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Data compilation and analysis for the description of the access area of the planned spent fuel repository in Forsmark – meteorology, hydrology and near-surface hydrogeology

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Keywords: Forsmark, Access area, Meteorology, Hydrology, Hydrogeology.

This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

Data in SKB's database can be changed for different reasons. Minor changes in SKB's database will not necessarily result in a revised report. Data revisions may also be presented as supplements, available at www.skb.se.

Summary

This is a background report for a multidisciplinary description of the access area of the planned spent fuel repository in Forsmark. As a contribution to the overall understanding of this part of the repository, the objective is to gather and analyse meteorological, hydrological and near-surface hydrogeological data, acquired posterior to the site investigation for SDM-Site. The report summarises the understanding of the hydrology and near-surface hydrogeology of Forsmark, as presented in SDM-Site. Moreover, the report presents and analyses post SDM-Site data for the access area, in terms of hydraulic properties of the regolith and the rock/regolith interface, meteorology and ice freeze/breakup times, surface-water levels, and groundwater levels in regolith and upper rock.

The findings from the evaluation of data gathered subsequently to SDM-Site, in and in the vicinity of the access area, do not contradict overall SDM-Site findings related to the hydrology and near-surface hydrogeology of the Forsmark area. Potentially important characteristics of the access area and its environs are the occurrence of coarse-grained, easily-drained artificial fill, and the proximity of the Forsmark nuclear power plant and the sea.

The average groundwater table is located at relatively large depths in some wells, possibly due to the presence of easily-drained fill. Groundwater flow is directed both from inland areas towards the coastline, and from regolith to rock. There is low or no correlation between the groundwater level in the upper part of the rock and the local topography, likely due to near-surface sheet joints with hydraulic connections to the sea. The average groundwater level in one of the percussion-drilled boreholes (HFM41), located north of the cooling-water canal, is below sea level, possibly due to the groundwater drainage below the reactor buildings of the Forsmark nuclear power plant.

Based on the findings of the report, it is recommended that the need for additional groundwater-monitoring wells for design and follow-up on the rock dump and subsurface accesses of the spent fuel repository is investigated. Moreover, there is a general need for further data and information on hydrogeological and other properties of the rock/regolith interface and the near-surface rock. This need motivates further drilling and investigation of short boreholes in rock equipped with short casings.

Sammanfattning

Detta är en underlagsrapport för en multidisciplinär beskrivning av tillfartsområdet för det planerade Kärnbränsleförvaret i Forsmark. Rapporten bidrar till den övergripande förståelsen av denna del av Kärnbränsleförvaret, genom sammanställning och analys av data inom meteorologi, hydrologi och ytnära hydrogeologi, insamlade efter platsundersökningen för SDM-Site.

Rapporten sammanfattar förståelsen av hydrologi och ytnära hydrogeologi utifrån beskrivningen i SDM-Site. Vidare presenterar och analyserar rapporten data rörande tillfartsområdet, insamlade efter SDM-Site, i termer av hydrauliska egenskaper i jord och i övergången mellan berg och jord, meteorologi och tider för isläggning/islossning, ytvattennivåer samt grundvattennivåer i jord och den övre delen av berget.

Utvärderingen av data insamlade efter SDM-Site, inom och i anslutning till tillfartsområdet, motsäger inte den övergripande förståelsen av Forsmarksområdets hydrologi och ytnära hydrogeologi. Potentiellt viktiga förhållanden i tillfartsområdet och dess omgivningar är förekomst av grovkornig, lättdränerad fyllning, samt närheten till Forsmarks kärnkraftverk och havet.

Grundvattenytan är i medeltal belägen på relativt stort djup i några grundvattenrör, möjligen på grund av den lättdränerade fyllningen. Grundvattenflödet är riktat från landområden mot havet, men också från jord till berg. Det finns endast svag eller ingen korrelation mellan grundvattennivån i den övre delen av berget och den lokala topografin, sannolikt som en effekt av ytnära bankningsplan som hydrauliskt är kopplade mot havet. I ett av de hammarborrade hålen (HFM41), beläget norr om kylvattenkanalen, är grundvattennivån i medeltal under havets nivå, möjligen på grund av grundvattendräneringen under kärnkraftverkets reaktorbyggnader.

Baserat på slutsatserna i rapporten rekommenderas undersökning av behovet av ytterligare grundvattenrör, för projektering och uppföljning av Kärnbränsleförvarets bergupplag och tillfarter. Vidare finns ett generellt behov av ytterligare data och information rörande hydrogeologiska och andra egenskaper i övergången mellan berg och jord och i de övre delarna av berget. Detta behov motiverar kompletterande borrning och undersökning av korta borrhål med korta foderrör.

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) has undertaken site characterisation with the objective of siting a spent nuclear fuel repository in Forsmark, Mideastern Sweden. Moreover, SKB has undertaken site characterisation at Forsmark for the siting of an extension of the existing repository for radioactive operational waste, SFR. The associated site-descriptive models are referred to as SDM-Site (SKB 2008) and SDM-PSU (SKB 2013) for the spent fuel repository and the SFR extension, respectively.

This report is a background report for a multidisciplinary description of the access area of the planned spent fuel repository (Figure 1-1). The objective of the access area description is to gather and analyse post SDM-Site data and thereby advance the overall understanding of this part of the repository. Among other disciplines, the main report (Follin 2018) includes a description of meteorology and the hydrology and near-surface hydrogeology of the access area and its surroundings (Figure 1-2). The present report provides a comprehensive presentation of data and data interpretations to support the findings and conclusions presented in the main report.

This report concerns hydrogeological properties data from regolith and the rock/regolith interface, and meteorological, hydrological and near-surface hydrogeological monitoring data that were collected subsequently to SDM-Site. Specifically, monitoring data and interpretation of such data are important as a background for understanding of the access area and interactions with its surroundings, design of surface and subsurface facilities, and assessment of environmental impacts during construction and operation of the spent fuel repository and SFR.

Specifically, planned activities and facilities in and in the vicinity of the access area include infilling of ponds and diversion of displaced surface water, upfilling of land areas, excavations and foundations for e.g. buildings and a rock dump, construction of bridge abutments, construction, reinforcement and grouting of subsurface accesses (ramp and shafts), and systems for handling of rock-dump leachates and storm water. Hence, monitoring data are of importance for design, planning and follow-up on specific construction activities and facility parts, and also for follow-up on environmental impacts in the surroundings.

Figure 1-1. *Schematic view of the access area and its surroundings (Follin 2018).*

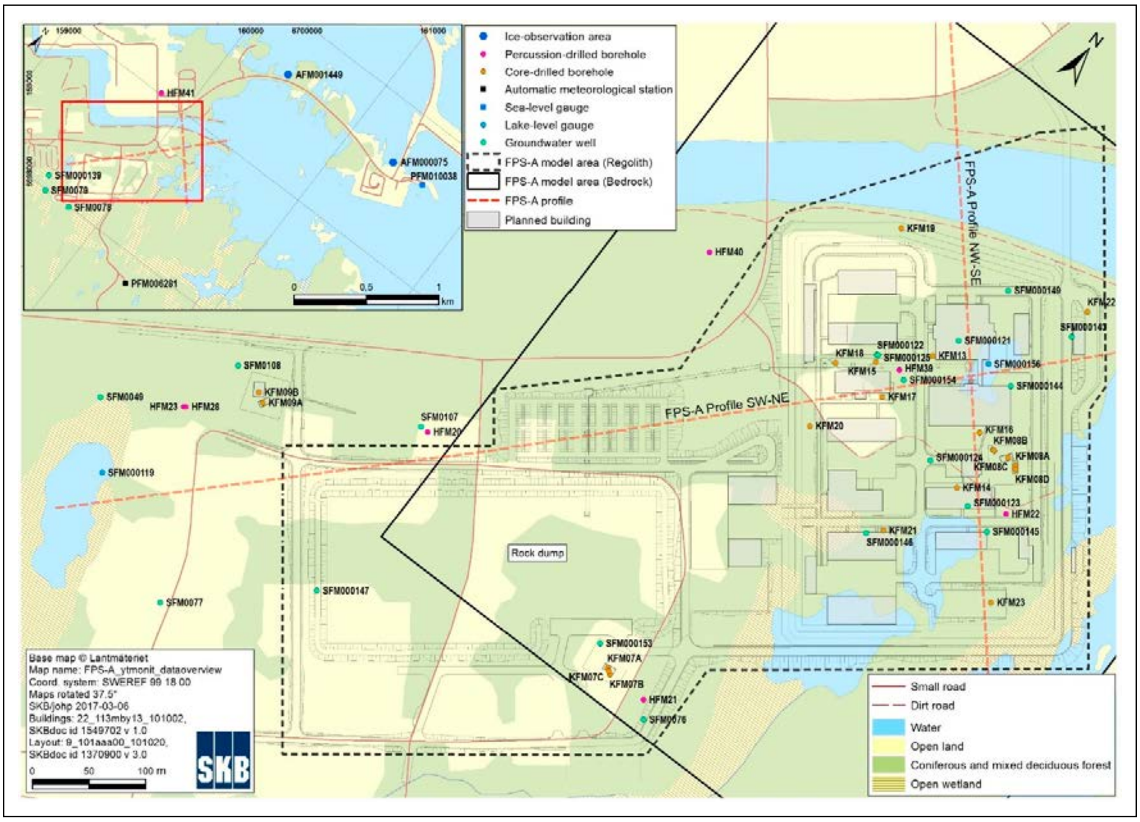


***Figure 1-2.** Planned buildings and rock dump, displayed on a background map showing present-day land use and locations of wells, gauges, meteorological stations and ice freeze/breakup observations in and around the access area. The map also shows the horizontal extents of the two SW–NE and NW–SE cross sections discussed in Chapter 4. The solid and dashed black lines represent "model areas" for geoscientific descriptions of the rock and the regolith, respectively (Follin 2018).*

Coordinates are in this report given in the coordinate systems SWEREF 99 18 00 (X,Y) and RHB 70 (Z), i.e. vertical (Z) coordinates are expressed in terms of elevation above the RHB 70 datum (0 m elevation). All presented and interpreted monitoring data are stored in SKB's Sicada database (Sicada delivery SKBdata_17_050). Unless stated otherwise, interpretations are based on daily sums or averages (time zone GMT+1, no DST), calculated from data with high temporal resolution (typically between 0.5 and 2 hours).

2 Summary of the hydrology and near-surface hydrogeology of the Forsmark area

This chapter provides a brief overview of the current understanding of the hydrology and near-surface hydrogeology of the Forsmark area, as presented in the SDM-Site modelling stage (Lindborg 2008, SKB 2008). The overview is focused on the following issues, for which additional data are available for the description of the access area (see Chapter 3):

- Hydraulic properties of the regolith and the rock/regolith interface.
- Groundwater in regolith: Groundwater levels and depths below ground surface, and the relations between groundwater level/depth and the local topography.
- Relations between groundwater levels in regolith and surface-water levels.
- Groundwater levels in the upper part of the rock: Relations with groundwater levels in regolith, topography and sea level.

At the SDM-Site modelling stage the following data, gathered up to up to the Forsmark 2.3 data freeze (March 31, 2007; Johansson and Öhman 2008), were available for the access area and its close surroundings (cf. Figure 1-2):

- **Hydrogeological properties of the regolith and the rock/regolith interface:** Hydraulic conductivity data obtained from single-hole (slug) tests and by estimations based on PSD (particle-size distribution) curves for regolith sampled during drilling of wells SFM0049, SFM0107 and -0108.
- **Meteorological monitoring:** Meteorological data from the Högmasten meteorological station (PFM010700), and also from the Storskäret (PFM010701) meteorological station (decommissioned in June 2007), from May 2003 up to the Forsmark 2.3 data freeze.
- **Monitoring of ice freeze/breakup:** Observations of ice freeze/breakup times in the nearby sea bay (AFM000075), from the 2002/2003 winter season to the 2006/2007 winter season.
- **Ground- and surface-water level monitoring:** Ground- and surface-water level data from groundwater-monitoring wells (SFM0049, SFM0076–79 and SFM0107) and the sea-level gauge PFM010038, up to the Forsmark 2.3 data freeze. The SFM0049 and PFM010038 monitoring was initiated in May 2003. Monitoring started in October 2005 at wells SFM0077–79 and in June 2006 at well SFM0107. SFM0076 was only monitored during a few weeks in 2005. Moreover, the Forsmark 2.3 data freeze includes groundwater level data from 15 percussion-drilled and core-drilled boreholes in and in the vicinity of the access area.

The dataset summarised above is presented, evaluated and utilised for site-descriptive modelling of hydrology and near-surface hydrogeology by Bosson et al. (2008), Johansson (2008) and Johansson and Öhman (2008). The map in Figure 2-1, produced as part of SR-PSU (Sohlenius et al. 2013), shows the surface distribution of regolith in the access area whereas the map in Figure 2-2 is an update based on post SDM-Site investigations (Follin 2018). Till is the dominant regolith type in the Forsmark area, whereas the regolith in large parts of the access area and its environs consists of artificial fill (Figure 2-3), especially along the cooling-water canal. The artificial fill, the extent of which is larger in the recently produced map, consists of a mixture of excavated rock and regolith excavated from the sea bottom (Hedenström and Sohlenius 2008). A typical top-to-bottom stratigraphy at lake bottoms is nested layers of gyttja, sand and gravel, and glacial and/or postglacial clay above till (Johansson 2008).

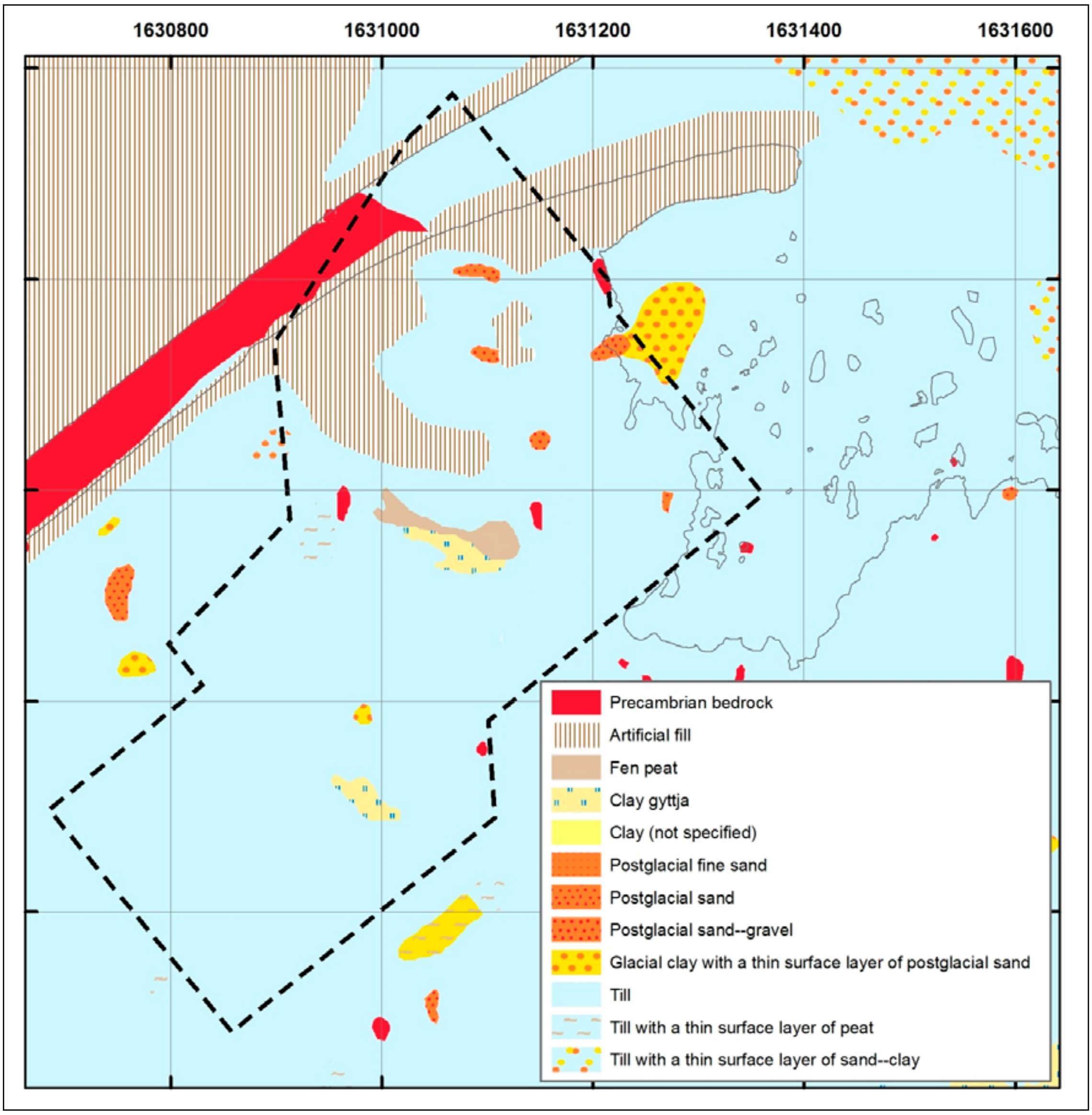


***Figure 2-1.** Surface distribution of regolith, according to the model produced as part of the SR-PSU safety assessment (Sohlenius et al. 2013).*

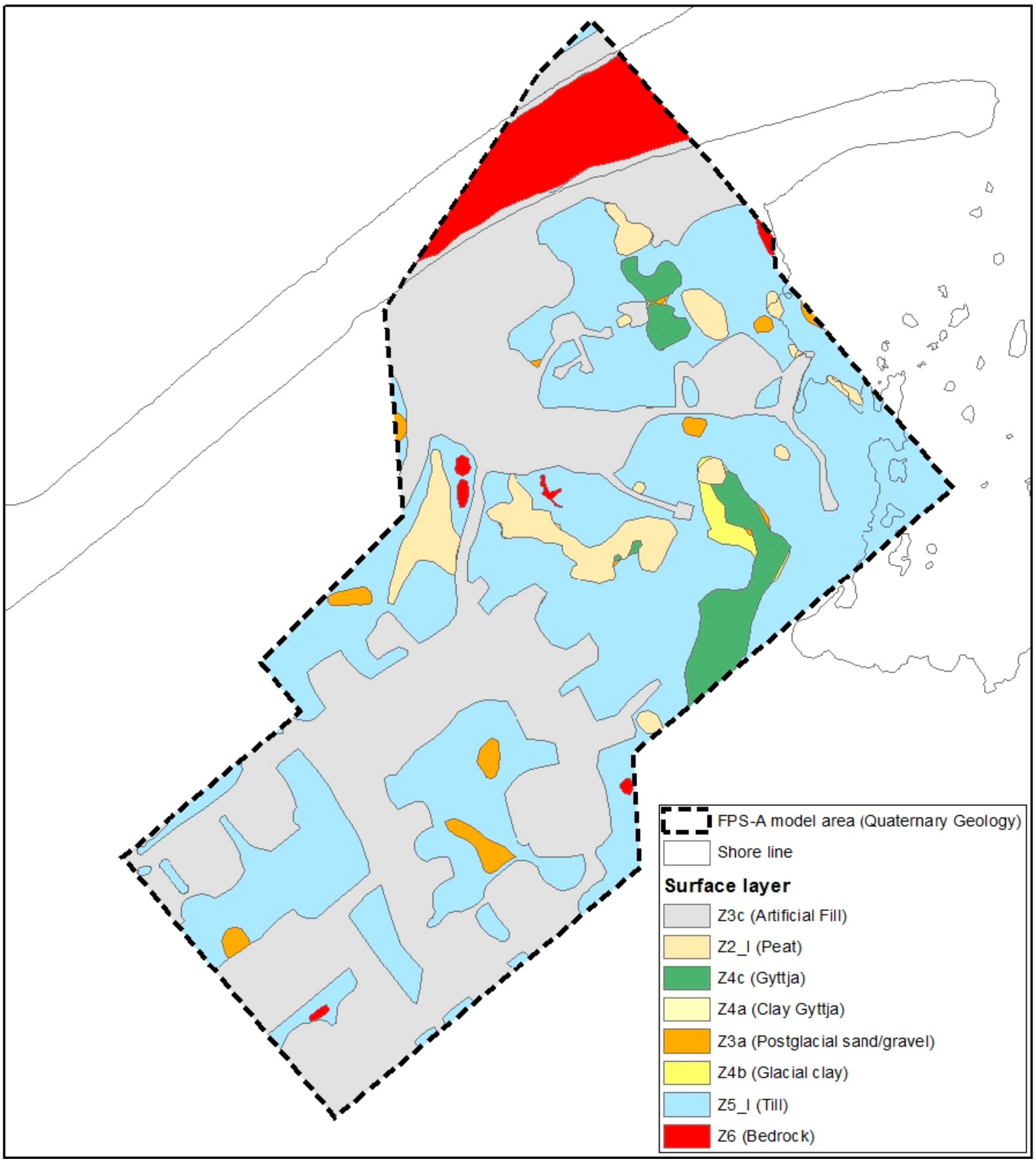


Figure 2-2. *Updated map of the surface distribution of regolith, based on post-SDM-Site investigations and earlier models (Follin 2018).*

Figure 2-3. Photograph of artificial-fill profile in a trench (Hedenström and Sohlenius 2008).

SDM-Site data on the hydraulic conductivity of regolith and the rock/regolith interface are obtained from single-hole (slug) tests and empirical relationships based on PSD (particle-size distribution) curves for regolith samples (Johansson 2008, Hedenström and Sohlenius 2008). The generally assigned horizontal hydraulic conductivity for different types of regolith at the SDM-Site modelling stage is summarised in Table 2-1, whereas Table 2-2 summarises results of slug tests and PSD analyses for wells installed in and in the vicinity of the access area. It should be noted that the screens of all slug-tested wells are located across the rock/regolith interface.

According to Table 2-2, few hydraulic-properties data were available for the access area and its close surroundings at the time of SDM-Site. However, the available data are in close agreement with the general parameterization for the whole Forsmark area (Table 2-1). Hydraulic data show that the vertical hydraulic conductivity of the till at Forsmark is significantly lower than the horizontal conductivity.

Table 2-1. Horizontal hydraulic conductivity of regolith and the rock/regolith interface according to the general SDM-Site parameterisation for the Forsmark area (Johansson 2008).

Regolith type	Horizontal hydraulic conductivity (m/s)
Till, depth < 0.6 m	
Fine and coarse	1.5×10^{-5}
Till, depth > 0.6 m	
Fine	1×10^{-7}
Coarse	1.5×10^{-6}
Rock/till interface	1.5×10^{-5}
Glaciofluvial and postglacial sand (and artificial fill)	1.5×10^{-4}
Glacial clay	
Depth < 0.6 m	1×10^{-6}
Depth > 0.6 m	1.5×10^{-8}
Postglacial clay-gyttja/gyttja clay	3×10^{-7}

Table 2-2. Hydraulic conductivity of regolith obtained from slug tests and analyses of PSD (particle-size distribution) curves in and in the vicinity of the access area (Johansson 2008, Hedenström and Sohlenius 2008). Note that data from PSD are given as intervals for three different estimation methods.

Well id	Slug test		PSD	
	Regolith type at screen level	Hydraulic conductivity (m/s)	Sampled regolith type	Hydraulic conductivity (m/s)
SFM0049	Gravelly till	9.8×10^{-5}	Clayey sandy till	2.6×10^{-7}–2.1×10^{-6}
SFM0107	Sandy till	2.3×10^{-6}	Sandy till	1.2×10^{-7}–6.3×10^{-7}
SFM0108	Sandy till	7.5×10^{-5}	Sandy till	8.8×10^{-7}–3.6×10^{-6}

The access area is located in the "Forsmark 1/2 rest catchment area" (area c 1.9 km^2; upper part of Figure 2-4), south of the cooling-water canal (Brunberg et al. 2004). The term "rest catchment area" implies that the catchment is drained by groundwater discharge and surface runoff directly to the sea. Except for a small lake (Lake Tjärnpussen, see gauge SFM000119 in Figure 1-2) and three small ponds close to the sea shoreline, this catchment does not contain larger lakes, streams or other surface waters. As part of SDM-Site (lower figure of Figure 2-4), the components of the long-term, site average annual average water balance were estimated as P (precipitation) = 560 mm/y, E (evapotranspiration) = 400–410 mm/y and R (runoff) = 150–160 mm/y (Johansson 2008). Due to the lack of larger streams, no stream-discharge data are available for the access area.

In general, the groundwater level in regolith closely follows the topography (Figure 2-5), with an observed shallow groundwater table for most wells and for most of the year (Figure 2-6; Johansson and Öhman 2008). Two of the wells (SFM0077 and -0107) that demonstrate deviating, large average depths to the groundwater table are located in the vicinity of the access area. Other wells with such deviating, large average depths to the groundwater table include e.g. SFM0059 and -0061, installed in high-conductive glaciofluvial material in the Börstilåsen esker (outside the access area).

An effect of the shallow groundwater table is rapid responses to precipitation events and evapotranspiration cycles, whereas such responses are notably weaker in wells with larger depths to the groundwater table. The average groundwater table is above sea level (0 m elevation) in all wells, whereas the groundwater table is below sea level in some wells during dry periods (Johansson 2008). Another implication of groundwater levels being close to the ground surface is that water divides for near-surface groundwater flow likely coincide with surface-water divides. The near-surface groundwater flow system is hence a reflection of the topography, with a general horizontal gradient from inland areas towards the sea.

The lakes at Forsmark are shallow, with maximum depths in the range 0.4 to 2 m. Monitoring of surface-water levels in lakes and groundwater levels in regolith below and in the vicinity of a number of lakes in the Forsmark area shows that hydraulic gradients between groundwater and surface water generally are small and temporally variable. Data show that lakes may act as recharge sources to underlying regolith in the riparian zone during dry summer periods, due to water losses by evapotranspiration (Johansson 2008). Elsewhere, lake sediments and underlying till have low vertical hydraulic conductivities, as indicated by e.g. hydraulic gradients and the presence of relict marine chemical signatures beneath the lakes.

Based on the data available at the time of SDM-Site, it was concluded that there is no or low correlations between groundwater levels in regolith and the sea level. The highest correlations (month-to-month coefficients of determination $r^2 \approx 0.55$–0.65) were observed for wells SFM0059 and -0061, installed in the Börstilåsen esker close to the sea coastline (but far away from the access area). It has also been observed that sea-water intrusion may occur into Lake Bolundsfjärden and other low-lying lakes close to the coastline, e.g. during the storm events "Gudrun" and "Per" in January 2005 and 2007, respectively.

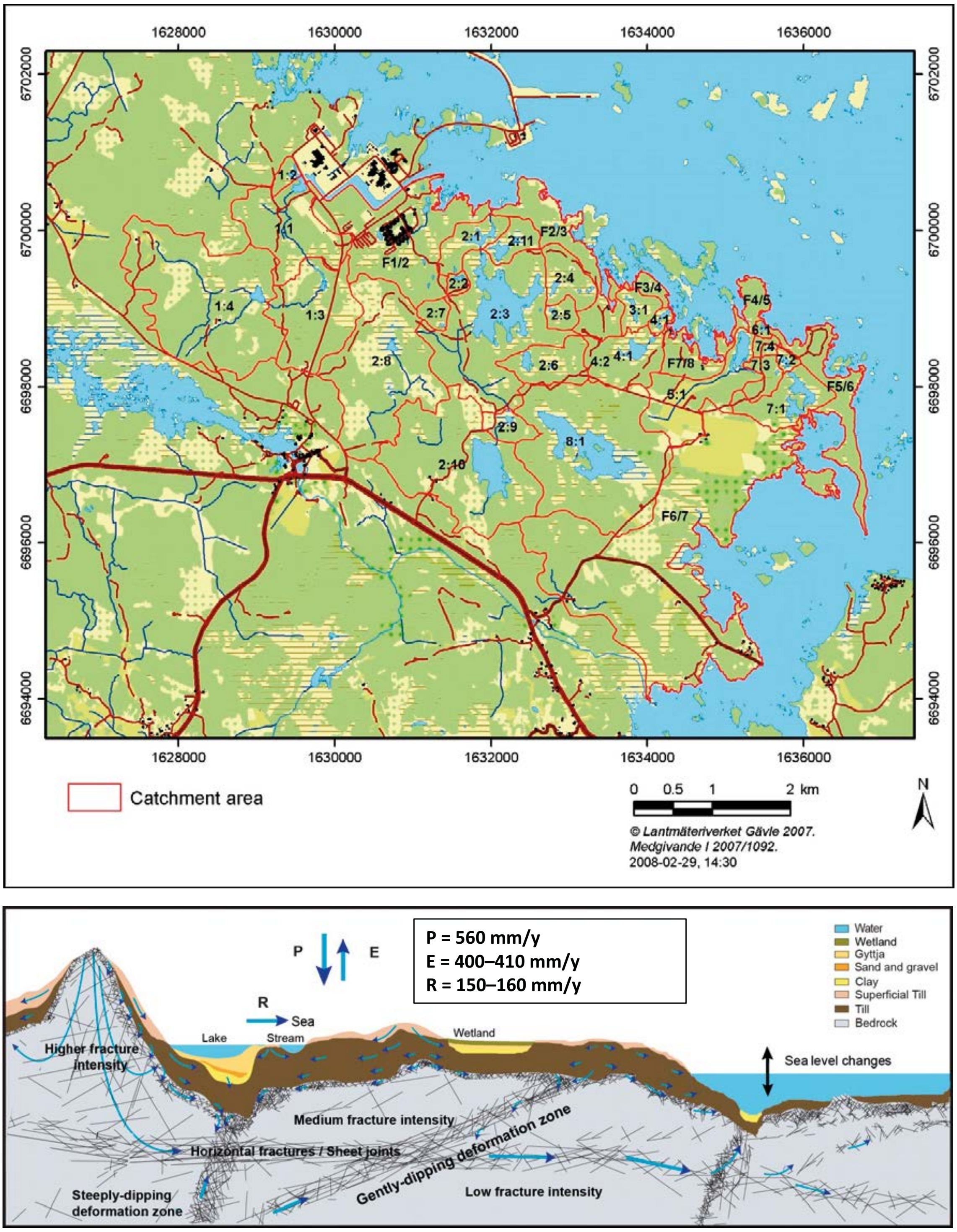


Figure 2-4. *Upper figure: Delineated catchment areas in the Forsmark landscape, with a flat, undulating topography (Brunberg et al. 2004). The access area is located in the "Forsmark 1/2 rest catchment area" (F1/2). Lower figure: Cross-section cartoon illustrating regolith and the upper c 150 m of the rock. P = precipitation, E = evapotranspiration, and R = runoff (modified after Figure 3-1 in Johansson 2008).*

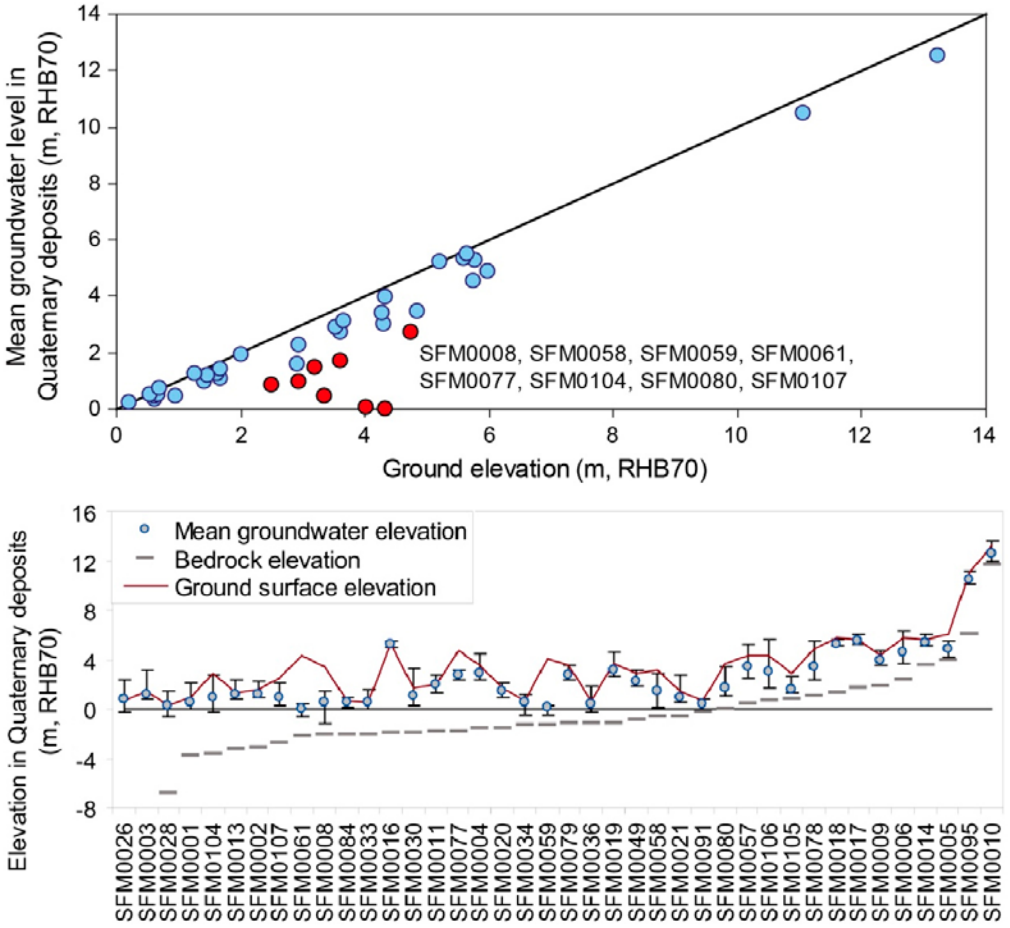


Figure 2-5. *Upper plot: Cross plot of average groundwater levels in monitoring wells installed in regolith versus ground-surface elevation. Lower plot: Average groundwater levels, local ground-surface elevations and rock-surface elevations, ranked according to rock-surface elevation (Johansson 2008).*

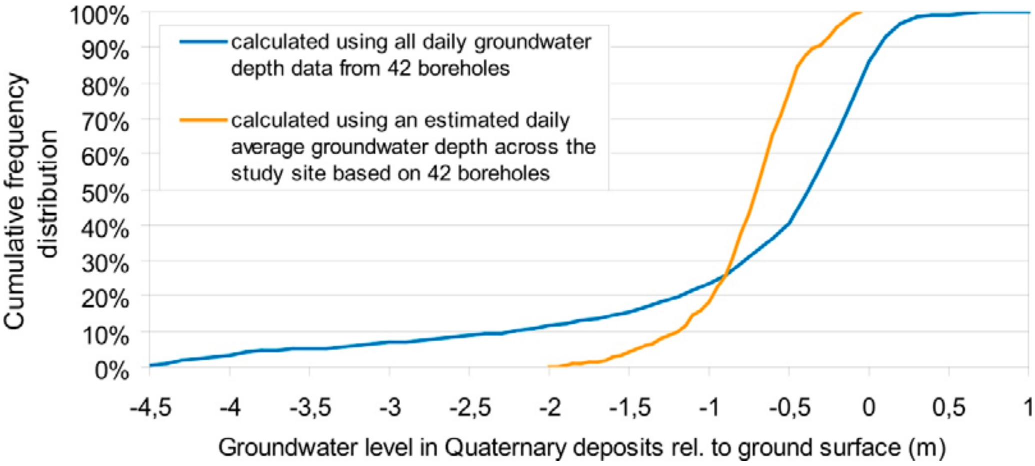


Figure 2-6. *Cumulative frequency distributions of depth to the groundwater table in regolith (Johansson and Öhman 2008). The orange curve is based on daily values of the "site average" depth to the groundwater table, whereas the blue curve is based on a pooled analysis of individual wells.*

Inside the tectonic lens (e.g. Follin et al. 2007), horizontal hydraulic gradients in the upper part of the rock are small and groundwater levels are below groundwater levels in regolith, hence indicating groundwater flow from regolith to rock. This suggests that local, small-scale recharge and discharge areas, involving groundwater flow systems in the regolith, overlie more large-scale flow systems associated with groundwater flow in the rock. On the other hand, groundwater levels in regolith are below groundwater levels in the upper part of the rock outside the lens.

