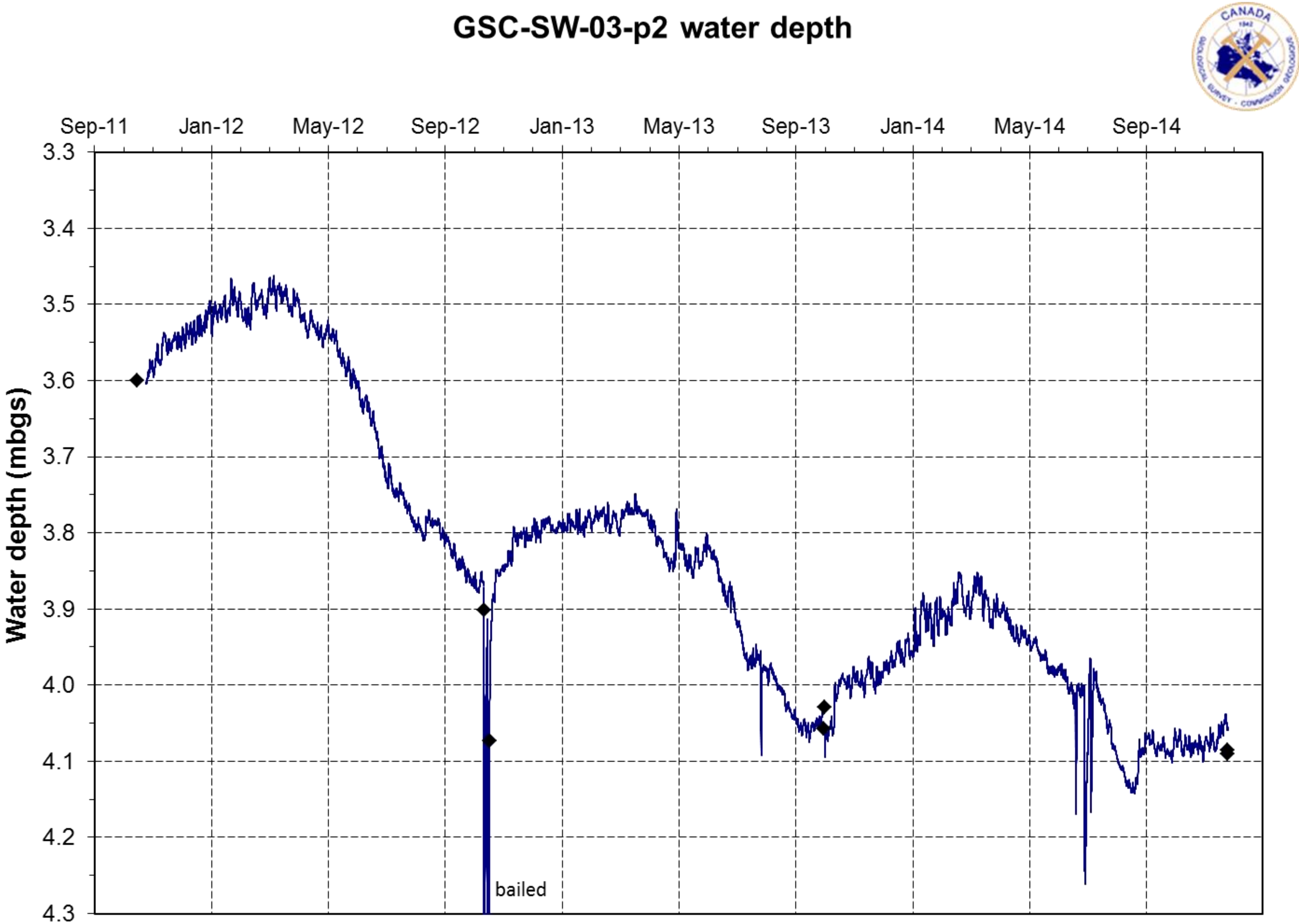


Figure 12. Groundwater elevation, GSC-SW-03-p2.

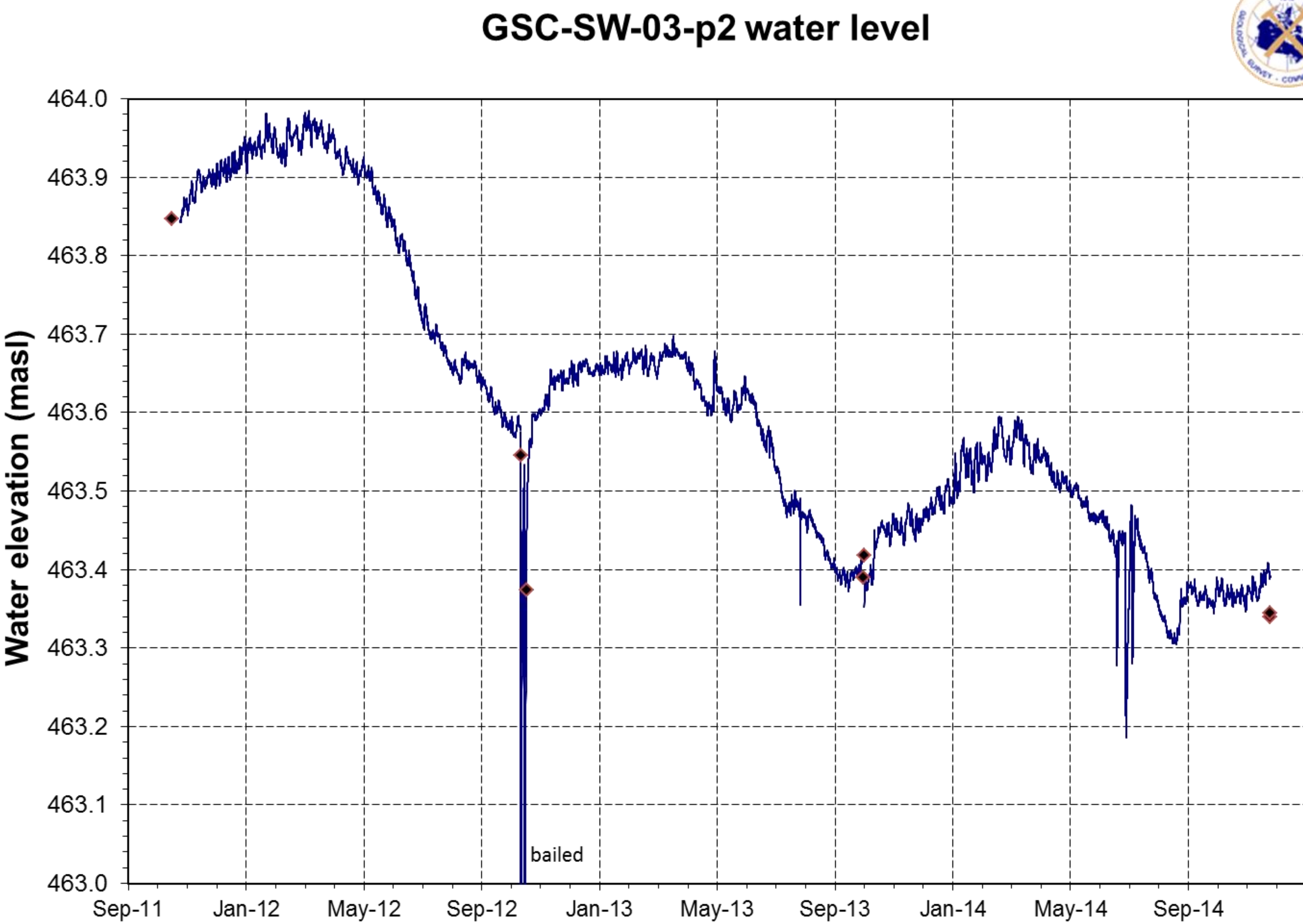


Figure 13. Groundwater elevations, GSC-SW-03-p1 and GSC-SW-03-p2

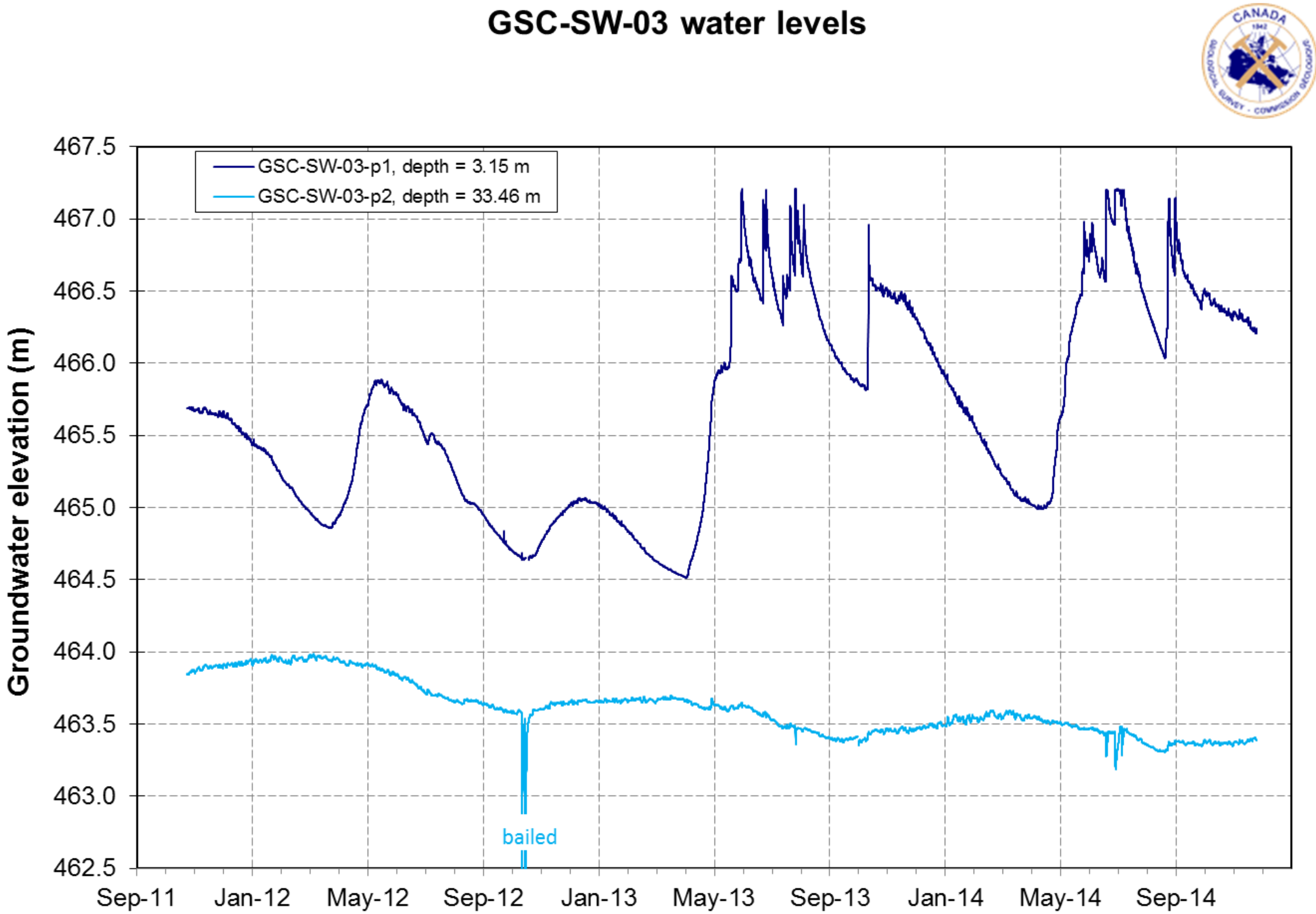


Figure 14. Water depth, GSC-SW-04-p1.

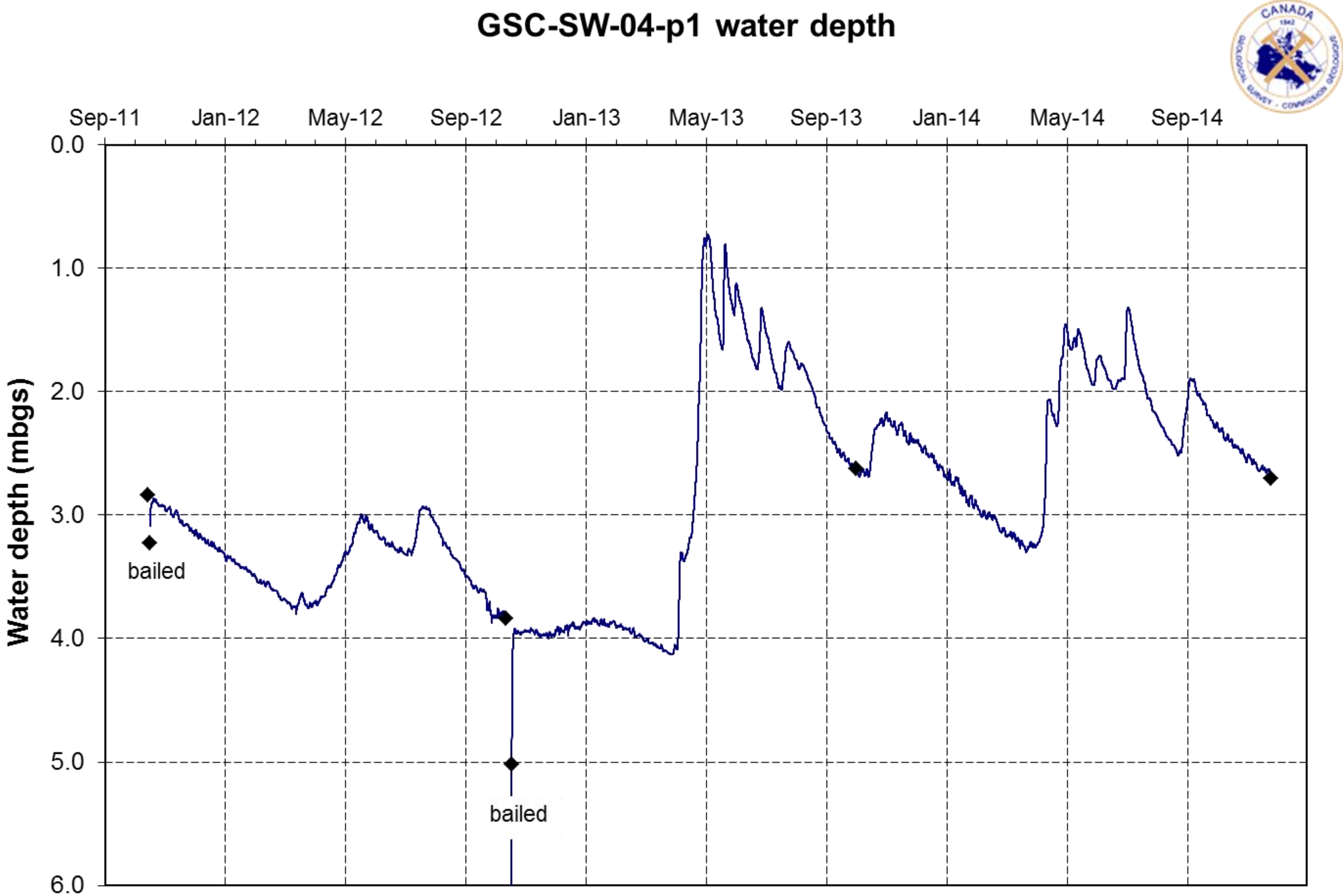


Figure 15. Groundwater elevation, GSC-SW-04-p1.

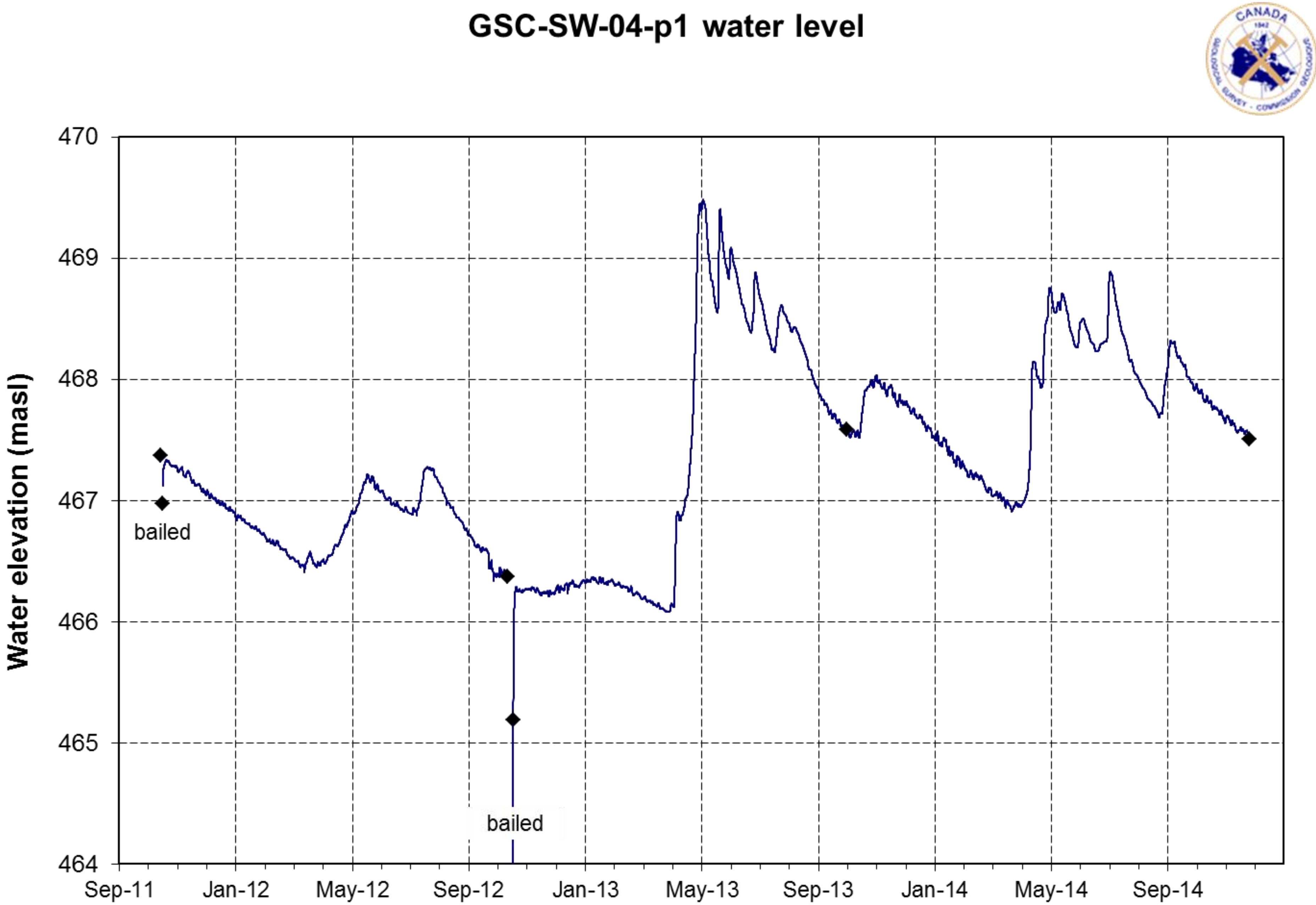


Figure 16. Water depth, GSC-SW-04-p2.

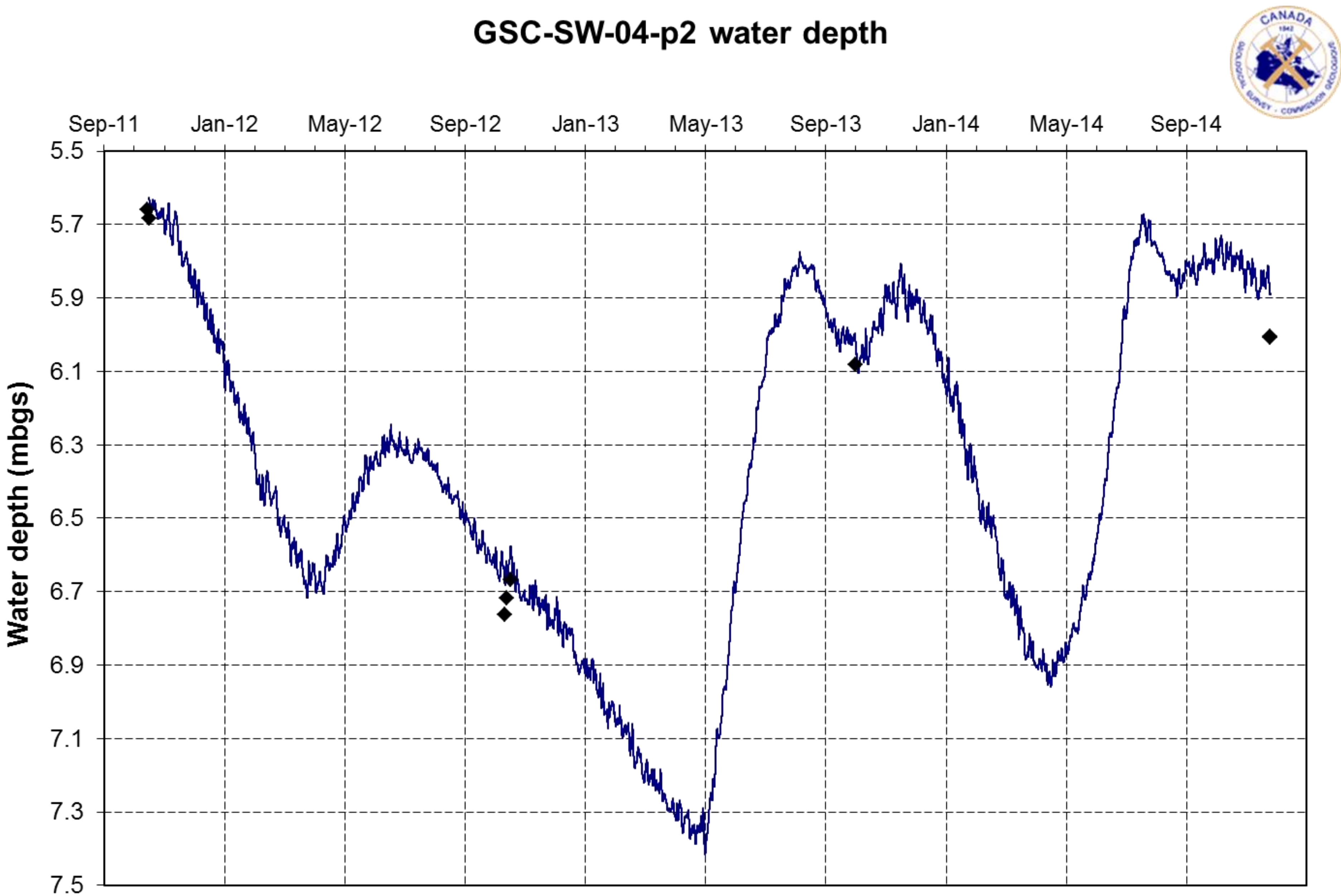


Figure 17. Groundwater elevation, GSC-SW-04-p2.

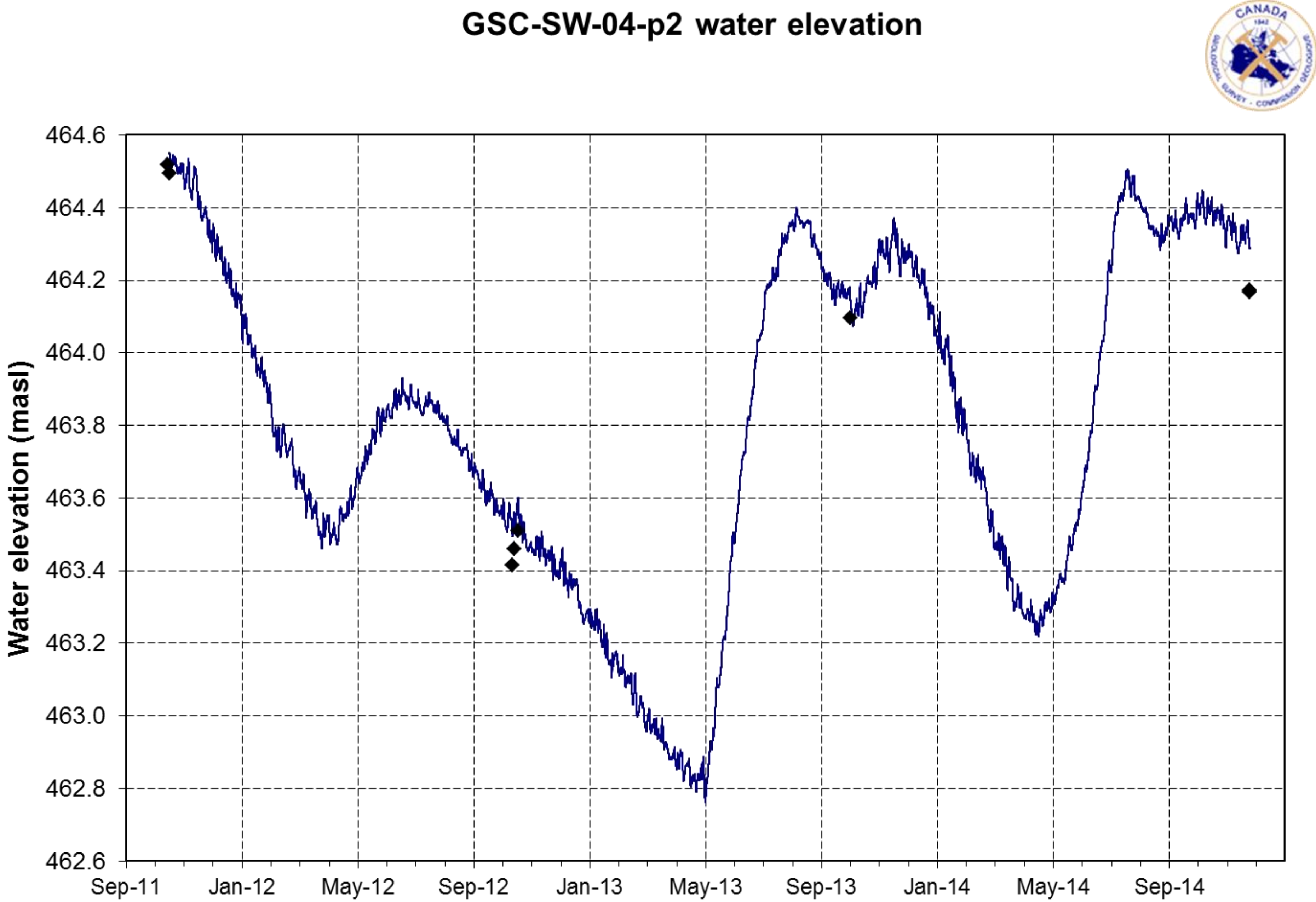


Figure 18. Groundwater elevations, GSC-SW-04-p1 and GSC-SW-04-p2

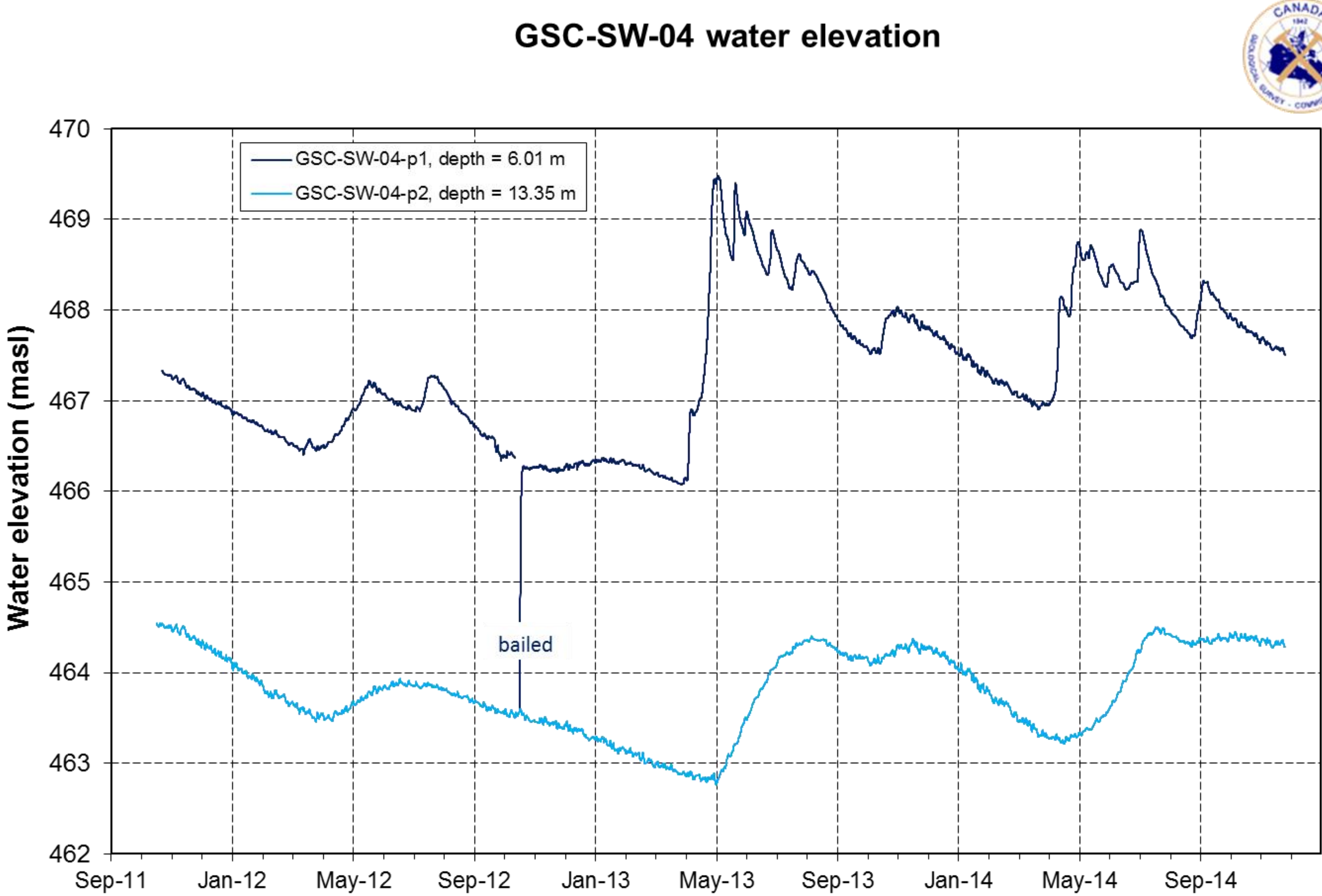


Figure 19. Water depth, GSC-SW-07-p1.

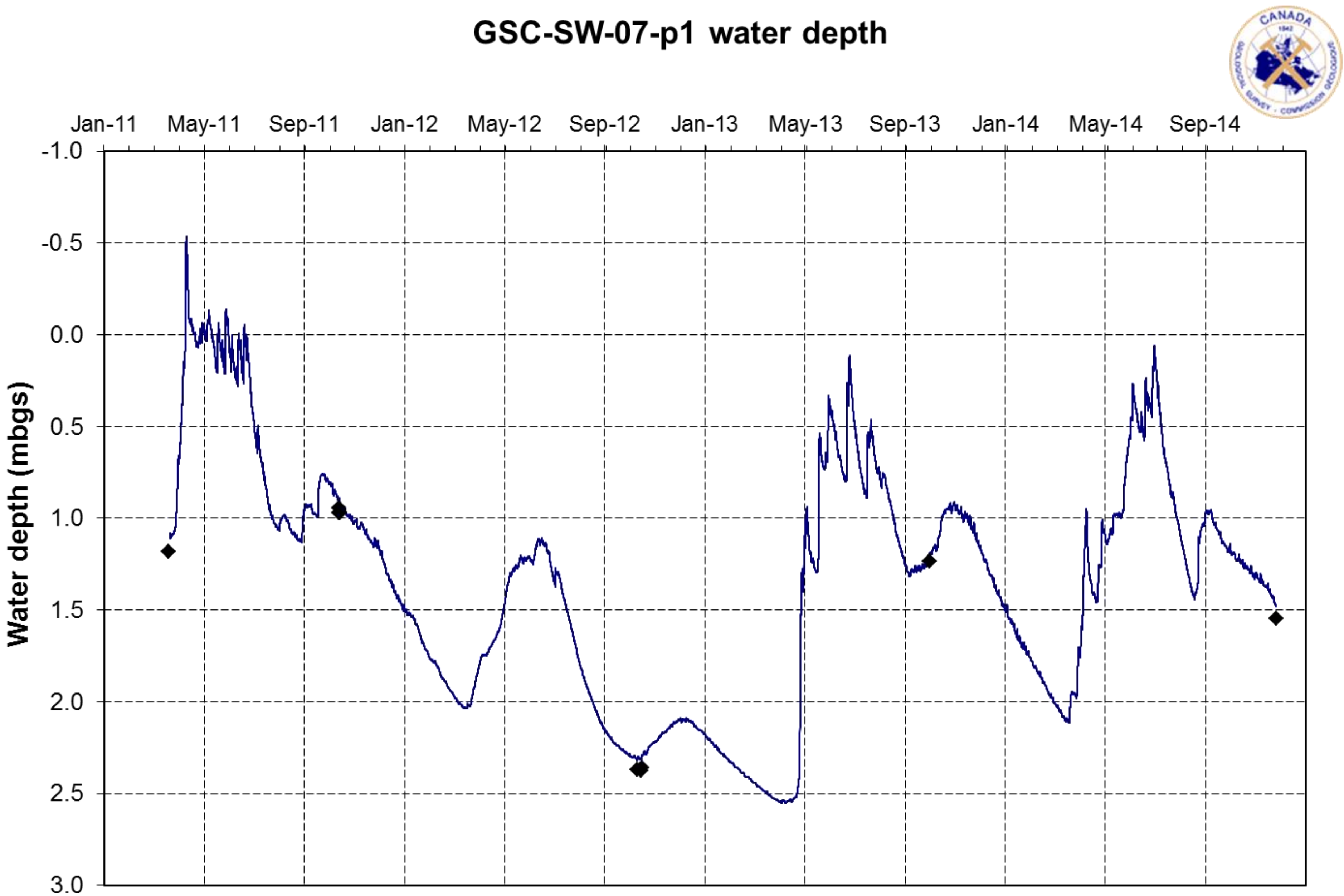


Figure 20. Groundwater elevation, GSC-SW-07-p1.