In the tectonic lens, well-connected sub-horizontal or gently dipping structures, including sheet joints, in the upper part of the rock may be in hydraulic contact with the sea, either directly or, more likely, indirectly via vertical fracture zones that outcrop below the sea (Johansson 2008). The sea level may hence act as a "drain" boundary condition for groundwater levels in fracture zones/sheet joints inside the lens, resulting in low groundwater levels with little correlation to the local topography (Figure 2-7). Moreover, compared to boreholes located outside the lens, correlations between groundwater levels in the upper part of the rock and the sea level are higher for boreholes inside the tectonic lens, with month-to-month coefficients of determination (r^2) of up to c. 0.4–0.5 (Johansson 2008).

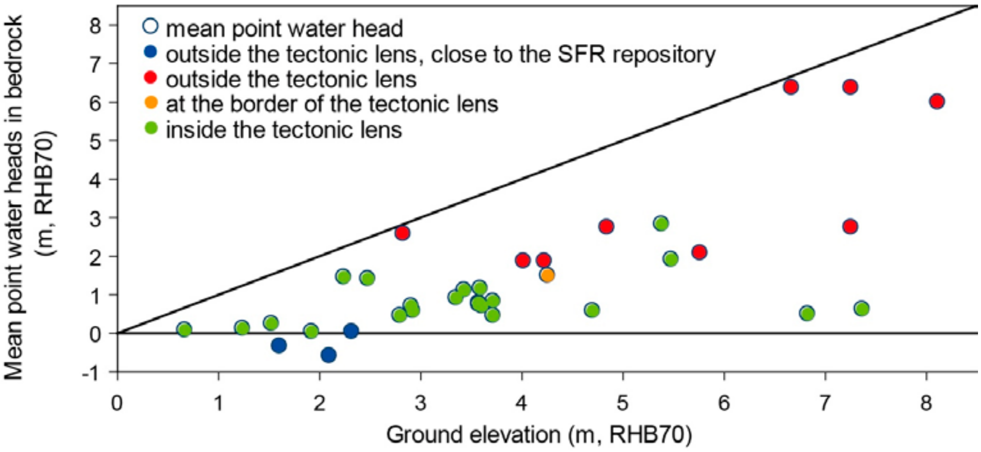


Figure 2-7. *Cross plot of average groundwater levels (interpreted as so-called point-water heads) in upper borehole sections of percussion-drilled boreholes versus ground-surface elevations (Johansson 2008).*

3 Data for the access-area description

This chapter gives a brief overview of data related to hydrology and near-surface hydrogeology gathered subsequently to SDM-Site. The post SDM-Site dataset comprises the following (cf. Figure 1-2 and Table 3-1):

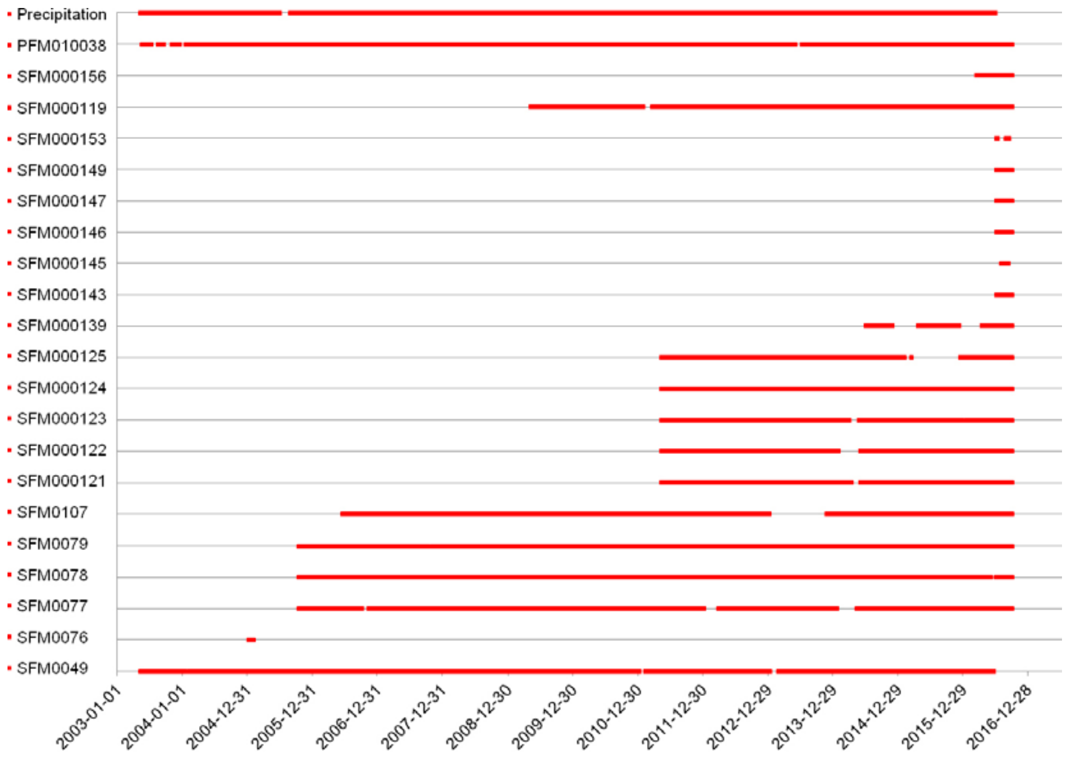
- **Hydrogeological properties of regolith and the rock/regolith interface:** Data from single-hole (slug) tests in previously untested groundwater monitoring wells (SFM0077–79, SFM000122, SFM000139, SFM000143–147, SFM000149, and SFM000153), of which all except SFM0077–79 are installed subsequently to SDM-Site.
- **Meteorological monitoring:** Meteorological data (e.g. precipitation, air temperature and potential evapotranspiration) gathered at the Högmasten and Storskäret meteorological stations (PFM010700, -010701) from the Forsmark 2.3 data freeze (March 31, 2007) up to June 2007 and June 2015, respectively, and from the Labbomasten meteorological station (PFM006281) from June 2015 and onwards (Wern and Jones 2007, 2008, Andersson and Jones 2009, 2010, 2011, 2012, 2014, Andersson 2013, Jones and Kindell 2015, 2016, Jones and Kindell 2017).
- **Monitoring of ice freeze/breakup times:** Observations of ice freeze/breakup times in the nearby sea bay (Nyberg and Wass 2008a, 2009a, 2010a, Wass 2011, 2012, 2013a, 2014a, 2015a, 2016a) from the 2007/2008 winter season to the 2015/2016 winter season. Specifically, there was one ice-observation area up to the 2014/2015 winter season (AFM000075) and two observation areas (also including AFM001449) from the 2015/2016 winter season.
- **Ground- and surface-water level monitoring:** Additional datasets from pre-existing groundwater-monitoring wells (SFM0049, SFM0077–79 and SFM0107) and the sea-level gauge PFM010038 (Nyberg and Wass 2008b, 2009b, 2010b, Wass 2013b, 2014b, 2015b, c, d, e, Geosigma 2016a, b, Wass 2016b, 2018, Ragvald and Wass 2017). The dataset also includes monitoring data from wells (SFM000121–125, -139, -143, -145, -146–147, -149 and -153) and lake-level gauges (SFM000119 and -156) installed subsequently to SDM-Site. Moreover, the dataset includes additional groundwater-level data (interpreted as so-called point-water heads) from 15 pre-existing percussion-drilled and core-drilled boreholes in and in the vicinity of the access area, and data from 14 boreholes drilled subsequently to SDM-Site.

Monitoring data periods available for the access-area description are summarised in Table 3-1 and Figure 3-1. It is noted that part of the post SDM-Site dataset was presented, evaluated and utilised for site-descriptive modelling of climate and surface hydrology within the framework of SR-PSU (the safety assessment for the SFR extension project). Specifically, the SR-PSU dataset includes data available up to the end of 2010 (Werner et al. 2013, 2014).

Table 3-1. Compilation of data periods for meteorological data, ice freeze/breakup time observations, hydrological data, and groundwater levels in regolith and rock, available at the time of this report. Dates are given as YYYY-MM-DD.

Data type and id	Data period
Meteorological data	
PFM010700 (Högmasten)	2003-05-12–2015-06-10 (station decommissioned)
PFM010701 (Storskäret)	2003-05-12–2007-06-30 (station decommissioned)
PFM006281 (Labbomasten)	2013-04-14–2016-06-30
Ice freeze and breakup in sea bay (winter seasons)	
AFM000075	2002/2003–2015/2016
AFM001449	2015/2016–2015/2016
Surface-water levels	
PFM010038 (sea level)	2003-05-22–2016-09-30
SFM000119 (Lake Tjärnpussen)	2009-05-07–2016-09-30
SFM000156 (nameless pond)	2016-03-15–2016-09-30
Groundwater levels in regolith	
SFM0049	2003-05-13–2016-06-20
SFM0076	2005-01-10–2005-02-02
SFM0077	2005-10-18–2016-09-30
SFM0078	2005-10-18–2016-09-30
SFM0079	2005-10-18–2016-09-30
SFM0107	2006-06-20–2016-09-30
SFM000121	2011-05-12–2016-09-30
SFM000122	2011-05-12–2016-09-30
SFM000123	2011-05-12–2016-09-30
SFM000124	2011-05-12–2016-09-30
SFM000125	2011-05-12–2016-09-30
SFM000139	2014-07-03–2016-09-30
SFM000143	2016-07-05–2016-09-30
SFM000144	No data (no pressure sensor installed)
SFM000145	2016-08-24–2016-09-30
SFM000146	2016-07-05–2016-09-30
SFM000147	2016-07-05–2016-09-30
SFM000149	2016-07-05–2016-09-30
SFM000153	2016-07-05–2016-09-14
SFM000154	No data (pressure sensor partially above water level)
Groundwater levels in rock (upper borehole section or open boreholes; length intervals in metres below the top of the borehole casing)	
HFM20 (0–48)	2005-03-10–2016-09-30
HFM21 (0–21)	2006-10-25–2016-09-30
HFM22 (0–222)	2004-09-13–2016-09-30
HFM23 (0–211.5)	2005-11-01–2016-09-30
HFM28 (0–151.2)	2006-05-18–2016-09-30
HFM38 (0–23)	2007-04-11–2016-09-30
HFM39 (0–151.2)	2011-07-11–2016-09-30
HFM40 (0–101.7)	2011-05-27–2016-09-30
HFM41 (0–101.5)	2011-06-08–2016-09-30
KFM07A (0–148)	2007-02-20–2016-09-30
KFM07B	
(0–298.93)	2006-05-03–2006-12-18
(0–74)	2007-02-20–2009-03-23
KFM07C (0–110)	2007-04-01–2016-09-30
KFM08A (0–161)	2007-10-24–2016-01-19
KFM08B (0–70)	2006-03-22–2016-06-08

Data type and id	Data period
KFM08C (0–145)	2007-04-12–2016-09-30
KFM08D (0–160)	2007-10-24–2013-02-04
KFM09A (0–300)	2006-11-07–2016-09-30
KFM09B (0–200)	2006-11-07–2016-07-04
KFM13 (0–150.21)	2011-07-08–2016-09-30
KFM14 (0–60.18)	2014-11-03–2016-09-30
KFM15 (0–62.3)	2011-07-08–2016-09-30
KFM16 (0–60.35)	2011-06-08–2016-09-30
KFM17 (0–60.45)	2011-07-11–2016-09-30
KFM18 (0–60.46)	2011-07-08–2016-09-30
KFM19 (0–102.37)	2011-07-07–2016-09-30
KFM20 (0–60.5)	2011-07-08–2016-09-30
KFM21 (0–101.6)	2011-07-11–2016-09-30
KFM22 (0–60.26)	2011-07-07–2016-09-30
KFM23 (0–100.64)	2011-07-12–2016-09-30



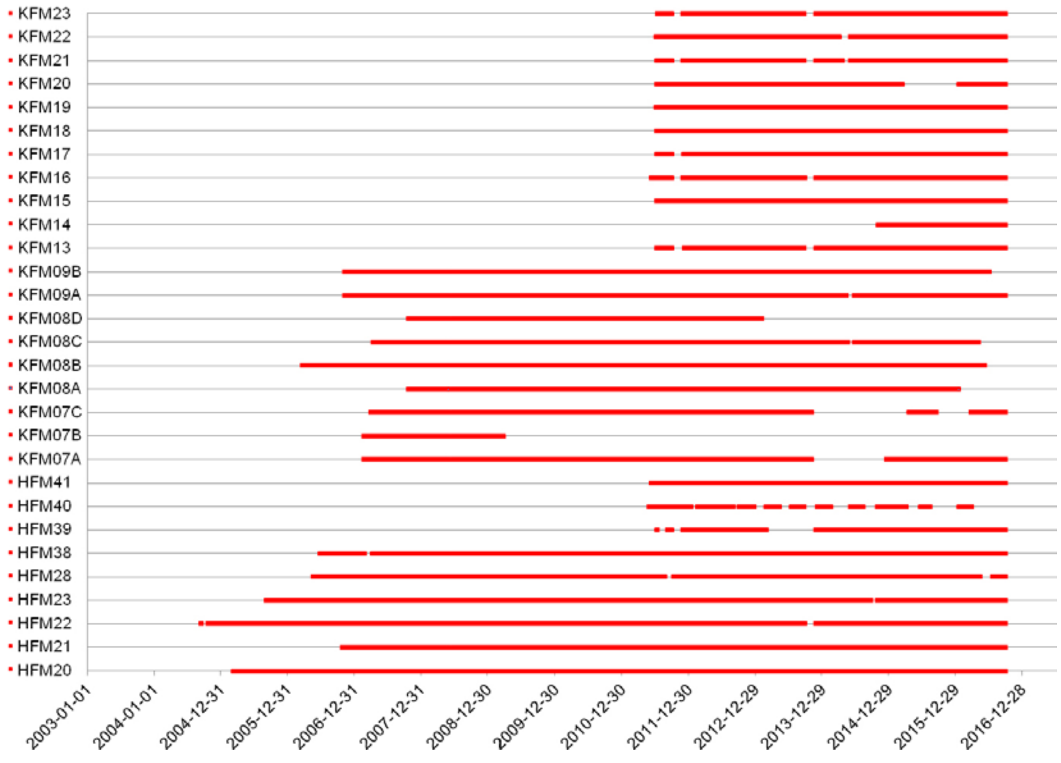


Figure 3-1. *Plots of monitoring-data periods available for the access-area description. Upper plot: Meteorology (here represented by precipitation measured at the Storskäret, Högmasten and Labbomasten stations), sea level (PFM010038), surface-water levels (SFM000119 and -156), and groundwater levels in wells installed in regolith. Lower plot: Groundwater levels in core-drilled (KFM-) and percussion-drilled boreholes (HFM-).*

4 Interpretations of the access-area dataset

4.1 Hydrogeological properties of the regolith and the rock/regolith interface

In and in the vicinity of the access area, SDM-Site data on the hydraulic conductivity of regolith and the rock/regolith interface were available from a few single-hole (slug) tests and also from empirical relationships based on PSD (particle-size distribution) curves for regolith samples (Chapter 2). These data are in close agreement with the general parameterization for the whole Forsmark area.

Appendix 2 presents results of supplementary slug tests performed in a number of previously untested groundwater-monitoring wells (SFM0077–79, SFM000122, SFM000139, SFM000143–147, SFM000149, and SFM000153). The measured initial water-level displacement was too small and/or the hydraulic response too quick to allow evaluation of the test in some wells (SFM0077, SFM000144 and -146). Moreover, SFM000143 is screened across the groundwater table, which makes slug-test evaluation difficult due to drainage effects, and the measured initial displacement was too small and the data fit poor for one of the tests in each of wells SFM000149 and -153.

The slug-test evaluation yields hydraulic conductivity values on the order of 10^{-6}–10^{-5} m/s, which is typical for till in Forsmark (cf. Chapter 2). The slug test in SFM0079, which is screened across the rock/regolith interface, yields a hydraulic conductivity of c 10^{-8}–10^{-7} m/s, which is typical for fine till.

It is noted that wells with small measured initial displacements and/or quick slug-test responses are also characterised by large average groundwater-table depths (SFM0077, -146 and -153; see Section 4.4). This could be due to occurrences of relatively coarse-grained, easily-drained artificial fill, i.e. a mixture of excavated rock and regolith, at these well locations. Wells with a hydraulic conductivity on the order of 10^{-6}–10^{-5} m/s typically have average groundwater-table depths of c 1 m (e.g. SFM0078 and SFM000122). On the other hand, well SFM0079, with a hydraulic conductivity of c 10^{-8}–10^{-7} m/s, has a relatively shallow average depth to the groundwater table (c 0.8 m).

4.2 Meteorological monitoring data

Table 4-1 presents annual accumulated precipitation (P; corrected for e.g. wind losses) and calculated potential evapotranspiration (PET), and annual average air temperature (T), measured at the Storskäret and Högmasten meteorological stations up to June 2007 and June 2015, respectively, and from the Labbomasten meteorological station from June 2015 to the end of September 2016. It is noted that subsequently to SDM-Site, except for 2007 and 2013 the annual accumulated P is above the estimated long-term average of 560 mm (cf. lower part of Figure 2-4).

Table 4-1. Annual accumulated precipitation (P; corrected for e.g. wind losses) and calculated potential evapotranspiration (PET), and annual average air temperature (T) during the period 2003–2016. StS = Storskäret (PFM010701), HöM = Högmasten (PFM010700) and LaM = Labbomasten (PFM006281) meteorological stations. Note that data are available only for parts of 2003 and 2016, and that there are gaps in the P, PET and T datasets.

Year	Accumulated precipitation (mm)			Accumulated potential evapotranspiration (mm)		Average air temperature (°C)		
	StS	HöM	LaM	HöM	LaM	StS	HöM	LaM
2003 (from May 12)	446	456	–	418	–	9.51	10.27	–
2004	519	488	–	509	–	6.30	6.50	–
2005	447	428	–	526	–	6.65	6.91	–
2006	523	535	–	538	–	7.31	7.50	–
2007 (up to Jun. 30 for the StS station)	203	440	–	524	–	4.91	7.02	–
2008	–	812	–	508	–	–	7.28	–
2009	–	591	–	492	–	–	6.65	–
2010	–	685	–	463	–	–	4.93	–
2011	–	649	–	484	–	–	7.21	–
2012	–	801	–	402	–	–	6.14	–
2013 (from Apr. 14, 6 and 5, resp. for the LaM station)	–	436	419	434	432	–	6.64	9.67
2014	–	587	615	518	550	–	7.71	7.32
2015 (up to Jun. 10 for the HöM station, from Jun. 29 for PET from the LaM station)	–	254	652	190	290	–	4.22	7.21
2016 (up to Sep. 30)	–	–	277	–	288	–	–	4.25

4.3 Ice freeze and breakup monitoring

Table 4-2 summarises results of the sea-bay ice-cover time observations up to the 2015/2016 winter season. The length of the ice-covered period demonstrates large inter-annual variations, both for the period up to (60–133 days) and subsequently to SDM-Site (9–146 days). In particular, the ice-covered period during the 2007/2008 winter season was exceptionally short (only approximately one week in total), and very long (almost 5 months) during the 2012/2013 winter season. It is also noted that there was equal length of the ice-covered period during the 2015/2016 winter season at the two observation areas AFM000075 and AFM001449 (cf. Figure 1-2).

Table 4-2. Ice freeze and breakup time observations at Forsmark during winter seasons from 2002–2003 to 2015–2016. Dates are given as YYYY-MM-DD.

Winter season	Ice freeze	Ice breakup	Ice-covered period (days)
Sea bay at SFR (AFM000075)			
2002/2003	2003-01-07	2003-03-31	83
2003/2004	2003-12-17	2004-04-13	120
2004/2005	2004-12-21 2005-01-27	2005-01-13 2005-04-07	95 (in total)
2005/2006	2005-12-12	2006-04-24	133
2006/2007	2007-01-22	2007-03-22	60
2007/2008	2008-01-23 2008-02-12 2008-02-18 2008-03-04	2008-01-24 2008-02-12 2008-02-21 2008-03-05	9 (in total)
2008/2009	2009-01-05	2009-04-09	94
2009/2010	2009-12-18	2010-04-23	126
2010/2011	2010-11-29	2011-04-13	136
2011/2012	2012-01-09	2012-03-26	77
2012/2013	2012-12-03	2013-04-28	146
2013/2014	2013-12-09	2014-02-26	79
2014/2015	2015-01-05	2015-03-12	66
AFM000075 and AFM001449			
2015/2016	2015-12-29	2016-03-28	90

4.4 Groundwater levels in regolith

Figure 4-1 shows topography-controlled boundaries of sub-catchment areas and flow directions within the Forsmark 1/2 rest catchment area (cf. Figure 2-4), as delineated using the high-resolution DEM presented in Follin (2018). Specifically, the figure shows sub-catchment areas for the outlets from the lakes and ponds in and in the vicinity of the access area, i.e. Lake Tjärnpussen and the three small ponds close to the sea shoreline. Hence, groundwater discharge and surface runoff from these areas pass through surface waters prior to drainage to the sea, whereas other areas in the Forsmark 1/2 rest catchment area are drained by groundwater discharge and surface runoff directly to the sea.

Table 4-3 presents groundwater level data available for the access-area description, including basic statistics (average and standard deviation) of groundwater levels and depths below ground surface. Subsequently to SDM-Site, 14 additional wells have been installed in and in the vicinity of the access area. Some of these wells were installed recently, i.e. available monitoring periods are short, and there are not yet any monitoring data from two of the wells (one of them is dry). Appendix 1 provides statistics (average, standard deviation, minimum and maximum groundwater levels) for individual years and three-month seasons.

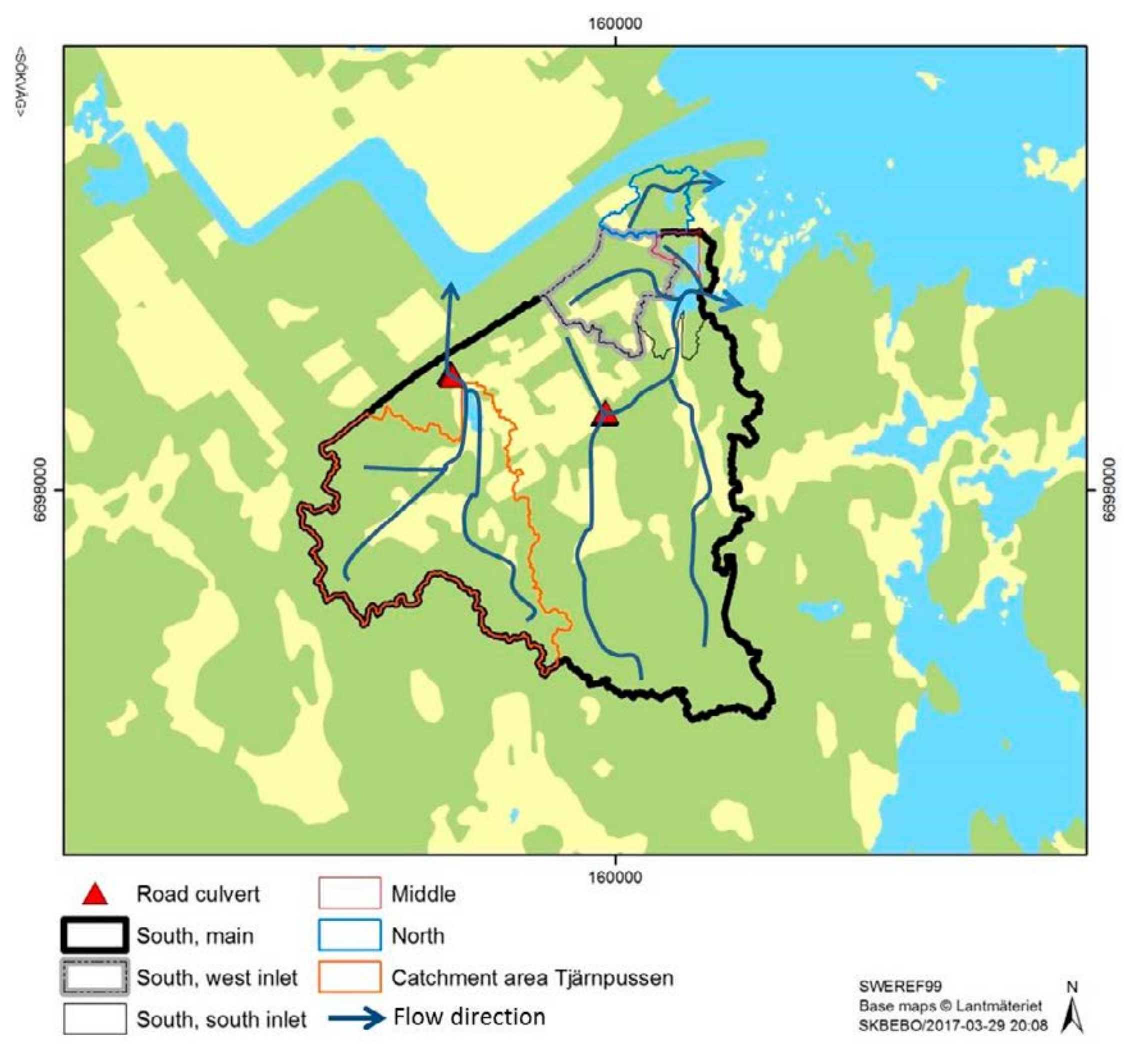


Figure 4-1. Topography-controlled sub-catchment area boundaries and flow directions within the Forsmark 1/2 rest catchment area (cf. Figure 2-4), delineated using the high-resolution DEM presented in Follin (2018). The map also shows road culverts, which locations are checked in the field. Culverts conduct water across road embankments, acting as catchment-area boundaries along road stretches without culverts.

Groundwater level datasets used in this report are quality controlled and stored in the Sicada database, but datasets have not been cleared from hydraulically disturbed data. Disturbances arise in connection with various activities in boreholes and wells, e.g. drilling, hydrochemical sampling and hydraulic testing, and could affect both the borehole or well where the activity takes place and surrounding boreholes and wells. Well SFM0049 is used as an example to assess the potential impact of disturbances on main groundwater-level statistics (average and standard deviation), see Figure 4-2. Specifically, this well is regularly sampled as part of the hydrochemical monitoring programme, and the water level in the well was thereby lowered by pumping on several occasions during the period analysed in this report. Removal of the corresponding data days (27 in total) yields an average groundwater level of 2.283 m (2.277 m before clearing) and a standard deviation of 2.226 m (2.244 m before). This indicates that hydraulic disturbances due to water sampling do not have a major influence on the groundwater-level statistics presented in this report.

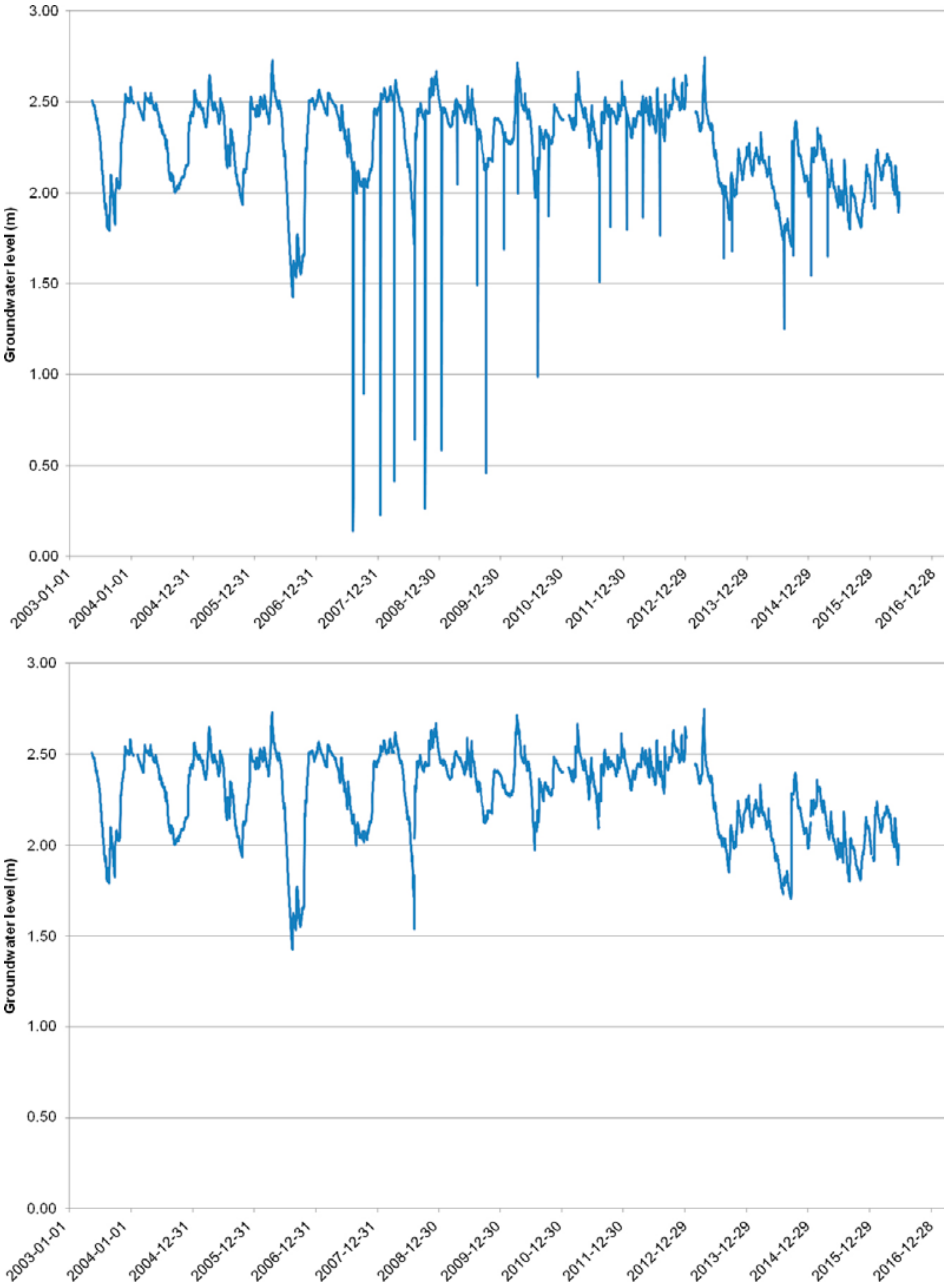


Figure 4-2. *Time-series plots of groundwater level in well SFM0049. Upper plot: Daily averages based on raw data. Bottom plot: Cleared dataset, in which totally 27 disturbed data days have been removed.*

Average groundwater-table depths are c 1 m below ground surface in many wells of Table 4-3. This is also illustrated in Figure 4-3, which shows a cross plot of average groundwater levels in wells installed in regolith versus local ground-surface elevations. Moreover, Figure 4-4 illustrates averages and intervals of groundwater levels in wells installed in regolith, local ground-surface elevations, and rock-surface elevations (cf. Figure 2-5). According to Figure 4-5 through Figure 4-7, the groundwater level in regolith has a descending trend from inland areas towards the coastline, which is due to the general topographic trend in conjunction with the close relation between groundwater level and topography. According to Table 4-3, the average groundwater table is located at larger depths, c 2–2.5 m, in some wells (SFM0076, -77, -146 and -153). This could be due to occurrences of relatively coarse-grained, easily-drained artificial fill, i.e. a mixture of excavated rock and regolith, at these well locations.

Table 4-3. Groundwater levels and depths in regolith. Std dev = standard deviation, m bgs = metres below ground surface. Dates are given as YYYY-MM-DD.