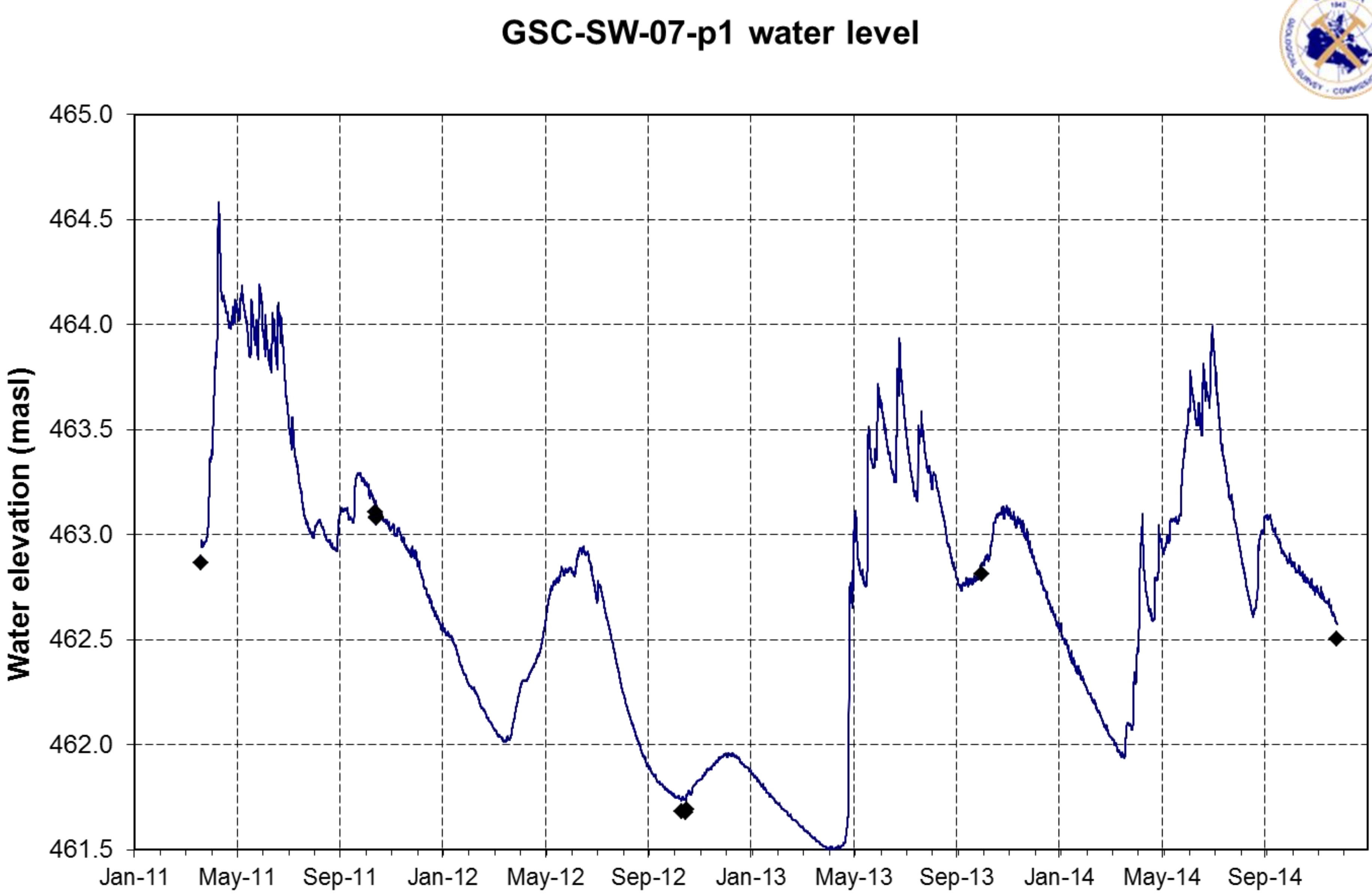


Figure 21. Water depth, GSC-SW-07-p2.

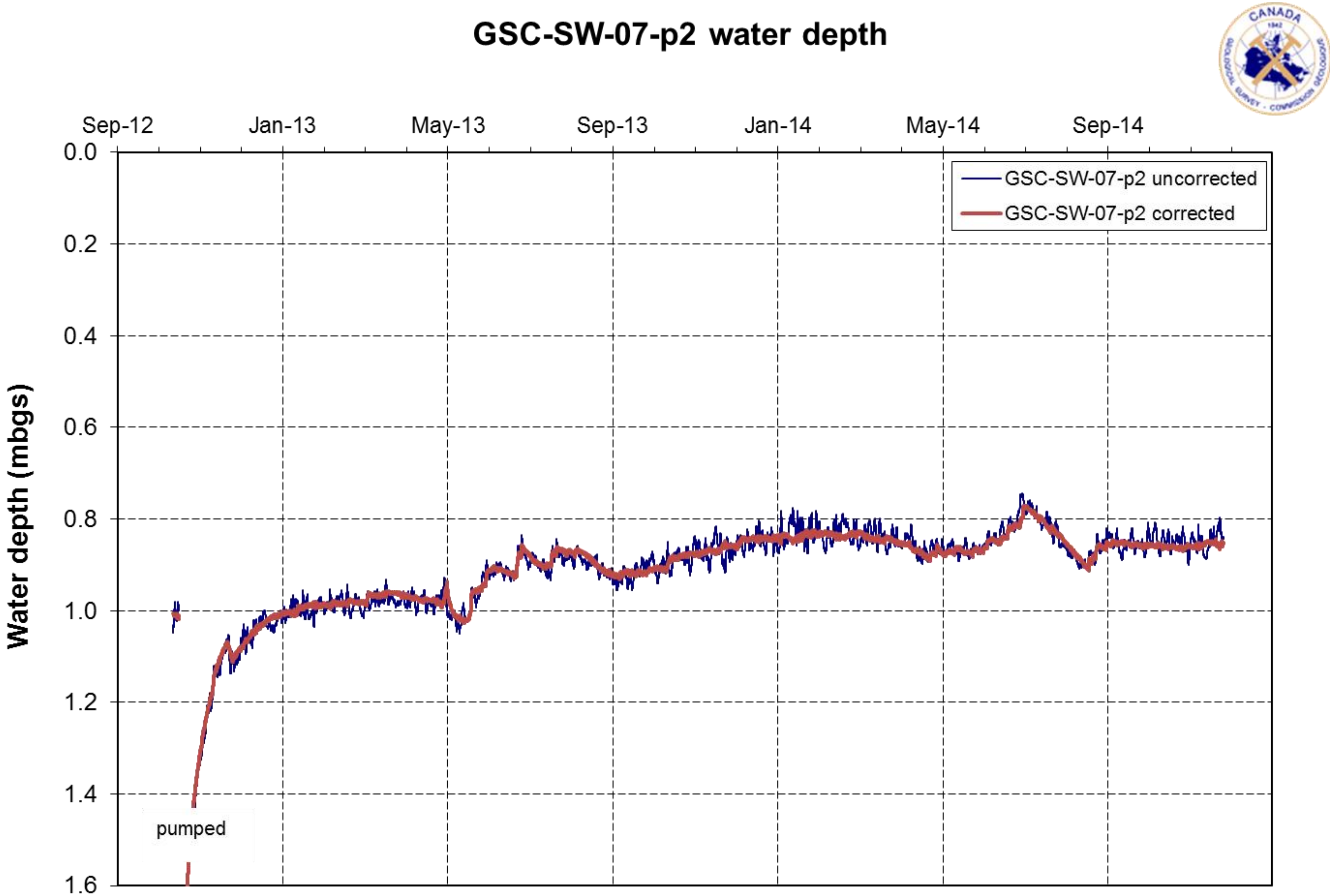


Figure 22. Groundwater elevation, GSC-SW-07-p2.

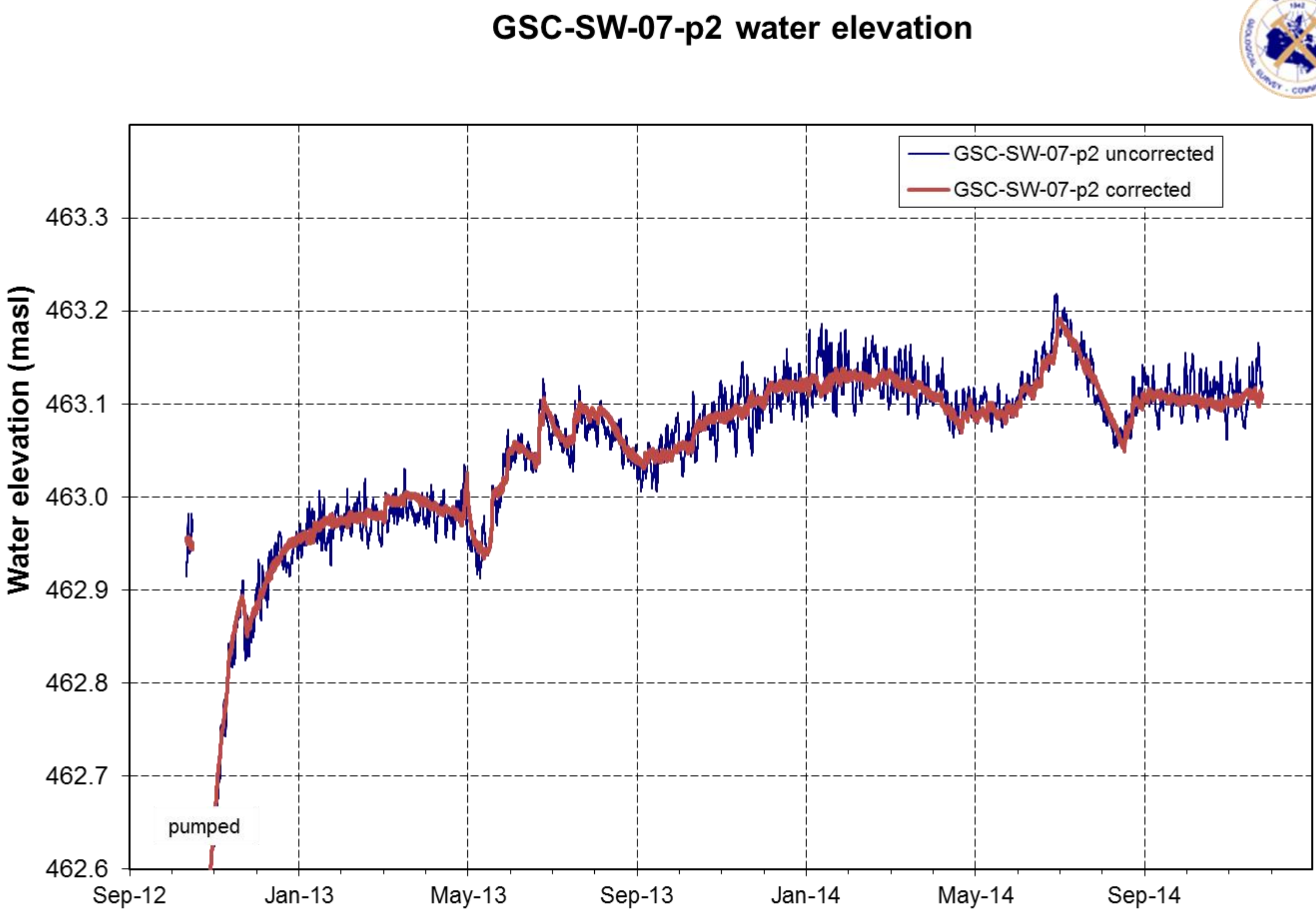


Figure 23. Groundwater elevations, GSC-SW-07-p1 and GSC-SW-07-p2

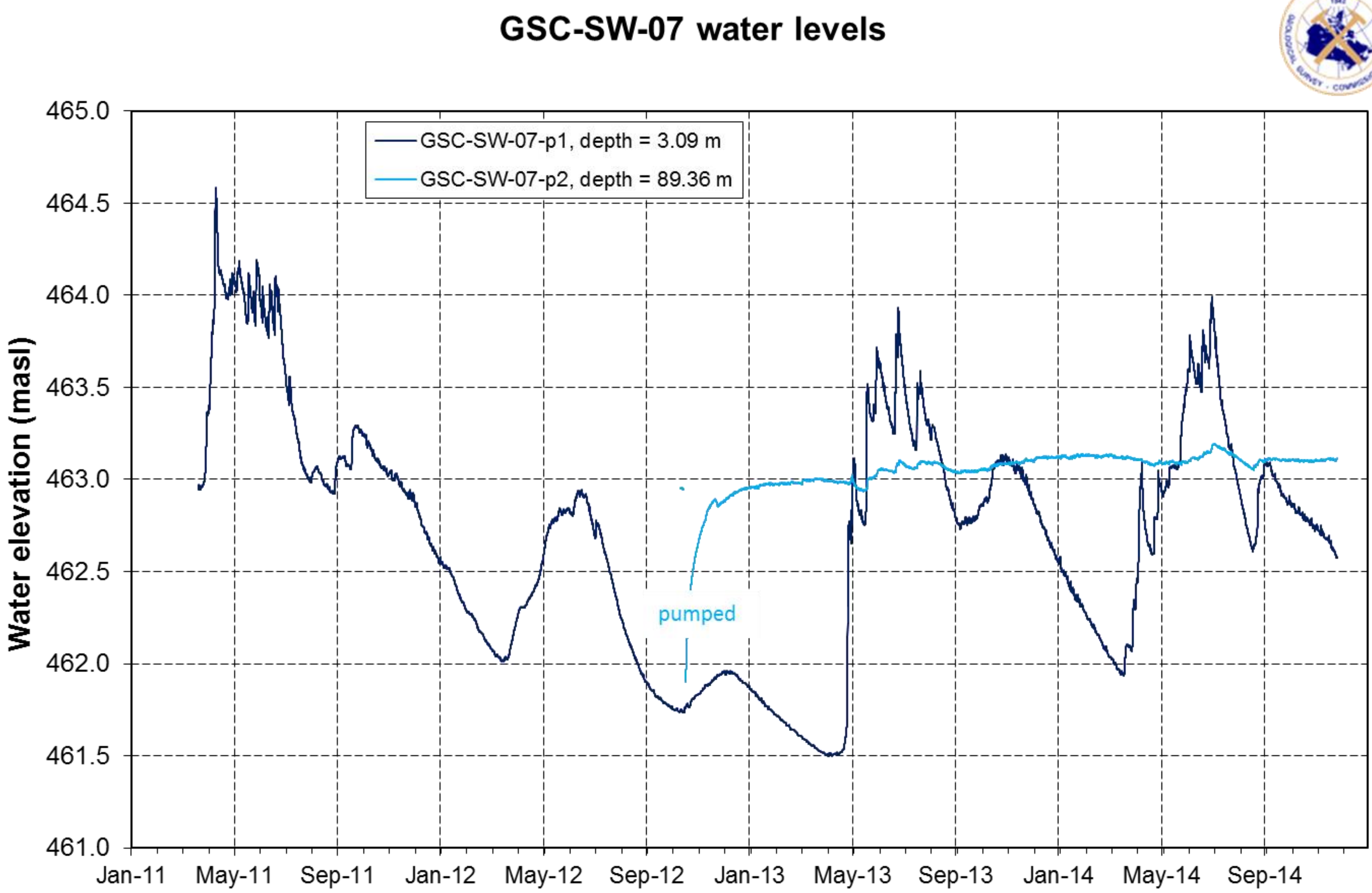


Figure 24. Groundwater temperature, GSC-SW-02-p1.