Well id	Data period	Groundwater level (m)		Average depth to groundwater table (m bgs)
		Average	Std dev	
SFM0049	2003-05-13–2016-06-20	2.28	0.24	0.65
SFM0076	2005-01-10–2005-02-02	1.53	0.16	1.83
SFM0077	2005-10-18–2016-09-30	2.75	0.14	2.00
SFM0078	2005-10-18–2016-09-30	3.61	0.78	1.23
SFM0079	2005-10-18–2016-09-30	2.82	0.20	0.77
SFM0107	2006-06-20–2016-09-30	1.12	0.33	1.38
SFM000121	2011-05-12–2016-09-30	0.45	0.26	0.80
SFM000122	2011-05-12–2016-09-30	1.09	0.38	1.36
SFM000123	2011-05-12–2016-09-30	0.09	0.15	0.63
SFM000124	2011-05-12–2016-09-30	0.26	0.31	1.06
SFM000125	2011-05-12–2016-09-30	1.11	0.38	1.53
SFM000139	2014-07-03–2016-09-30	2.77	0.06	0.11
SFM000143	2016-07-05–2016-09-30	−0.12	0.15	0.89
SFM000144	No data			
SFM000145	2016-08-24–2016-09-30	0.02	0.06	0.44
SFM000146	2016-07-05–2016-09-30	−0.35	0.21	2.55
SFM000147	2016-07-05–2016-09-30	0.83	0.34	1.35
SFM000149	2016-07-05–2016-09-30	0.06	0.05	0.42
SFM000153	2016-07-05–2016-09-14	1.58	0.16	1.79
SFM000154	No data			

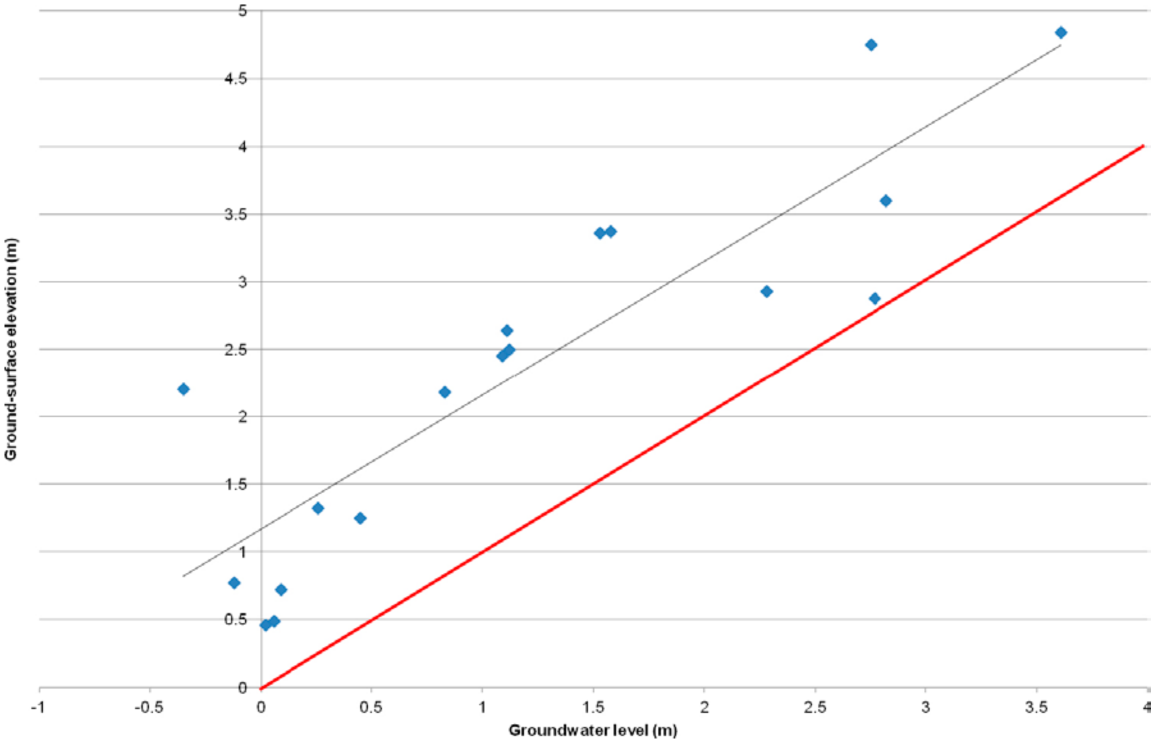
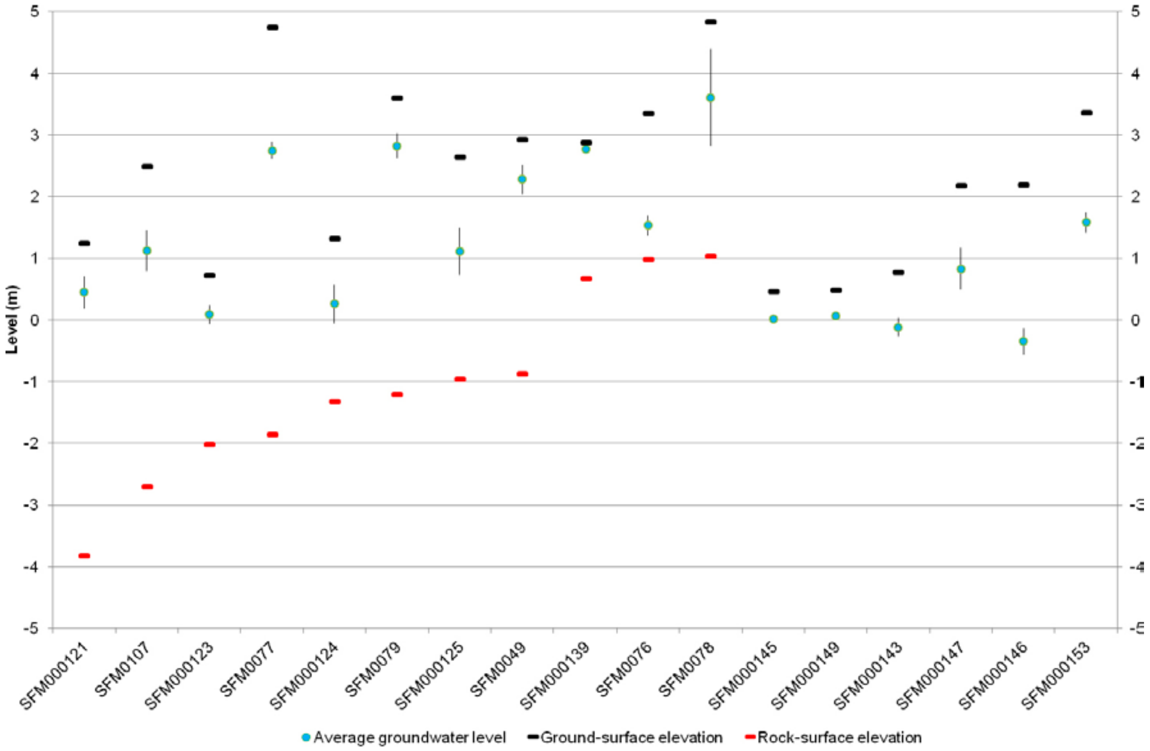


Figure 4-3. *Cross plot of average groundwater levels in wells installed in regolith versus local ground-surface elevations. The black line is a linear match against data, whereas the red line represents a perfect linear groundwater-level/ground-surface elevation relationship.*



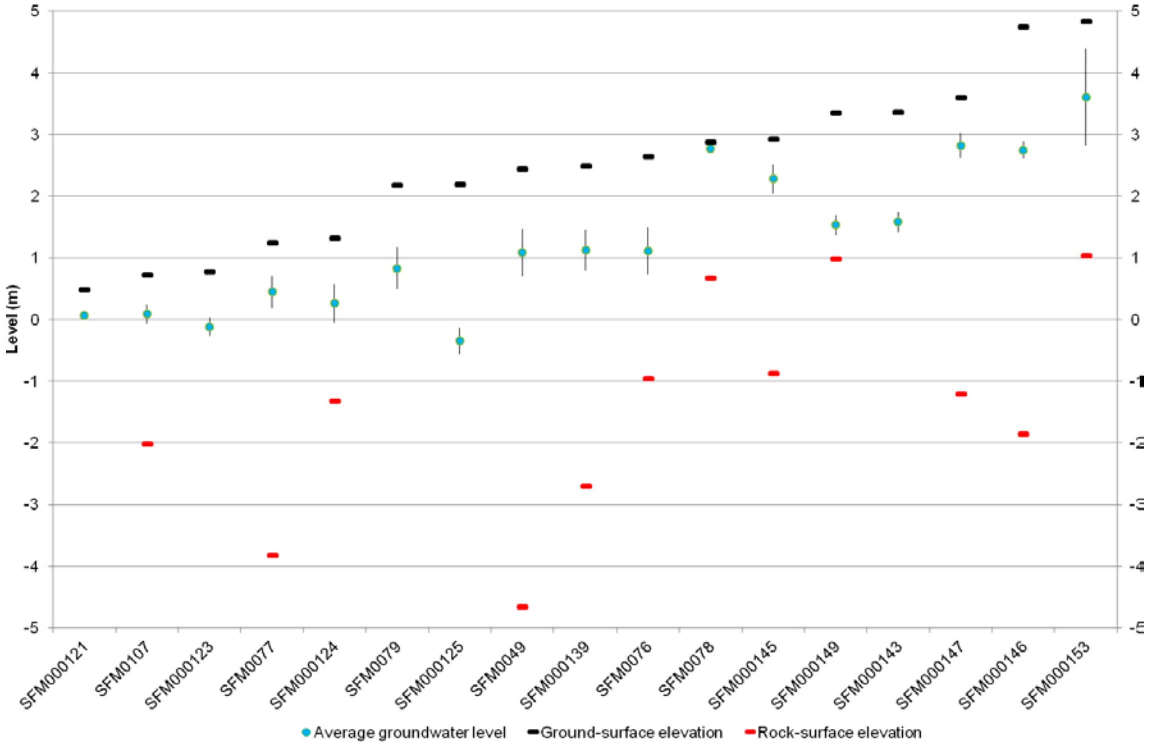


Figure 4-4. *Averages and intervals (average ± 1 std dev) of groundwater levels in wells installed in regolith, local ground-surface elevations (black lines) and rock-surface elevations (red lines), ranked according to rock-surface elevations (upper plot) and ground-surface elevations (lower plot). Note that SFM000143, -145–147, -149 and -153 are sorted according to ground-surface elevation in the upper and lower plots (rock-surface elevation data are missing).*

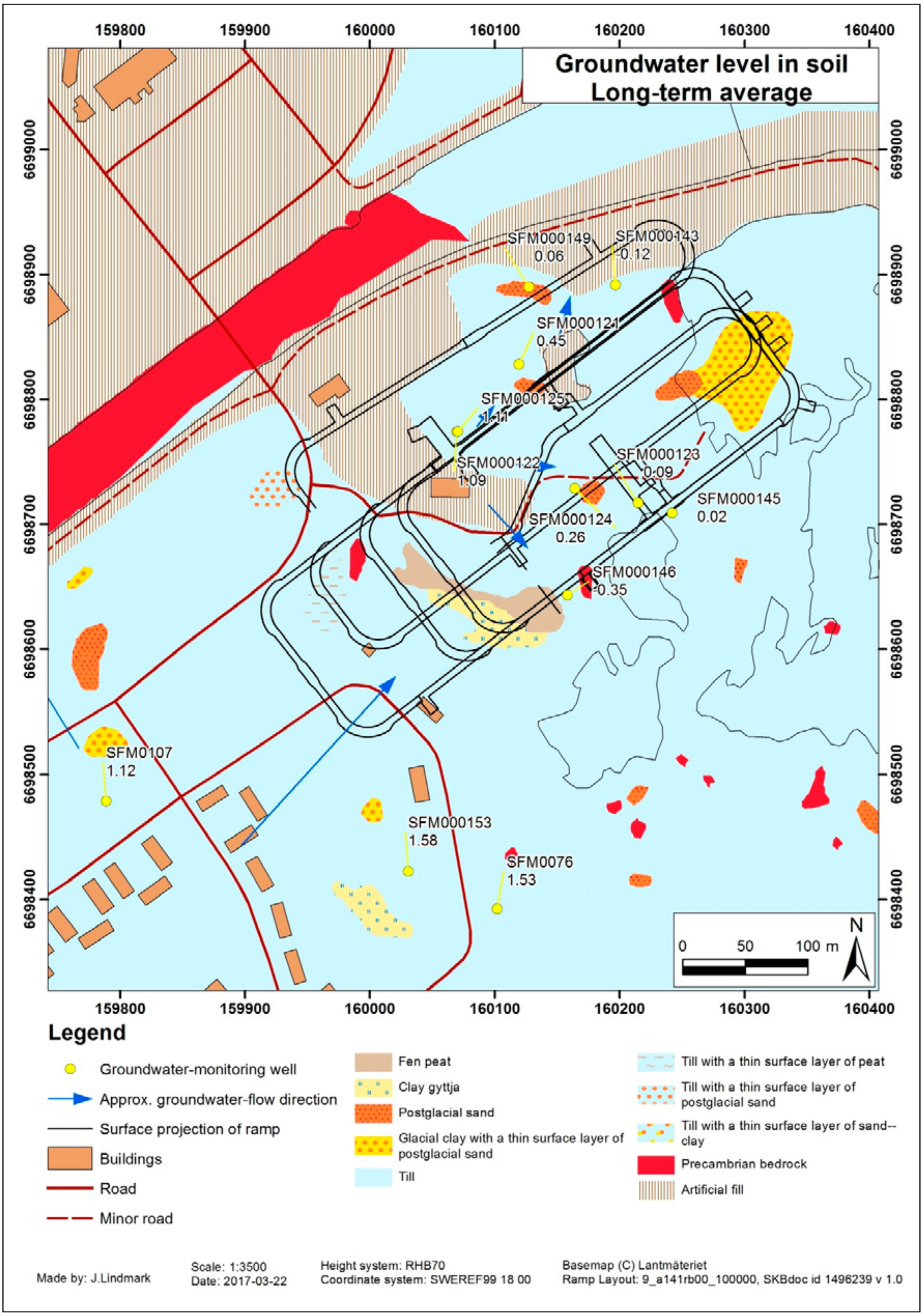


Figure 4-5. *Interpreted horizontal groundwater-flow directions (arrows), based on overall average groundwater levels (numbers below each well id, in metres) in monitoring wells installed in regolith. The average sea level is approximately 0 m in the RHB 70 elevation system.*

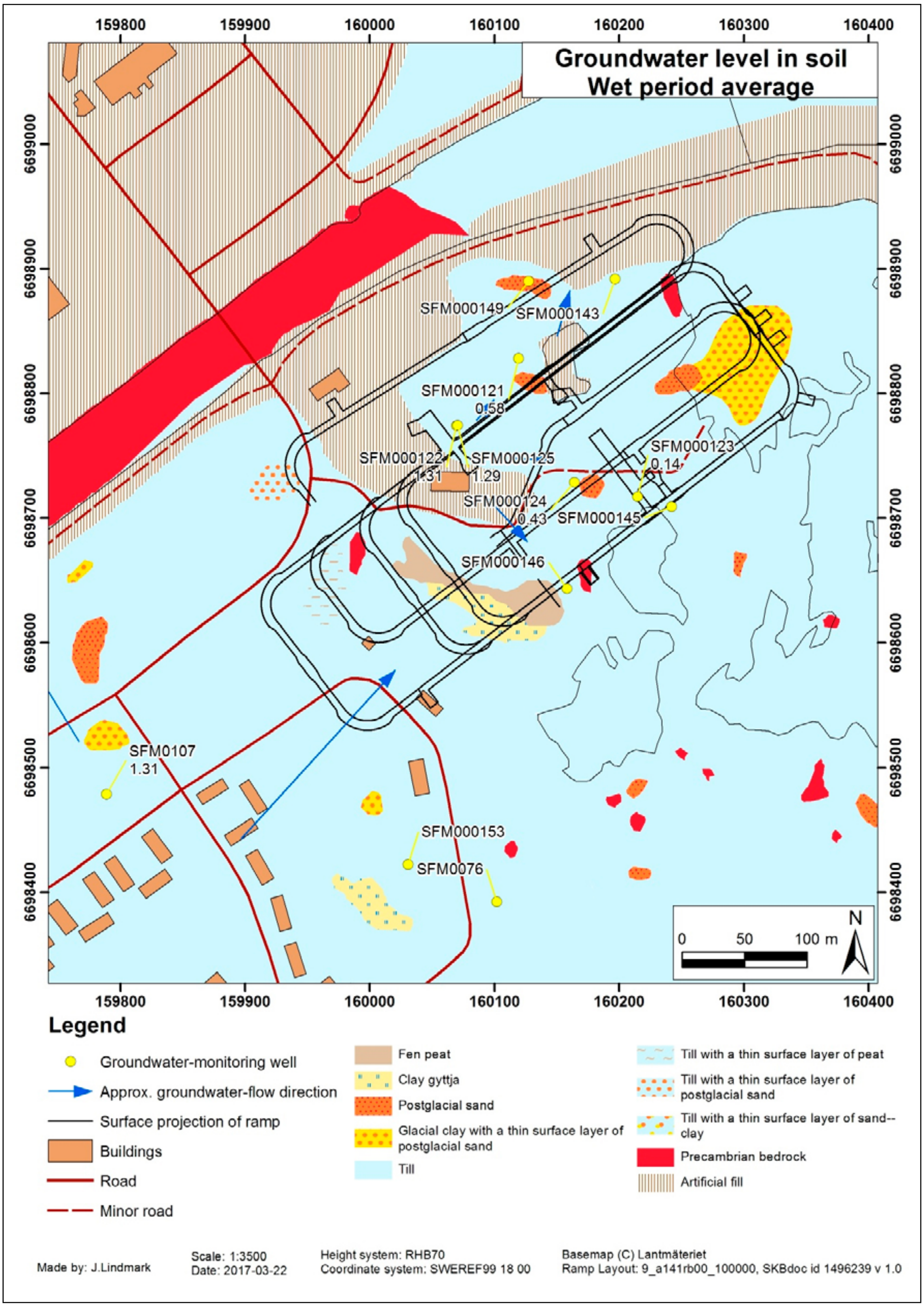


Figure 4-6. *Interpreted horizontal groundwater-flow directions (arrows), based on average groundwater levels (numbers below each well id, in metres) in monitoring wells installed in regolith. Interpreted flow directions are based on wet-period averages (March–May). The average sea level is approximately 0 m in the RHB 70 elevation system.*

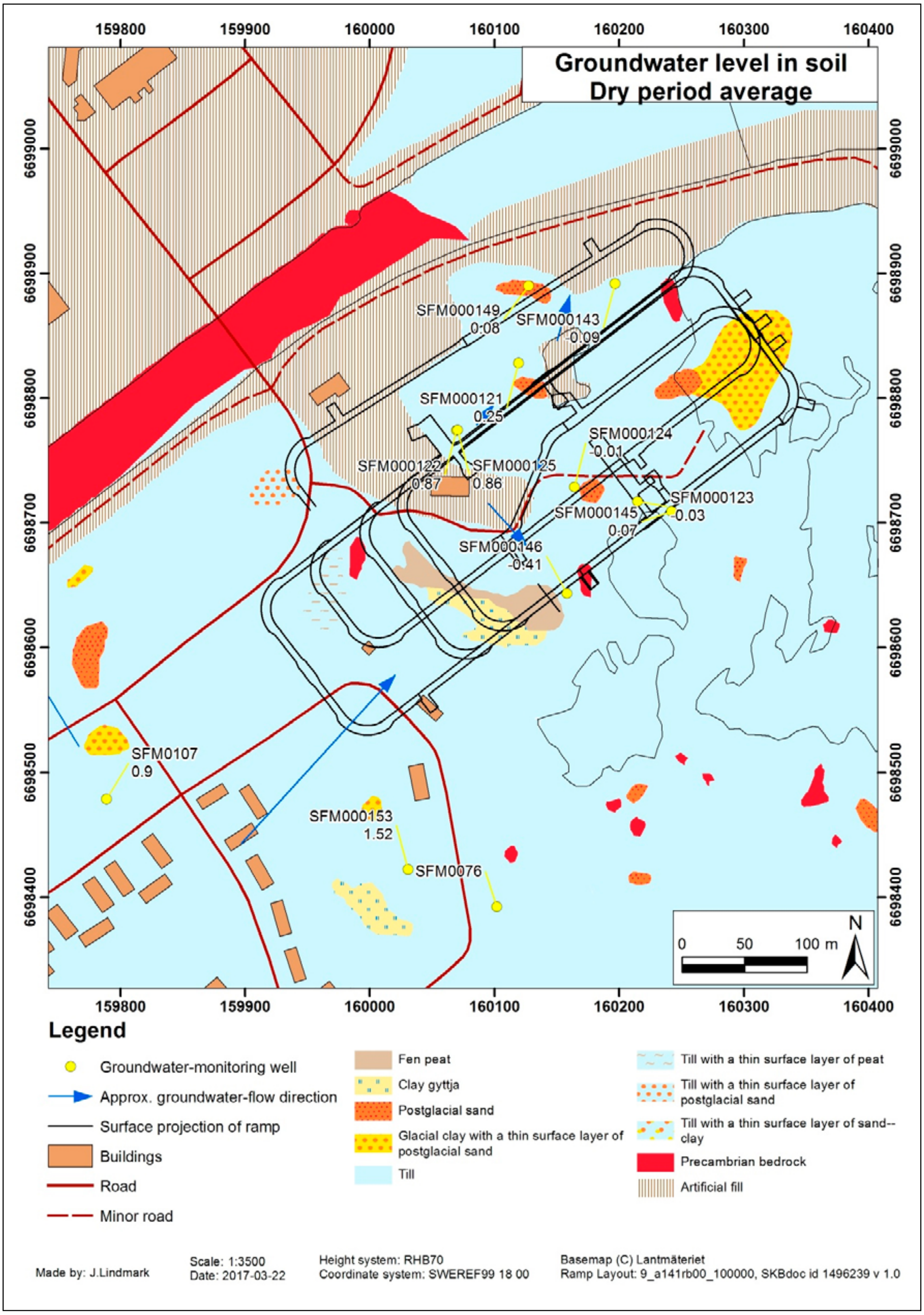


Figure 4-7. *Interpreted horizontal groundwater-flow directions (arrows), based on average groundwater levels (numbers below each well id, in metres) in monitoring wells installed in regolith. Interpreted flow directions are based on dry-period averages (June–August). The average sea level is approximately 0 m in the RHB 70 elevation system.*

4.5 Relations between groundwater levels in regolith and surface-water levels

Table 4-4 presents surface-water level data available for the access-area description, including basic statistics (average and standard deviation) of surface-water levels and -depths. Subsequently to SDM-Site, a surface-water level gauge (SFM000156) has been installed in one of ponds in the access area. However, it was installed recently and the available monitoring period is therefore short.

Table 4-4. Surface-water levels and depths in lakes and ponds. PFM010038 is SKB's sea-level gauge. Std dev = standard deviation. Dates are given as YYYY-MM-DD.

Gauge id	Data period	Surface-water level		Average surface-water depth (m)
		Average (m)	Std dev (m)	
SFM000119	2009-05-07–2016-09-30	2.83	0.14	–1.19
SFM000156	2016-03-15–2016-09-30	0.38	0.11	–1.26
PFM010038	2003-05-22–2016-09-30	–0.06	0.21	–

Table 4-5 analyses correlations (in terms of correlation coefficients, $0 \leq r \leq 1$, based on daily averages) between groundwater levels in wells installed in regolith and the sea level (PFM010038). Potential groundwater level/sea level time lags are analysed by calculating correlation coefficients for both same-day daily averages and for daily averages with two-day displacements (r values analysed for daily average groundwater levels lagging two days behind daily average sea levels). As expected, the correlation is low for most wells ($r < 0.5$). However, the correlation is rather high ($r > 0.5$) for some of the wells installed close to the coastline (SFM000143, -145 and -149, see Figure 4-8 though Figure 4-10). The correlation is also relatively high ($r \approx 0.5$) for well SFM000123, which is installed in the vicinity of a near-coastal pond. Time-lag effects are particularly evident for well SFM000143 (cf. Figure 4-8), for which the same-day correlation coefficient is $r = 0.74$ and the two-day displacement is $r = 0.84$.

It is noted that there are periods when rainfall yields increasing groundwater levels even though the sea level is decreasing, e.g. August 28–30, 2016 (preliminary, not yet quality-controlled precipitation data). It can hence be concluded that in areas along the coastline, groundwater levels in regolith are influenced by both the sea level and groundwater rainfall/snow-melt induced groundwater recharge, with some degree of time lag (on the order of one or a few days) in relation to sea-level changes.

Table 4-5. Correlations (expressed as correlation coefficients, r) between daily averages of groundwater level in regolith and sea level (PFM010038). The analysis is based on daily averages and common data days. Dates are given as YYYY-MM-DD.

Well id	Start	Correlation coefficient r	
		Same day	Two day-displacement
SFM0049	2003-05-22–2016-06-20	0.06	0.06
SFM0076	2005-01-10–2005-02-02	0.71	0.83
SFM0077	2005-10-18–2016-09-30	0.22	0.22
SFM0078	2005-10-18–2016-09-30	0.07	0.08
SFM0079	2005-10-18–2016-09-30	0.01	0.01
SFM0107	2006-06-20–2016-09-30	0.17	0.18
SFM000121	2011-05-12–2016-09-30	0.25	0.24
SFM000122	2011-05-12–2016-09-30	0.24	0.25
SFM000123	2011-05-12–2016-09-30	0.48	0.47
SFM000124	2011-05-12–2016-09-30	0.18	0.17
SFM000125	2011-05-12–2016-09-30	0.25	0.26
SFM000139	2014-07-03–2016-09-30	−0.04	0.04
SFM000143	2016-07-05–2016-09-30	0.74	0.84
SFM000145	2016-08-24–2016-09-30	0.85	0.84
SFM000146	2016-07-05–2016-09-30	−0.22	−0.16
SFM000147	2016-07-05–2016-09-30	0.20	0.22
SFM000149	2016-07-05–2016-09-30	0.52	0.52
SFM000153	2016-07-05–2016-09-14	0.20	0.28

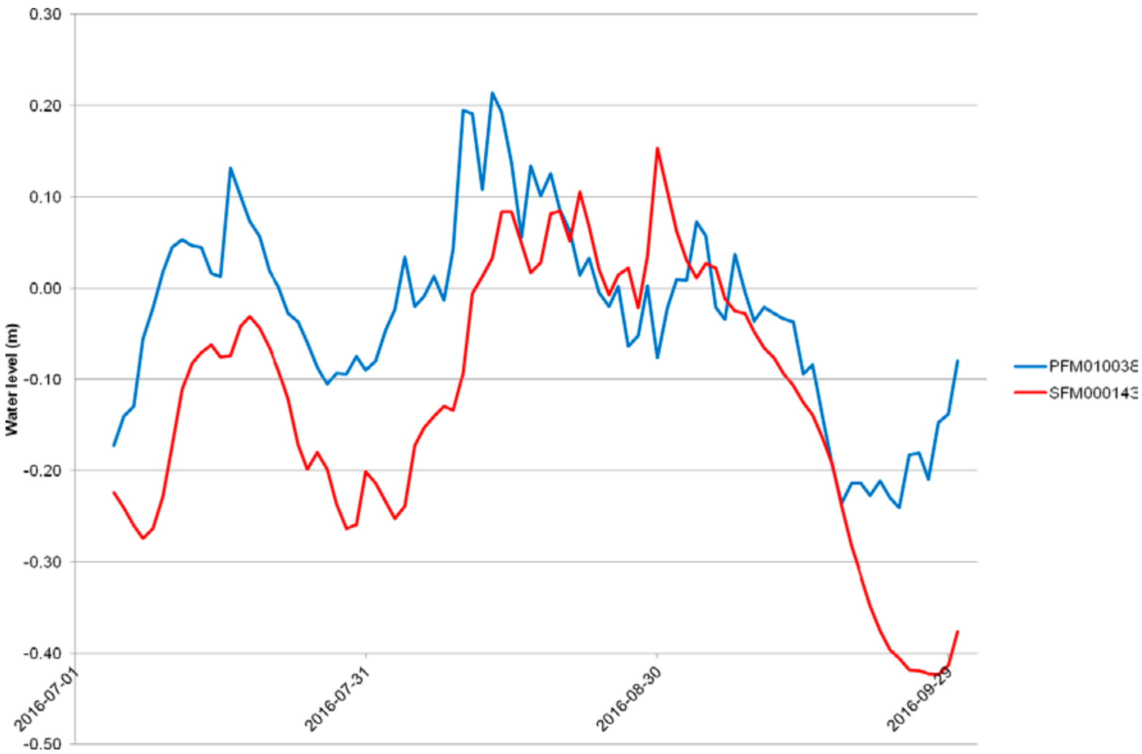


Figure 4-8. *Time-series plot of sea level (PFM010038, blue line) and groundwater level in well SFM000143 (red line).*

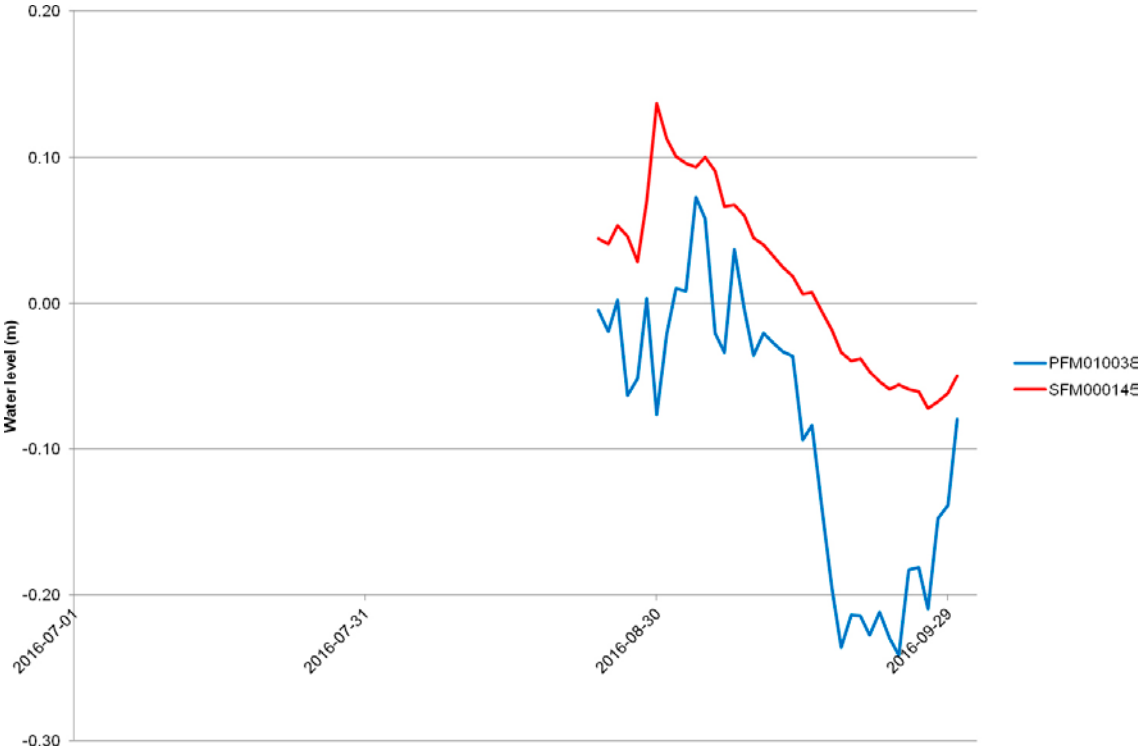


Figure 4-9. *Time-series plot of sea level (PFM010038, blue) and groundwater level in well SFM000145 (red).*

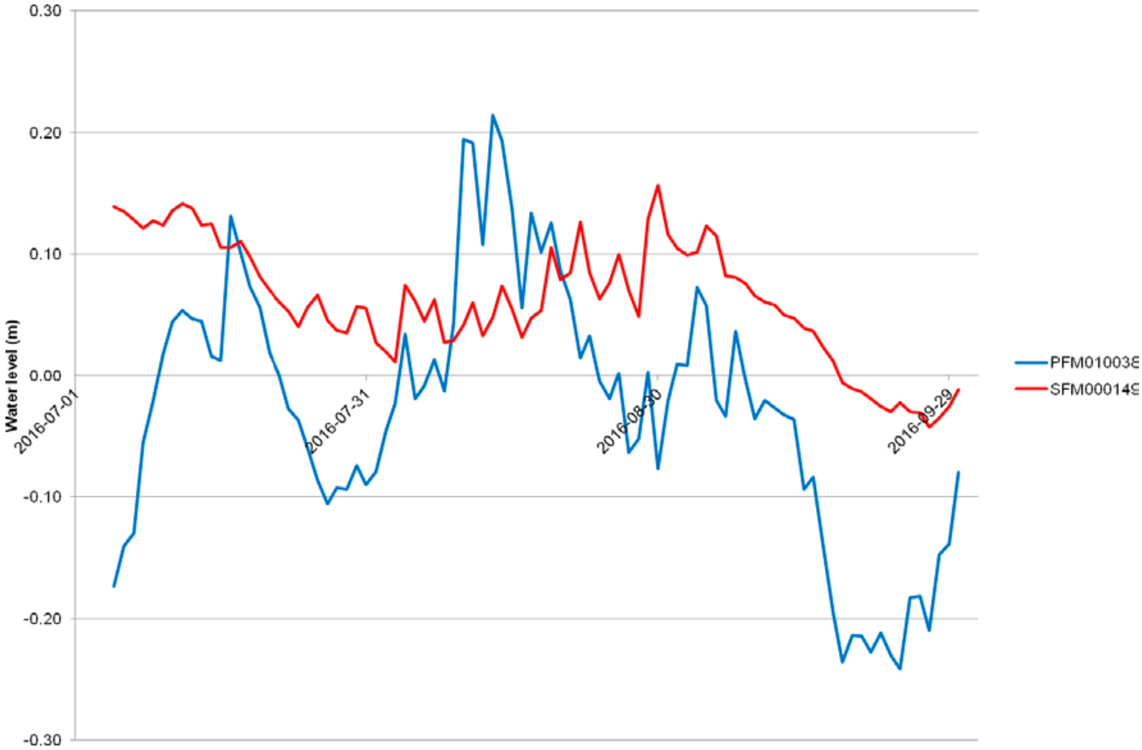


***Figure 4-10.** Time-series plot of sea level (PFM010038, blue) and groundwater level in well SFM000149 (red).*

Table 4-6 presents correlations (correlation coefficients, r) and surface water/groundwater level differences for surface-water level gauges SFM000119 and SFM000156 (a positive difference means that the surface-water level is higher than the groundwater level). According to the table, the surface-water level of Lake Tjärnpussen (SFM000119) is above the groundwater level in well SFM0049, installed at the shoreline at the downstream end of the lake (cf. Figure 1-2 and Figure 4-1). Moreover, there is some degree of correlation between the surface-water level of the lake and the near-shore groundwater level (r ≈ 0.5), see Figure 4-11. The hydraulic gradient at the downstream end of the lake may be influenced by easily-drained washout gravel and coarse till, observed during drilling of SFM0049 (Johansson 2003). The groundwater level in well SFM0077 (Figure 4-12), installed further from the lake, is closer to the surface-water level of the lake (r ≈ 0.5).

The surface-water level of the nameless pond (SFM000156) is always above the groundwater level in wells SFM000143 and -149, installed east and north of the pond, respectively, and the surface-water level is also above and shows no correlation to the sea level (note that the SFM000156 time series is short), see Figure 4-14 through Figure 4-16. The groundwater level in well SFM000121, installed northwest of the pond, drops below the surface-water level of the pond, and also below sea level, during the summer of 2016 (Figure 4-13).

Table 4-6. Surface water/groundwater level correlations (correlation coefficients, r) and differences (m). The analysis is based on daily averages and common data days.

Gauge id	SFM0049		SFM0077		SFM000121		SFM000143		SFM000149		PFM010038	
	r	Diff. (m)	r	Diff. (m)	r	Diff. (m)	r	Diff. (m)	r	Diff. (m)	r	Diff. (m).
SFM000119	0.52	0.58	0.52	0.08								
SFM000156					0.97	0.10	0.08	0.39	0.76	0.21	–0.61	0.51

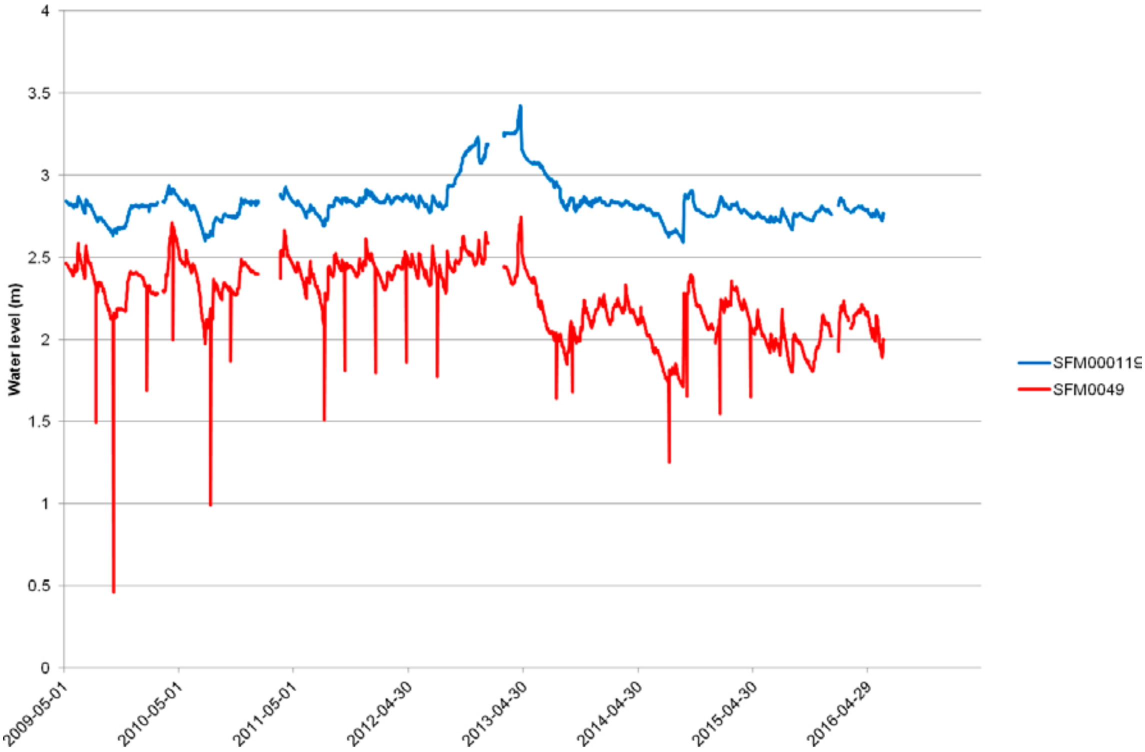


***Figure 4-11.** Time-series plots of surface-water level at gauge SFM000119 (blue) and groundwater level in well SFM0049 (red).*

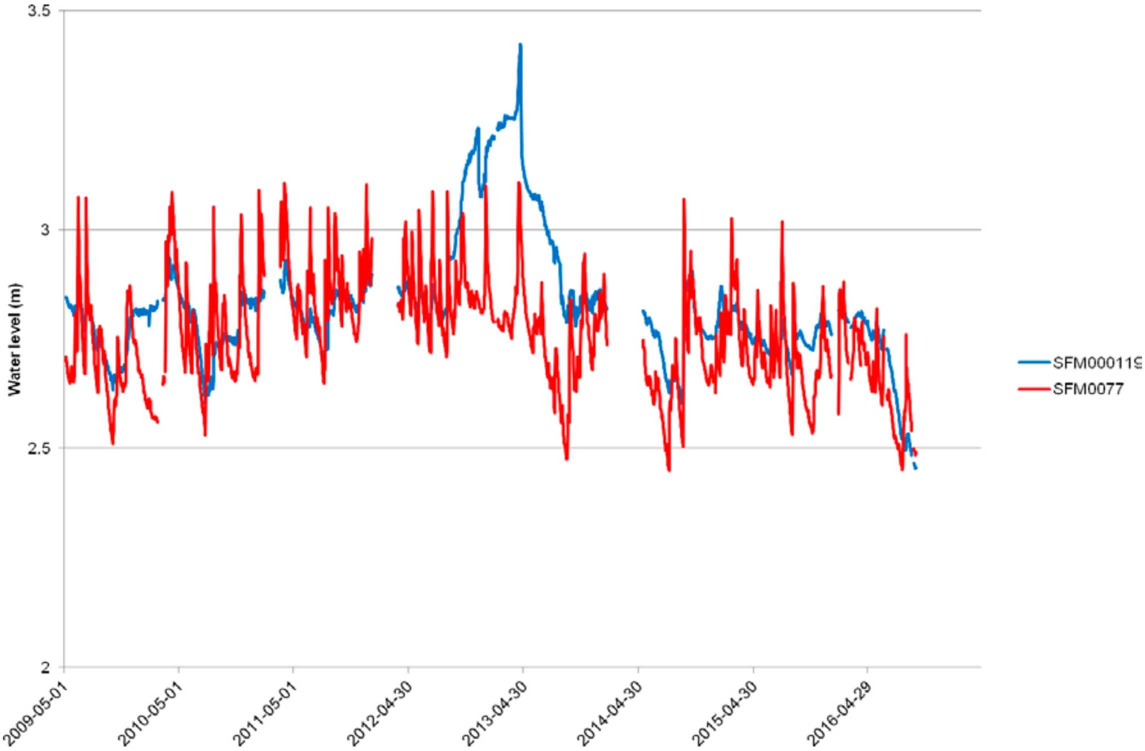


***Figure 4-12.** Time-series plots of surface-water level at gauge SFM000119 (blue) and groundwater level in well SFM0077 (red).*

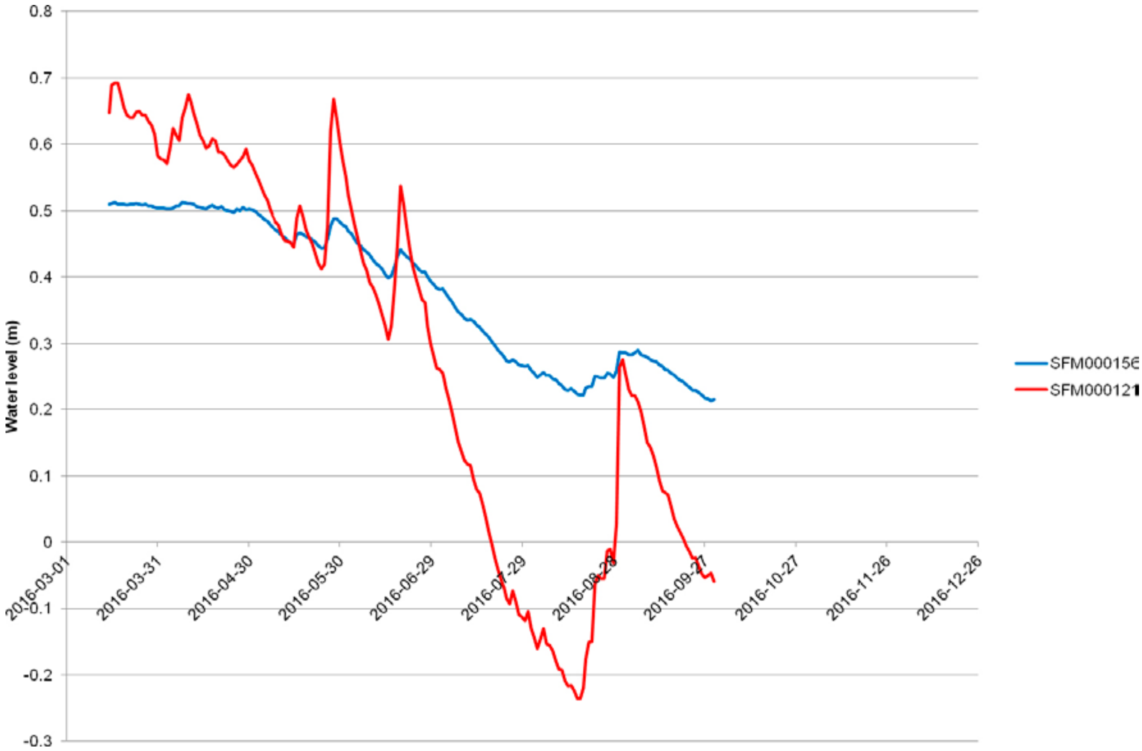


Figure 4-13. *Time-series plots of surface-water level at gauge SFM000156 (blue) and groundwater level in well SFM000121 (red).*

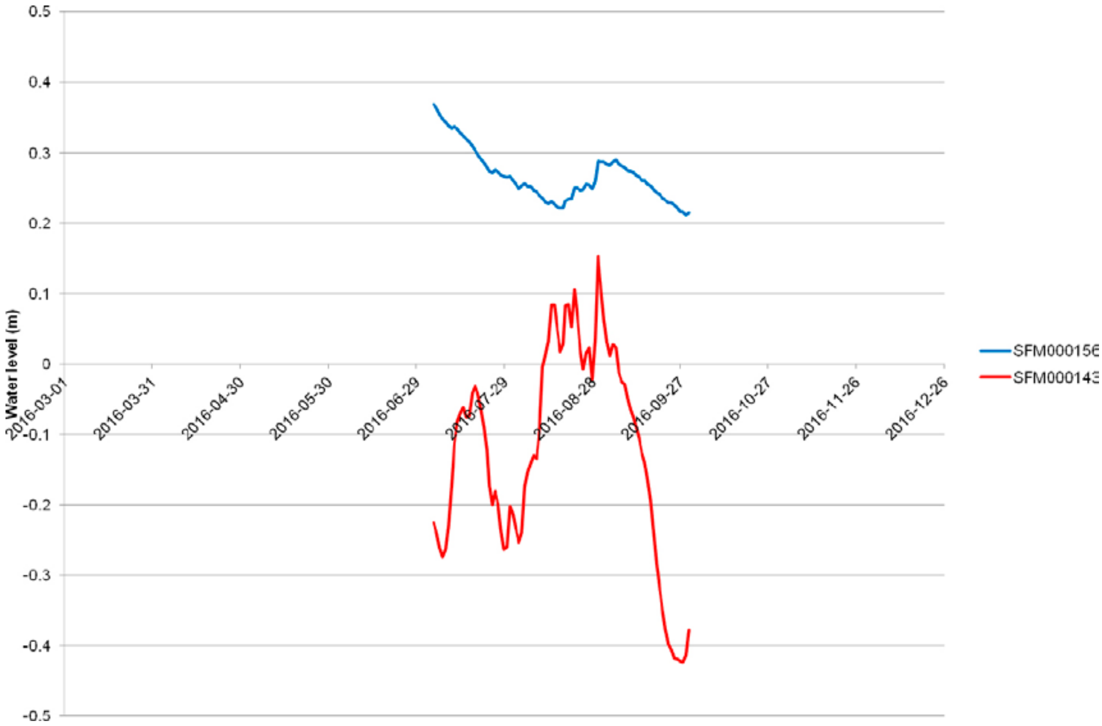


Figure 4-14. *Time-series plots of surface-water level at gauge SFM000156 (blue) and groundwater level in well SFM000143 (red).*

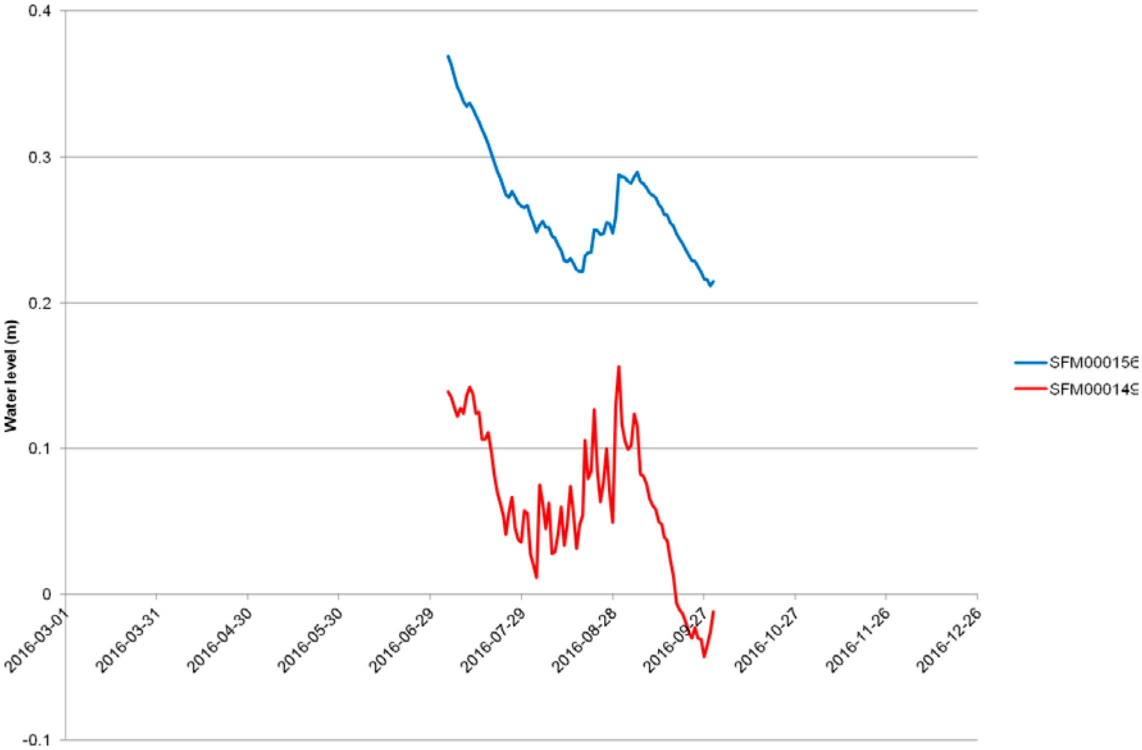


Figure 4-15. *Time-series plots of surface-water level at gauge SFM000156 (blue) and groundwater level in well SFM000149 (red).*

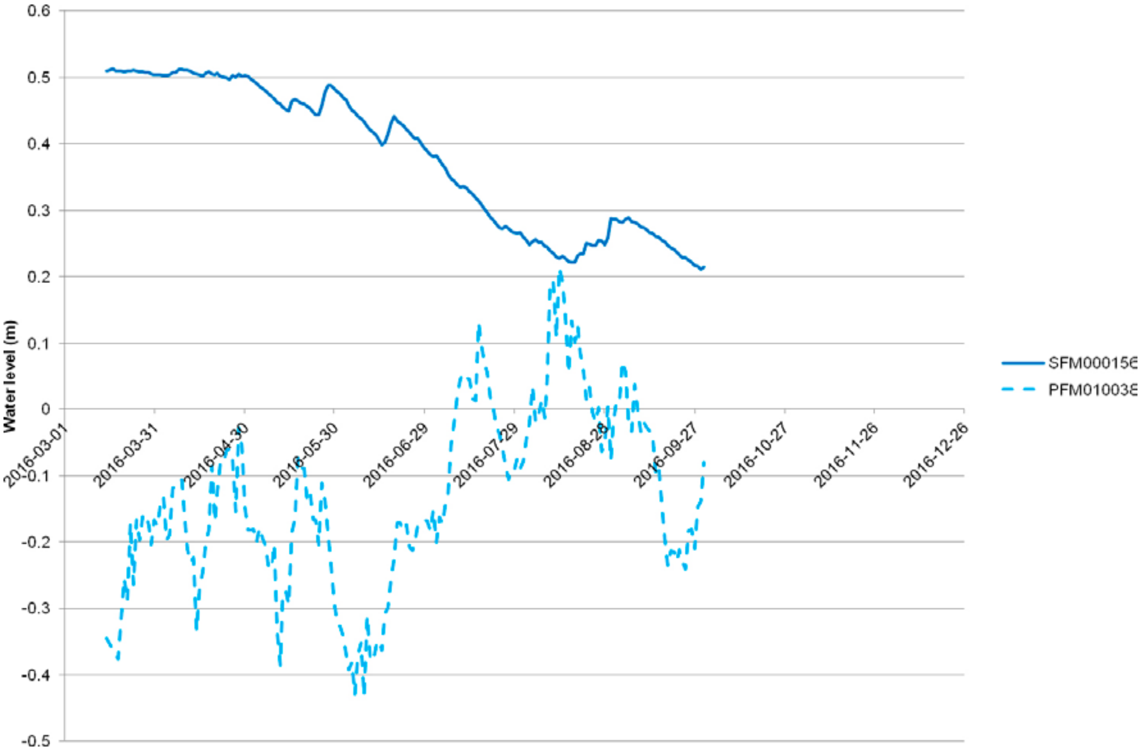


Figure 4-16. *Time-series plot of surface-water level at gauge SFM000156 (solid line) and sea level at gauge PFM010038 (dashed line).*

4.6 Groundwater levels in the upper part of the rock

Table 4-7 presents groundwater-level data available for the access-area description, including basic statistics (average and standard deviation) of groundwater levels and depths in upper borehole sections or open boreholes in rock (Figure 1-2). Subsequently to SDM-Site, monitoring has been initiated in 14 additional percussion-drilled and core-drilled boreholes in and in the vicinity of the access area. Appendix 1 provides statistics (average, standard deviation, minimum and maximum groundwater levels) for individual years and three-month seasons.

Table 4-7. Groundwater levels (interpreted as so-called point-water heads) and depths in upper borehole sections or open boreholes in rock. Std dev = standard deviation, m bgs = metres below ground surface. Dates are given as YYYY-MM-DD. Note that boreholes are equipped with an impermeable casing that extends some depth into the rock.

Borehole id (length interval, m)	Data period	Groundwater level (m)		Average depth to groundwater level (m bgs)
		Average	Std dev	
HFM20 (0–48)	2005-03-10–2016-09-30	0.94	0.36	1.74
HFM21 (0–21)	2006-10-25–2016-09-30	0.63	0.29	3.09
HFM22 (0–222)	2004-09-13–2016-09-30	0.03	0.67	1.21
HFM23 (0–211.5)	2005-11-01–2016-09-30	1.71	0.62	2.24
HFM28 (0–151.2)	2006-05-18–2016-09-30	2.11	0.40	1.90
HFM38 (0–23)	2007-04-11–2016-09-30	–0.14	0.93	2.00
HFM39 (0–151.2)	2011-07-11–2016-09-30	1.07	0.38	2.98
HFM40 (0–101.7)	2011-05-27–2016-09-30	0.01	0.21	2.14
HFM41 (0–101.5)	2011-06-08–2016-09-30	–0.54	0.22	3.74
KFM07A (0–148)	2007-02-20–2016-09-30	0.30	0.34	2.78
KFM07B		0.26	0.19	2.95
(0–298.93)	2006-05-03–2006-12-18			
(0–74)	2007-02-20–2009-03-23			
KFM07C (0–110)	2007-04-01–2016-09-30	0.40	0.34	2.80
KFM08A (0–161)	2007-10-24–2016-01-19	0.35	0.20	2.01
KFM08B (0–70)	2006-03-22–2016-06-08	0.07	0.25	2.03
KFM08C (0–145)	2007-04-12–2016-09-30	0.07	0.21	2.21
KFM08D (0–160)	2007-10-24–2013-02-04	0.30	0.18	2.00
KFM09A (0–300)	2006-11-07–2016-09-30	1.91	0.33	2.23
KFM09B (0–200)	2006-11-07–2016-07-04	0.06	0.28	4.10
KFM13 (0–150.21)	2011-07-08–2016-09-30	0.54	0.30	1.96
KFM14 (0–60.18)	2014-11-03–2016-09-30	0.21	0.16	1.56
KFM15 (0–62.3)	2011-07-08–2016-09-30	1.11	0.38	1.39
KFM16 (0–60.35)	2011-06-08–2016-09-30	0.12	0.27	1.18
KFM17 (0–60.45)	2011-07-11–2016-09-30	0.57	0.27	2.87
KFM18 (0–60.46)	2011-07-08–2016-09-30	0.99	0.38	2.28
KFM19 (0–102.37)	2011-07-07–2016-09-30	–0.03	0.22	2.55
KFM20 (0–60.5)	2011-07-08–2016-09-30	1.02	0.25	1.58
KFM21 (0–101.6)	2011-07-11–2016-09-30	0.20	0.24	2.21
KFM22 (0–60.26)	2011-07-07–2016-09-30	–0.04	0.22	2.54
KFM23 (0–100.64)	2011-07-12–2016-09-30	0.28	0.25	1.69

Figure 4-17 shows a cross plot of average groundwater levels in upper borehole sections or open boreholes versus local ground-surface elevations (cf. Figure 2-7). Moreover, Figure 4-18 and Figure 4-19 illustrate averages and intervals of groundwater levels, local ground-surface elevations, and rock-surface elevations. According to these figures, there is little correlation between the groundwater level in the upper part of the rock and the local topography. This phenomenon is likely due to hydraulic contacts with the sea, which acts as a "drain" boundary condition for groundwater levels in fracture zones/sheet joints inside the tectonic lens (cf. Chapter 2). The average groundwater level in some boreholes is close to or even below sea level. In particular, the average groundwater level in percussion-drilled borehole HFM41, located north of the cooling-water canal, is c 0.5 m below sea level, possibly due to groundwater drainage below the reactor buildings of the Forsmark nuclear power plant.

According to Figure 4-19 through Figure 4-21, the groundwater level in the upper part of the rock has a descending trend from inland areas towards the coastline. The cross sections in Figure 4-22 use the RDM (regolith depth and stratigraphy model; Follin 2018) as background cartoon to illustrate interpreted two-dimensional groundwater flow in the planes of the SW–NE and NW–SE cross sections (cf. Figure 1-2). Interpreted flow directions are based on average groundwater levels in regolith and upper part of the rock. As shown in Figure 4-22, groundwater flow is directed both from inland areas towards the coastline and from regolith to rock.

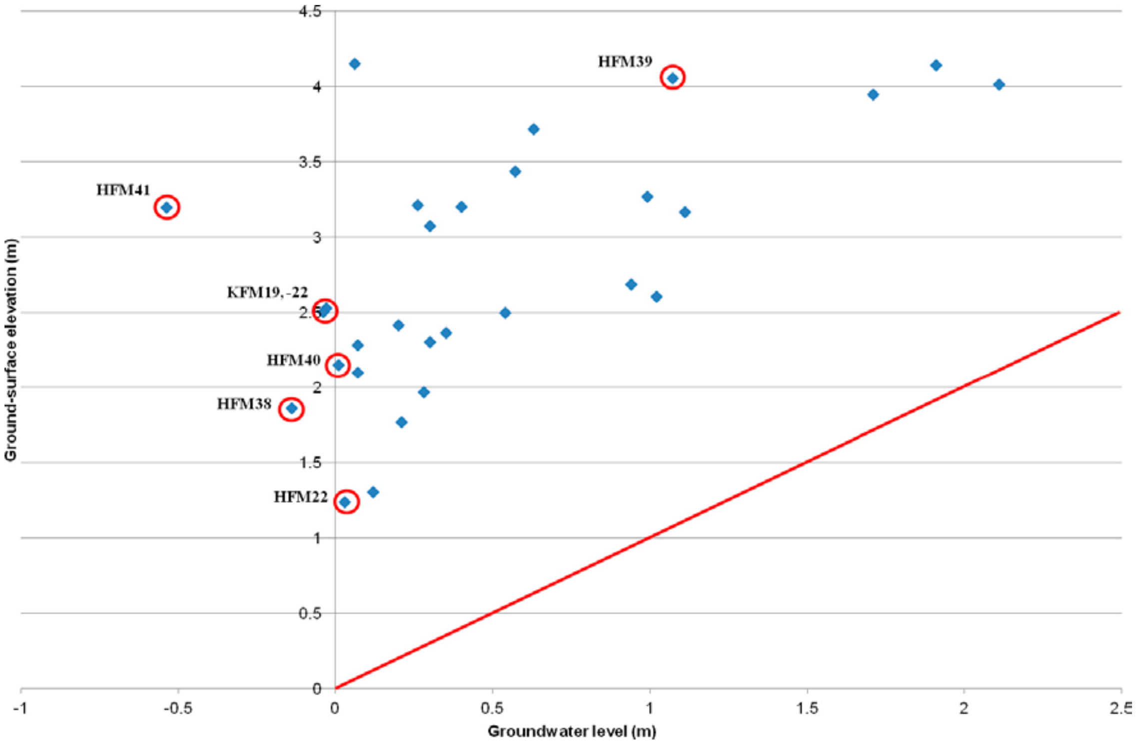


Figure 4-17. *Cross plot of average groundwater levels in percussion- and core-drilled boreholes (upper borehole sections in sectioned boreholes) versus local ground-surface elevations. The red line represents a perfect linear groundwater-level/ground-surface elevation relationship.*

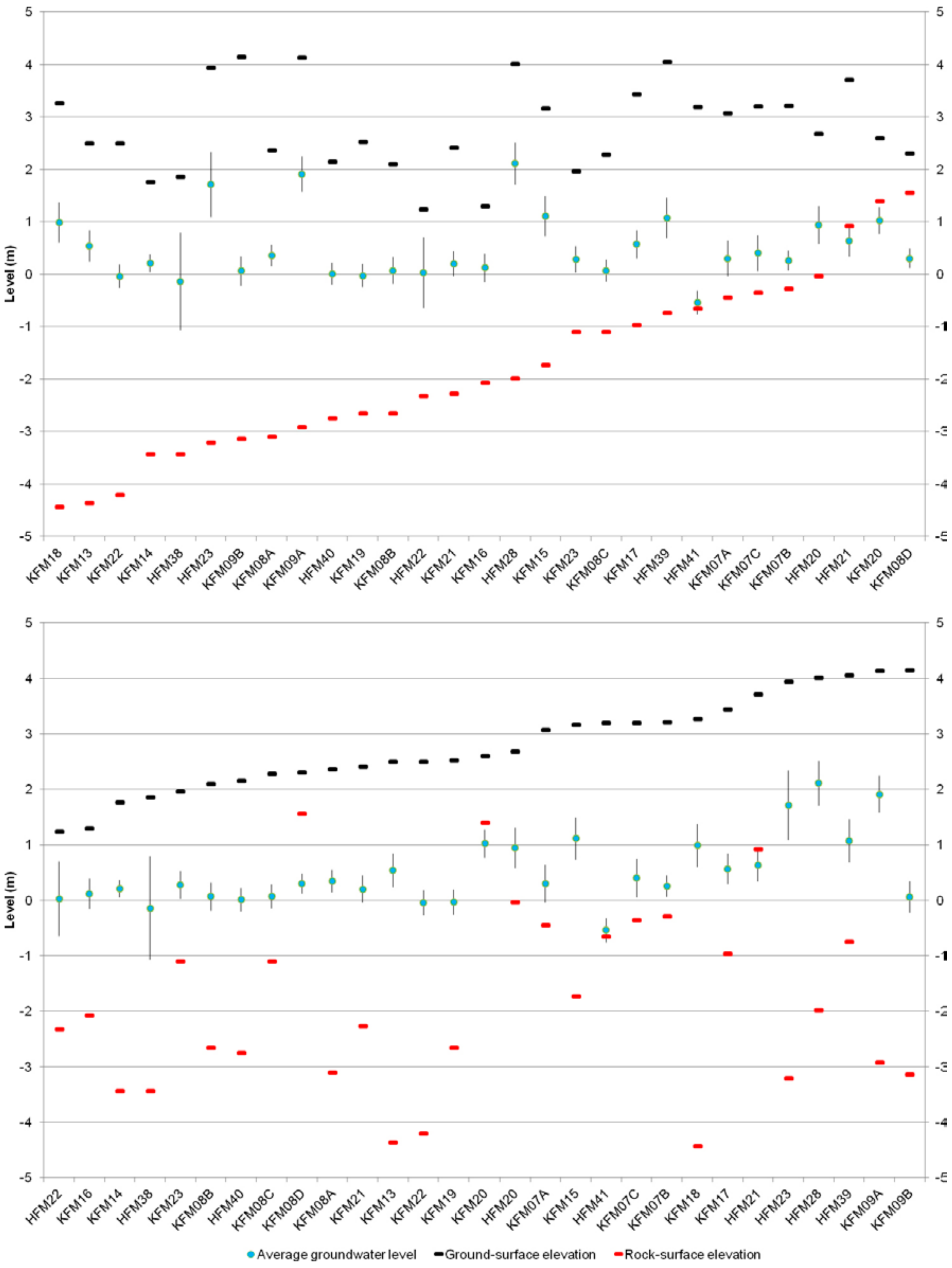


***Figure 4-18.** Averages and intervals (average ± 1 std dev) of groundwater levels, local ground-surface elevations (black lines) and rock-surface elevations (red lines), ranked according to rock-surface elevations (upper plot) and ground-surface elevations (lower plot).*

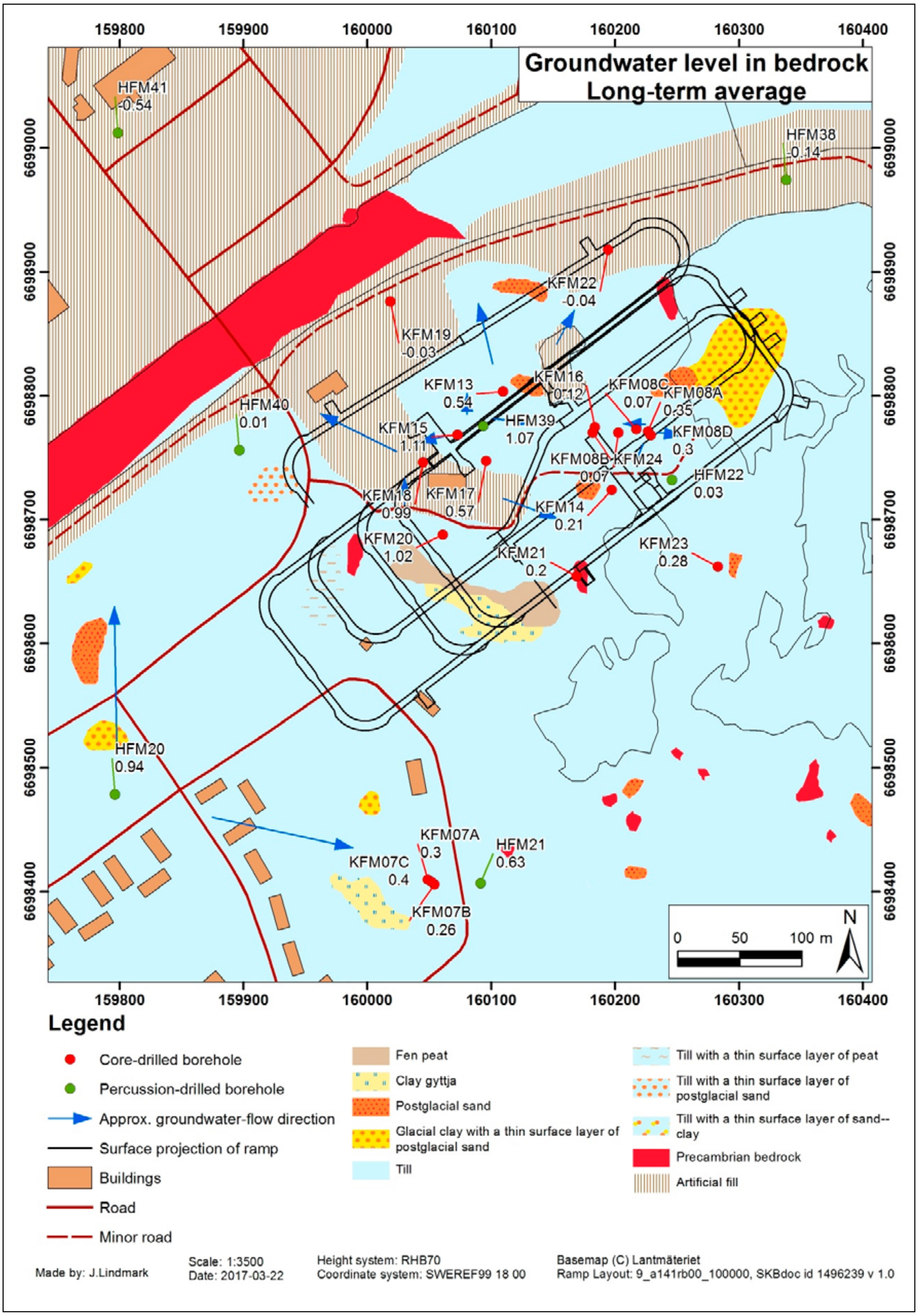


Figure 4-19. *Interpreted horizontal groundwater-flow directions (arrows), based on overall average groundwater levels (numbers below each borehole id, in metres) in upper borehole sections or open boreholes in rock. The average sea level is approximately 0 m in the RHB 70 elevation system.*

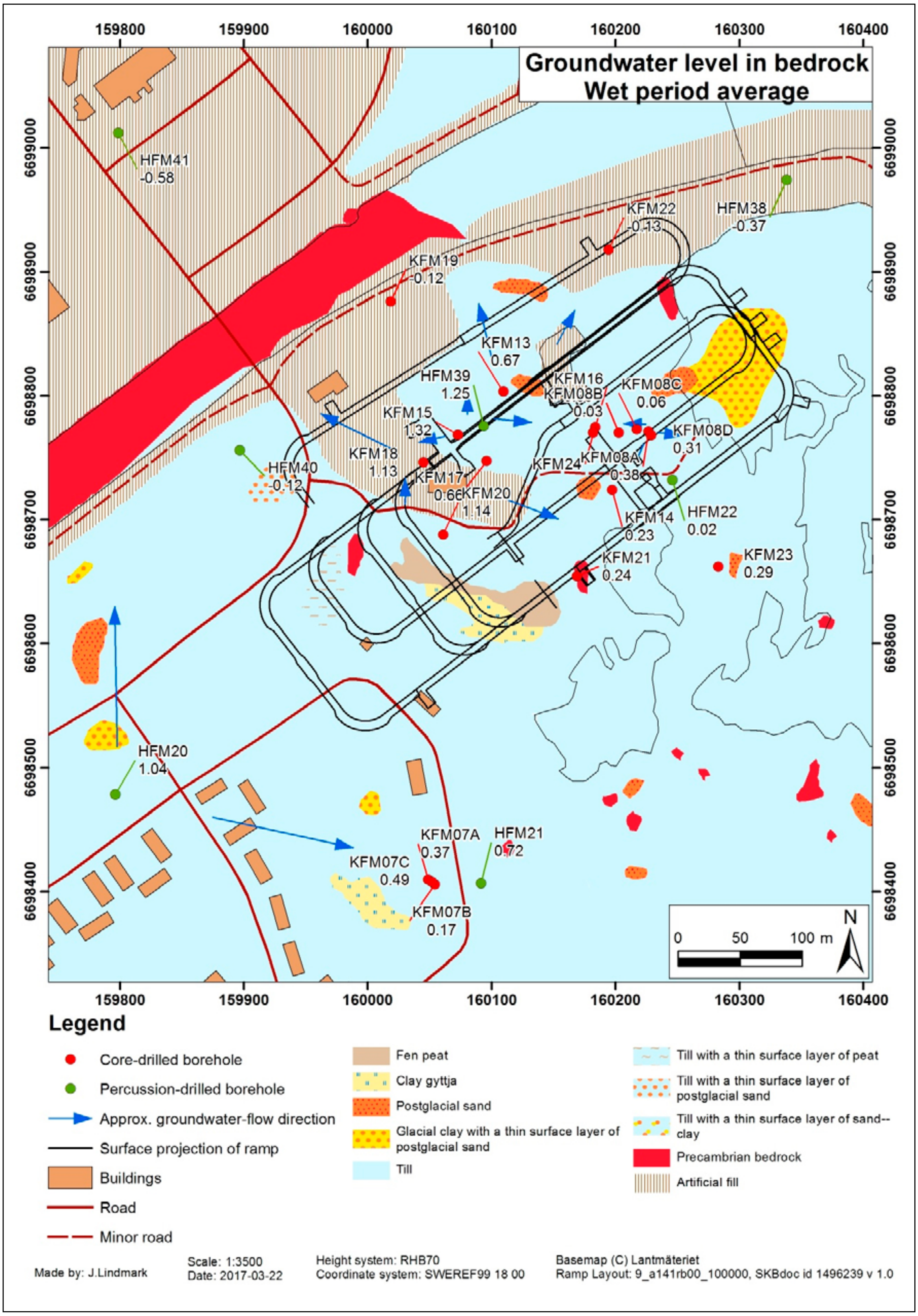


Figure 4-20. *Interpreted horizontal groundwater-flow directions (arrows), based on average groundwater levels (numbers below each borehole id, in metres) in upper borehole sections or open boreholes in rock. Interpreted flow directions are based on wet-period averages (March–May). The average sea level is approximately 0 m in the RHB 70 elevation system.*