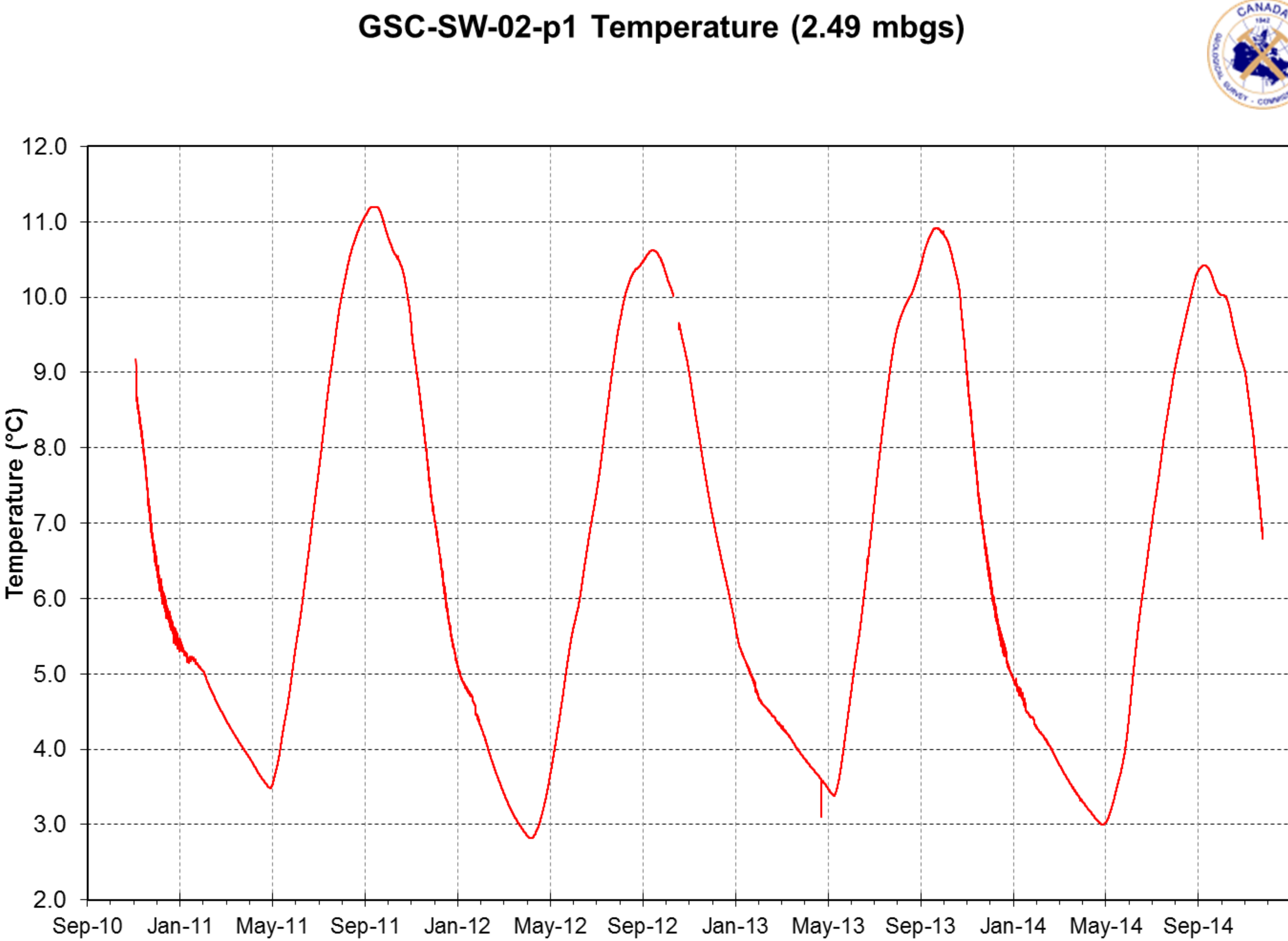


Figure 25. Groundwater temperature, GSC-SW-02-p2.

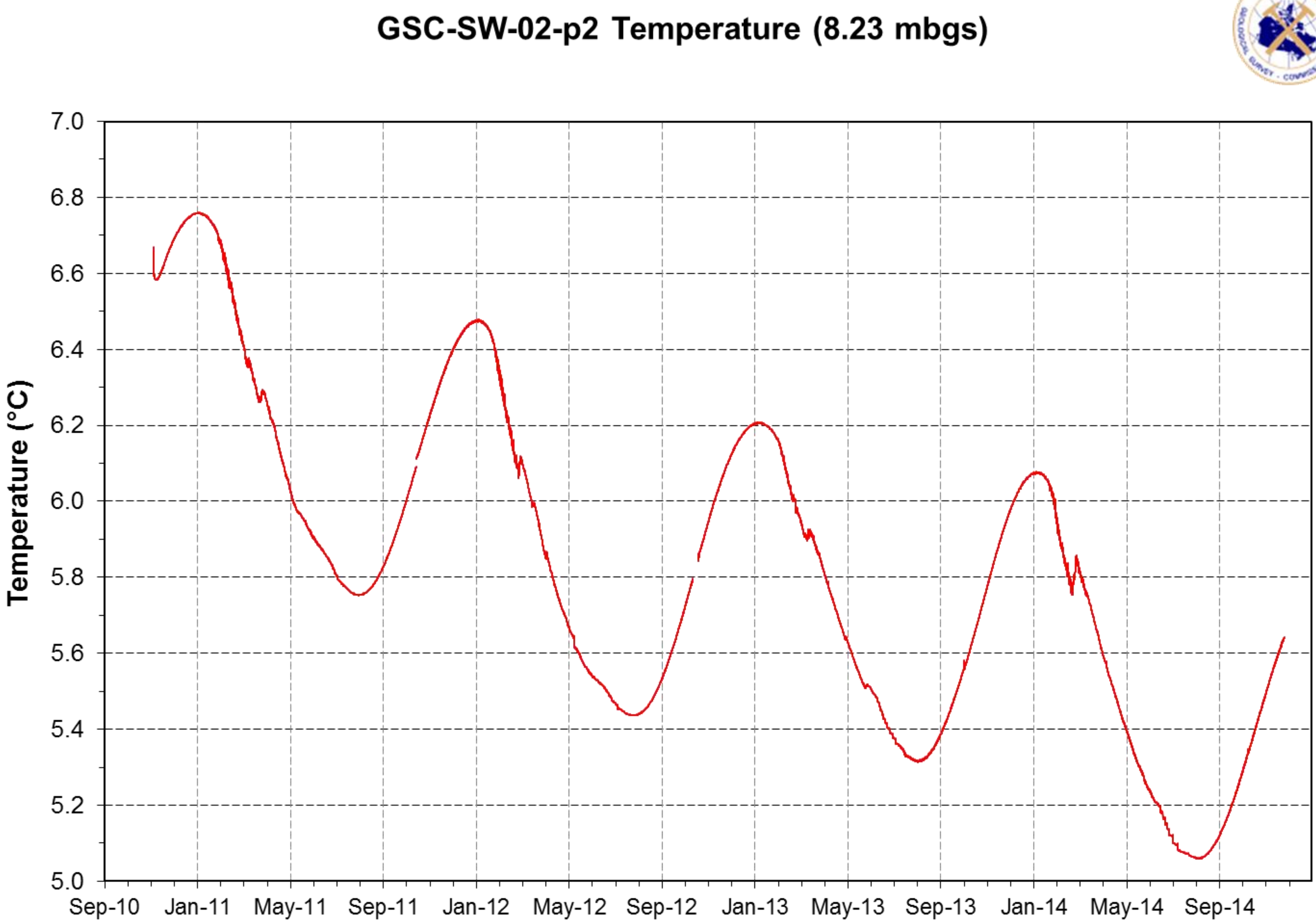


Figure 26. Groundwater temperature, GSC-SW-03-p1. Note the change in depth in October 2012.

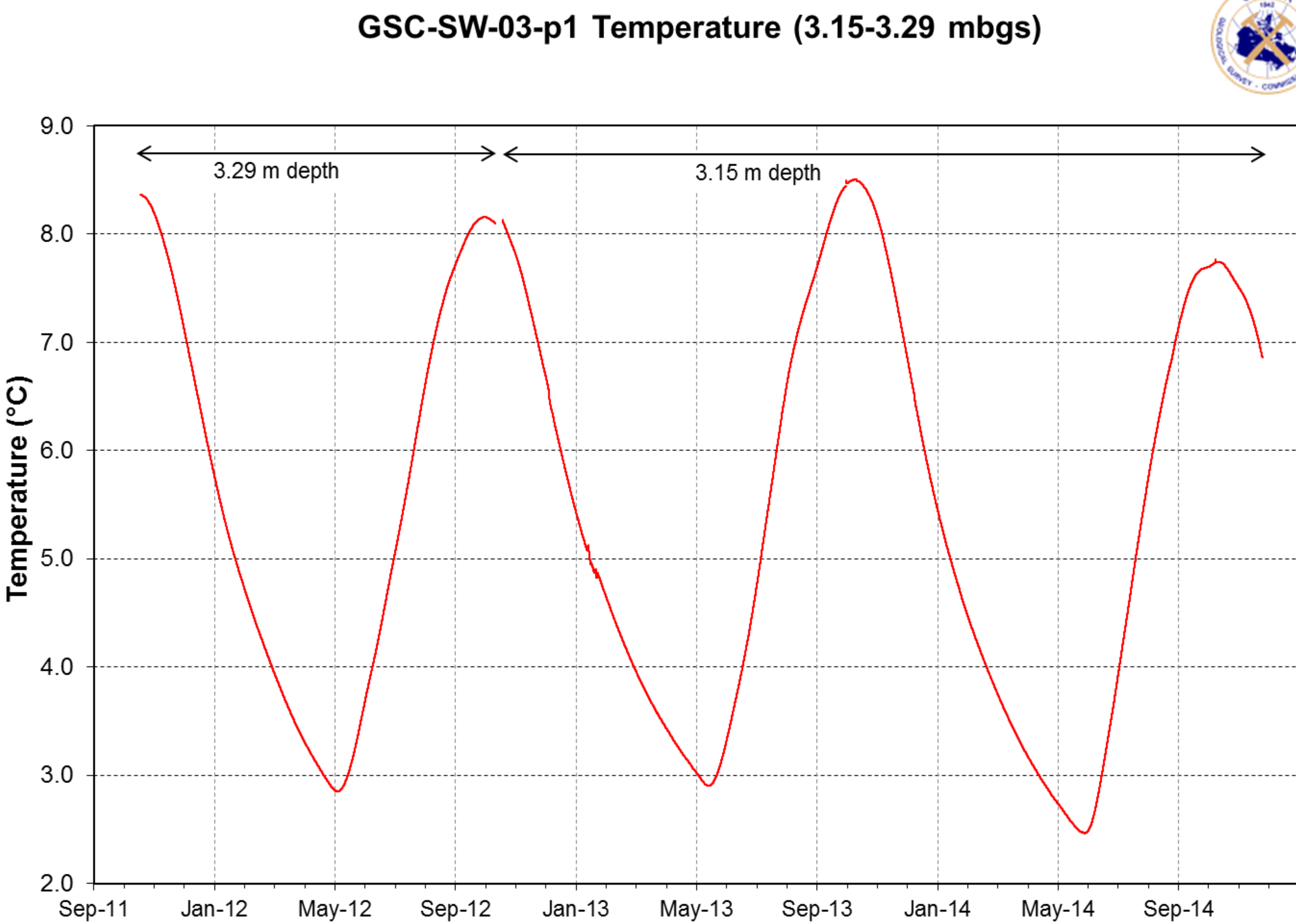


Figure 27. Groundwater temperature, GSC-SW-03-p2.

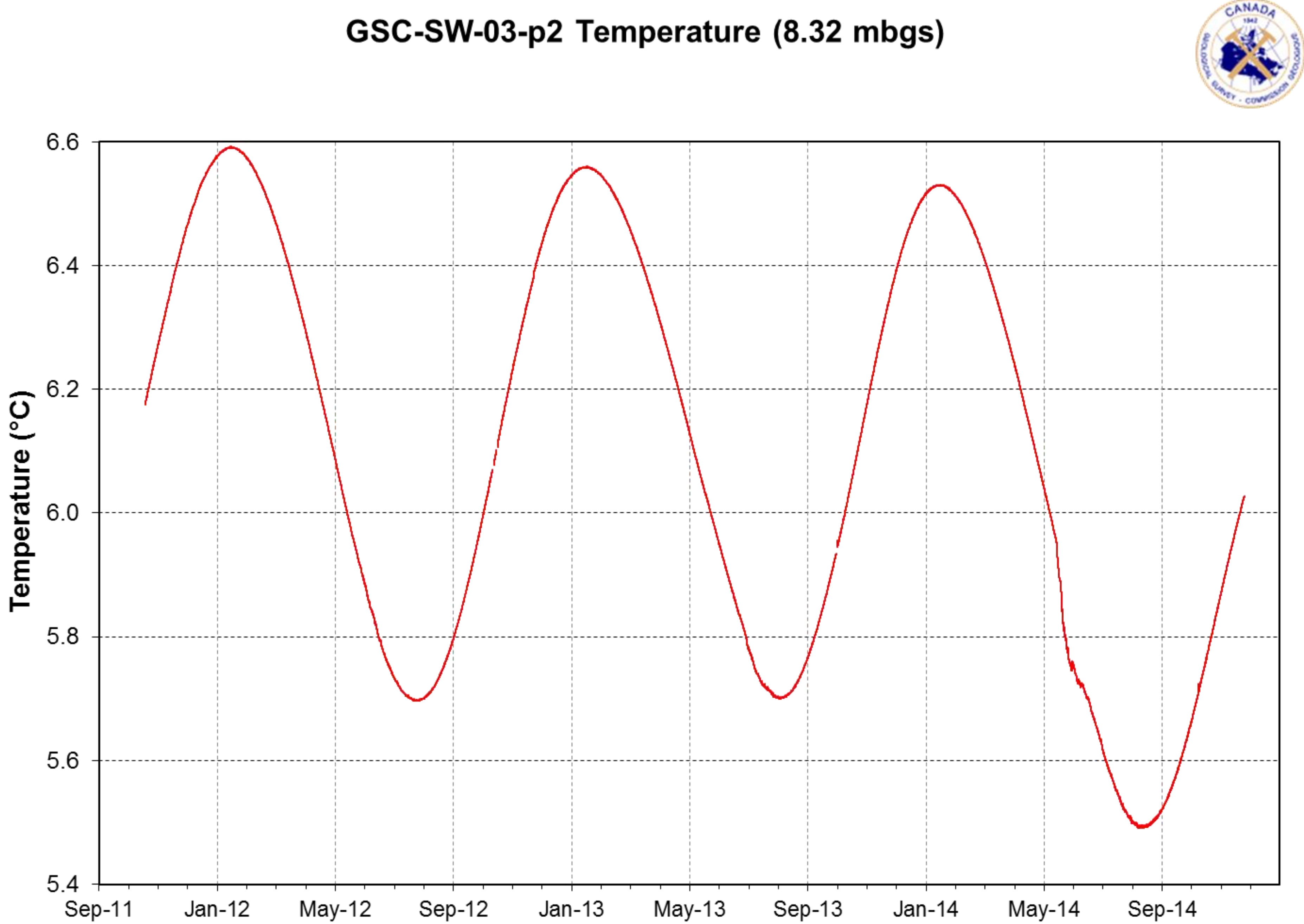


Figure 28. Groundwater temperature, GSC-SW-04-p1.

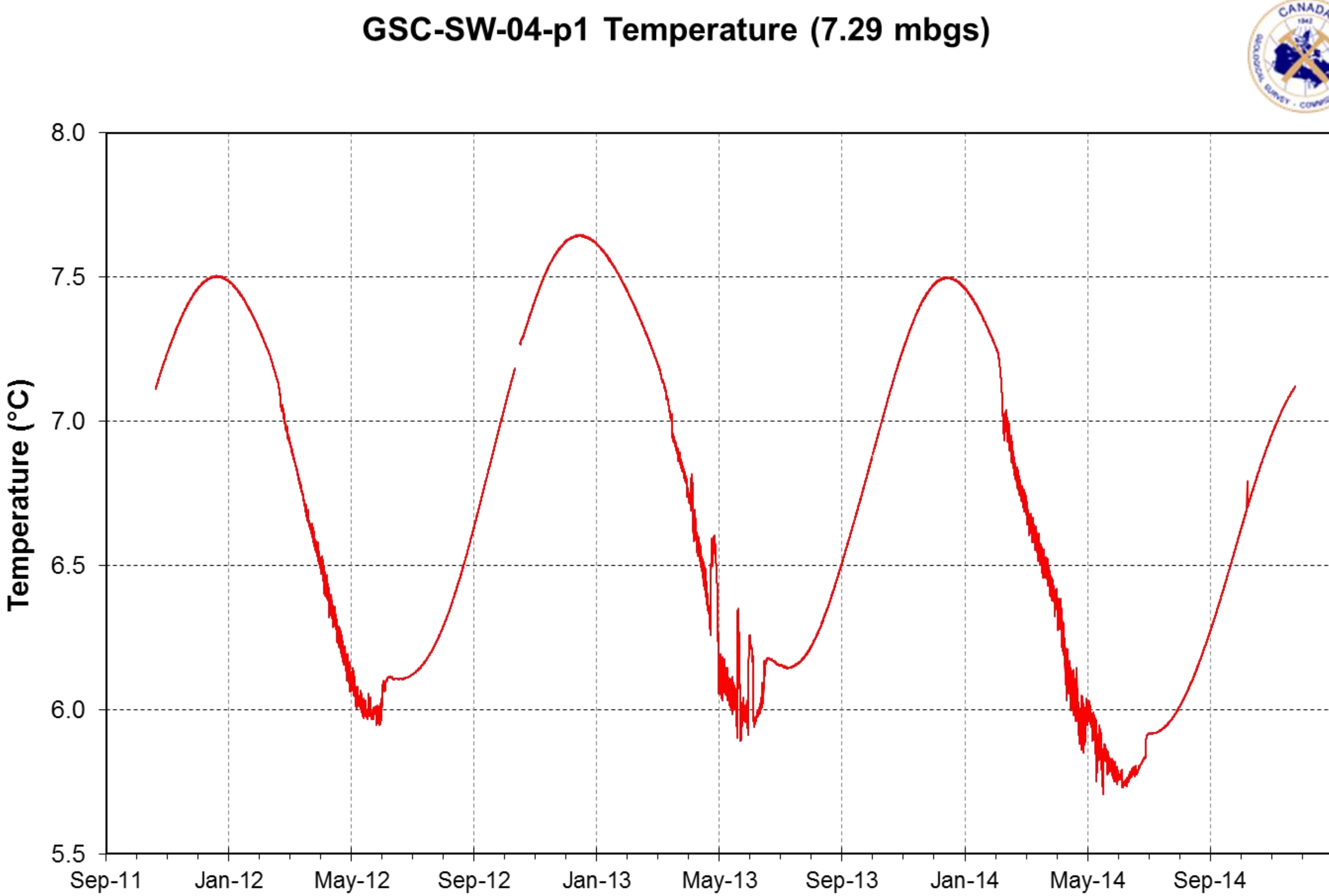


Figure 29. Groundwater temperature, GSC-SW-04-p2.