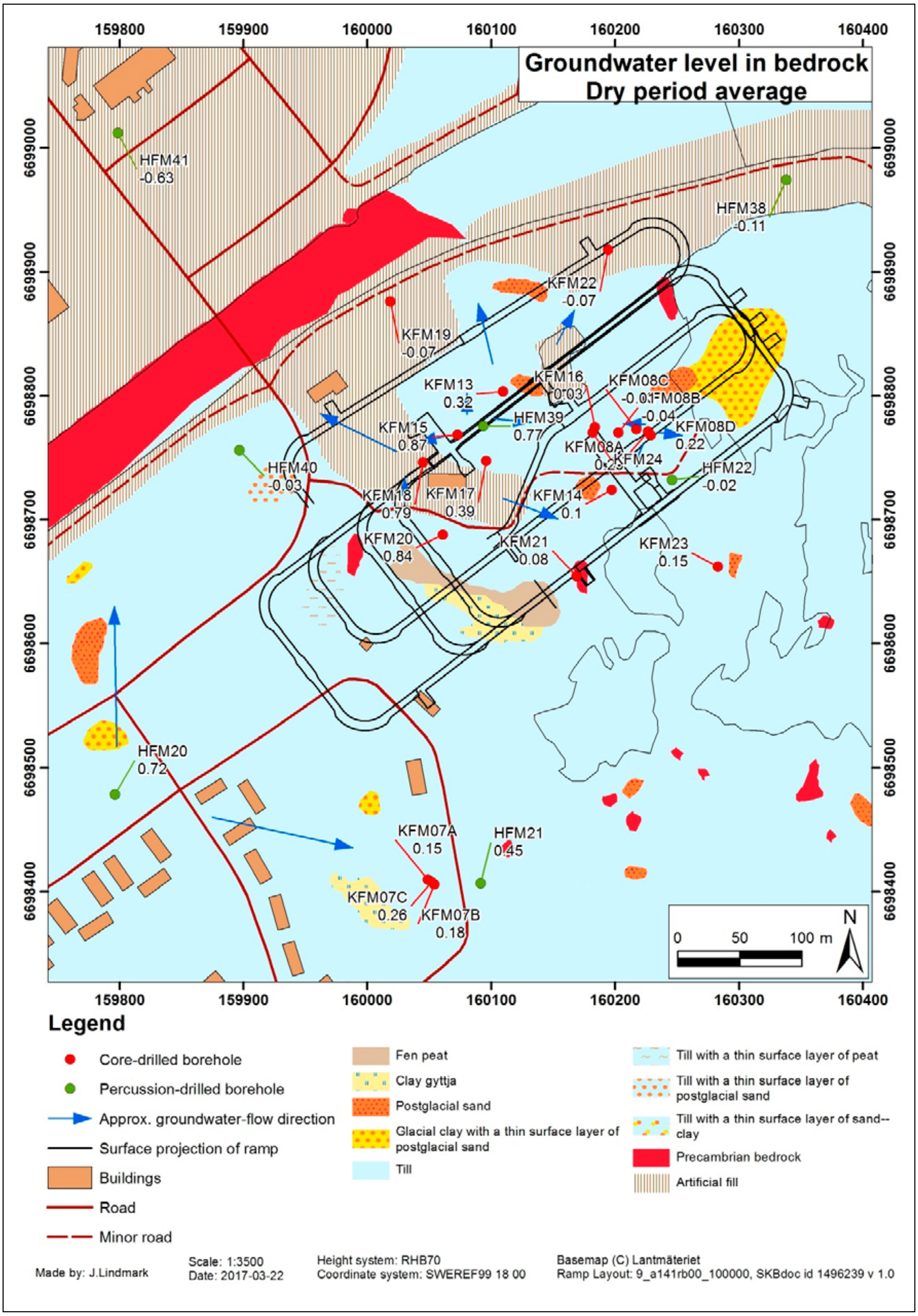


Figure 4-21. *Interpreted horizontal groundwater-flow directions (arrows), based on average groundwater levels (numbers below each borehole id, in metres) in upper borehole sections or open boreholes in rock. Interpreted flow directions are based on dry-period averages (June–August). The average sea level is approximately 0 m in the RHB 70 elevation system.*

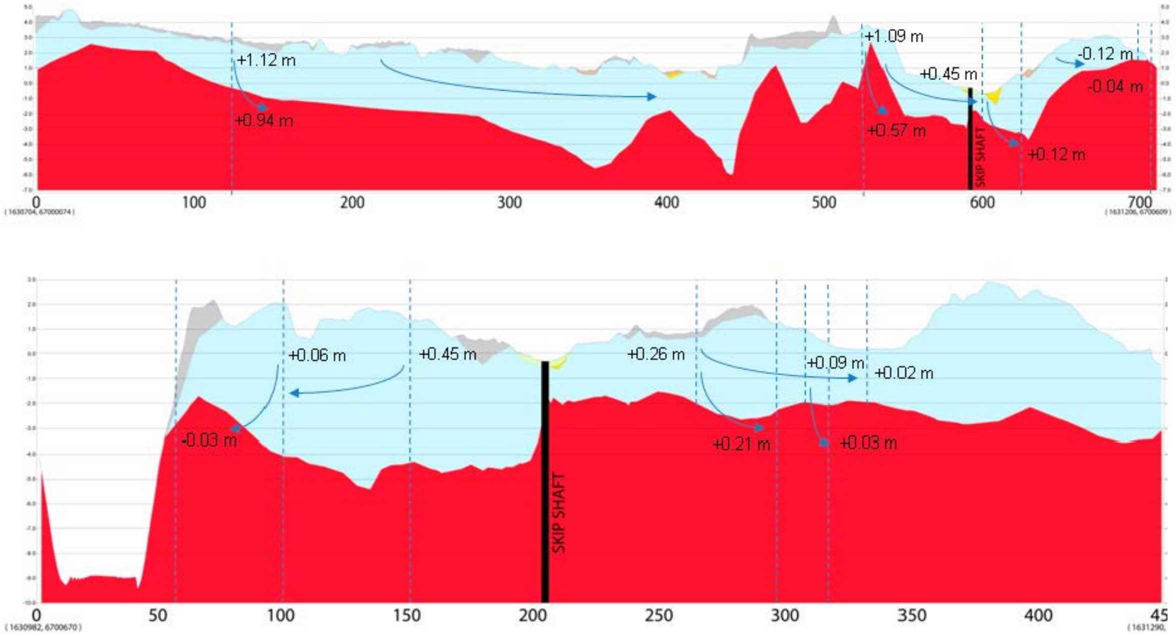


Figure 4-22. *Interpreted two-dimensional groundwater flow directions (arrows) in and between regolith and rock in the planes of the SW–NE (upper figure) and NW–SE (bottom figure) cross sections (cf. Figure 1-2). Interpreted flow directions in the upper figure are based on average groundwater levels (from SW to NE) in SFM0107, HFM20, KFM17, SFM000122, SFM000121, KFM16, SFM000143 and KFM22 (cf. Table 4-3 and Table 4-7). The bottom figure is based on average groundwater levels (from NW to SE) in KFM19, SFM000149, SFM000121, SFM000124, KFM14, SFM000123, HFM22 and SFM000145. The average sea level is approximately 0 m in the RHB 70 elevation system.*

Table 4-8 analyses correlations (in terms of correlation coefficients, r, based on daily averages) between groundwater levels in upper borehole sections or open boreholes in rock and the sea level (PFM010038). The correlation is rather high ($r > 0.5$) for some of the boreholes (KFM08C, -08D, -14 and -16), whereas the correlation is very high (r close to 1) for HFM40, KFM19 and -22. As can be seen in Figure 4-23, time lags are short compared to groundwater-level responses in regolith to sea-level variations (cf. Figure 4-8 through Figure 4-10). Groundwater/sea interactions are associated with movement of water in porous media (regolith), whereas pressure changes are transmitted relatively fast in the fracture network of the rock, characterised by high transmissivity T and low storativity (i.e. high hydraulic diffusivity T/S).

Table 4-8. Correlations (expressed as correlation coefficients, r) between groundwater level in upper borehole sections (or open boreholes) in rock and sea level (PFM010038). The analysis is based on daily averages and common data days. Dates are given as YYYY-MM-DD.

Borehole id (length interval, m)	Data period	r
HFM20 (0–48)	2005-03-10–2016-09-30	0.17
HFM21	2006-10-25–2016-09-30	0.11
HFM22 (0–222)	2004-09-13–2016-09-30	0.04
HFM23	2005-11-01–2016-09-30	0.13
HFM28	2006-05-18–2016-09-30	0.07
HFM38	2007-04-11–2016-09-30	0.21
HFM39 (0–151.2)	2011-07-11–2016-09-30	0.26
HFM40	2011-05-27–2016-09-30	0.99
HFM41	2011-06-08–2016-09-30	0.42
KFM07A	2007-02-20–2016-01-19	0.01
KFM07B		–0.08
(0–298.93)	2006-05-03–2006-12-18	
(0–74)	2007-02-20–2009-03-23	
KFM07C (0–110)	2007-04-01–2016-09-30	0.06
KFMA08A (0–161)	2007-02-20–2016-09-30	0.31
KFM08B (0–70)	2007-04-01–2016-09-30	0.50
KFM08C (0–145)	2007-10-24–2016-01-19	0.61
KFM08D (0–160)	2006-03-22–2016-06-08	0.52
KFM09A (0–300)	2007-04-12–2016-09-30	0.05
KFM09B (0–200)	2007-10-24–2013-02-04	0.24
KFM13 (0–150.21)	2006-11-07–2016-09-30	0.22
KFM14 (0–60.18)	2006-11-07–2016-07-04	0.75
KFM15 (0–62.3)	2011-07-08–2016-09-30	0.23
KFM16 (0–60.35)	2014-11-03–2016-09-30	0.56
KFM17 (0–60.45)	2011-07-08–2016-09-30	0.33
KFM18 (0–60.46)	2011-06-08–2016-09-30	0.20
KFM19 (0–102.37)	2011-07-11–2016-09-30	0.95
KFM20 (0–60.50)	2011-07-08–2016-09-30	0.18
KFM21 (0–101.06)	2011-07-07–2016-09-30	0.32
KFM22 (0–60.26)	2011-07-08–2016-09-30	0.96
KFM23 (0–100.64)	2011-07-11–2016-09-30	0.49

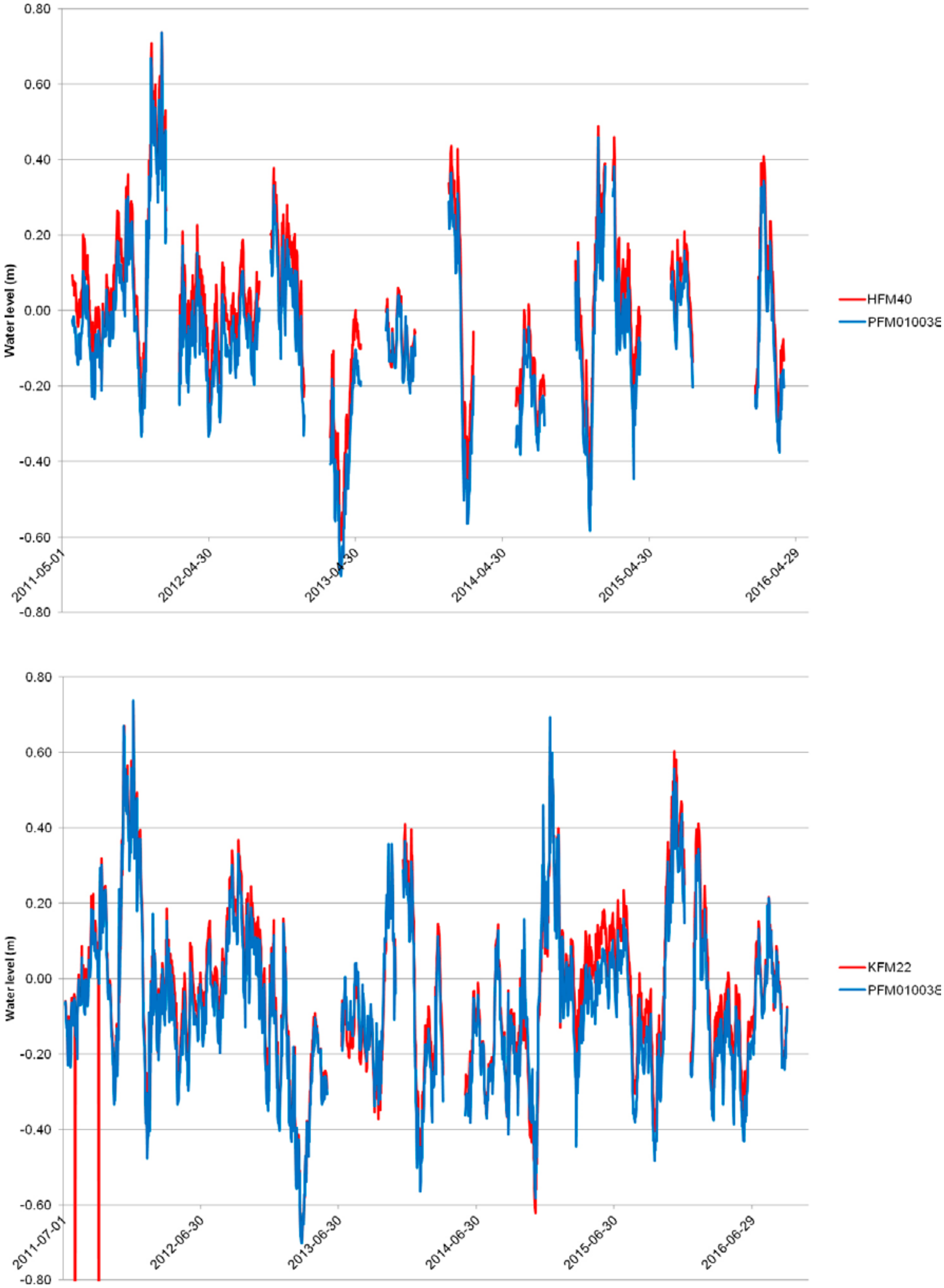


Figure 4-23. *Time-series plots of groundwater levels in boreholes HFM40 (upper plot) and KFM22 (lower plot), and sea level (PFM010038).*

Table 4-9 through Table 4-12 (separate tables, for clarity) present groundwater-level differences and correlations (correlation coefficients, r) for upper borehole sections (or open boreholes) and nearby wells installed in regolith. A positive difference means that the groundwater level in rock is higher than the groundwater level in regolith, which indicates upward flow. Note that well SFM0076 (close to HFM21 and KFM07A–C) is excluded due to the short data period, and that there are no wells close to HFM38 and -40.

According to these tables, there are different vertical gradient directions for different borehole/well combinations. Most groundwater-level differences are negative, i.e. the groundwater level in the upper part of the rock is below the groundwater level in the regolith, which indicates downward flow. However, the groundwater level in e.g. KFM13–23 is above the groundwater level in the regolith for some well combinations, possibly due to occurrences of relatively coarse-grained, easily-drained artificial fill, i.e. a mixture of excavated rock and regolith, at some well locations. Correlations are quite high for many borehole/well combinations, e.g. HFM20, -22, -39, KFM08A, -08C, -08D, KFM13–23 and nearby wells (see examples in Figure 4-24 and Figure 4-25).

Table 4-9. Groundwater-level differences (m) for upper borehole sections (or open boreholes) and nearby wells installed in regolith. The analysis is based on daily averages and common data days. Positive values indicate upward flow from rock to regolith, and negative values indicate downward flow.

Borehole id (length interval, m)	Well id (SFM-)							
	0049	0077	0107	000121	000122	000123	000124	000125
HFM20 (0–48)	–	–	–0.15	–	–	–	–	–
HFM21	–	–	–	–	–	–	–	–
HFM22 (0–222)	–	–	–	–	–	0.12	–0.05	–
HFM23	–0.56	–1.02	–	–	–	–	–	–
HFM28	–0.14	–0.64	–	–	–	–	–	–
HFM38	–	–	–	–	–	–	–	–
HFM39 (0–151.2)	–	–	–	0.59	–0.04	–	–	–0.07
HFM40	–	–	–	–	–	–	–	–
HFM41	–	–	–	–	–	–	–	–
KFM07A–C	–	–	–	–	–	–	–	–
KFMA08A (0–161)	–	–	–	–	–	0.25	0.07	–
KFM08B (0–70)	–	–	–	–	–	0.00	–0.18	–
KFM08C (0–145)	–	–	–	–	–	–0.02	–0.20	–
KFM08D (0–160)	–	–	–	–	–	0.20	0.00	–
KFM09A (0–300)	–0.37	–0.86	–	–	–	–	–	–
KFM09B (0–200)	–2.23	–2.72	–	–	–	–	–	–
KFM13 (0–150.21)	–	–	–	0.09	–0.55	0.44	0.27	–0.56
KFM14 (0–60.18)	–	–	–	–0.21	–0.80	0.11	–0.05	–0.72
KFM15 (0–62.3)	–	–	–	0.67	0.01	1.12	0.87	–0.01
KFM16 (0–60.35)	–	–	–	–0.33	–0.96	0.03	–0.14	–0.98
KFM17 (0–60.45)	–	–	–	0.12	–0.51	0.48	0.30	–0.54
KFM18 (0–60.46)	–	–	–	0.54	–0.10	0.89	0.72	–0.12
KFM19 (0–102.37)	–	–	–	–0.48	–1.11	–0.12	–0.29	–1.14
KFM20 (0–60.50)	–	–	–	0.56	–0.07	0.93	0.75	–0.08
KFM21 (0–101.06)	–	–	–	–0.25	–0.88	0.11	–0.07	–0.90
KFM22 (0–60.26)	–	–	–	–0.49	–1.17	–0.15	–0.35	–1.20
KFM23 (0–100.64)	–	–	–	–0.17	–0.80	0.18	0.01	–0.83

Table 4-10. Groundwater-level differences (m) for upper borehole sections (or open boreholes) and nearby wells installed in regolith. The analysis is based on daily averages and common data days. Positive values indicate upward flow from rock to regolith, and negative values indicate downward flow.

Borehole id (length interval, m)	Well id (SFM-) 000143	000145	000146	000147	000149	000153
HFM20 (0–48)	–	–	–	–	–	–
HFM21	–	–		–	–	–
HFM22 (0–222)	–	0.02	–	–	–	–
HFM23	–	–		–		–
HFM28	–	–		–		–
HFM38	–	–		–		–
HFM39 (0–151.2)	–	–		–		–
HFM40	–	–		–		–
HFM41	–	–		–		–
KFM07A	–	–		–		–1.33
KFM07B	–	–	–	–	–	–
KFM07C	–	–	–	–	–	–1.27
KFMA08A (0–161)	–	–	–	–	–	–
KFM08B (0–70)	–	–	–	–	–	–
KFM08C (0–145)	–	–	–	–	–	–
KFM08D (0–160)	–	–	–	–	–	–
KFM09A (0–300)	–	–	–	–		–
KFM09B (0–200)	–	–	–	–		–
KFM13 (0–150.21)	0.18	0.13	0.41	–	–0.0002	–
KFM14 (0–60.18)	0.16	0.01	0.39	–	–0.03	–
KFM15 (0–62.3)	0.52	0.46	0.75	–	0.34	–
KFM16 (0–60.35)	0.13	–0.02	0.36	–	–0.05	–
KFM17 (0–60.45)	0.28	0.19	0.51	–	0.10	–
KFM18 (0–60.46)	0.57	0.46	0.79	–	0.38	–
KFM19 (0–102.37)	0.10	–0.10	0.32	–	–0.09	–
KFM20 (0–60.50)	0.67	0.58	0.90	–	0.49	–
KFM21 (0–101.06)	0.14	0.03	0.37	–	–0.04	–
KFM22 (0–60.26)	0.11	–0.09	0.34	–	–0.07	–
KFM23 (0–100.64)	0.24	0.09	0.47	–	0.05	–

Table 4-11. Groundwater-level correlations (expressed as correlation coefficients, r) for upper borehole sections (or open boreholes) and nearby wells installed in regolith. The analysis is based on daily averages and common data days.

Borehole id (length interval, m)	Well id (SFM-)							
	0049	0077	0107	000121	000122	000123	000124	000125
HFM20 (0–48)	–	–	0.87	–	–	–	–	–
HFM21	–	–	–	–	–	–	–	–
HFM22 (0–222)	–	–	–	–	–	0.90	0.74	–
HFM23	0.26	0.38	–	–	–	–	–	–
HFM28	0.52	0.57	–	–	–	–	–	–
HFM38	–	–	–	–	–	–	–	–
HFM39 (0–151.2)	–	–	–	0.91	0.97	–	–	0.98
HFM40	–	–	–	–	–	–	–	–
HFM41	–	–	–	–	–	–	–	–
KFM07A–C	–	–	–	–	–	–	–	–
KFMA08A (0–161)	–	–	–	–	–	0.83	0.83	–
KFM08B (0–70)	–	–	–	–	–	0.53	0.41	–
KFM08C (0–145)	–	–	–	–	–	0.79	0.55	–
KFM08D (0–160)	–	–	–	–	–	0.83	0.63	–
KFM09A (0–300)	0.46	0.56	–	–	–	–	–	–
KFM09B (0–200)	0.55	0.52	–	–	–	–	–	–
KFM13 (0–150.21)				0.93	0.82	0.85	0.89	0.84
KFM14 (0–60.18)				0.77	0.58	0.92	0.74	0.61
KFM15 (0–62.3)				0.85	0.88	0.75	0.78	0.88
KFM16 (0–60.35)	–	–	–	0.46	0.39	0.54	0.43	0.39
KFM17 (0–60.45)	–	–	–	0.87	0.83	0.83	0.84	0.84
KFM18 (0–60.46)	–	–	–	0.72	0.79	0.65	0.69	0.78
KFM19 (0–102.37)	–	–	–	0.33	0.32	0.55	0.27	0.30
KFM20 (0–60.50)	–	–	–	0.90	0.82	0.79	0.88	0.85
KFM21 (0–101.06)	–	–	–	0.55	0.47	0.61	0.55	0.47
KFM22 (0–60.26)	–	–	–	0.30	0.36	0.53	0.30	0.37
KFM23 (0–100.64)	–	–	–	0.58	0.51	0.65	0.56	0.51

Table 4-12. Groundwater-level correlations (expressed as correlation coefficients, r) for upper borehole sections (or open boreholes) and nearby wells installed in regolith. The analysis is based on daily averages and common data days.

Borehole id (length interval, m)	Well id (SFM-)					
	000143	000145	000146	000147	000149	000153
HFM20 (0–48)	–	–	–	–	–	–
HFM21	–	–	–	–	–	–
HFM22 (0–222)	–	0.90	–	–	–	–
HFM23	–	–	–	–	–	–
HFM28	–	–	–	–	–	–
HFM38	–	–	–	–	–	
HFM39 (0–151.2)	–	–	–	–	–	–
HFM40	–	–	–	–	–	–
HFM41	–	–	–	–	–	–
KFM07A	–	–	–	–	–	0.39
KFM07B	–	–	–	–	–	–
KFM07C	–	–	–		–	0.42
KFMA08A (0–161)	–	–	–	–	–	–
KFM08B (0–70)	–	–	–	–	–	–
KFM08C (0–145)	–	–	–	–	–	–
KFM08D (0–160)	–	–	–	–	–	–
KFM09A (0–300)	–	–	–	–	–	–
KFM09B (0–200)	–	–	–	–	–	–
KFM13 (0–150.21)	0.04	0.78	0.96	–	0.42	–
KFM14 (0–60.18)	0.70	0.90	0.60		0.80	–
KFM15 (0–62.3)	–0.06	0.62	0.94	–	0.42	–
KFM16 (0–60.35)	0.75	0.93	0.45	–	0.80	–
KFM17 (0–60.45)	0.02	0.68	0.96	–	0.44	–
KFM18 (0–60.46)	–0.06	0.64	0.91	–	0.49	–
KFM19 (0–102.37)	0.76	0.87	–0.13		0.58	–
KFM20 (0–60.50)	0.03	0.82	0.92	–	0.56	–
KFM21 (0–101.06)	0.61	0.98	0.66	–	0.47	–
KFM22 (0–60.26)	0.71	0.85	–0.16	–	0.58	–
KFM23 (0–100.64)	0.74	0.91	0.54	–	0.82	–

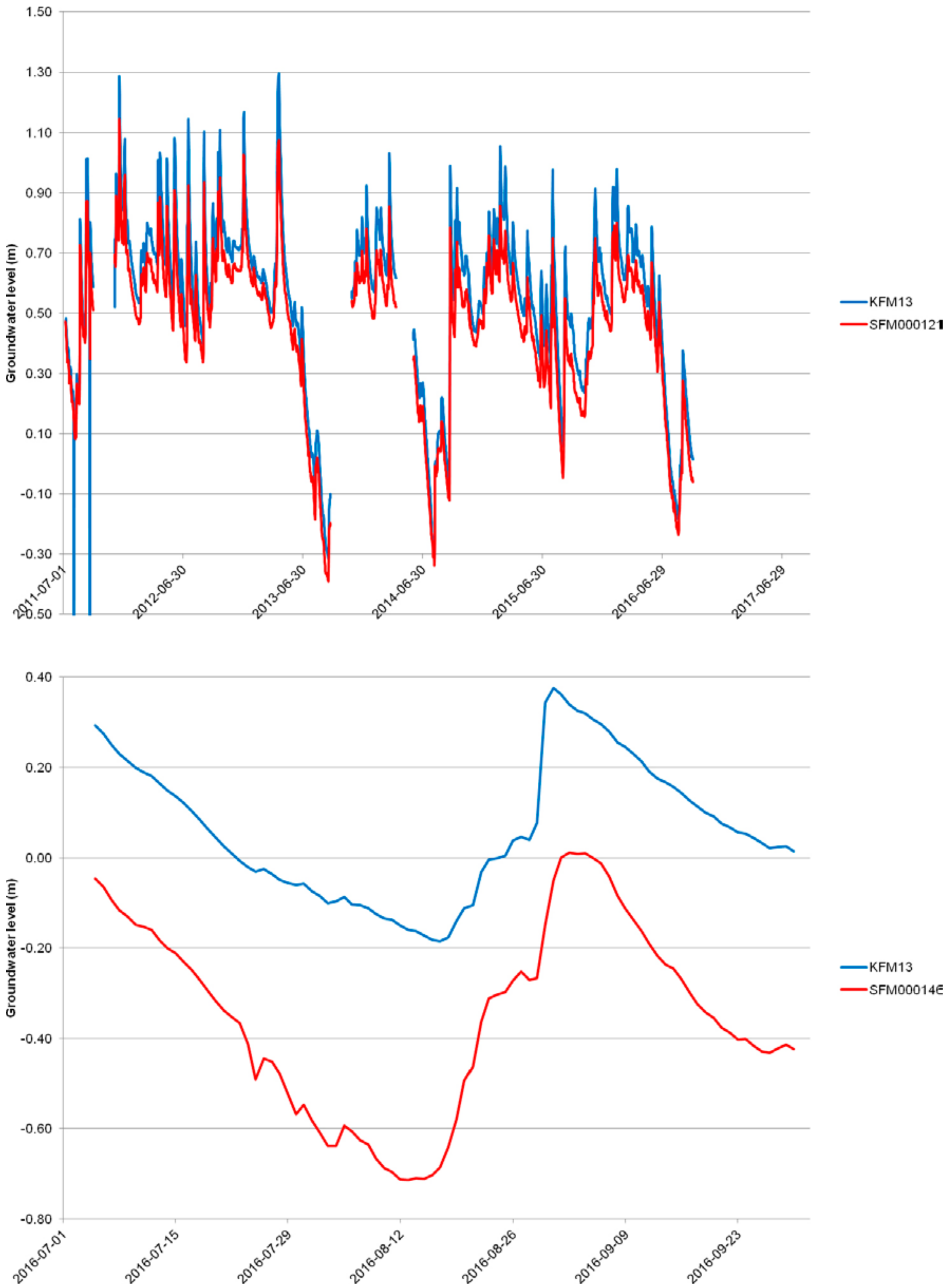


***Figure 4-24.** Time-series plots of groundwater levels in borehole KFM13 (blue) and wells SFM000121 (upper plot) and SFM000146 (lower plot).*

***Figure 4-25.** Time-series plot of groundwater levels in borehole HFM22 (blue) and well SFM000145 (red).*

Figure 4-26 analyses potential effects of the local topography on interpreted vertical gradient directions. Specifically, the figure plots groundwater-level differences for borehole sections (or open boreholes) and nearby wells, installed in regolith within approximately 100 m or less from the borehole (cf. Table 4-9 and Table 4-10), as function of corresponding ground-surface elevation differences. For almost all data points with positive groundwater-level differences, i.e. groundwater level in rock higher than groundwater level in regolith, indicating upward flow, the ground-surface elevation difference is also positive. This means that the ground-surface elevation is lower at the well than at the borehole, which may influence the interpretation of the vertical flow direction between regolith and rock. Remaining data points have negative groundwater-level differences, i.e. groundwater level in rock below groundwater level in regolith, indicating downward flow, irrespective of the ground-surface elevation difference. Hence, in addition to potential effects of coarse-grained regolith, the small-scale undulating topography may influence interpretation of vertical hydraulic gradients between regolith and rock.

Knowledge of hydraulic disturbances in the rock enables further analyses of interactions between groundwater in regolith and rock. Specifically, so called flow logging, associated with groundwater-level drawdown in boreholes in rock, was performed in HFM39–41 and KFM13–23 during September–October 2011. Other disturbances associated with groundwater-level drawdown in boreholes in rock include interference tests, using KFM16 and -23 as pumping boreholes (November–December 2011), and so-called air-lift pumping that was performed in the percussion-drilled part of the most recent borehole KFM24 (drilled close to KFM16 and KFM08B in Figure 1-2) on March 31, 2016.

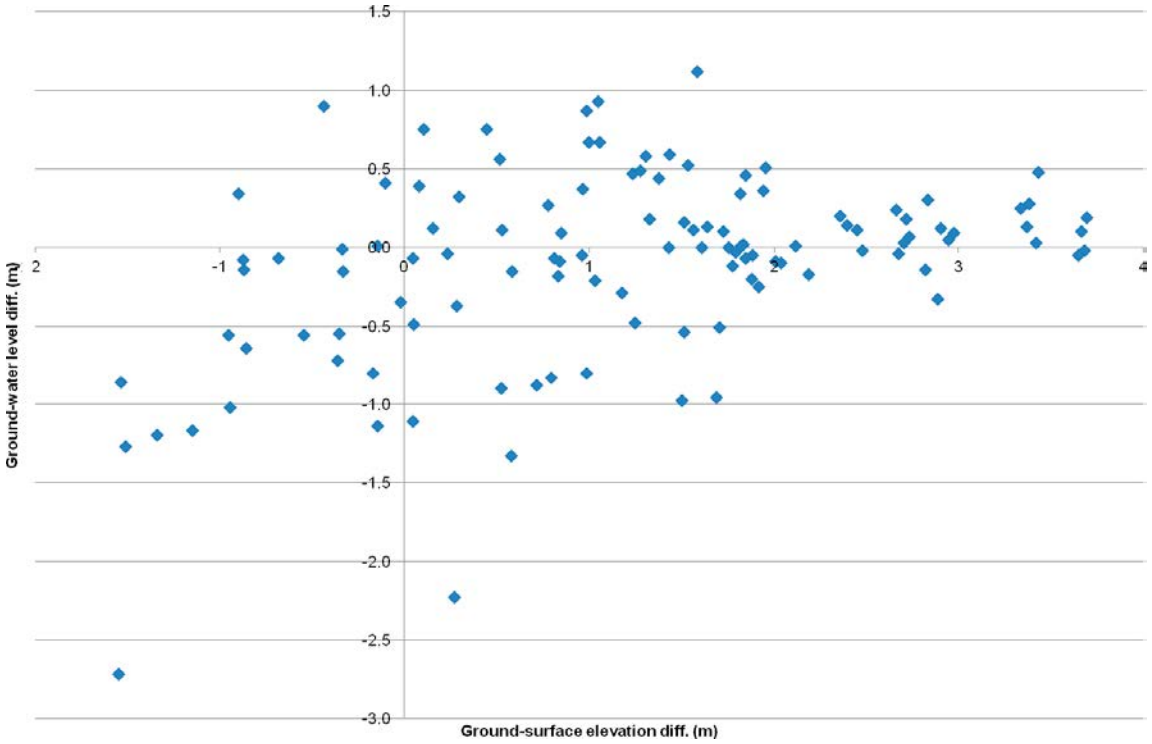


***Figure 4-26.** Groundwater-level differences as function of ground-surface elevation differences, illustrating potential effects of local topography on interpretation of vertical hydraulic gradients between regolith and rock.*

Figure 4-27 through Figure 4-36 show plots of groundwater-level time series for nearby wells that were monitored during these test intervals (SFM000121–125), as well as flow logging, interference test and air-lift pumping intervals. As can be seen in these figures, groundwater-level responses to flow logging can be observed for wells SFM000121, -122 and -125, whereas responses to the interference tests can be noted for wells SFM000123 and -125. Moreover, the groundwater level in well SFM000121 appears to respond to the air-lift pumping in KFM24. Hence, analyses of both natural (undisturbed) and known hydraulic disturbances indicate that the hydraulic contact between regolith and rock likely varies across the access area.