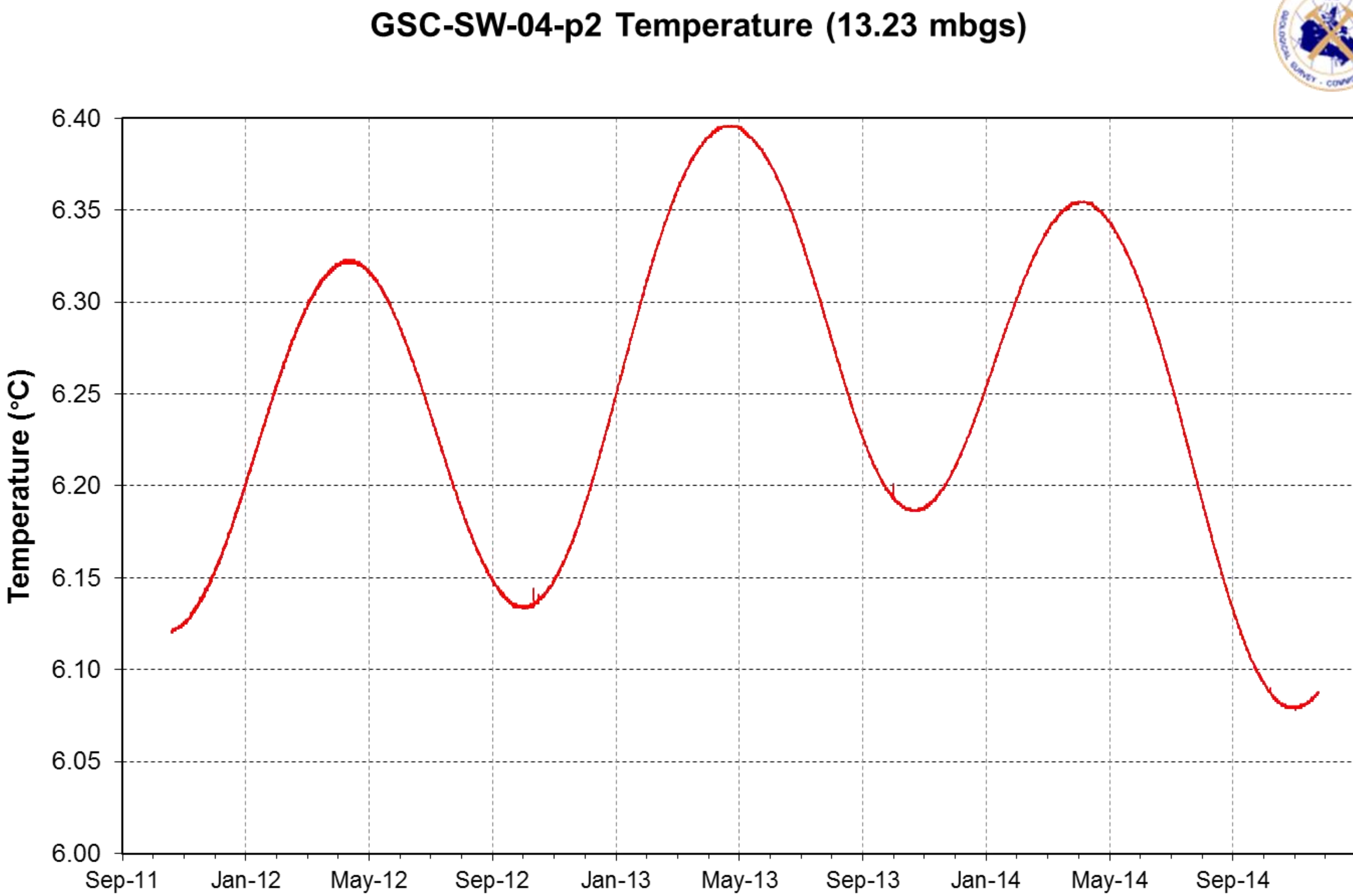


Figure 30. Groundwater temperature, GSC-SW-07-p1.

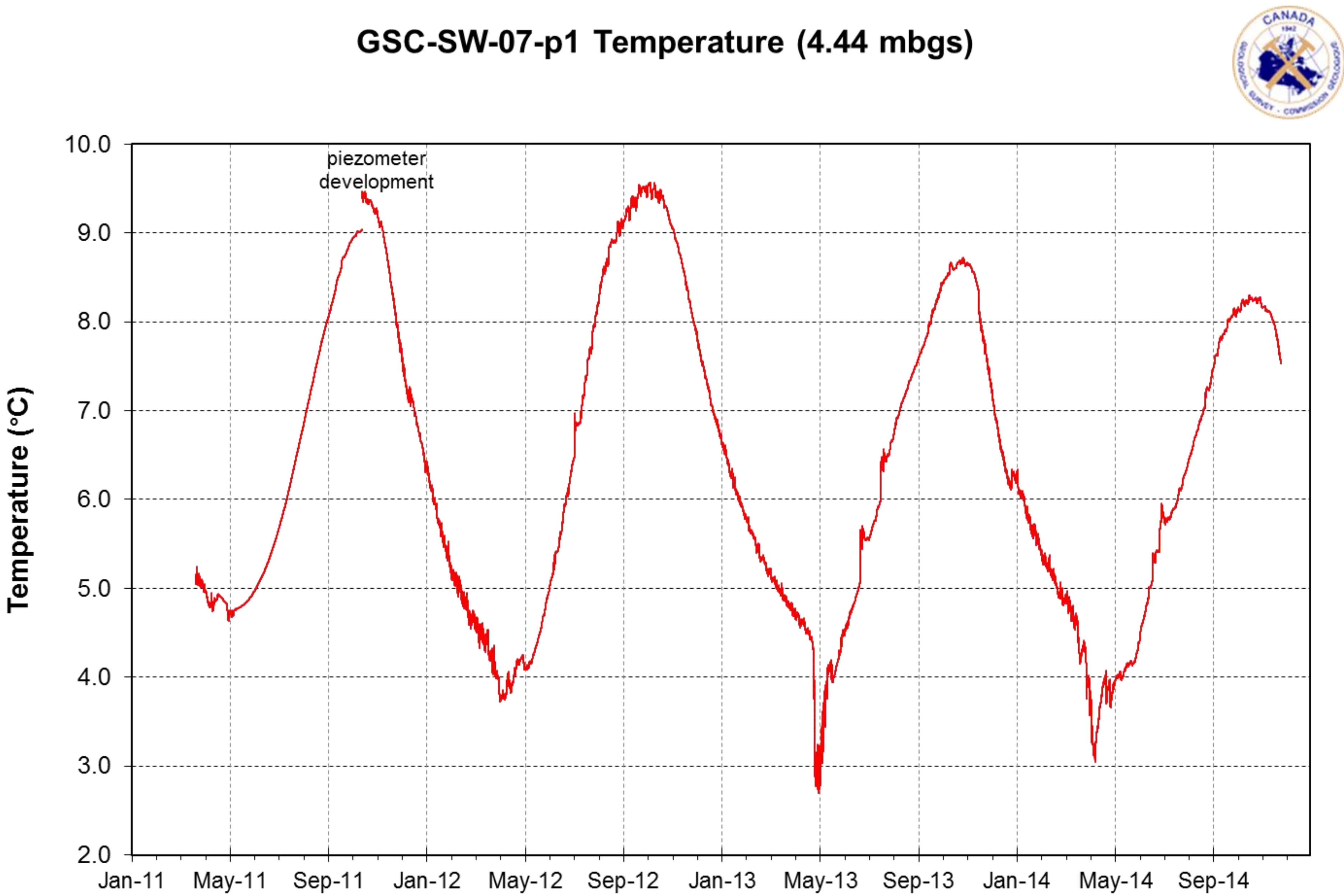


Figure 31. Groundwater temperature, GSC-SW-07-p2.

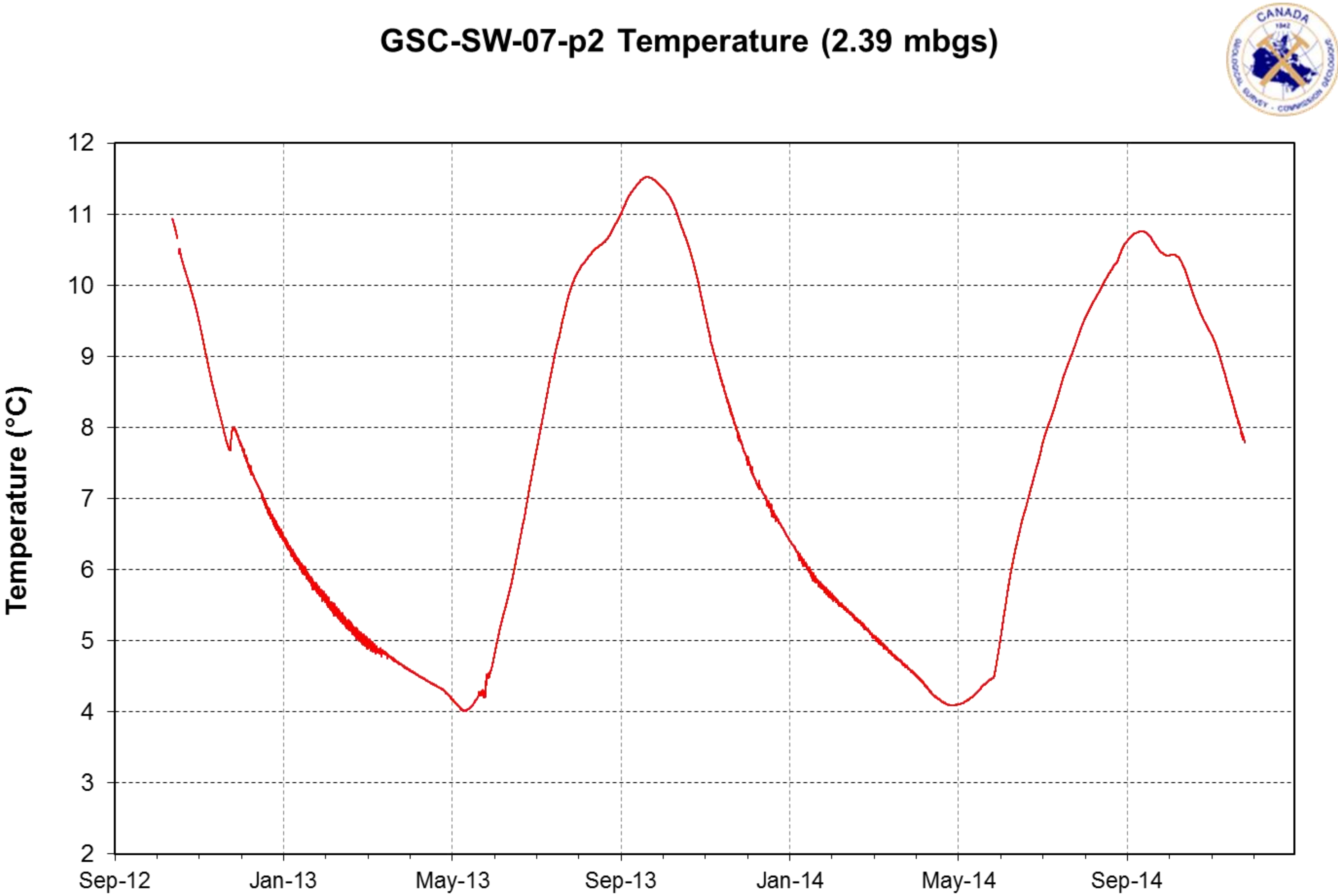


Figure 32. Groundwater temperature and water depth, GSC-SW-02-p1.

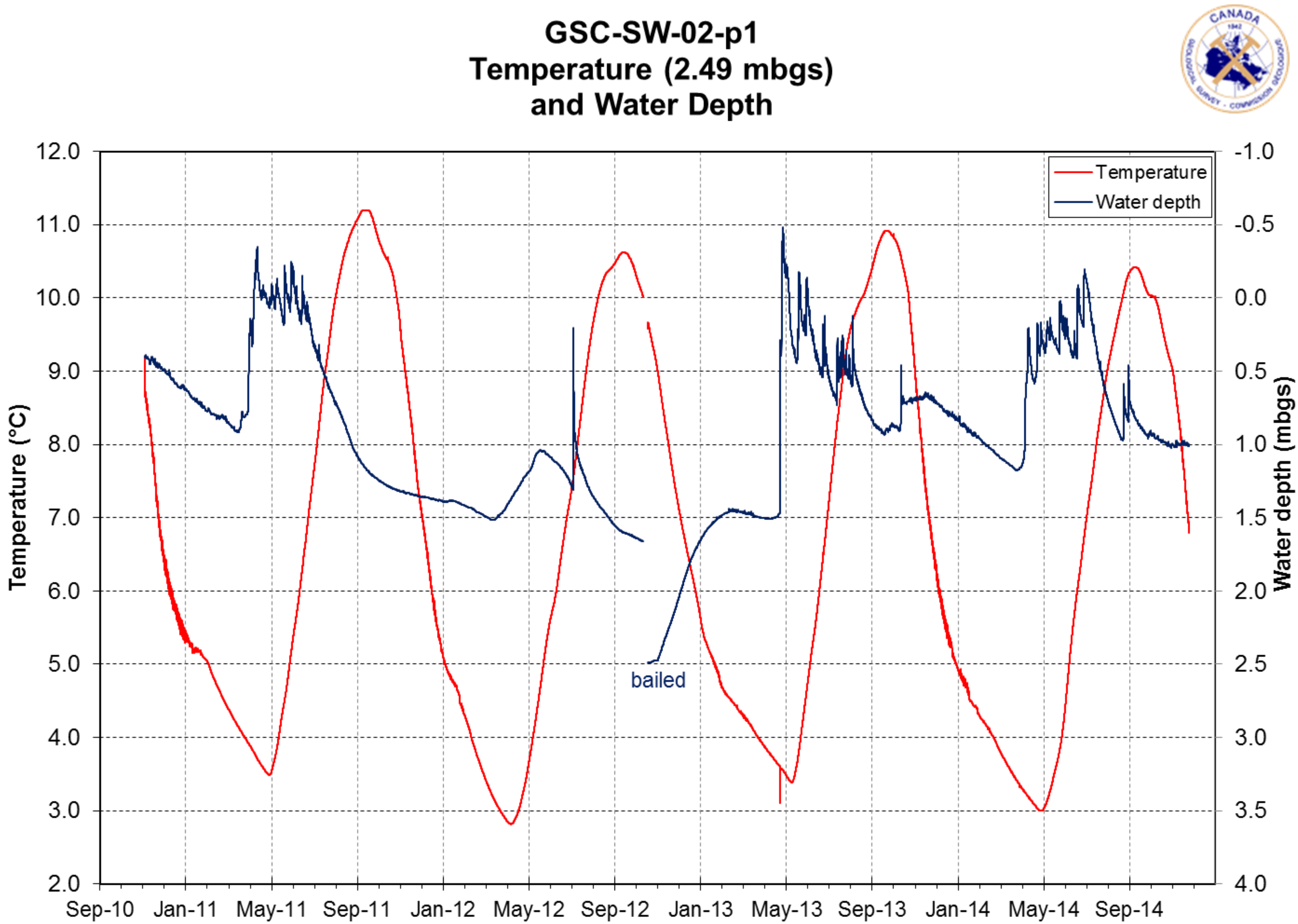


Figure 33. Groundwater temperature and water depth, GSC-SW-02-p2.

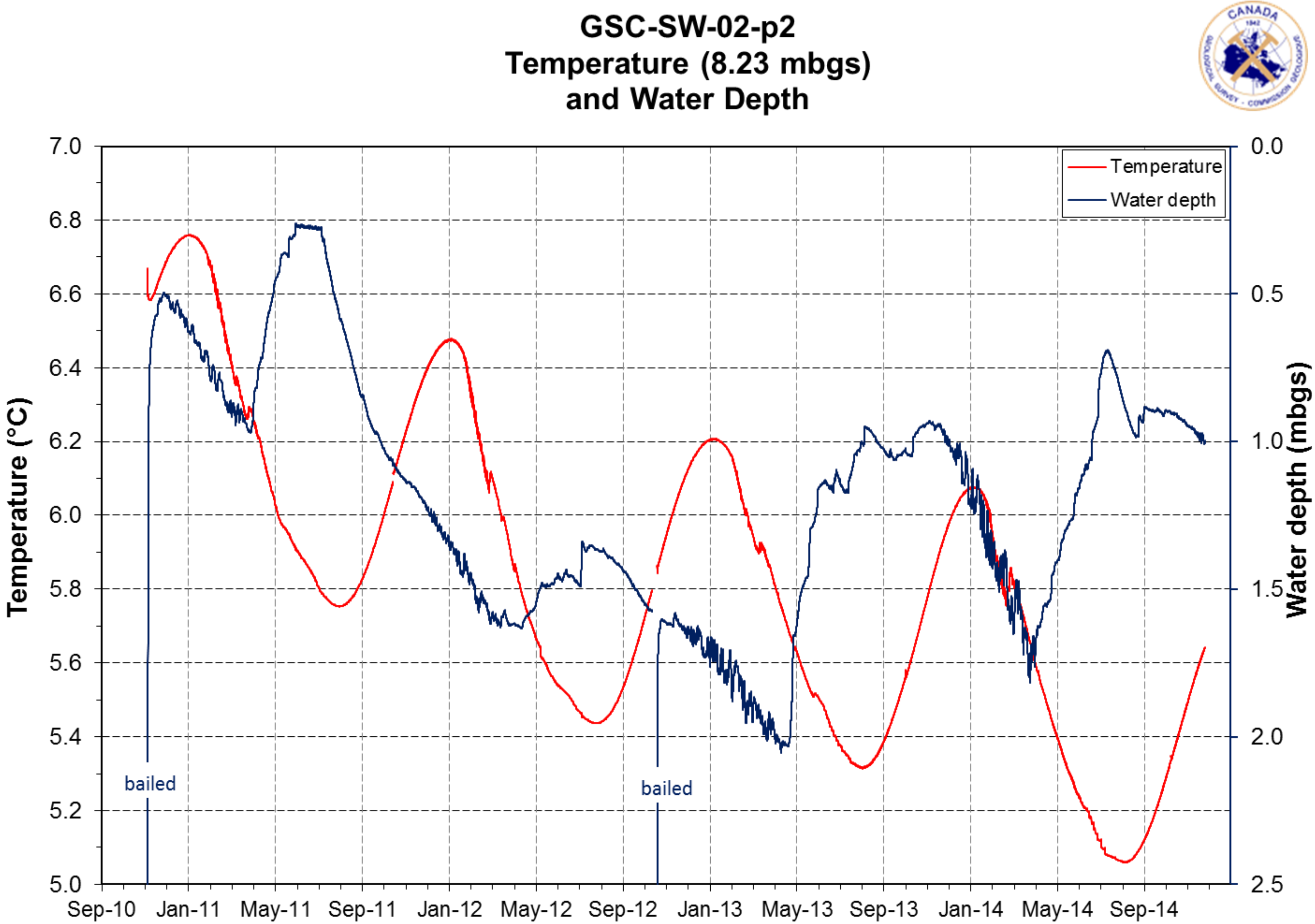


Figure 34. Groundwater temperature and water depth, GSC-SW-03-p1.

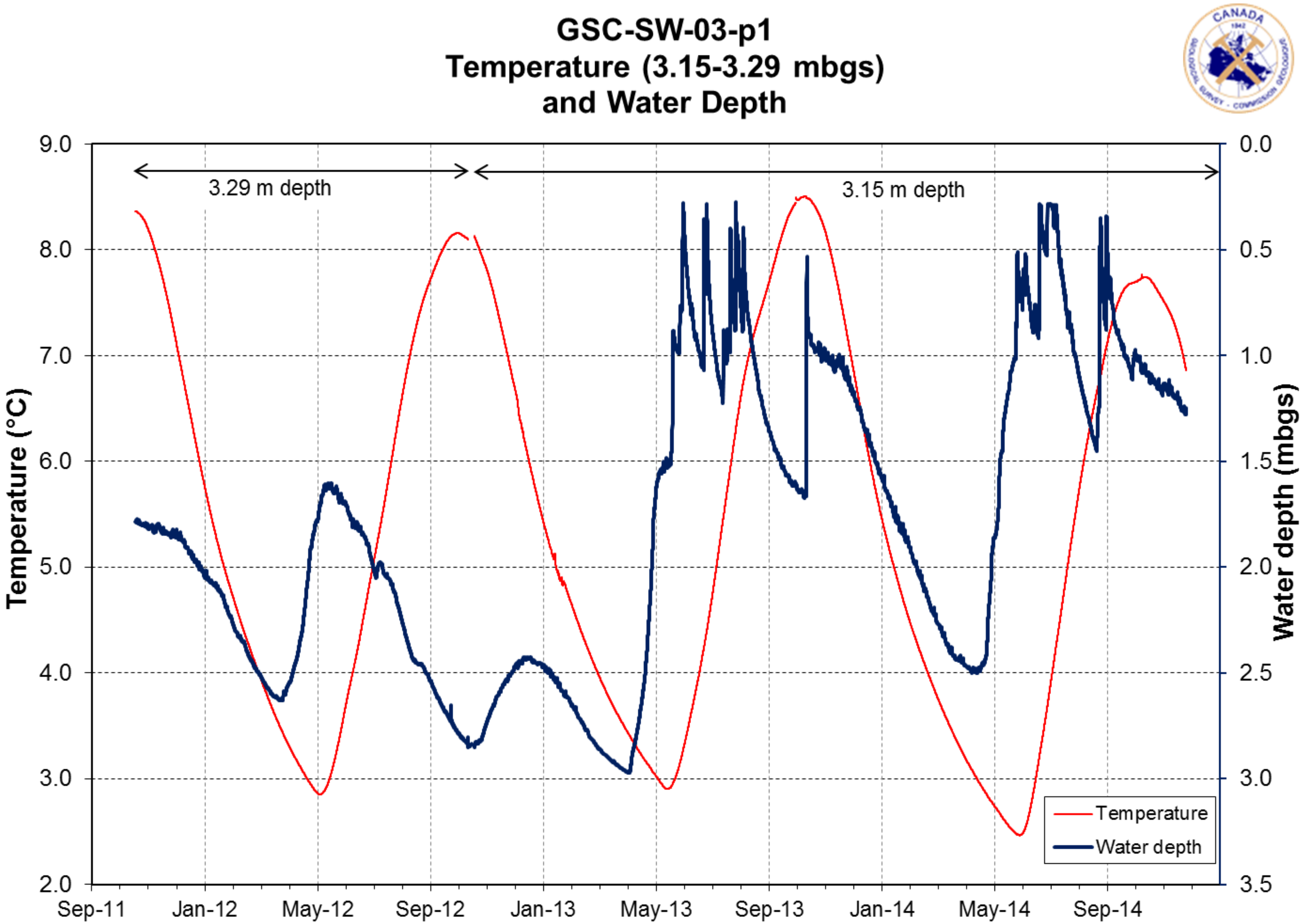


Figure 35. Groundwater temperature and water depth, GSC-SW-03-p2.

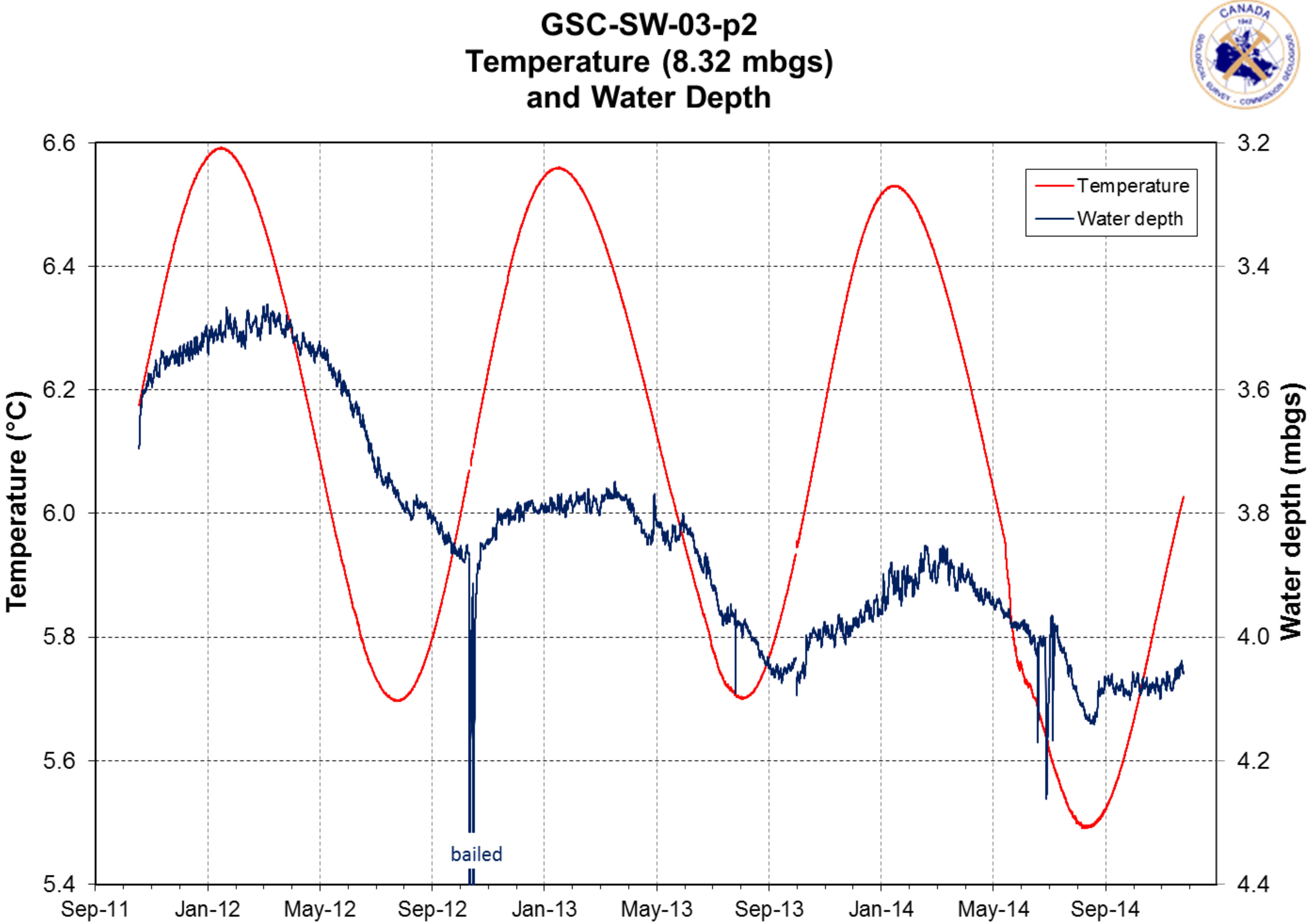


Figure 36. Groundwater temperature and water depth, GSC-SW-04-p1.

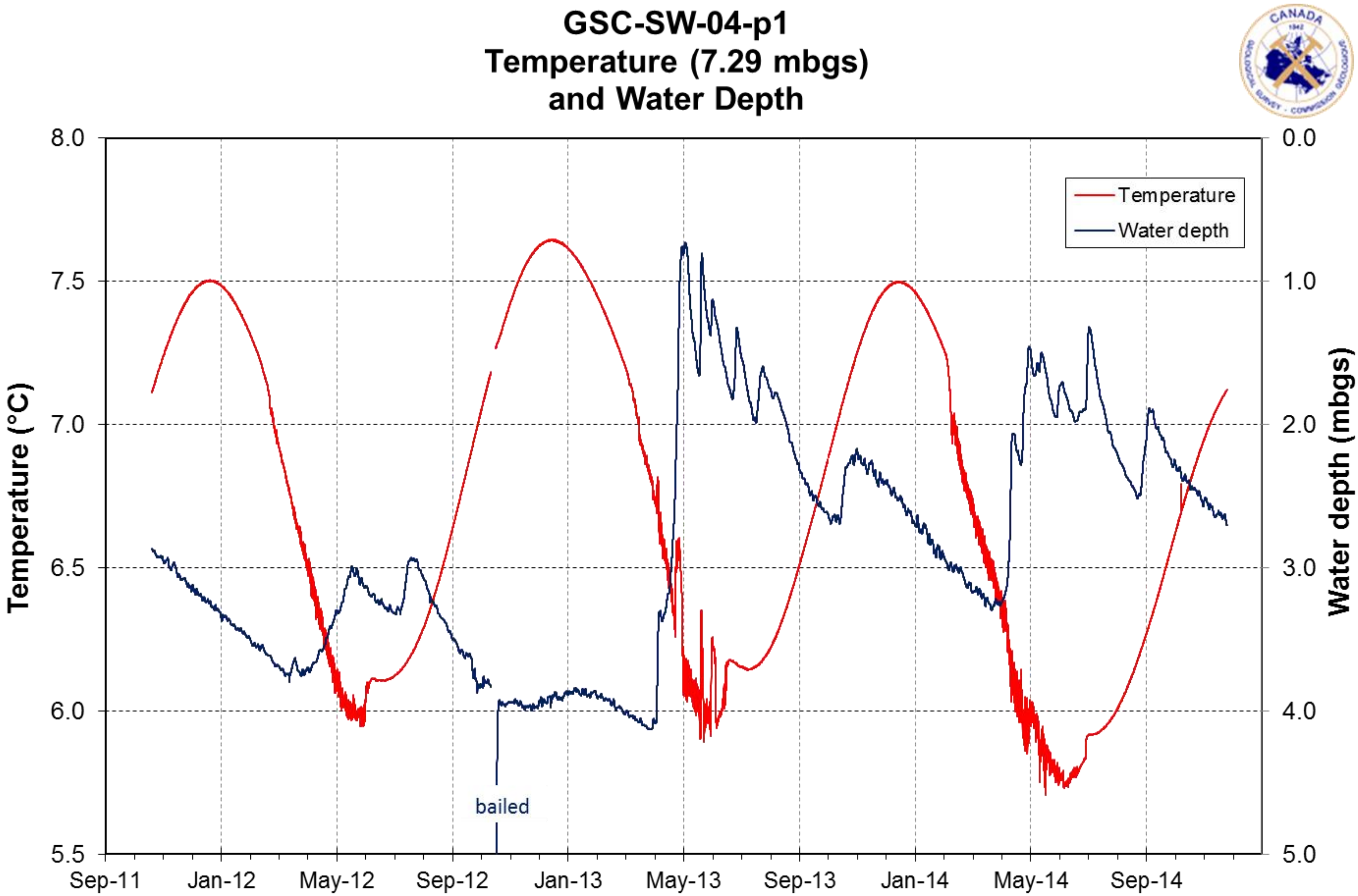


Figure 37. Groundwater temperature and water depth, GSC-SW-04-p2.