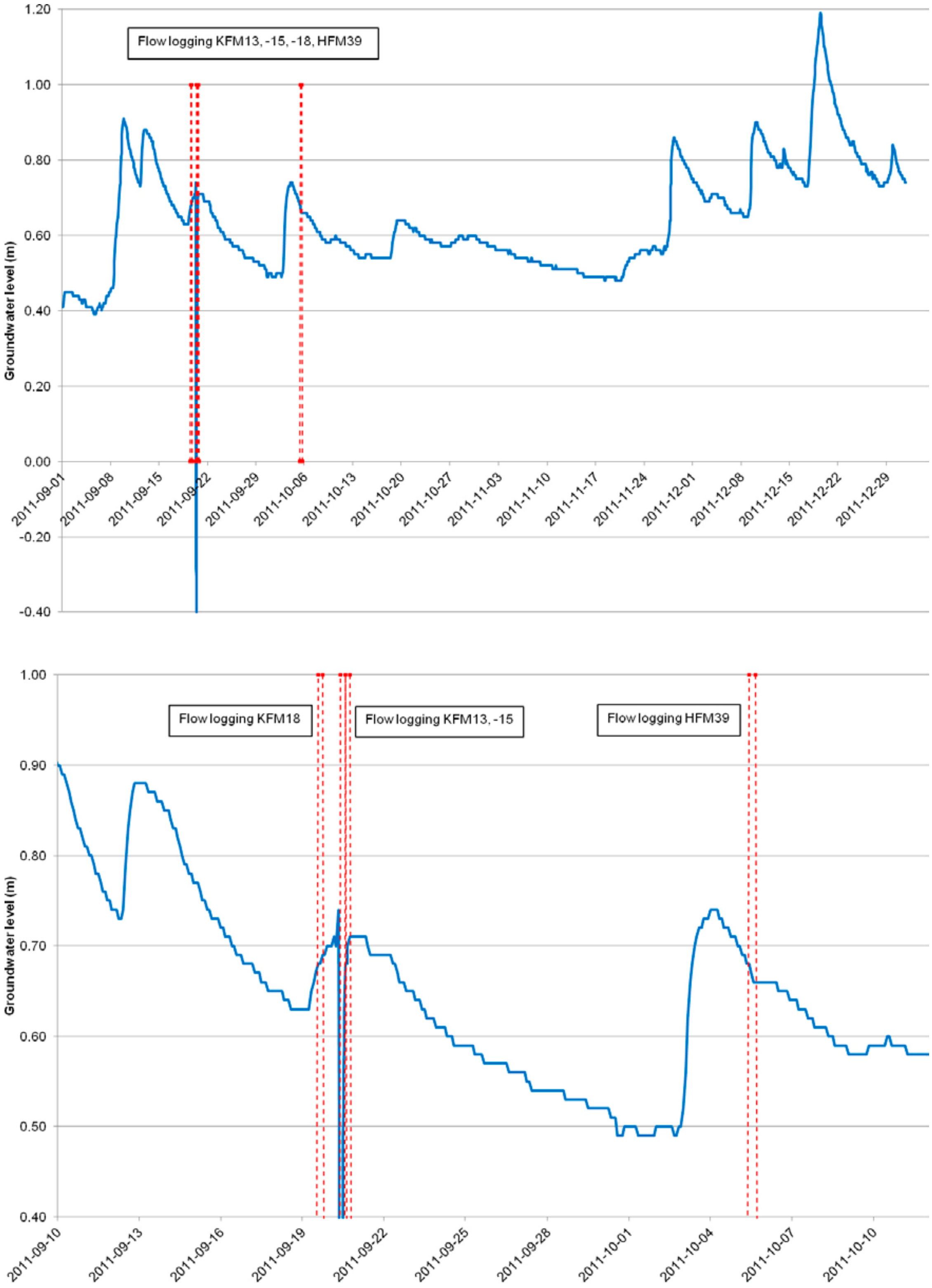


Figure 4-27. *Time-series plots of groundwater level in well SFM000121 and flow-logging intervals at boreholes KFM13, -15, -18 and HFM39.*

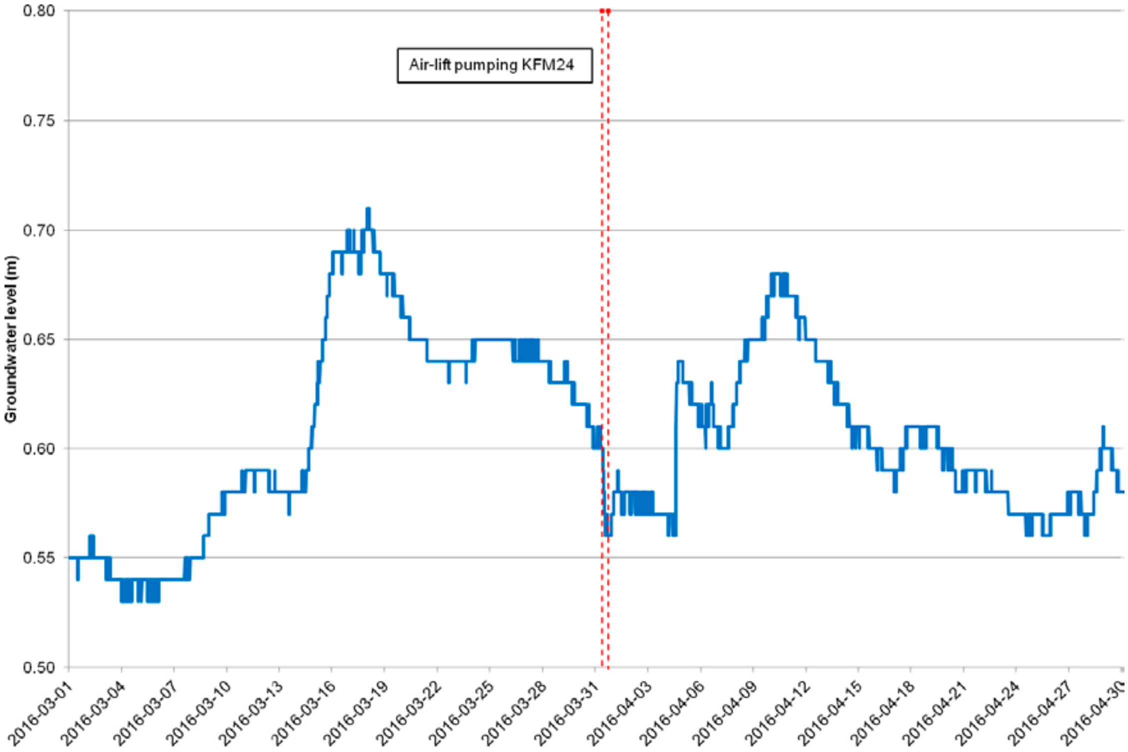
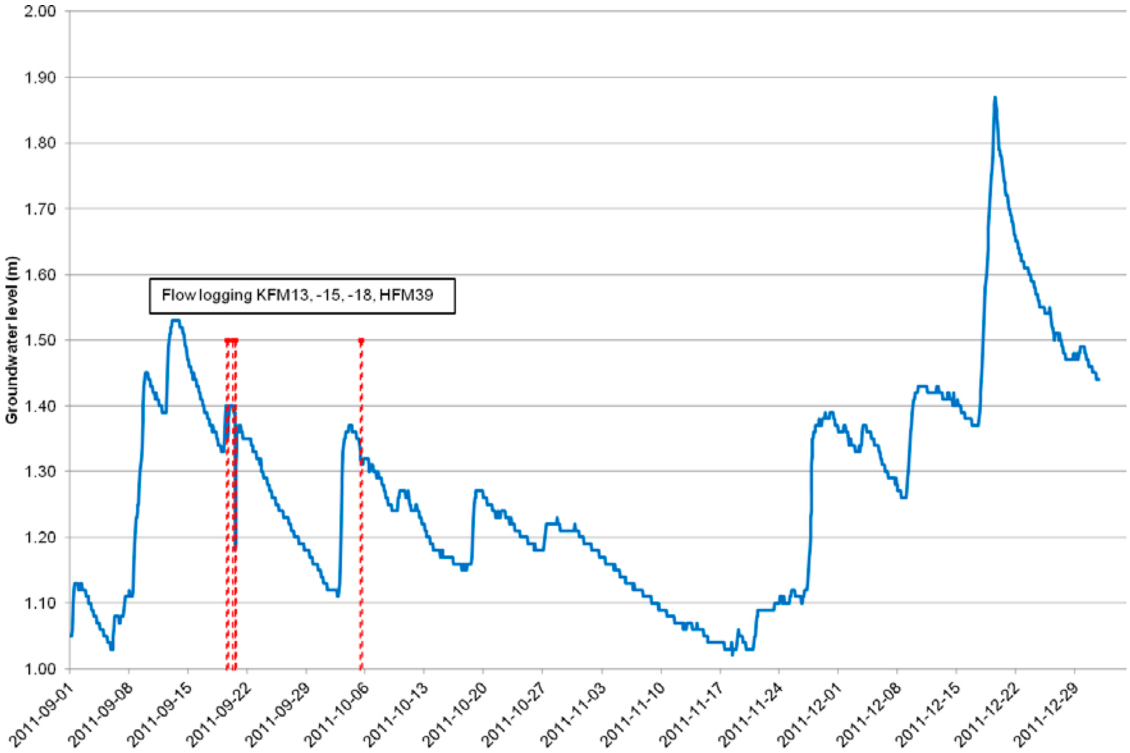


***Figure 4-28.** Time-series plot of groundwater level in well SFM000121 and air-lift pumping interval at borehole KFM24.*



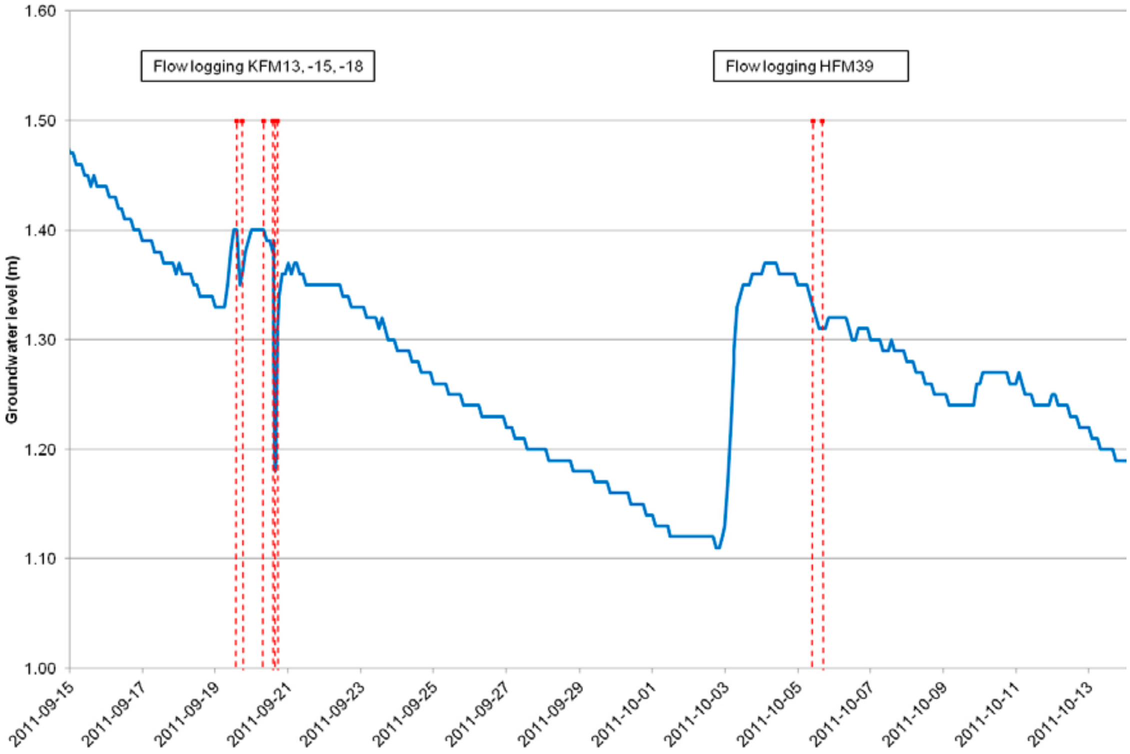


Figure 4-29. *Time-series plots of groundwater level in well SFM000122 and flow-logging intervals at boreholes KFM13, -15, -18 and HFM39.*

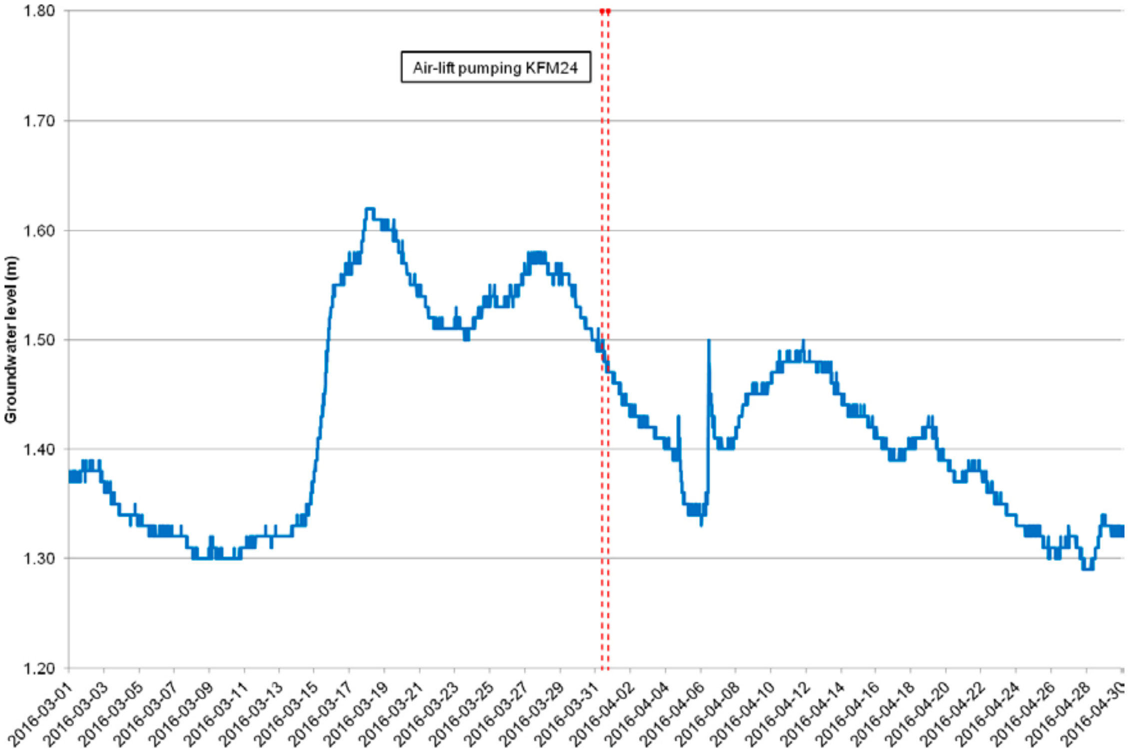


Figure 4-30. *Time-series plot of groundwater level in well SFM000122 and air-lift pumping interval at borehole KFM24.*

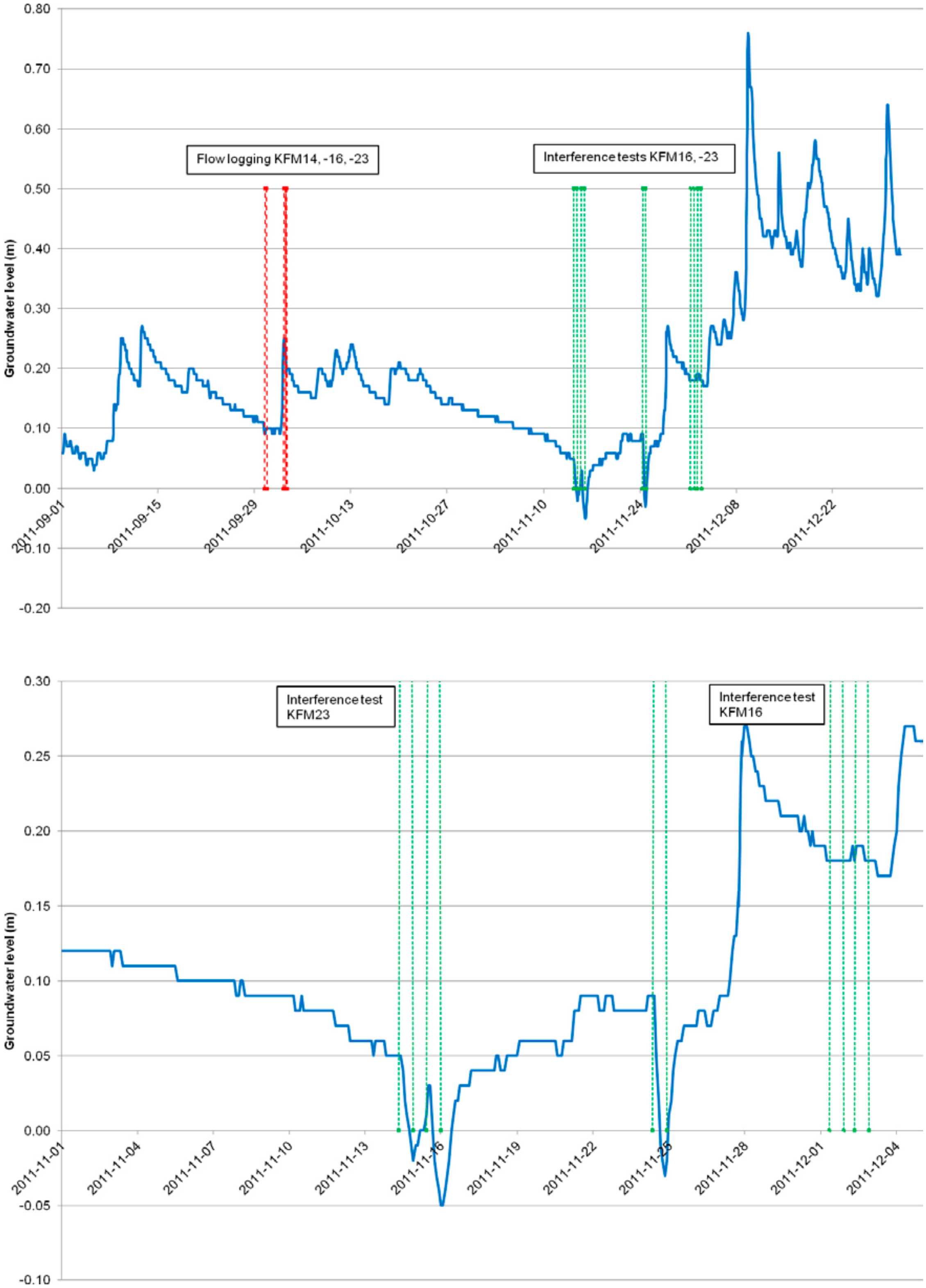


Figure 4-31. *Time-series plots of groundwater level in well SFM000123, flow-logging intervals at boreholes KFM14, -16, -23, and interference-test intervals at boreholes KFM16 and -23.*

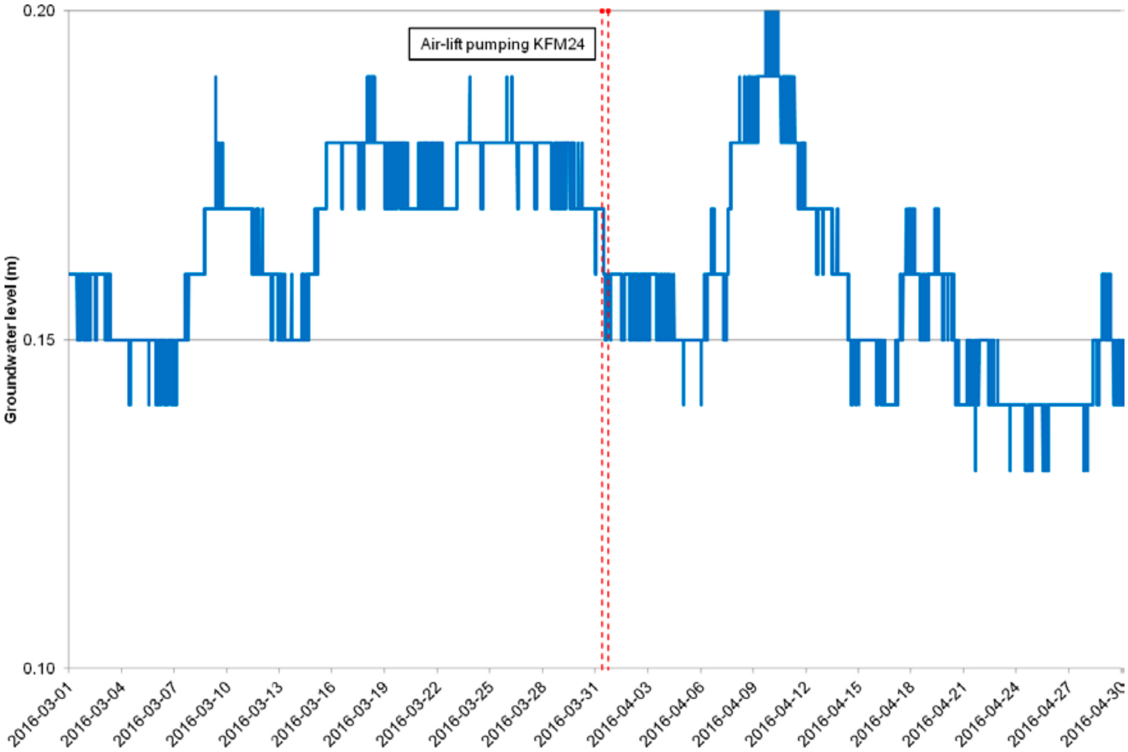
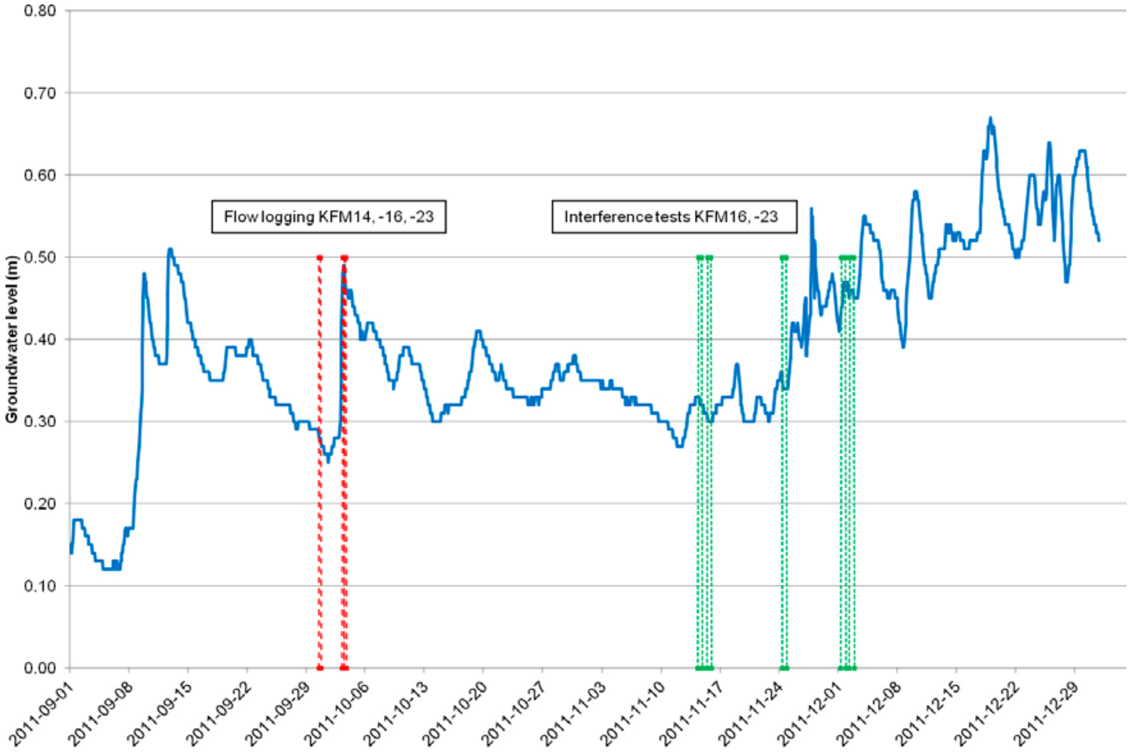


Figure 4-32. *Time-series plot of groundwater level in well SFM000123 and air-lift pumping interval at borehole KFM24.*



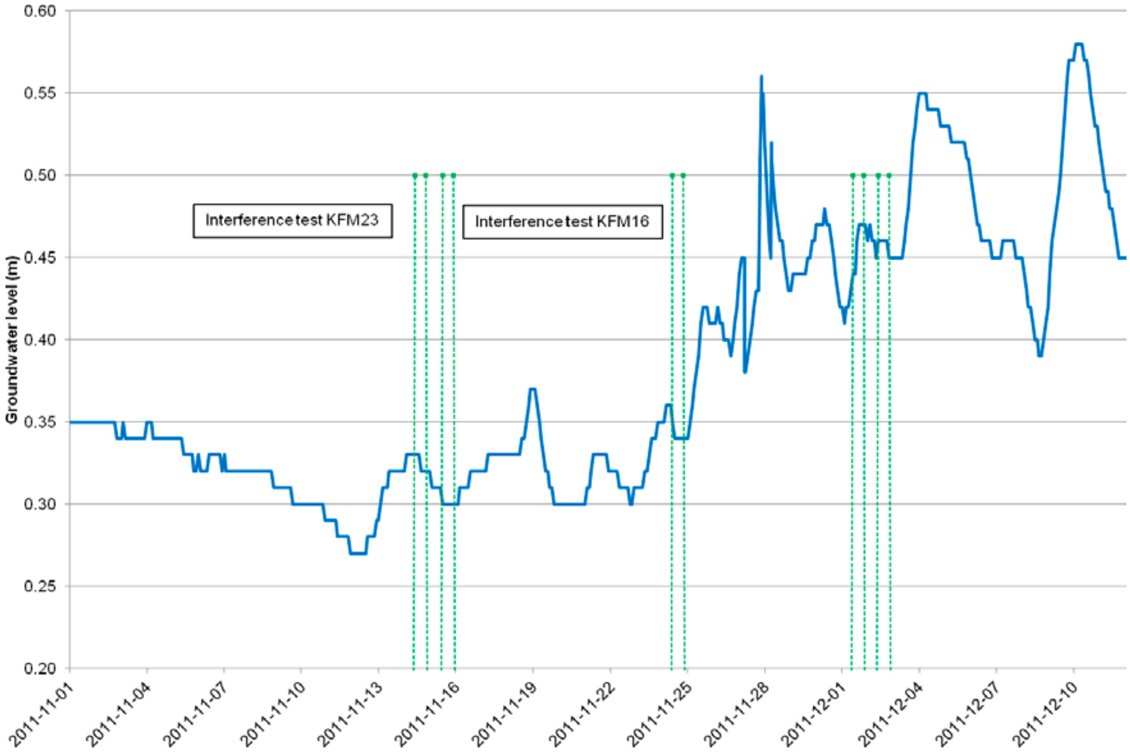


Figure 4-33. *Time-series plots of groundwater level in well SFM000124, flow-logging intervals at boreholes KFM14, -16, -23, and interference-test intervals at boreholes KFM16 and -23.*

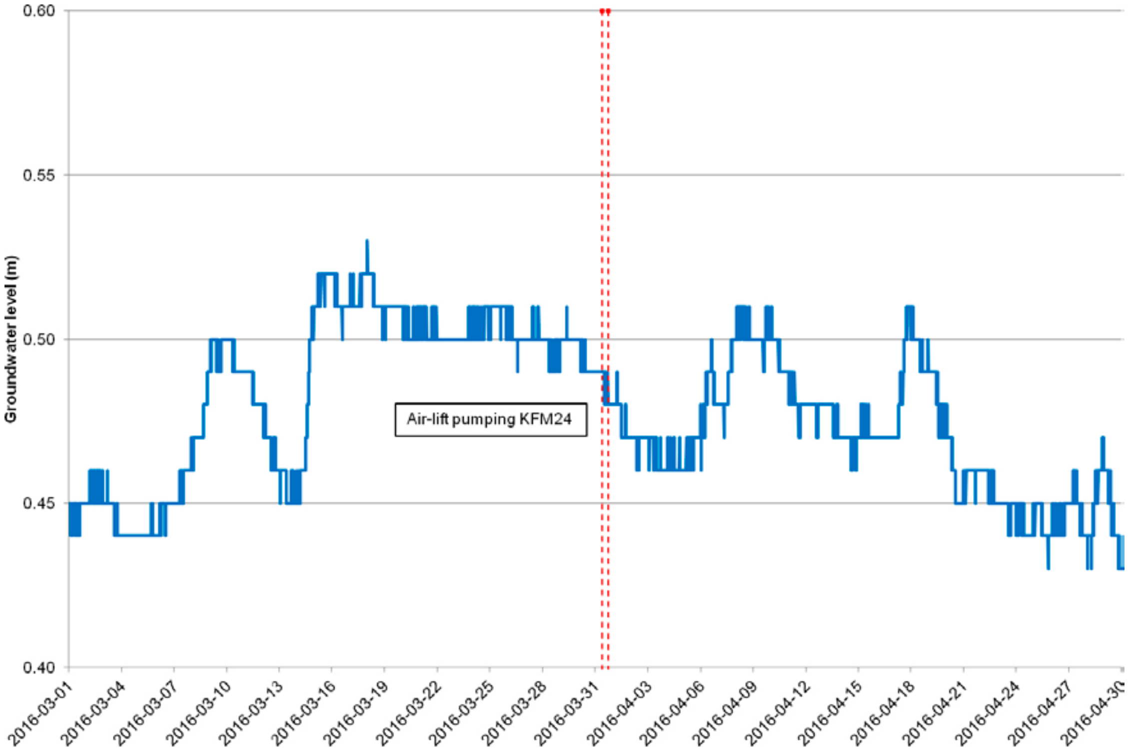
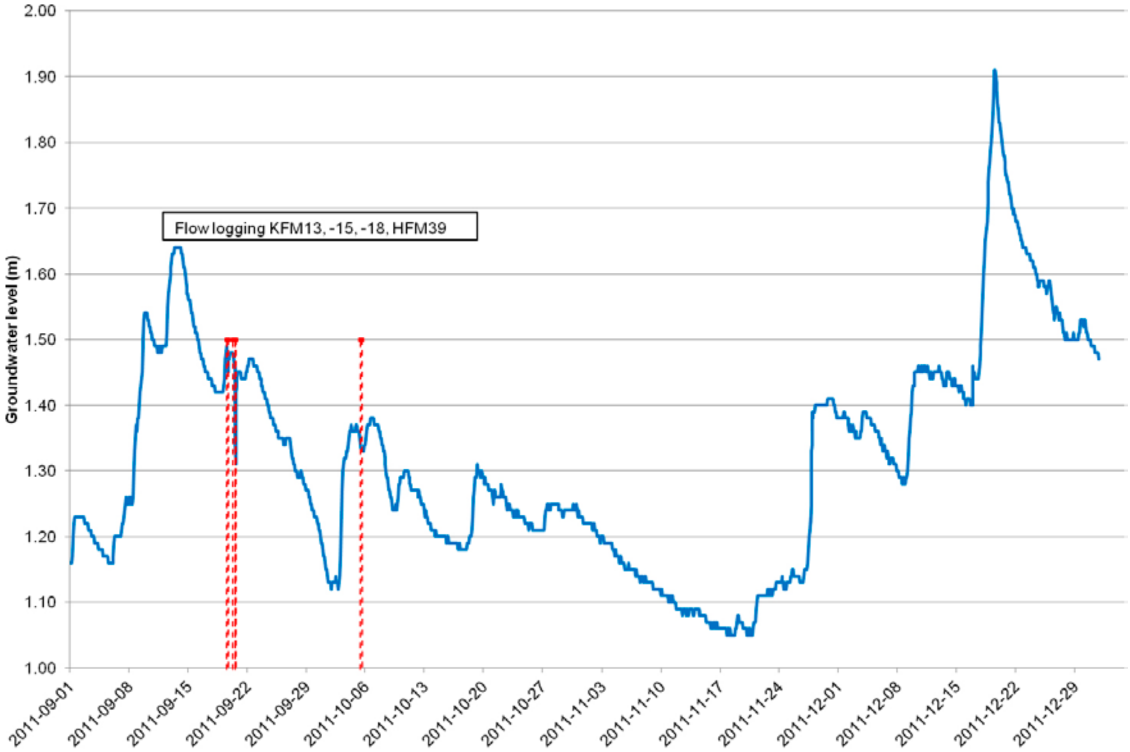


Figure 4-34. *Time-series plot of groundwater level in well SFM000124 and air-lift pumping interval at borehole KFM24.*



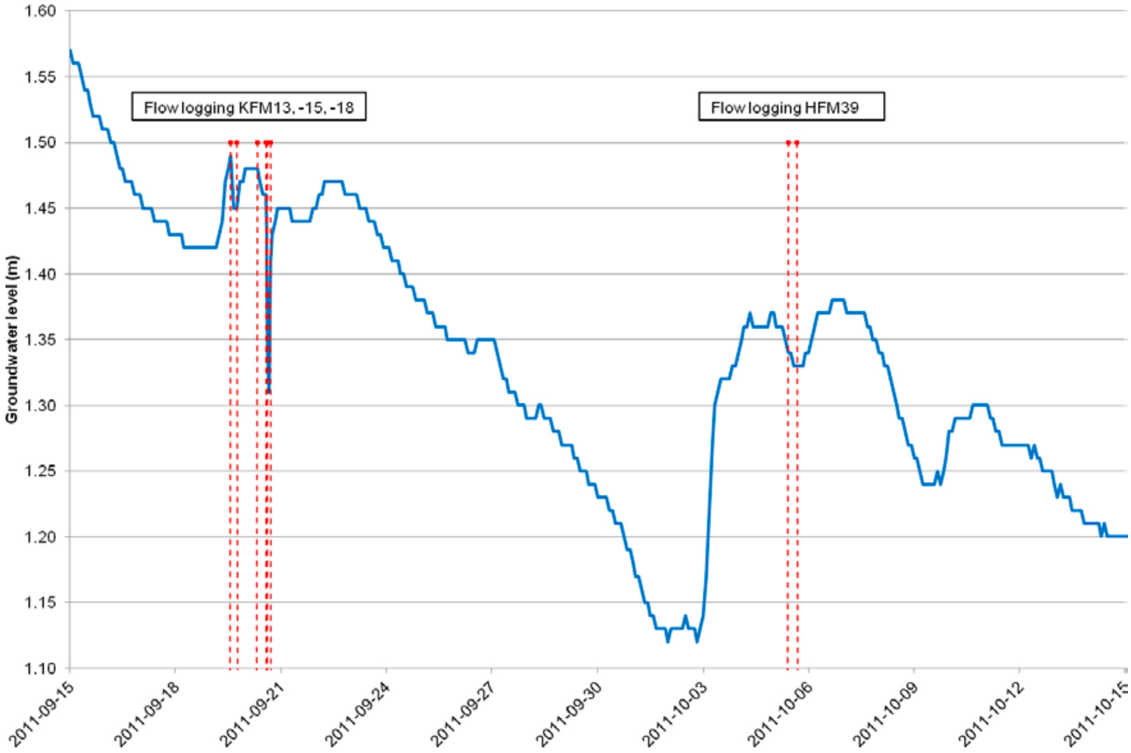


Figure 4-35. *Time-series plots of groundwater level in well SFM000125 and flow-logging intervals at boreholes KFM13, -15, -18, and HFM39.*

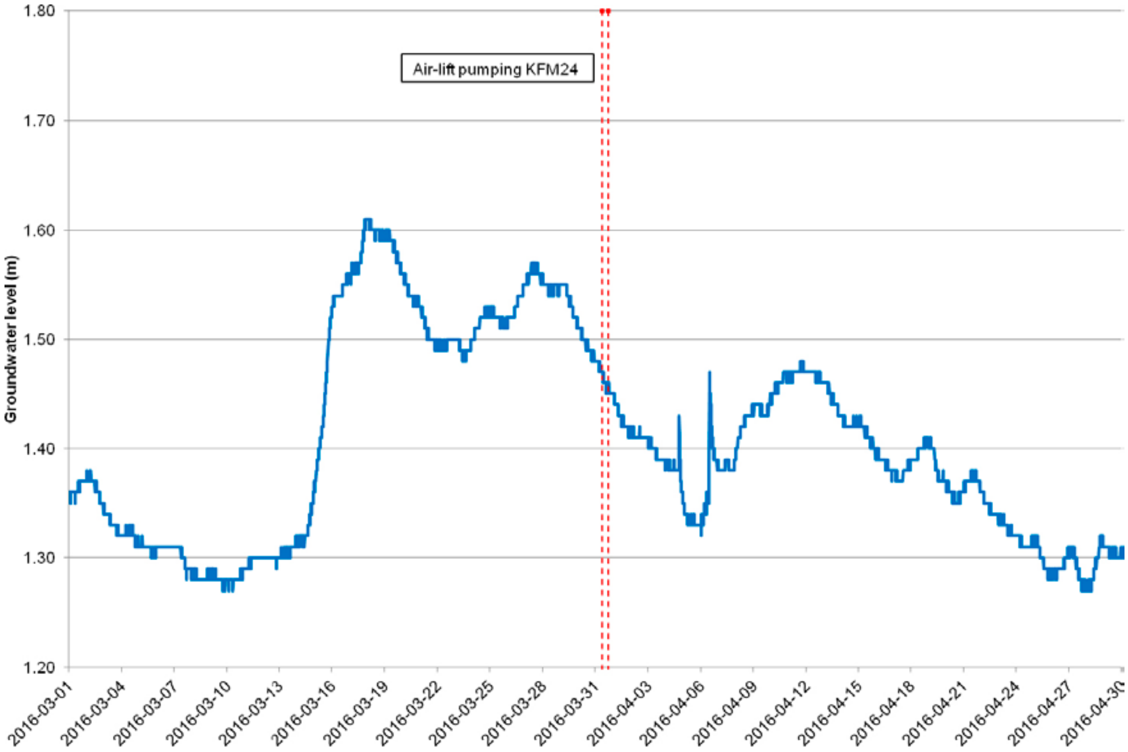


Figure 4-36. *Time-series plot of groundwater level in well SFM000125 and air-lift pumping interval at borehole KFM24.*

Based on overall averages, the cartoon in Figure 4-37 illustrates relative relations between ground- and rock-surface elevations, groundwater levels in monitoring wells installed in regolith, and groundwater levels in percussion- and core-drilled boreholes with different casing depths. Specifically, monitoring wells (in some cases installed across the regolith/rock interface) are equipped with an impermeable casing some depth into the regolith, whereas percussion-drilled boreholes and short (on the order of 100 m) core-drilled boreholes have a casing across the regolith and a few metres into the upper part of the rock. For stability reasons, deep core-drilled boreholes typically have a casing that extends some 100 m into the rock.