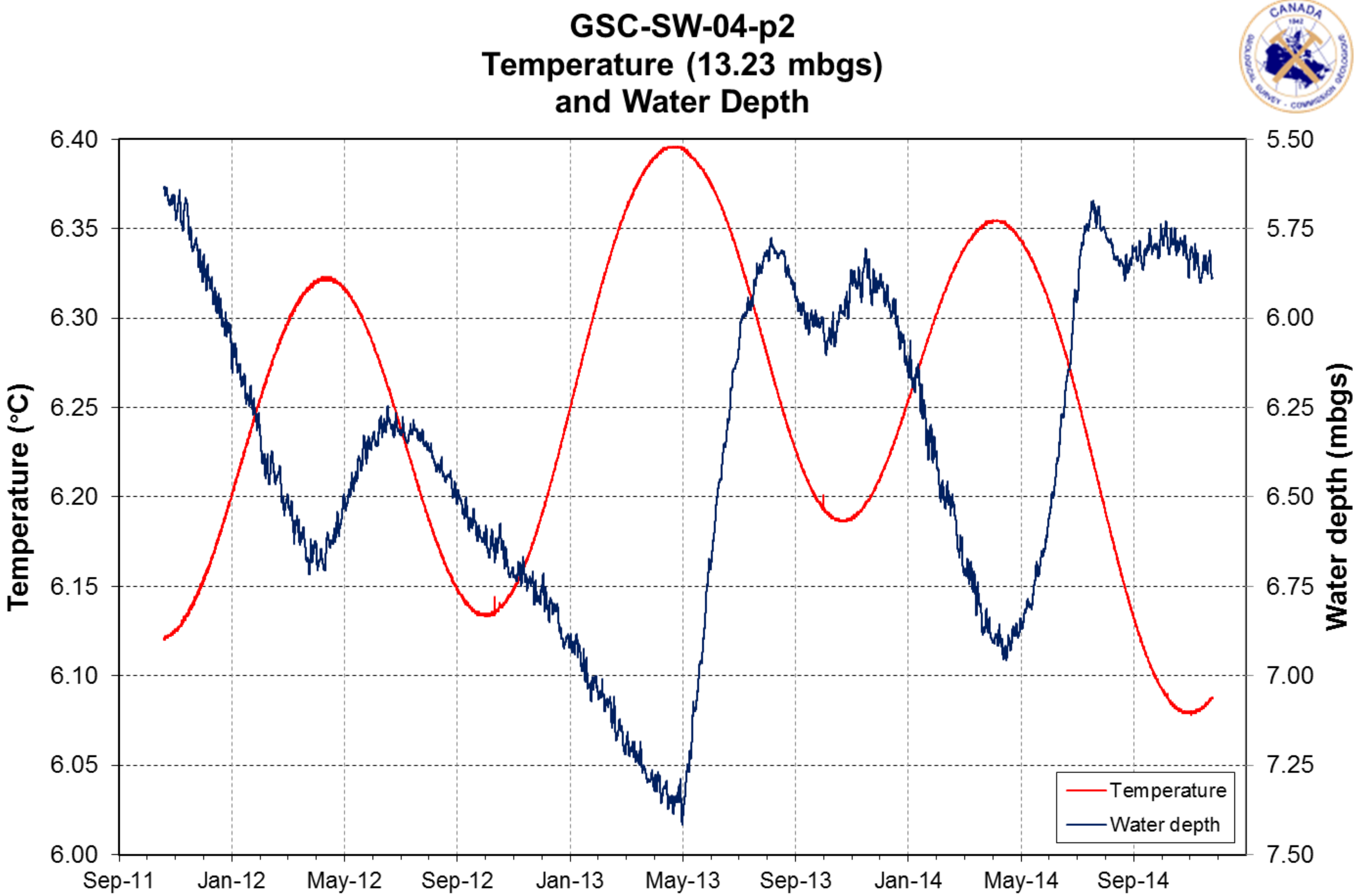


Figure 38. Groundwater temperature and water depth, GSC-SW-07-p1.

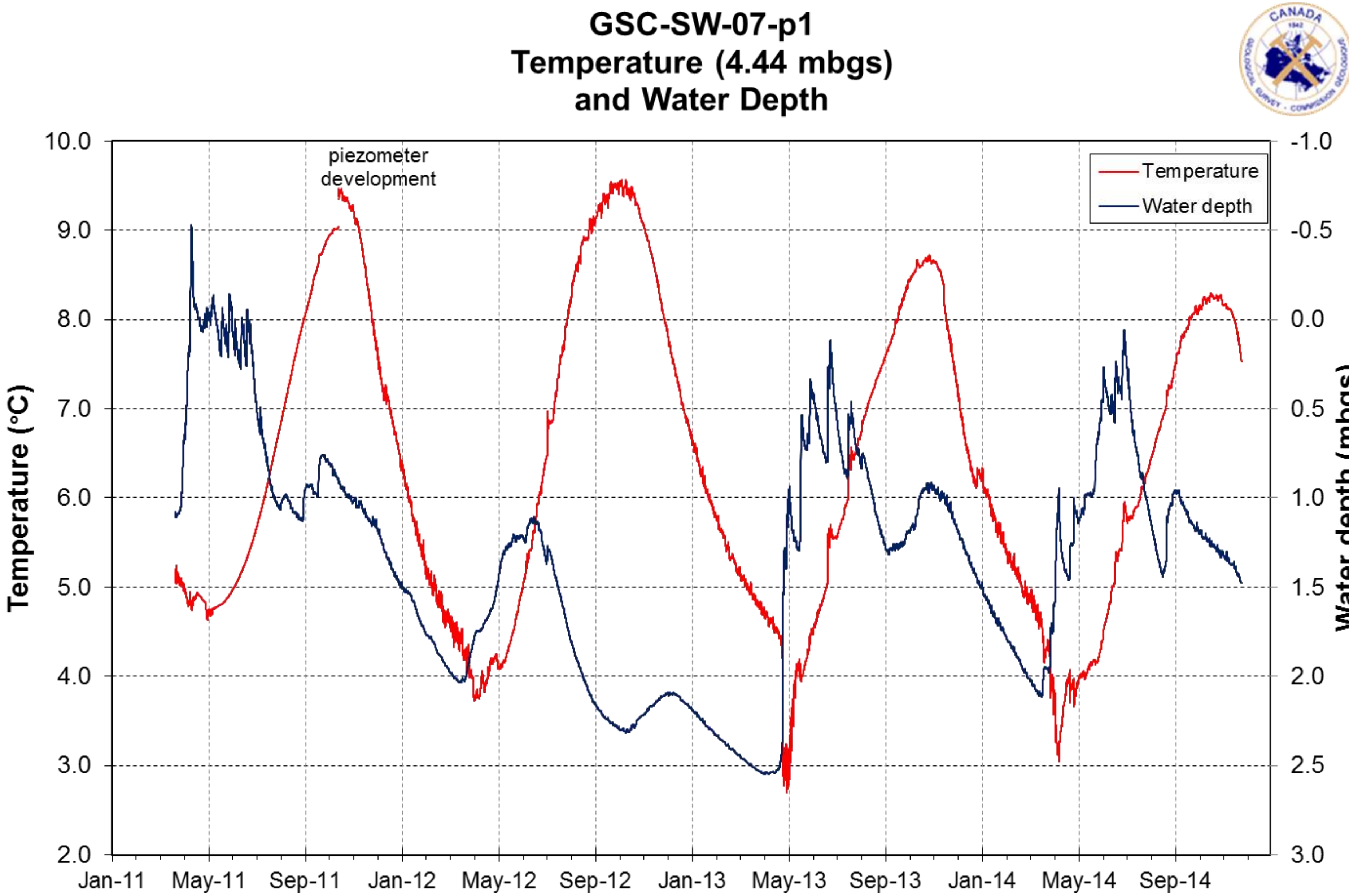
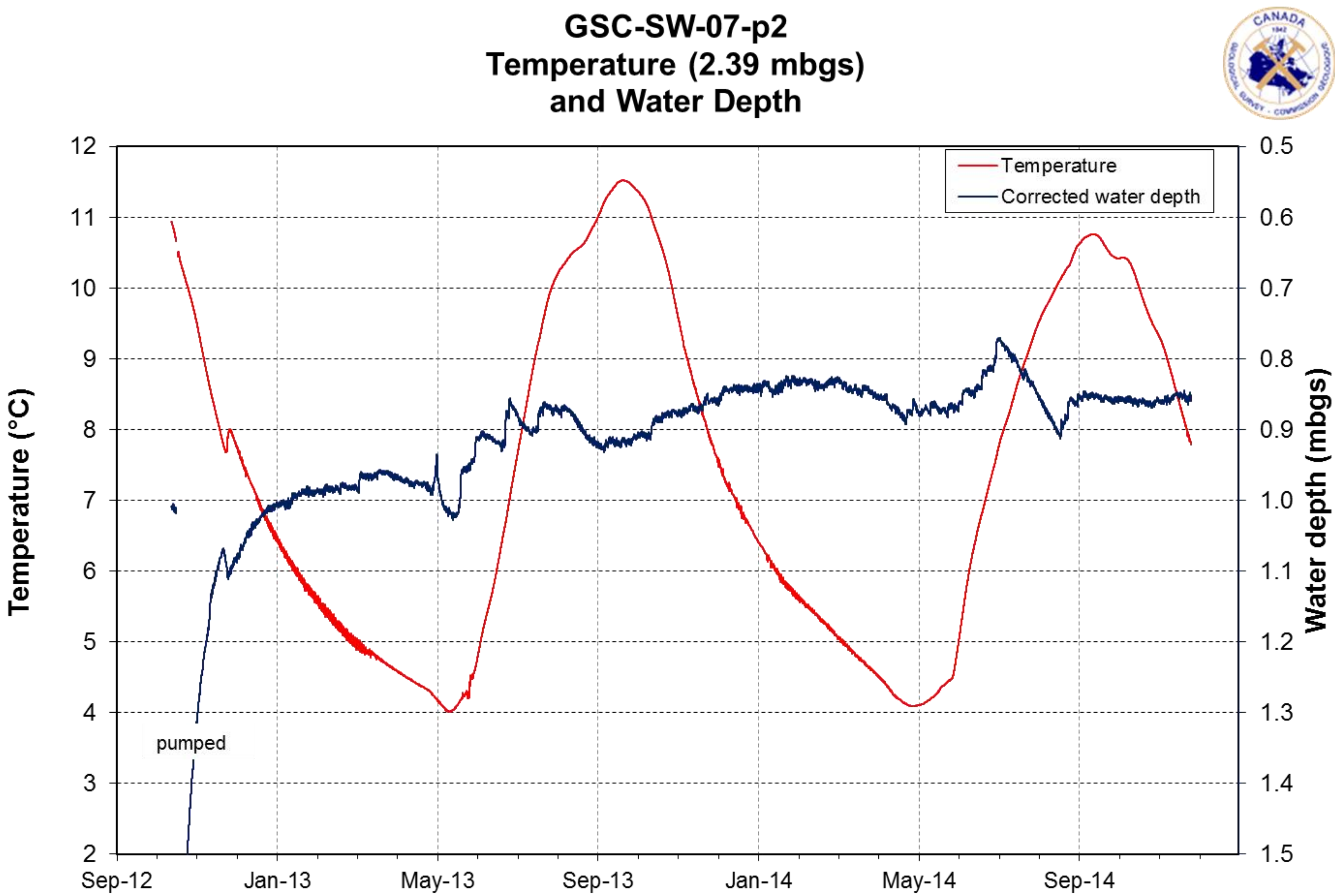


Figure 39. Groundwater temperature and water depth, GSC-SW-07-p2.



Tables

Table 1. Surveyed piezometer locations, and top of casing (TOC) elevations.

GSC piezometer ID	UTM E NAD83, Zone 14	UTM W NAD83, Zone 14	Quarter section	Elevation of top of PVC casing (masl)
GSC-SW-02-p1	457407.457	5455732.399	SW-33-3-16-W1	470.463
GSC-SW-02-p2	457407.521	5455733.882	SW-33-3-16-W1	470.465
GSC-SW-03-p1	445875.127	5467231.145	SE-6-5-17-W1	468.178
GSC-SW-03-p2	445875.168	5467231.140	SE-6-5-17-W1	468.120
GSC-SW-04-p1	468203.059	5443940.314	NW-21-2-15-W1	470.937
GSC-SW-04-p2	468204.519	5443940.391	NW-21-2-15-W1	470.944
GSC-SW-07-p1	478596.030	5429099.325	NW-4-1-14-W1	464.871
GSC-SW-07-p2	478597.815	5429099.165	NW-4-1-14-W1	464.923

Note: UTM locations differ slightly from those published in Hinton and Sharpe (2014) and Crow et al. (2012) because the wells were subsequently re-surveyed for location and elevation by Manitoba CWS.

Table 2. Piezometer installation data.

GSC piezometer	Stick up (mags)	Depth to screen top (mbgs)	Depth to screen bottom (mbgs)	Mid-screen depth (mbgs)	Screen length (m)	Total casing depth (mbgs)
GSC-SW-02-p1	0.737	1.25	2.75	2.00	1.50	2.76[a]
GSC-SW-02-p2	0.771	9.43	10.40	9.92	0.97	10.38[a]
GSC-SW-03-p1	0.690	2.80	3.50	3.15	0.70	3.56[a]
GSC-SW-03-p2	0.690	31.96	34.95	33.46	2.99	35.01[a]
GSC-SW-04-p1	0.730	4.51	7.50	6.01	2.99	7.52[a]
GSC-SW-04-p2	0.767	11.85	14.85	13.35	3.00	14.85[a]
GSC-SW-07-p1	0.821	1.59	4.59	3.09	3.00	4.64
GSC-SW-07-p2	0.961	87.83	90.88	89.36	3.05	96.98

Note: [a]Correction from Hinton and Sharpe (2014); calculated from total casing length at installation rather than from measured depth to bottom based on a tag line because soft sediment was not penetrated in one instance. Total casing depth beneath ground surface equals total length of casing minus stick up.

Table 3. Piezometer development and Levelogger deployment dates.

Piezometer	Date developed	Deployment start date	Comments
GSC-SW-02-p1	4 Nov 2010	4 Nov 2010	
GSC-SW-02-p2	4 Nov 2010	4 Nov 2010	
GSC-SW-03-p1	16 Oct 2011	16 Oct 2011	
GSC-SW-03-p2	16 Oct 2011	16 Oct 2011	
GSC-SW-04-p1	17 Oct 2011	17 Oct 2011	
GSC-SW-04-p2	17 Oct 2011	17 Oct 2011	
GSC-SW-07-p1	15 Oct 2011	23 Mar 2011	
GSC-SW-07-p2	23 Mar 2011	15 Oct 2011	Developed by air lifting. Did not measure during first deployment from 15 Oct 2011-11 Oct 2012 due to a programming error.

Table 4. Manual water level data, site GSC-SW-02

	Depth to water from measuring point (m)		Groundwater elevation (masl)		Depth below ground surface (m)		Notes
Date-time (CST)	GSC-SW-02-p1	GSC-SW-02-p2	GSC-SW-02-p1	GSC-SW-02-p2	GSC-SW-02-p1	GSC-SW-02-p2	
4-Nov-2010 08:30	1.147	5.016	469.316	465.449	0.410	4.245	-p2 recovering from drilling. Then both piezometers developed.
14-Oct-2011 15:45	2.020	1.799	468.443	468.666	1.283	1.028	
17-Oct-2011 07:07	2.028	1.817	468.435	468.648	1.291	1.046	
11-Oct-2012 10:28	2.401	2.317	468.062	468.148	1.664	1.546	
12-Oct-2012 16:02	2.880	2.453	467.583	468.012	2.143	1.682	recovering from bail tests
17-Oct-2012 11:30							Visited site but did not measure, CWS still sampling. Sampling completed on 18-Oct-2012.
1-Oct-2013 08:33	1.614	1.759	468.849	468.706	0.877	0.988	
25-Nov-2014 11:38	1.737	1.736	468.726	468.729	1.000	0.965	
25-Nov-2014 13:18	1.739	1.746	468.724	468.719	1.002	0.975	
26-Nov-2014 09:24	1.753	1.768	468.710	468.697	1.016	0.997	

Note: measuring point is top of PVC.

Table 5. Manual water level data, site GSC-SW-03

	Depth to water from measuring point (m)		Groundwater elevation (masl)		Depth below ground surface (m)		Notes
Date-time (CST)	GSC-SW-03-p1	GSC-SW-03-p2	GSC-SW-03-p1	GSC-SW-03-p2	GSC-SW-03-p1	GSC-SW-03-p2	
16-Oct-2011 13:25	2.470	4.290	465.708	463.830	1.780	3.600	
11-Oct-2012 08:40	3.535	4.592	464.643	463.528	2.845	3.902	
17-Oct-2012 10:48	3.511	4.763	464.667	463.357	2.821	4.073	
30-Sep-2013 13:10	2.282	4.747	465.896	463.373	1.592	4.057	
1-Oct-2013 08:03	2.302	4.719	465.876	463.401	1.612	4.029	
25-Nov-2014 08:41	1.978	4.780	466.200	463.340	1.288	4.090	
25-Nov-2014 10:50	1.980	4.775	466.198	463.345	1.290	4.085	
26-Nov-2014 08:45	2.006	4.766	466.172	463.354	1.316	4.076	
26-Nov-2014 09:06		4.764		463.356		4.074	

Table 6. Manual water level data, site GSC-SW-04.

	Depth to water from measuring point (m)		Groundwater elevation (masl)		Depth below ground surface (m)		Notes
Date-time (CST)	GSC-SW-04-p1	GSC-SW-04-p2	GSC-SW-04-p1	GSC-SW-04-p2	GSC-SW-04-p1	GSC-SW-04-p2	
15-Oct-2011 13:03	3.567	6.427	467.370	464.517	2.837	5.660	-p1 and -p2 pumped after measurements
17-Oct-2011 08:35	3.959	6.449	466.978	464.495	3.229	5.682	-p1 still recovering when measured
11-Oct-2012 14:10	4.565	7.530	466.372	463.414	3.835	6.763	
13-Oct-2012 15:24	4.734	7.485	466.203	463.459	4.004	6.718	-p1 recovering from bail test
17-Oct-2012 12:06	5.746	7.435	465.191	463.509	5.016	6.668	CWS finished sampling 16-Oct-2012. -p1 still recovering when measured
1-Oct-2013 10:25	3.353	6.848	467.584	464.096	2.623	6.081	
25-Nov-2014 14:20	3.430	6.773	467.507	464.171	2.700	6.006	
25-Nov-2014 15:30	3.436	6.776	467.501	464.168	2.706	6.009	
26-Nov-2014 10:12	3.217	6.830	467.720	464.114	2.487	6.063	-p1 still recovering from slug test

Table 7. Manual water level data, site GSC-SW-07

	Depth to water from measuring point (m)		Groundwater elevation (masl)		Depth below ground surface (m)		Notes
Date-time (CST)	GSC-SW-07-p1	GSC-SW-07-p2	GSC-SW-07-p1	GSC-SW-07-p2	GSC-SW-07-p1	GSC-SW-07-p2	
23-Mar-2011 09:45	2.004		462.867		1.183		-p1 recovered overnight after drilling and installation
15-Oct-2011 08:10	1.765		463.106		0.944		measured before-p1 developed, water muddy
15-Oct-2011 10:10		1.560		463.363		0.599	measured before -p2 was pumped out with submersible pump
16-Oct-2011 07:30	1.790	2.161	463.081	462.762	0.969	1.200	bail tested, packer installed in -p2 after measurement
17-Oct-2011 07:07	1.791		463.080		0.970		
11-Oct-2012 16:30	3.191		461.680		2.370		
16-Oct-2012 09:30	3.195	1.980	461.676	462.943	2.374	1.019	Removed packer from -p2 and let recover, sampled later this day by CWS
17-Oct-2012 12:45	3.179	3.118	461.692	461.805	2.358	2.157	put packer back in -p2, CWS finished sampling 16-Oct-2012
1-Oct-2013 12:30	2.058		462.813		1.237		left packer in -p2
25-Nov-2014 16:10	2.367		462.504		1.546		left packer in -p2

Table 8. Average groundwater temperatures.

Piezometer	Measurement depth (m)	Period of monitoring	Average temperature (°C)	Temperature range (°C)	Comments
GSC-SW-02-p1	2.49	4Nov2010 – 25Nov2014	6.64	2.82 – 11.20	
GSC-SW-02-p2	8.23	4Nov2010 – 25Nov2014	5.83	5.06 - 6.76	Downward trend
GSC-SW-03-p1	3.15 - 3.29	16Oct2011 – 25Nov2014	5.46	2.46 – 8.69	Change in logger depth in October 2012
GSC-SW-03-p2	8.32	16Oct2011 – 25Nov2014	6.10	5.49 – 6.92	
GSC-SW-04-p1	7.29	17Oct2011 – 25Nov2014	6.73	5.71 – 7.65	Responds to spring melt
GSC-SW-04-p2	13.23	17Oct2011 – 25Nov2014	6.25	6.08 – 6.40	
GSC-SW-07-p1	4.44	23Mar2011– 25Nov2014	6.37	2.70 – 9.57	Responds to spring melt. Sudden change after well development.
GSC-SW-07-p2	2.39	11Oct2012 – 25Nov2014	7.36	4.01-11.52	

Appendices

Appendix A: Photographs

Photographs illustrate piezometer installations, their relative placements and local topographic and drainage conditions.

Photograph A1. Site GSC-SW-02 showing slight ditch in which piezometers are located. Piezometers from left to right: CWS well G05OA010, GSC-SW-02-p2, GSC-SW-02-p1. Photograph taken 26 November 2014, facing northeast.

Photograph A2. Site GSC-SW-03. Piezometers from left to right: GSC-SW-03-p1, GSC-SW-03-p2, CWS well G05OA009. Photograph taken 26 November 2014, facing north.

Photograph A3. Ditch facing east from site GSC-SW-03. Loading station well in the distance. Photograph taken 26 November 2014.

Photograph A4. Site GSC-SW-04. Piezometers from left to right: CWS well G05OA008, GSC-SW-04-p2, GSC-SW-04-p1. Photograph taken 26 November 2014, facing southeast.

Photograph A5. Charles Logan retrieving Levelogger from piezometer GSC-SW-04-p1 for download. Note two cables in piezometer: one for the Levelogger, the other for the Barologger. Photograph taken 26 November 2014, facing southwest.

Photograph A6. Piezometer GSC-SW-07-p2 with the packer installed. Photograph taken 1 October 2013.

Photograph A7. Site GSC-SW-07 showing swale/ditch in which piezometers are located. Piezometers from left to right: GSC-SW-07-p2, GSC-SW-07-p1. Photograph taken 1 October 2013, facing west.

Photograph A8. Heavy snowfall during the winter of 2010-11 completely filled the swale/ditch at site GSC-SW-07 and required snow removal prior to drilling. Photograph taken 16 March 2011, facing west.

Photograph A9. Swale/ditch along the roadside at site GSC-SW-07. Photograph taken 1 October 2013, facing east.

Photograph A10. Swale/ditch along the roadside at site GSC-SW-07 prior to drilling and piezometer installation. Photograph taken 3 November 2010, facing west approximately 15 m east of the eventual drilling location.

Appendix B: Barometric levels

Figure B1. Barometric levels GSC-SW-02.

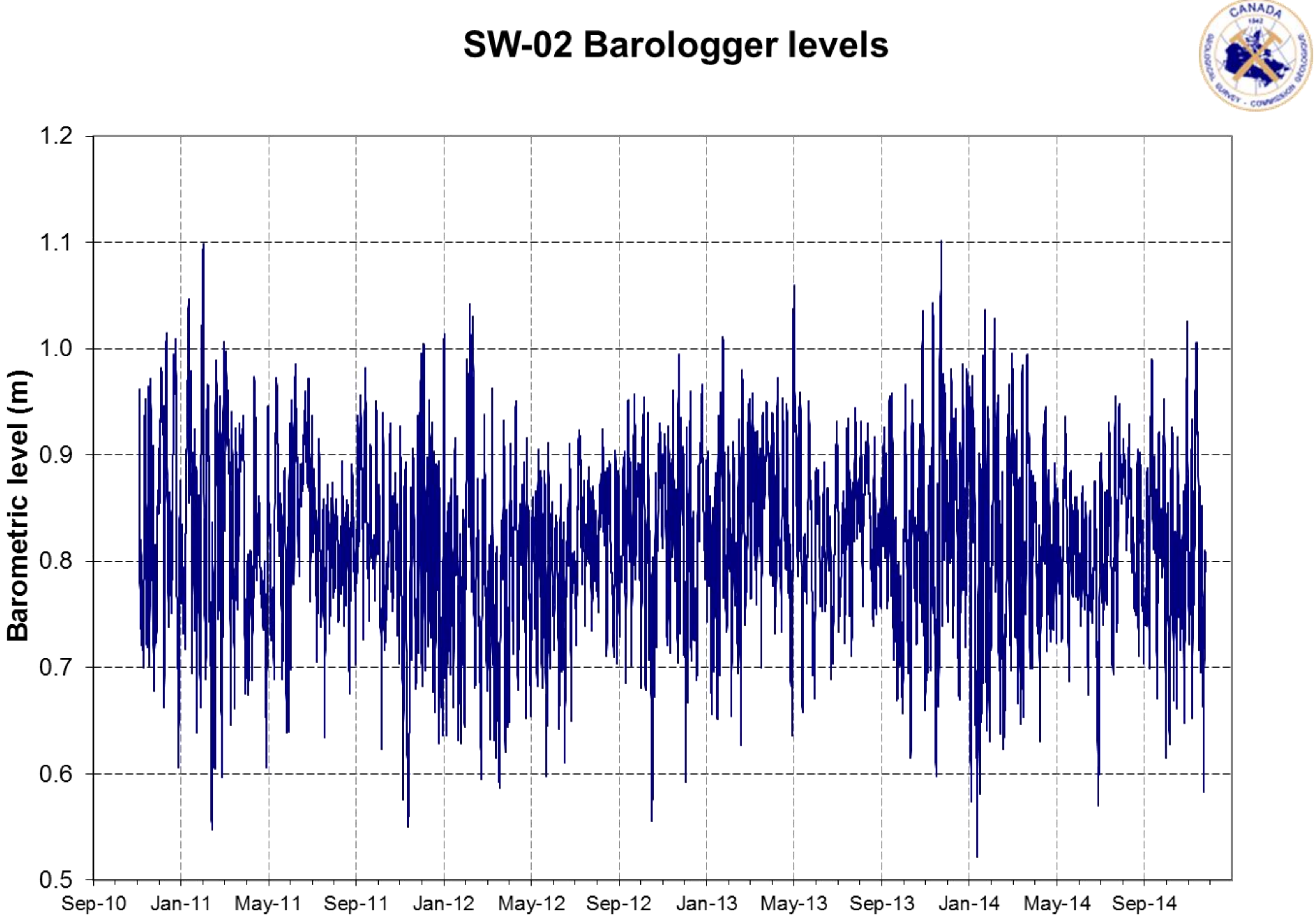


Figure B2. Barometric levels GSC-SW-03.

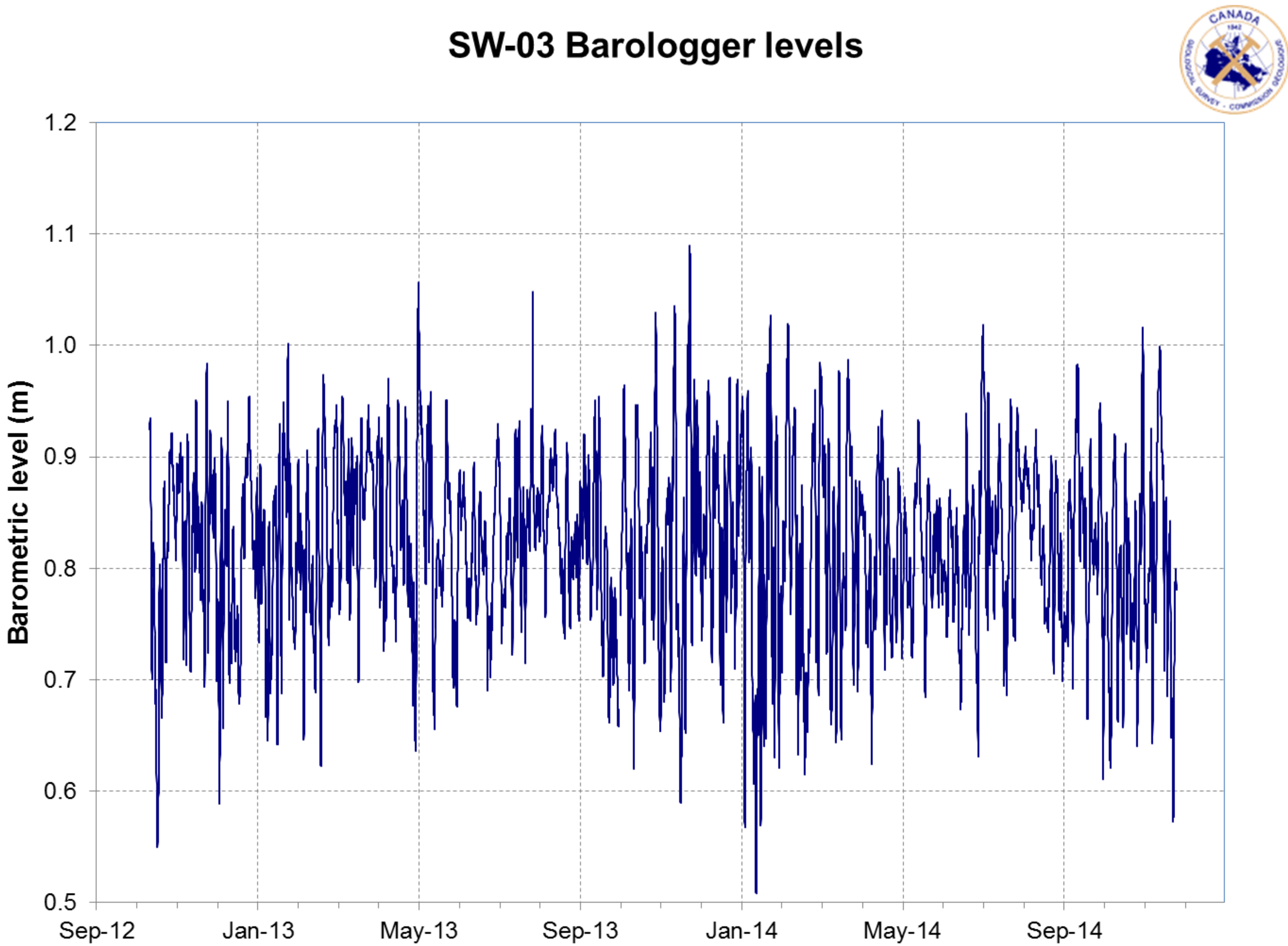


Figure B3. Barometric levels GSC-SW-04.

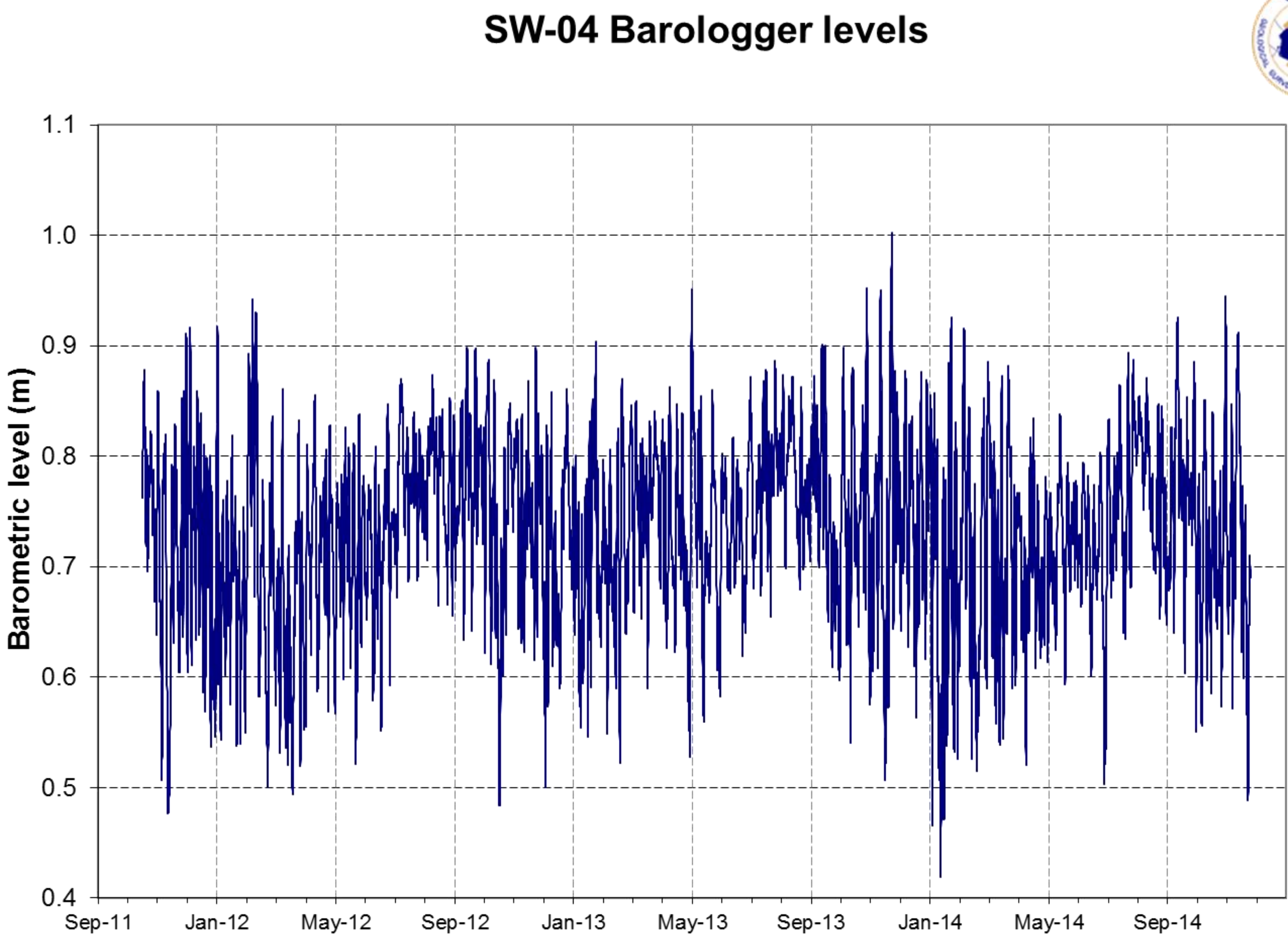


Figure B4. Barometric levels GSC-SW-07.