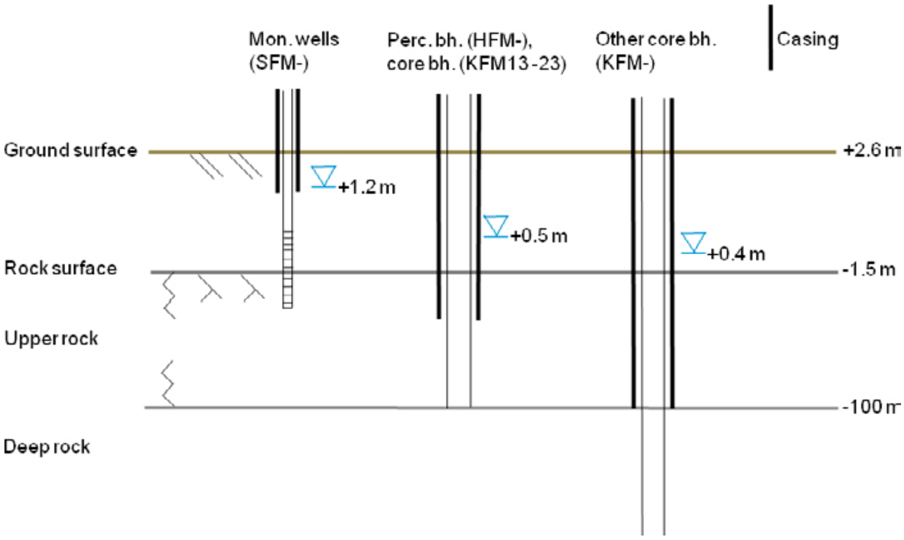


Figure 4-37. *Cartoon, based on overall averages, illustrating relative relations between ground- and rock-surface elevations, groundwater levels in monitoring wells installed in regolith, and groundwater levels in percussion- and core-drilled boreholes with different casing depths. Note that neither well/borehole dimensions nor depths are to scale.*

5 Discussion and conclusions

The findings from the evaluation of data from recent hydraulic tests and monitoring data gathered subsequently to SDM-Site, in and in the vicinity of the access area, do not contradict overall SDM-Site findings related to the hydrology and near-surface hydrogeology of the Forsmark area. A potentially important characteristic of the access area and its environs is the occurrence of coarse-grained, easily-drained artificial fill, which in practise may be difficult to distinguish from native regolith. The presence of fill may cause local deviations from overall Forsmark characteristics, for instance in terms of relations between groundwater levels, topography and surface-water levels.

Another potentially important characteristic of the access area is the vicinity to the Forsmark nuclear power plant, and also the vicinity to the sea. Data evaluations indicate that groundwater flow is directed both from inland areas towards the coastline and from regolith to rock. There is low or no correlation between the groundwater level in the upper part of the rock and the local topography, likely due to near-surface sheet joints with hydraulic connections to the sea. That is, the sheet joints act as a "draining" boundary condition for the groundwater levels in the rock within the tectonic lens. It is noted that the average groundwater level in one of the percussion-drilled boreholes (HFM41), located north of the cooling-water canal, is approximately 0.5 m below sea level, possibly due to the groundwater drainage below the reactor buildings of the Forsmark nuclear power plant.

At the present stage, the description of hydrology and near-surface hydrogeology in and in the vicinity of the access area is associated with the following main uncertainties:

- The regolith in large part of the access area and its environs consists of artificial fill (a mixture of excavated rock and regolith), the extent of which is larger according to recent regolith mapping than previously thought and reported in connection with SDM-Site. Evaluation of presently available groundwater-level time series shows that the average groundwater table is located at relatively large depths in some wells, possibly due to coarse-grained, easily-drained artificial fill. There is a low density of regolith-investigation points and monitoring wells primarily in the area of the planned rock dump, which causes uncertainties regarding hydrological and near-surface hydrogeological properties and processes in this area.
- Subsequently to SDM-Site, monitoring has been initiated in a number of additional groundwater-monitoring wells, surface-water level gauges, and percussion-drilled and core-drilled boreholes in rock, within and in the vicinity of the access area. However, some of these installations, e.g. most of the monitoring wells, were installed quite recently (during 2016), and presently available time series are yet short. Short time series cause uncertainties related to the evaluation of many aspects addressed in this report, including relations between groundwater levels, topography and surface-water levels. Hence, continued monitoring and data evaluations are required to further address such issues.

Planned infilling and upfilling activities need to be considered in the design of a programme for long-term monitoring in the access area and its surroundings. For instance, monitoring of potential hydrogeological effects of the rock dump and shafts and ramp of the spent fuel repository requires access to suitably located wells, gauges and boreholes, also for the pre-construction period. It is therefore recommended that a strategy is developed that considers a subset of existing wells, gauges and boreholes that need to be kept for long-term monitoring.

Among the wells and gauges of this report, it is judged that wells SFM0049, SFM0076–79, SFM0107, SFM000119, SFM000139, SFM000147 and SFM000153 are of relevance for design and follow up of the rock dump for the spent fuel repository and its surroundings. Moreover, SFM000121–125, SFM000146, and SFM000154 are relevant for design and follow up of subsurface accesses to the spent fuel repository, whereas SFM000143–145, SFM000149 and SFM000156 (gauge in one of the ponds to be infilled) are of relevance for design and follow up of infilling of ponds.

Based on this overview, it is recommended that the need for additional groundwater-monitoring wells for design and follow-up on the rock dump and subsurface accesses of the spent fuel repository is investigated. These facility parts will be in operation during the lifetime of the spent fuel repository and may cause relatively large hydrogeological effects, which also provide information of relevance for general site understanding. Finally, there is a general need for more data and information on hydrogeological and other properties of the rock/regolith interface and the near-surface rock. This need, which includes e.g. depth to rock and occurrences and properties of fracture-filling materials, motivates further drilling and investigation of short (say, 30–50 m) boreholes in rock equipped with short casings so that the uppermost rock can be properly characterised and monitored.

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Appendix 1

Detailed groundwater-level statistics

This appendix presents detailed groundwater-level statistics (average, standard deviation, minimum and maximum) for individual years and three-month seasons. Note that e.g. “05” in the tables means year 2005.

SFM0049	03	04	05	06	07	08	09	10	11	12	13	14	15	16
Average	2.21	2.31	2.34	2.21	2.30	2.40	2.36	2.35	2.41	2.44	2.21	2.07	2.05	2.10
St. dev.	0.24	0.18	0.18	0.38	0.25	0.30	0.18	0.16	0.11	0.09	0.21	0.18	0.14	0.09
Min	1.79	2.00	1.93	1.43	0.14	0.23	0.46	0.99	1.51	1.77	1.64	1.25	1.54	1.89
Max	2.58	2.55	2.65	2.73	2.57	2.67	2.59	2.72	2.67	2.63	2.75	2.40	2.36	2.24

SFM0076	05
Average	1.53
St. dev.	0.16
Min	1.31
Max	1.31

SFM0077	05	06	07	08	09	10	11	12	13	14	15	16
Average	2.79	2.70	2.73	2.82	2.73	2.74	2.86	2.85	2.76	2.69	2.72	2.65
St. dev.	0.11	0.15	0.23	0.14	0.09	0.13	0.09	0.07	0.11	0.11	0.09	0.10
Min	2.49	2.30	−1.16	2.49	2.51	2.53	2.65	2.71	2.47	2.45	2.53	2.45
Max	3.06	3.07	3.03	3.11	3.07	3.09	3.11	3.09	3.11	3.07	3.03	2.88

SFM0078	05	06	07	08	09	10	11	12	13	14	15	16
Average	3.19	3.34	3.24	3.84	3.47	3.64	3.86	4.15	3.42	3.61	3.68	3.47
St. dev.	0.81	1.03	0.78	0.83	0.69	0.54	0.49	0.24	0.86	0.86	0.51	0.92
Min	1.81	1.33	0.44	1.50	2.09	2.35	2.38	3.36	1.67	1.80	2.69	1.82
Max	4.29	4.52	4.52	4.60	4.37	4.59	4.60	4.56	4.59	4.47	4.50	4.45

SFM0079	05	06	07	08	09	10	11	12	13	14	15	16
Average	2.79	2.66	2.73	2.84	2.81	2.81	2.85	2.94	3.01	2.81	2.82	2.75
St. dev.	0.10	0.34	0.19	0.21	0.12	0.14	0.10	0.12	0.19	0.14	0.09	0.17
Min	2.54	0.57	0.97	2.18	2.57	2.43	2.57	2.74	2.68	2.49	2.62	2.37
Max	2.96	3.12	3.02	3.19	3.01	3.22	3.12	3.20	3.44	3.06	3.05	3.03

SFM0107	06	07	08	09	10	11	12	13	14	15	16
Average	0.70	0.94	1.22	1.07	1.11	1.26	1.37	1.20	1.05	1.17	1.11
St. dev.	0.52	0.30	0.39	0.26	0.25	0.20	0.13	0.21	0.29	0.20	0.32
Min	−0.31	0.28	0.01	0.45	0.53	0.72	1.05	1.01	0.27	0.71	0.42
Max	1.55	1.54	1.86	1.58	1.83	1.84	1.70	1.74	1.50	1.67	1.59

SFM000121	11	12	13	14	15	16
Average	0.52	0.61	0.39	0.37	0.44	0.37
St. dev.	0.22	0.13	0.32	0.28	0.18	0.29
Min	−0.37	0.34	−0.39	−0.34	−0.05	−0.24
Max	1.15	0.96	1.08	0.85	0.86	0.80

SFM000122	11	12	13	14	15	16
Average	1.14	1.30	1.07	0.83	1.11	0.98
St. dev.	0.25	0.16	0.38	0.52	0.27	0.47
Min	0.55	0.95	0.10	−0.54	0.53	0.13
Max	1.81	1.74	2.00	1.71	1.80	1.80

SFM000123	11	12	13	14	15	16
Average	0.11	0.16	0.04	0.06	0.12	0.06
St. dev.	0.15	0.09	0.17	0.17	0.14	0.13
Min	−0.16	−0.01	−0.32	−0.32	−0.17	−0.19
Max	0.60	0.63	0.47	0.36	0.59	0.39

SFM000124	11	12	13	14	15	16
Average	0.19	0.44	0.19	0.24	0.29	0.18
St. dev.	0.28	0.10	0.37	0.35	0.23	0.36
Min	−0.53	0.14	−0.64	−0.60	−0.33	−0.62
Max	0.64	0.68	0.73	0.65	0.71	0.63

SFM000125	11	12	13	14	15	16
Average	1.18	1.31	1.09	0.99	1.17	0.97
St. dev.	0.25	0.16	0.38	0.44	0.18	0.47
Min	0.57	0.96	0.12	0.00	0.77	0.11
Max	1.86	1.76	2.02	1.71	1.55	1.78

SFM000139	14	15	16
Average	2.80	2.78	2.72
St. dev.	0.07	0.02	0.07
Min	2.68	2.71	2.60
Max	2.92	2.83	2.82

SFM000143	16
Average	−0.12
St. dev.	0.15
Min	−0.42
Max	0.15

SFM000145	16
Average	0.02
St. dev.	0.06
Min	−0.07
Max	0.14

SFM000146	16
Average	−0.35
St. dev.	0.21
Min	−0.71
Max	0.01

SFM000147	16
Average	0.83
St. dev.	0.34
Min	0.29
Max	1.54

SFM000149	16
Average	0.06
St. dev.	0.05
Min	−0.04
Max	0.16

SFM000153	16
Average	1.58
St. dev.	0.16
Min	1.36
Max	1.85

SFM0049	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	2.37	2.40	2.17	2.18
St. dev.	0.18	0.17	0.25	0.26
Min	0.23	0.41	0.14	0.26
Max	2.67	2.75	2.59	2.63

SFM0077	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	2.77	2.79	2.71	2.75
St. dev.	0.18	0.12	0.13	0.13
Min	−1.16	2.57	2.30	2.47
Max	3.11	3.11	3.09	3.09

SFM0078	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	4.10	4.08	2.99	3.24
St. dev.	0.30	0.30	0.73	0.86
Min	0.44	2.97	1.41	1.33
Max	4.60	4.60	4.48	4.55

SFM0079	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	2.93	2.91	2.68	2.77
St. dev.	0.14	0.13	0.19	0.21
Min	0.97	2.65	1.93	0.57
Max	3.28	3.44	3.07	3.18

SFM0107	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.26	1.31	0.90	1.03
St. dev.	0.19	0.19	0.37	0.32
Min	0.84	0.83	−0.31	0.22
Max	1.86	1.84	1.70	1.76

SFM000121	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.62	0.58	0.25	0.41
St. dev.	0.12	0.12	0.26	0.28
Min	0.39	0.31	−0.37	−0.39
Max	1.15	1.08	0.92	0.95

SFM000122	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.23	1.31	0.87	1.03
St. dev.	0.33	0.19	0.34	0.42
Min	−0.54	0.96	0.13	−0.47
Max	1.86	2.00	1.74	1.71

SFM000123	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.23	0.14	−0.03	0.08
St. dev.	0.12	0.08	0.12	0.14
Min	0.04	−0.02	−0.32	−0.32
Max	0.63	0.42	0.33	0.34

SFM000124	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.47	0.43	−0.01	0.20
St. dev.	0.09	0.11	0.32	0.31
Min	0.27	−0.18	−0.64	−0.63
Max	0.71	0.73	0.63	0.61

SFM000125	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.25	1.29	0.86	1.10
St. dev.	0.32	0.18	0.36	0.43
Min	0.01	0.94	0.11	0.00
Max	1.89	2.02	1.76	1.73

SFM000139	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	2.81	2.80	2.74	2.79
St. dev.	0.01	0.02	0.06	0.07
Min	2.80	2.75	2.60	2.64
Max	2.83	2.83	2.83	2.92

SFM000143	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average			−0.09	−0.19
St. dev.			0.12	0.17
Min			−0.27	−0.42
Max			0.15	0.06

SFM000145	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average			0.07	0.00
St. dev.			0.04	0.06
Min			0.03	−0.07
Max			0.14	0.10

SFM000146	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average			−0.41	−0.24
St. dev.			0.21	0.16
Min			−0.71	−0.43
Max			−0.05	0.01

SFM000147	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average			0.77	0.91
St. dev.			0.40	0.23
Min			0.29	0.56
Max			1.54	1.23

SFM000149	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average			0.08	0.03
St. dev.			0.04	0.05
Min			0.01	−0.04
Max			0.16	0.12

SFM000153	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average			1.52	1.62
St. dev.			0.14	0.16
Min			1.36	1.36
Max			1.85	1.85

HFM20	05	06	07	08	09	10	11	12	13	14	15	16
Average	0.72	0.60	0.67	0.98	0.97	1.01	1.17	1.20	0.96	0.96	1.12	0.91
St. dev.	0.26	0.42	0.36	0.44	0.23	0.22	0.21	0.25	0.36	0.38	0.19	0.28
Min	0.00	−0.32	−0.11	−0.06	0.42	0.36	0.61	0.00	0.00	0.00	0.64	0.32
Max	1.45	1.36	1.23	1.59	1.40	1.59	1.74	1.57	1.74	1.44	1.58	1.34

HFM21	06	07	08	09	10	11	12	13	14	15	16
Average	0.77	0.29	0.69	0.62	0.71	0.76	0.83	0.60	0.60	0.66	0.53
St. dev.	0.13	0.49	0.26	0.14	0.35	0.15	0.10	0.26	0.24	0.16	0.22
Min	0.36	−6.57	−0.01	0.27	0.12	0.46	0.62	−0.07	−0.01	0.29	0.08
Max	0.93	0.83	1.04	0.83	2.69	1.19	1.11	1.09	0.97	1.00	0.92

HFM22	04	05	06	07	08	09	10	11	12	13	14	15	16
Average	−0.39	−0.30	−0.66	−0.67	0.33	0.22	0.22	0.28	0.32	0.14	0.16	0.26	0.17
St. dev.	0.44	0.90	1.22	1.13	0.21	0.09	0.13	0.18	0.11	0.18	0.17	0.16	0.14
Min	−1.30	−4.79	−5.28	−6.42	−0.23	−0.02	−0.07	−0.54	0.08	−0.22	−0.22	−0.07	−0.08
Max	0.31	0.64	0.62	0.59	0.68	0.43	0.49	0.74	0.78	0.58	0.52	0.68	0.56

HFM23	05	06	07	08	09	10	11	12	13	14	15	16
Average	0.79	1.15	1.44	1.71	1.65	1.76	1.95	2.06	1.87	1.81	1.92	1.91
St. dev.	2.12	1.17	0.29	0.34	0.16	0.18	0.16	0.10	0.27	0.28	0.17	0.22
Min	−8.51	−8.52	0.77	0.60	1.28	1.28	1.50	1.84	1.05	1.04	1.49	1.32
Max	2.06	1.88	1.99	2.14	1.91	2.08	2.34	2.35	2.26	2.18	2.18	2.24

HFM38	07	08	09	10	11	12	13	14	15	16
Average	−0.08	0.01	−0.14	−0.15	−0.07	−0.02	−0.17	−0.67	0.01	−0.08
St. dev.	0.12	0.20	0.13	0.14	0.17	0.14	0.19	2.74	0.17	0.12
Min	−0.49	−0.40	−0.45	−0.54	−0.42	−0.27	−0.59	−15.22	−0.31	−0.29
Max	0.31	0.44	0.25	0.27	0.49	0.44	0.39	0.29	0.38	0.31

HFM39	11	12	13	14	15	16
Average	1.33	1.25	1.25	0.95	1.05	0.91
St. dev.	0.25	0.21	0.21	0.43	0.30	0.48
Min	0.84	0.84	0.99	0.07	0.42	0.02
Max	1.85	1.82	1.92	1.70	1.81	1.81

HFM40	11	12	13	14	15	16
Average	0.10	0.05	−0.10	−0.10	0.08	0.03
St. dev.	0.20	0.15	0.25	0.21	0.14	0.21
Min	−0.27	−0.24	−0.61	−0.50	−0.33	−0.31
Max	0.71	0.74	0.66	0.49	0.46	0.41

HFM41	11	12	13	14	15	16
Average	−0.72	−0.58	−0.57	−0.55	−0.41	−0.50
St. dev.	0.42	0.17	0.15	0.13	0.15	0.17
Min	−4.33	−0.99	−0.84	−0.93	−0.65	−0.83
Max	−0.26	−0.21	−0.22	−0.24	−0.06	−0.14

KFM07A	07	08	09	10	11	12	13	14	15	16
Average	−0.37	0.41	0.32	0.33	0.40	0.46	0.25	0.54	0.43	0.35
St. dev.	0.65	0.23	0.09	0.13	0.15	0.11	0.18	0.04	0.16	0.17
Min	−1.45	−0.24	0.10	−0.02	0.09	0.24	−0.14	0.48	0.10	0.07
Max	0.48	0.77	0.51	0.60	0.83	0.84	0.61	0.61	0.79	0.77

KFM07B	07	08	09
Average	0.15	0.30	0.54
St. dev.	0.14	0.17	0.00
Min	−0.61	0.16	0.54
Max	0.52	0.54	0.54

KFM07C	07	08	09	10	11	12	13	15	16
Average	−0.28	0.56	0.46	0.47	0.53	0.58	0.37	0.43	0.34
St. dev.	0.64	0.23	0.09	0.13	0.15	0.10	0.18	0.09	0.12
Min	−1.32	−0.09	0.23	0.11	0.20	0.37	−0.04	0.17	0.13
Max	0.64	0.92	0.65	0.74	0.97	0.98	0.72	0.62	0.53

KFM08A	07	08	09	10	11	12	13	14	15	16
Average	0.28	0.39	0.40	0.34	0.38	0.46	0.23	0.27	0.38	0.41
St. dev.	0.07	0.07	0.09	0.11	0.24	0.11	0.31	0.26	0.17	0.03
Min	0.14	0.20	0.26	0.15	0.04	0.18	−0.49	−0.43	−0.05	0.37
Max	0.44	0.53	0.60	0.55	2.26	0.73	0.94	0.65	0.76	0.46

KFM08B	06	07	08	09	10	11	12	13	14	15	16
Average	−0.09	−0.04	0.18	0.05	0.02	0.09	0.20	0.05	0.06	0.16	−0.01
St. dev.	0.32	0.21	0.19	0.09	0.12	0.38	0.14	0.22	0.21	0.17	0.52
Min	−1.28	−1.06	−0.26	−0.17	−0.29	−4.07	−0.11	−0.29	−0.71	−0.22	−5.94
Max	0.51	0.51	0.59	0.34	0.33	1.61	0.68	0.70	0.58	0.67	0.41

KFM08C	07	08	09	10	11	12	13	14	15	16
Average	−0.22	0.19	0.06	0.06	0.12	0.17	−0.02	0.00	0.15	0.14
St. dev.	0.34	0.20	0.10	0.13	0.17	0.13	0.18	0.15	0.18	0.15
Min	−2.73	−0.25	−0.20	−0.31	−0.33	−0.17	−0.35	−0.28	−0.21	−0.14
Max	0.29	0.61	0.39	0.39	0.65	0.72	0.55	0.45	0.68	0.48

KFM08D	07	08	09	10	11	12	13
Average	0.00	0.37	0.25	0.26	0.32	0.37	0.40
St. dev.	0.35	0.20	0.08	0.12	0.16	0.12	0.01
Min	−0.66	−0.20	0.03	−0.04	−0.50	0.11	0.38
Max	0.48	0.71	0.44	0.51	0.76	0.81	0.42

KFM09A	06	07	08	09	10	11	12	13	14	15	16
Average	1.56	1.49	1.86	1.80	1.92	2.12	2.22	1.96	1.91	1.99	1.91
St. dev.	0.05	0.29	0.38	0.19	0.20	0.16	0.11	0.33	0.37	0.17	0.33
Min	1.48	0.76	0.59	1.31	1.37	1.63	1.97	0.97	0.90	1.53	1.09
Max	1.65	1.93	2.31	2.09	2.30	2.50	2.48	2.45	2.28	2.29	2.33

KFM09B	06	07	08	09	10	11	12	13	14	15	16
Average	0.40	−0.29	0.16	0.04	0.04	0.19	0.23	−0.03	0.03	0.09	0.05
St. dev.	0.13	0.45	0.30	0.16	0.17	0.17	0.11	0.28	0.26	0.17	0.10
Min	0.00	−1.18	−0.72	−0.29	−0.44	−0.26	0.00	−0.66	−0.59	−0.30	−0.12
Max	0.57	0.49	0.55	0.31	0.43	0.68	0.52	0.46	0.43	0.49	0.32

KFM13	11	12	13	14	15	16
Average	0.52	0.71	0.47	0.47	0.56	0.45
St. dev.	0.53	0.14	0.35	0.29	0.19	0.30
Min	−3.15	0.40	−0.32	−0.32	0.06	−0.18
Max	1.29	1.14	1.30	1.03	1.05	0.98

KFM14	14	15	16
Average	0.24	0.24	0.16
St. dev.	0.12	0.17	0.14
Min	0.04	−0.11	−0.10
Max	0.49	0.69	0.56

KFM15	11	12	13	14	15	16
Average	1.15	1.31	1.08	0.98	1.13	1.00
St. dev.	0.36	0.16	0.37	0.48	0.28	0.47
Min	−1.61	0.97	0.13	−0.54	0.54	0.15
Max	1.83	1.77	2.02	1.72	1.84	1.81

KFM16	11	12	13	14	15	16
Average	0.12	0.26	0.07	0.05	0.16	0.04
St. dev.	0.69	0.12	0.17	0.16	0.18	0.26
Min	−4.52	−0.03	−0.23	−0.72	−0.19	−3.53
Max	0.73	0.78	0.61	0.48	0.66	0.48

KFM17	11	12	13	14	15	16
Average	0.61	0.75	0.53	0.51	0.58	0.45
St. dev.	0.55	0.11	0.27	0.25	0.18	0.23
Min	−3.10	0.51	−0.12	−0.08	0.18	0.02
Max	1.22	1.12	1.09	0.91	0.94	0.90

KFM18	11	12	13	14	15	16
Average	1.01	1.19	0.98	0.92	0.99	0.80
St. dev.	0.75	0.13	0.33	0.39	0.21	0.29
Min	−8.01	0.89	0.10	−0.17	0.58	0.25
Max	1.64	1.54	1.70	1.49	1.52	1.28

KFM19	11	12	13	14	15	16
Average	0.08	0.05	−0.09	−0.12	0.04	−0.08
St. dev.	0.31	0.17	0.21	0.17	0.22	0.16
Min	−2.09	−0.41	−0.62	−0.53	−0.43	−0.45
Max	0.70	0.75	0.68	0.48	0.72	0.37

KFM20	11	12	13	14	15	16
Average	1.07	1.18	0.98	0.96	1.11	0.90
St. dev.	0.30	0.07	0.28	0.24	0.12	0.28
Min	−1.69	0.94	0.17	0.32	0.80	0.32
Max	1.33	1.31	1.35	1.24	1.32	1.26

KFM21	11	12	13	14	15	16
Average	0.15	0.29	0.15	0.17	0.24	0.15
St. dev.	0.76	0.08	0.17	0.15	0.12	0.12
Min	−5.86	0.14	−0.21	−0.17	−0.01	−0.08
Max	0.69	0.74	0.59	0.46	0.67	0.46

KFM22	11	12	13	14	15	16
Average	0.05	0.02	−0.14	−0.15	0.07	−0.05
St. dev.	0.28	0.18	0.23	0.18	0.21	0.16
Min	−1.71	−0.45	−0.70	−0.62	−0.40	−0.36
Max	0.67	0.73	0.67	0.40	0.67	0.41

KFM23	11	12	13	14	15	16
Average	0.29	0.39	0.22	0.22	0.31	0.23
St. dev.	0.78	0.11	0.18	0.16	0.17	0.14
Min	−6.02	0.16	−0.12	−0.15	−0.04	−0.01
Max	0.84	0.88	0.67	0.58	0.76	0.63

HFM20	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.15	1.04	0.72	0.88
St. dev.	0.19	0.26	0.38	0.42
Min	0.45	0.00	−0.32	−0.01
Max	1.74	1.74	1.58	1.59

HFM21	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.78	0.72	0.45	0.58
St. dev.	0.16	0.27	0.26	0.35
Min	0.26	−6.57	−0.29	−0.29
Max	2.39	1.09	0.94	2.69

HFM22	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.03	0.02	−0.02	0.07
St. dev.	0.90	0.78	0.38	0.48
Min	−5.28	−5.01	−1.46	−6.42
Max	0.78	0.63	0.44	0.67

HFM23	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.90	1.80	1.57	1.59
St. dev.	0.20	0.72	0.42	0.85
Min	1.16	−8.52	−1.63	−8.51
Max	2.35	2.25	2.21	2.24

HFM28	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	2.29	2.29	1.87	2.00
St. dev.	0.21	0.23	0.47	0.42
Min	1.82	1.08	0.06	0.95
Max	2.72	2.69	2.62	2.66

HFM38	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	−0.01	−0.37	−0.11	−0.06
St. dev.	0.22	1.79	0.09	0.15
Min	−0.54	−15.22	−0.31	−0.49
Max	0.49	0.40	0.10	0.40

HFM39	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.22	1.25	0.77	1.01
St. dev.	0.28	0.19	0.39	0.42
Min	0.07	0.90	0.02	0.09
Max	1.92	1.81	1.82	1.80

HFM40	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.15	−0.12	−0.03	0.05
St. dev.	0.27	0.18	0.11	0.17
Min	−0.50	−0.61	−0.33	−0.37
Max	0.74	0.23	0.21	0.38

HFM41	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	−0.43	−0.58	−0.63	−0.52
St. dev.	0.20	0.13	0.19	0.27
Min	−0.83	−0.98	−2.47	−4.33
Max	−0.06	−0.34	−0.31	−0.22

KFM07A	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.45	0.37	0.15	0.24
St. dev.	0.24	0.17	0.42	0.40
Min	−0.82	−0.83	−1.43	−1.45
Max	0.84	0.70	0.57	0.75

KFM07B	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.35	0.17	0.18	0.34
St. dev.	0.19	0.21	0.01	0.19
Min	0.01	−0.61	0.16	0.15
Max	0.54	0.54	0.19	0.54

KFM07C	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.55	0.49	0.26	0.36
St. dev.	0.24	0.12	0.41	0.42
Min	−0.66	0.24	−1.27	−1.32
Max	0.98	0.84	0.70	0.90

KFM08A	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.40	0.38	0.29	0.35
St. dev.	0.12	0.12	0.29	0.21
Min	0.05	0.17	−0.43	−0.49
Max	0.81	0.94	2.26	0.73

KFM08B	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.18	0.03	−0.04	0.09
St. dev.	0.26	0.29	0.20	0.20
Min	−4.07	−5.94	−1.90	−1.06
Max	0.70	1.61	0.29	0.59

KFM08C	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.17	0.06	−0.01	0.06
St. dev.	0.21	0.13	0.18	0.26
Min	−0.32	−0.35	−0.69	−2.73
Max	0.72	0.55	0.29	0.61

KFM08D	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.34	0.31	0.22	0.32
St. dev.	0.22	0.12	0.14	0.17
Min	−0.66	0.08	−0.50	−0.49
Max	0.81	0.66	0.47	0.67

KFM09A	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	2.04	2.05	1.72	1.84
St. dev.	0.21	0.20	0.37	0.36
Min	1.48	1.46	0.59	0.97
Max	2.50	2.45	2.34	2.41

KFM09B	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.20	0.13	−0.13	0.01
St. dev.	0.17	0.13	0.31	0.35
Min	−0.52	−0.45	−1.18	−1.08
Max	0.68	0.52	0.38	0.57

KFM13	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.71	0.67	0.32	0.48
St. dev.	0.14	0.14	0.30	0.37
Min	0.44	0.43	−2.30	−3.15
Max	1.29	1.30	1.14	1.11

KFM14	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.38	0.23	0.10	0.10
St. dev.	0.15	0.06	0.10	0.13
Min	0.03	−0.10	−0.11	−0.09
Max	0.69	0.40	0.33	0.42

KFM15	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.25	1.32	0.87	1.04
St. dev.	0.33	0.19	0.36	0.43
Min	−0.54	0.97	−1.61	−0.78
Max	1.84	2.02	1.77	1.72

KFM16	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.28	0.09	0.03	0.12
St. dev.	0.19	0.21	0.34	0.22
Min	−0.14	−3.53	−4.52	−2.04
Max	0.78	0.35	0.36	0.44

KFM17	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.73	0.66	0.39	0.53
St. dev.	0.16	0.12	0.26	0.33
Min	0.23	0.43	−1.61	−3.10
Max	1.22	1.09	1.01	1.02

KFM18	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.13	1.13	0.79	0.94
St. dev.	0.26	0.15	0.30	0.54
Min	−0.17	0.82	−1.68	−8.01
Max	1.64	1.70	1.54	1.50

KFM19	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.10	−0.12	−0.07	−0.01
St. dev.	0.28	0.15	0.16	0.21
Min	−0.53	−0.62	−2.09	−1.83
Max	0.75	0.21	0.21	0.46

KFM20	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	1.11	1.14	0.84	1.02
St. dev.	0.12	0.10	0.30	0.29
Min	0.78	0.90	−1.69	−0.81
Max	1.33	1.35	1.31	1.28

KFM21	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.33	0.24	0.08	0.16
St. dev.	0.12	0.06	0.19	0.40
Min	0.13	0.10	−3.28	−5.86
Max	0.74	0.46	0.40	0.44

KFM22	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.09	−0.13	−0.07	−0.04
St. dev.	0.29	0.18	0.15	0.21
Min	−0.62	−0.70	−1.71	−1.56
Max	0.73	0.19	0.24	0.48

KFM23	Dec.–Feb.	Mar.–May	Jun.–Aug.	Sep.–Nov.
Average	0.43	0.29	0.15	0.26
St. dev.	0.17	0.09	0.36	0.18
Min	0.11	0.02	−6.02	−0.14
Max	0.88	0.49	0.52	0.55

Appendix 2

Slug tests in groundwater-monitoring wells

This appendix presents results of single-hole hydraulic (slug) tests, performed during the period November 24–December 8, 2016, in a number of previously untested groundwater-monitoring wells in the access area and its surroundings. Table A2-1 lists the tested wells and associated well data, whereas Table A2-2 describes start times and durations of falling- and rising-head tests, and diameter/length of the slug used in each test. The results of the slug-test data evaluation are presented and commented in Table A2-3, and Table A2-4 provides a list of raw data files, converted files and AQTESOLV® files.

The objective of a slug test is to cause an instantaneous rise or drop of the water level in a well (denoted falling-head test and rising-head test, respectively). The hydraulic conductivity, and, for some evaluation types also the storativity, of the regolith and/or rock surrounding the well screen are thereafter estimated by evaluation of the subsequent, transient hydraulic (water level) response in the well.

The tests evaluated here were performed using custom-made solid slugs (dummies) with a diameter of 0.04 and 0.016 m, respectively. Hydraulic responses were measured using pressure sensors with integrated data loggers, specifically a Level TROLL® 700 (In-Situ, Inc.) in wells SFM0077 and -78, and a miniTROLL® SSP-100 in the other wells. In the evaluations, the radius of in-hole equipment is set to 0.004 m (slug wire 0.0025 m and data cable 0.0015 m). Evaluation of the data from the tests was done using the AQTESOLV® ver. 4.0 software (HydroSOLVE, Inc.). Specifically, data were evaluated using the Cooper et al. (1967) method, which is suggested as a standard evaluation method in SKB's method description for slug tests (SKBdoc 1230437 ver 1.0, SKB-internal document). For further details on the performance and methods for evaluation of slug tests, see e.g. Butler (1998) and Werner and Johansson (2003).

Table A2-1. List of tested wells and associated well data.

Well id (SFM00-)	Scr. length (m)	Inner rad., casing and scr. (m)	Initial WL displacement (m)			Dist. ToC–scr. bottom (m)	Man. meas. WLD from ToC (m)	WCH above scr. bottom (m)	WCH above scr. top (m)	Depth ToC–press. sensor (m)	WCH above press. sensor (m)
			Exp.	FHT	RHT						
77	1	0.025	0.96	0.0016	−0.0029	8.00	2.22	4.78	3.78	6.00	3.78
78	1	0.025	0.64	0.47	−0.51	5.50	2.37	2.13	1.13	4.20	1.83
79	1	0.025	0.64	0.61	−0.62	6.70	1.41	4.29	3.29	4.00	2.59
0122	0.5	0.01365[1]/ 0.0095[2]	0.69	0.80	−0.72	7.50	1.75	5.75	5.25	5.00	3.25
0139	1	0.0205	0.15	0.11	−0.17	3.00	0.93	2.07	1.07	2.5	1.57
0143	1	0.025	0.16	0.12	−0.08	3.00	2.21	0.79	−0.21	2.90	0.69
0144	1	0.025	0.64	0.07	−0.02	4.00	2.18	1.82	0.82	3.60	1.42
0145	1	0.025	0.64	0.53	−0.59	3.00	1.29	1.71	0.71	2.90	1.61
0146	1	0.025	0.64	0.20	−0.15	4.00	2.77	1.23	0.23	3.90	1.03
0147	1	0.025	0.64	0.56	−0.44	3.00	0.89	2.11	1.11	2.90	2.01
0149	1	0.025	0.32	0.07	−0.27	3.05	1.16	1.89	0.89	2.80	1.64
0153	1	0.025	0.64	0.29	−0.41	4.00	1.88	2.12	1.12	3.7	1.82

[1] SFM000122 well casing.
[2] SFM000122 well screen.
Scr. = screen.
rad. = radius.
WL = water level.
exp. = expected.
FHT = falling-head test.
RHT = rising-head test.
WLD = water-level depth.
ToC = top of casing.
WCH = water-column height.

Table A2-2. Start times and durations (tp, tF) of falling- and rising-head tests, and diameter/length of the slug used in each test. Dates and times are given as YYYY-MM-DD hh:mm.

Well id (SFM00-)	Falling-head test		Rising-head test		Slug diameter/length (m)
	Start	tp (s)	Start	tF (s)	
77	2016-11-24 15:36	< 60	2016-11-24 15:40	< 60	0.04/1.5
78	2016-11-24 10:26	4400	2016-11-24 11:58	8220	0.04/1.0
79	2016-11-24 12:28	27350	2016-11-25 08:02	30890	0.04/1.0
0122	2016-12-07 13:30	27870	2016-12-08 09:35	220	0.016/2.0
0139	2016-11-24 13:10	510	2016-11-24 13:20	3010	0.016/1.0
0143	2016-11-28 08:35		2016-11-28 12:43		0.04/0.25
0144	2016-11-28 11:00		2016-11-28 12:31		0.04/1.0
0145	2016-12-02 09:59	1610	2016-12-02 10:27	4610	0.04/1.0
0146	2016-12-05 10:36		2016-12-05 15:02		0.04/1.0
0147	2016-11-25 08:33 2016-11-25 08:51	20 20	2016-11-25 08:36 2016-11-25 08:53	640 2140	0.04/1.0
0149	2016-11-30 12:03 2016-11-30 12:07	 3440	 2016-11-30 15:15		0.04/1.0 (failed test) 0.04/0.5
0153	2016-11-25 12:40		2016-11-25 13:33	1030	0.05/1.0

As shown in Table A2-3 and Figure A2-1 to Figure A2-10, the slug-test evaluation yields hydraulic conductivity values on the order of 10^{-6}–10^{-5} m/s, which is typical for till in Forsmark (cf. Table 2-1 and Table 2-2 in the main text). The slug test in SFM0079, which is screened across the rock/regolith interface, yields a hydraulic conductivity of c 10^{-8}–10^{-7} m/s, which is typical for fine till (Table 2-1 in the main text).

On the other hand, the measured initial water-level displacement was too small and/or the hydraulic response too quick to allow evaluation of the test in some wells (SFM0077, SFM000144 and -146). For instance, the data-logging interval was too sparse (one minute) to allow evaluation of the quick response in SFM0077. The quick SFM0077 response is illustrated in Figure A2-1 using the Cooper et al. (1967) method. Specifically, this synthetic example yields a hydraulic conductivity of 2×10^{-4} m/s, based on an expected initial water-level displacement of 0.96 m, and residual displacements of 0.3 m at 10 s, 0.125 m at 20 s, and 0.025 m at 60 s (the measured initial displacements in SFM0077 were 0.0016 and −0.0029 m; see Table A2-1), The example clearly shows that the data-logging interval during the test was too sparse to capture the quick response.

SFM000143 is screened across the groundwater table, which makes slug-test evaluation difficult due to drainage effects. It is also noted that the hydraulic response in well SFM000122 was much quicker to the rising-head test compared to the initial, falling-head test. This may indicate that the screen of the well was clogged during the falling-head test, which cleared away sediments from the well screen prior to the subsequent rising-head test. Moreover, the measured initial displacement was too small and the data fit was poor for one of the tests in each of wells SFM000149 and -153 (rising- and falling-head test, respectively).

Wells with small measured initial displacements and/or quick slug-test responses are also characterised by large average groundwater-table depths (SFM0077, -146 and -153; see Table 4-3 in the main text). As commented in the main text, this could be due to occurrences of relatively coarse-grained, easily-drained artificial fill, i.e. a mixture of excavated rock and regolith, at these well locations. Wells with a hydraulic conductivity on the order of 10^{-6}–10^{-5} m/s have typical average groundwater-table depths of c 1 m (e.g. SFM0078 and SFM000122). On the other hand, well SFM0079, with a hydraulic conductivity of c 10^{-8}–10^{-7} m/s, has a relatively shallow average depth to the groundwater table (c 0.8 m).

Table A2-3. Well-screen depth (metres below ground surface), type of regolith at screen depth, results of and comments to the slug-test evaluations. “QFM” refers to probing id codes in Sicada.

Well id (SFM00-)	Scr. depth (m bgs)	Regolith type at scr. depth	Approx. evaluated hydraulic conductivity (m/s)	Comments
77	5.73–6.73	Across interface till/rock		Measured initial water-level displacement too small and response too quick (< 60 seconds) for data-logging interval (one minute).
78	3.1–4.1	Across interface till/rock	1.5×10^{-6}	
79	4.1–5.1	Boulder, across interface till/rock	5×10^{-8}–1×10^{-7}	
0122	6.6–7.1	Unknown	3×10^{-5}	
0139	1.2–2.2	Peat, clay, till	8×10^{-6}–1×10^{-5}	
0143	0.5–1.5	QFM000028: 0.2–0.8 Somewhat sandy silty gravel till 0.8–1.5 Somewhat sandy gravelly silty till		Screened across the groundwater table, drainage effects.
0144	1.5–2.5	QFM000034: 1–2 Somewhat gravelly sandy silty till		Very quick response.
0145	1–2	QFM000043: 0.8–2 Sandy silty till	2–5×10^{-6}	
0146	2.1–3.1	QFM000047: 0.6–1.5 Till		Poor data fit, potentially due to screen clogging.
0147	1.4–2.4	QFM000084: 1–2 Sandy silty till	5×10^{-4}–1×10^{-3} 2–5×10^{-5}	Falling-head test. Rising-head test.
0149	1.25–2.25	QFM000101: 1.4–3.0 Somewhat sandy gravelly silty till	1×10^{-6} m/s	Poor data fit for rising-head test, potentially due to screen clogging.
0153	2.2–3.2	QFM000111: 1.4–2.0 Sandy silty till	1×10^{-5} m/s	Poor data fit for falling-head test, potentially due to screen clogging.

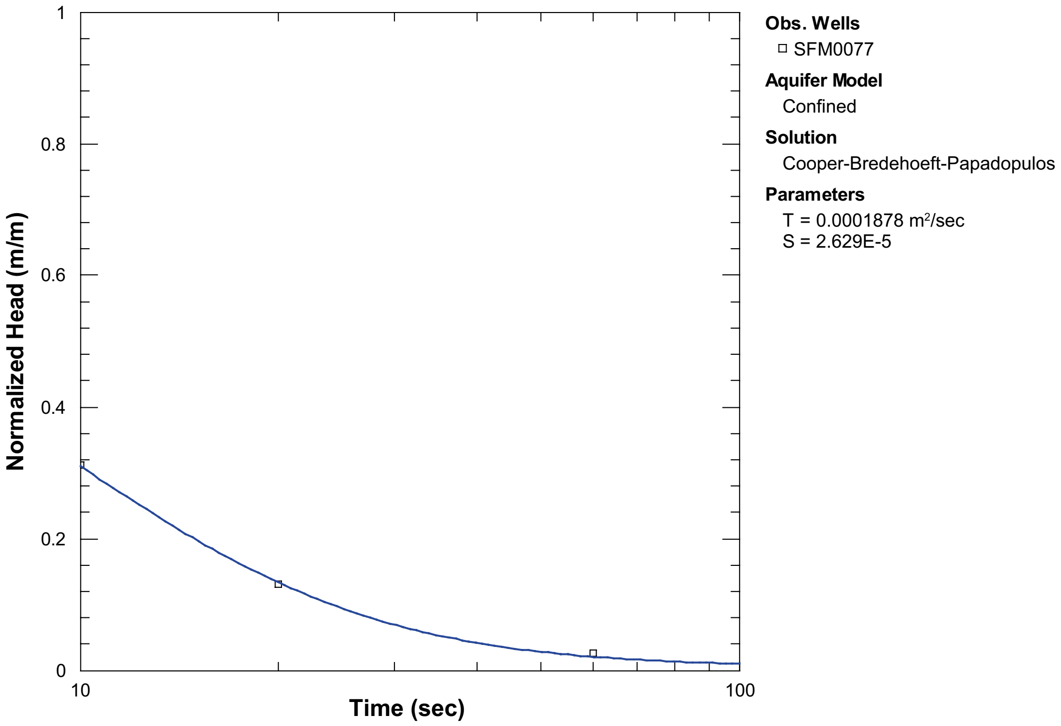


***Figure A2-1.** Synthetic slug-test example using the Cooper et al. (1967) method, mimicking the quick hydraulic response in well SFM0077.*

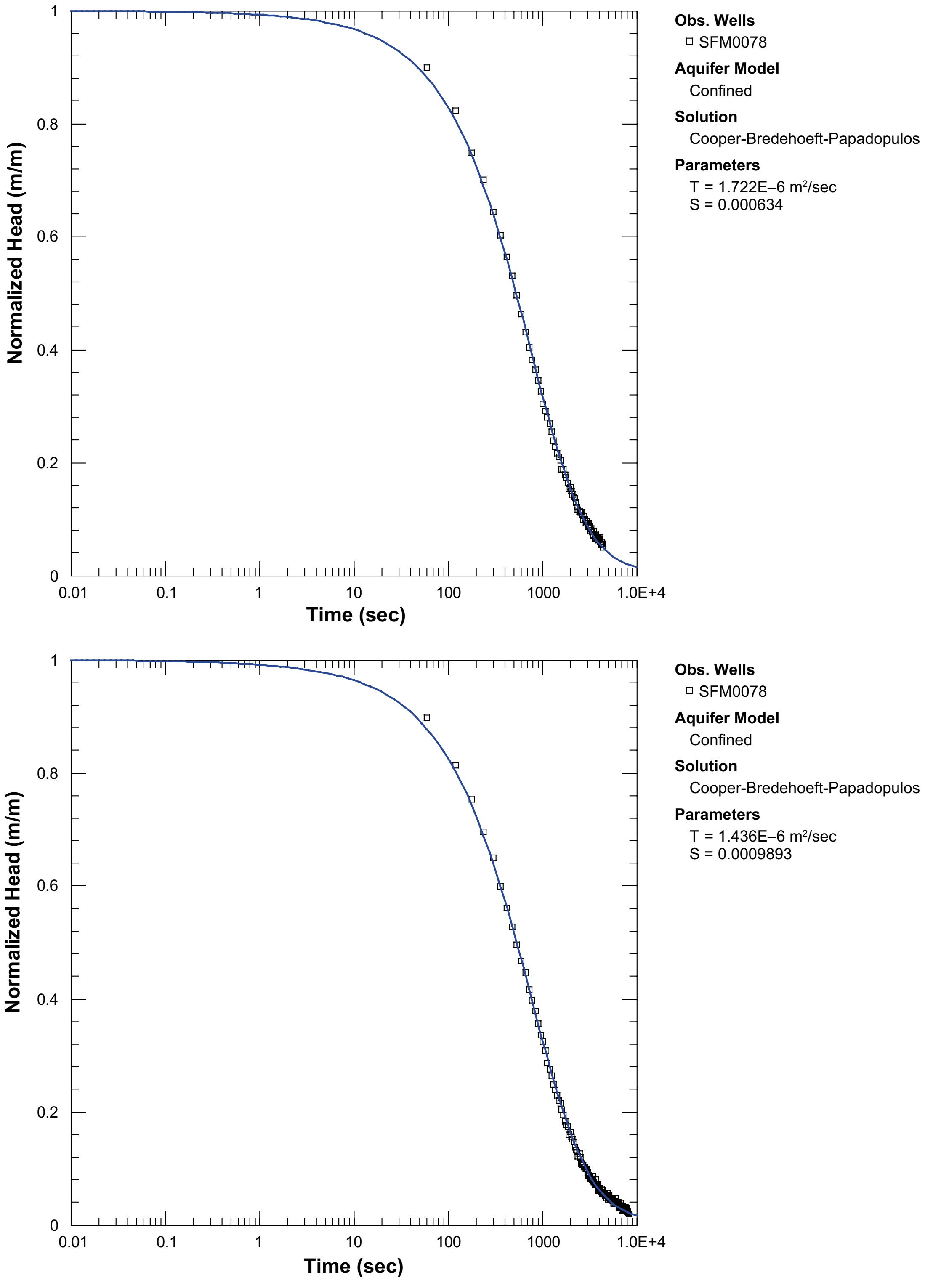
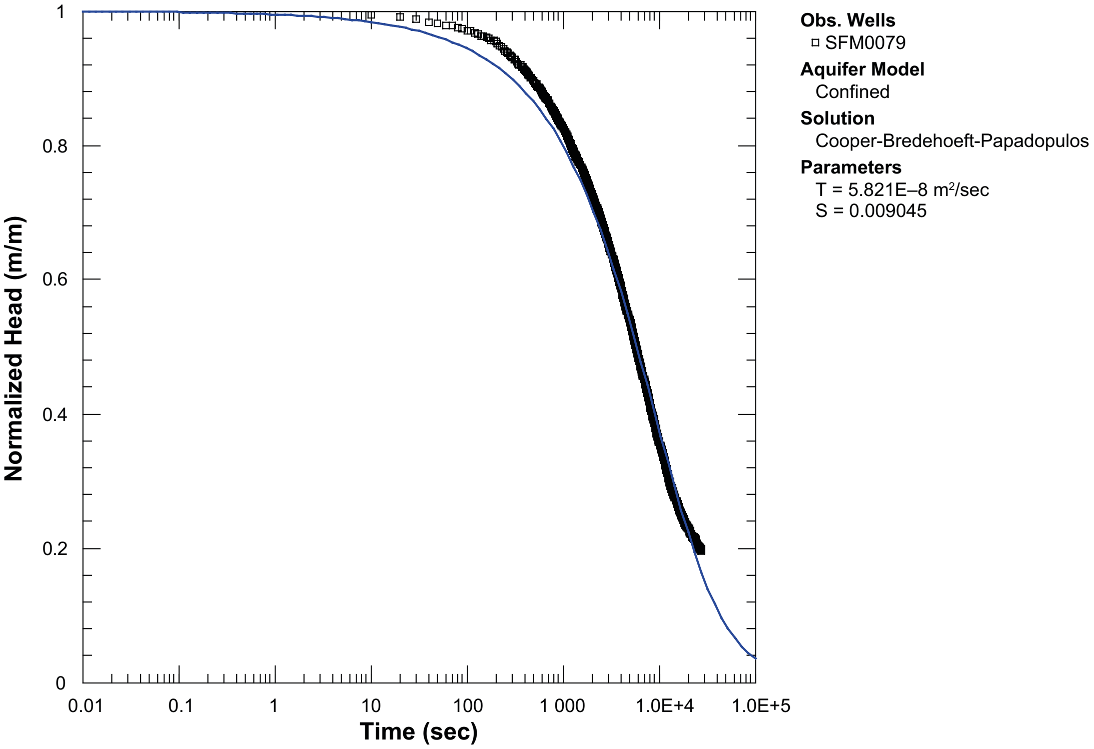


Figure A2-2. *Evaluation of falling-head test (upper plot) and rising-head test (lower plot) in well SFM0078.*



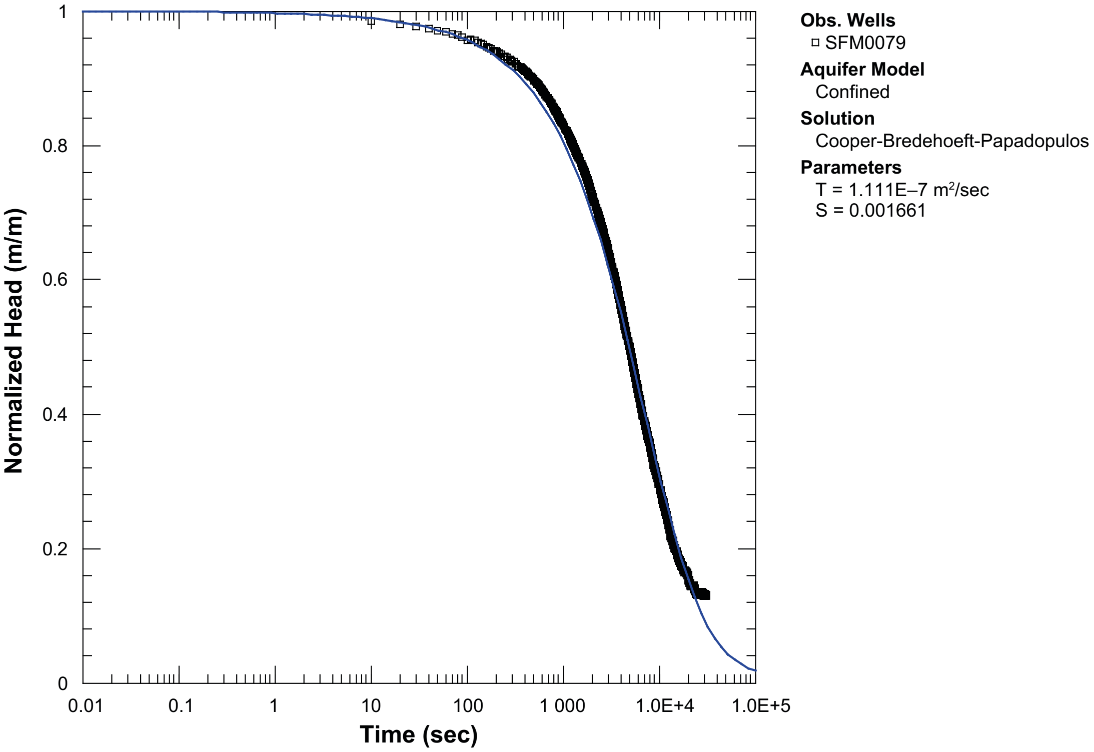
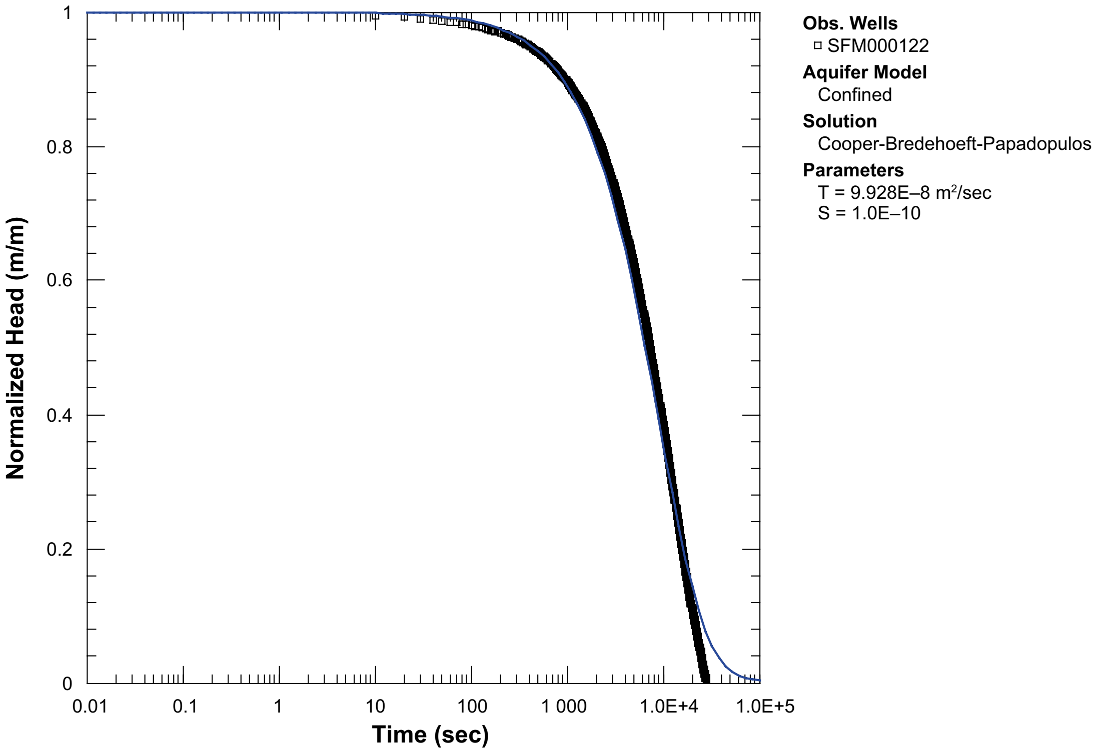


Figure A2-3. *Evaluation of falling-head test (upper plot) and rising-head test (lower plot) in well SFM0079.*



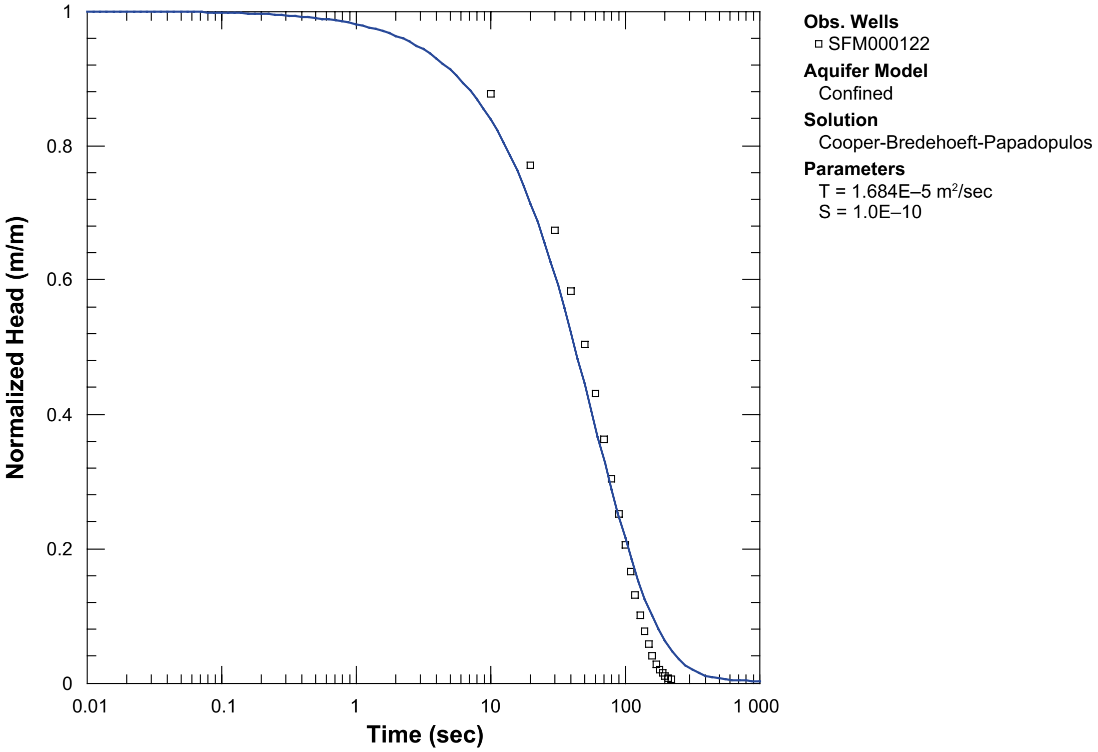
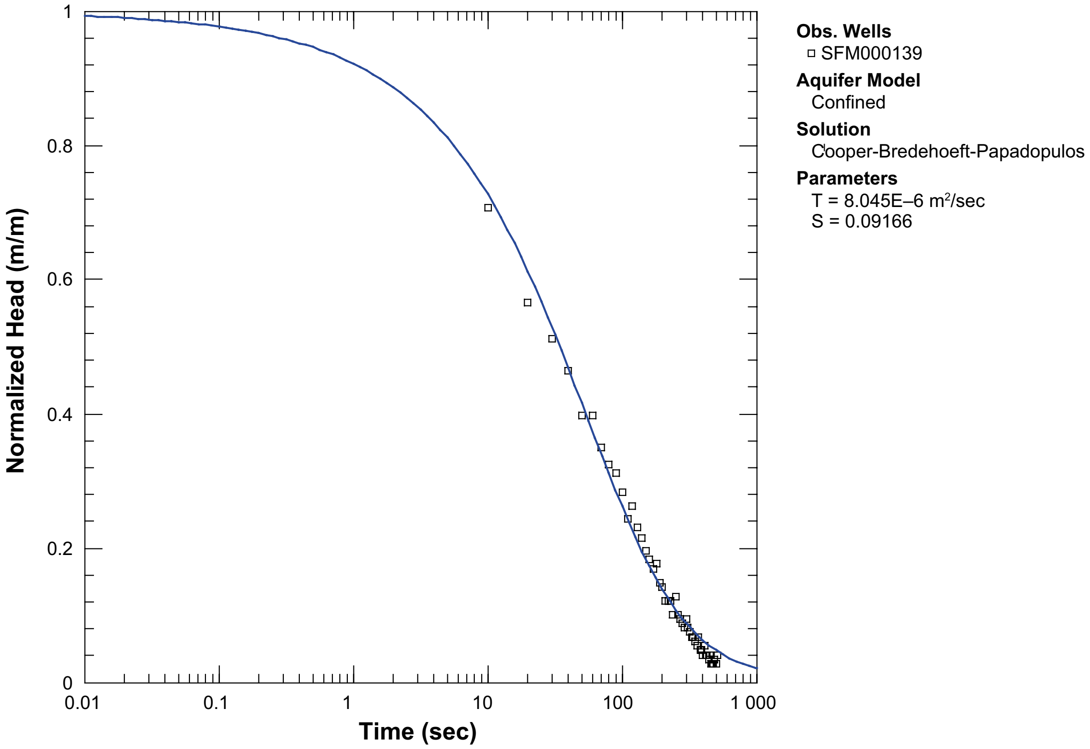


Figure A2-4. *Evaluation of falling-head test (upper plot) and rising-head test (lower plot) in well SFM000122. Note that the response during the rising-head test was much quicker compared to the falling-head test.*



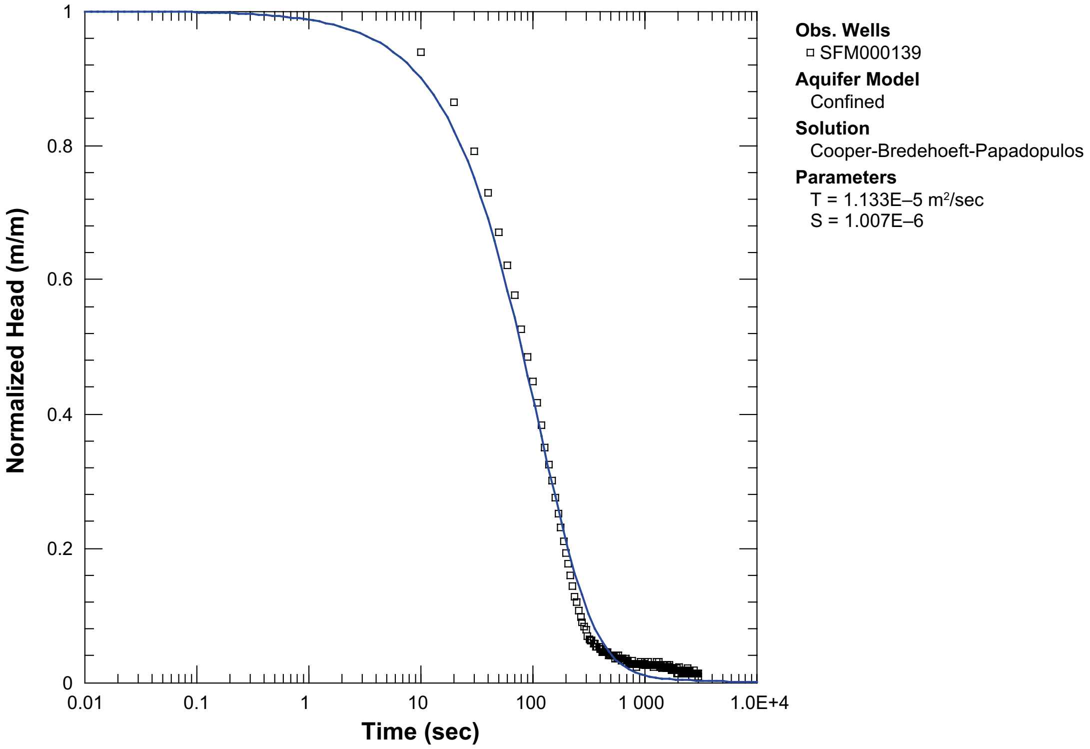
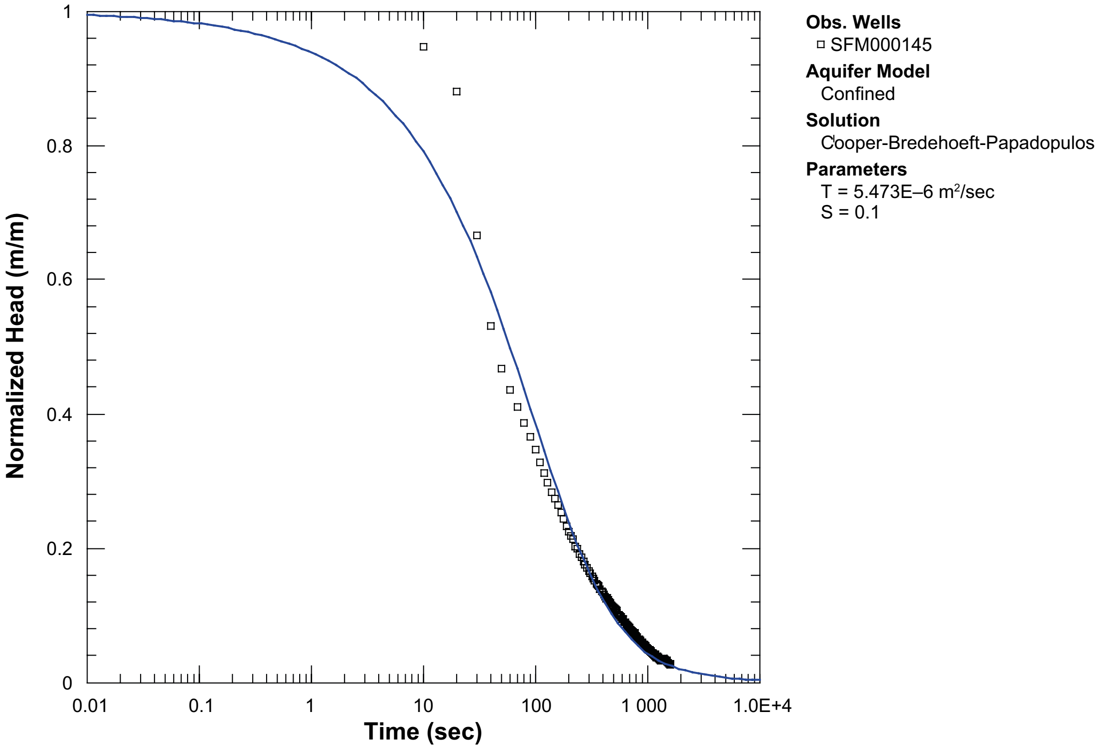


Figure A2-5. *Evaluation of falling-head test (upper plot) and rising-head test (lower plot) in well SFM000139.*



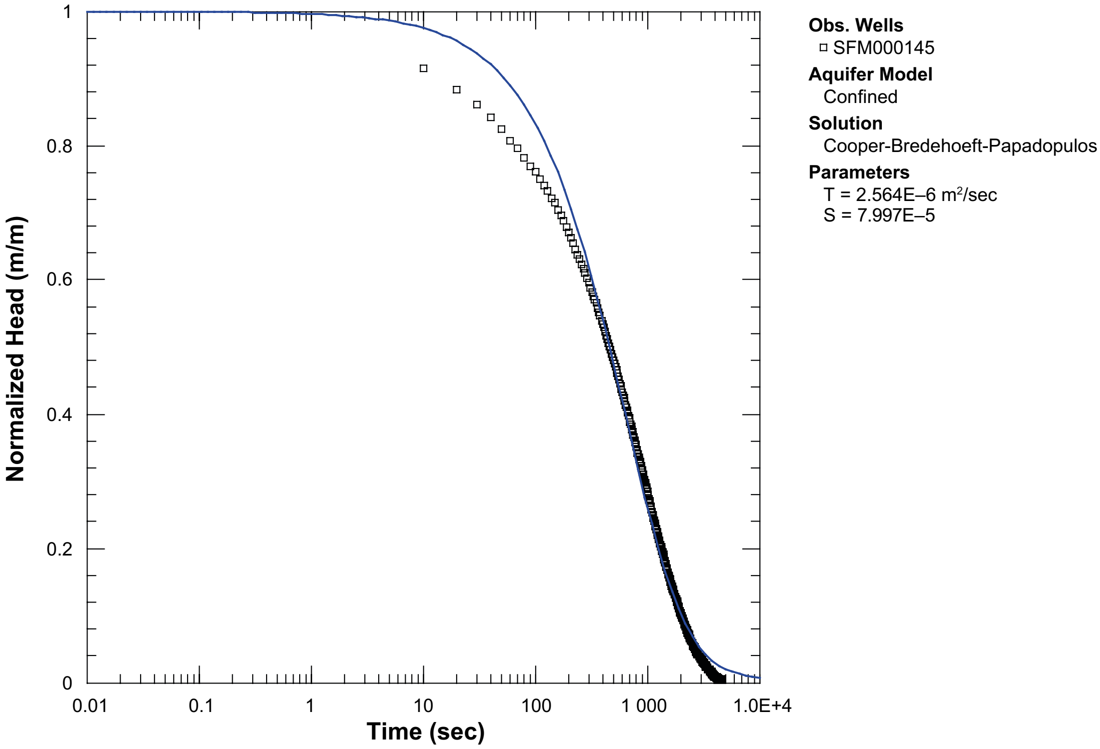
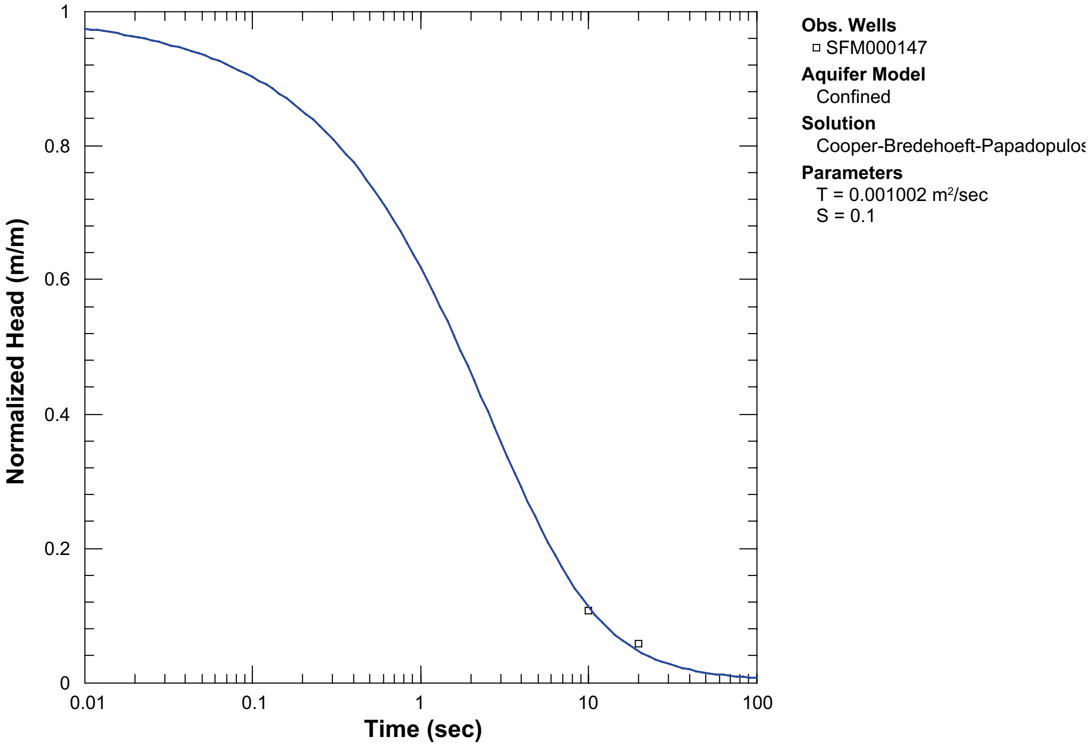


Figure A2-6. *Evaluation of falling-head test (upper plot) and rising-head test (lower plot) in well SFM000145.*



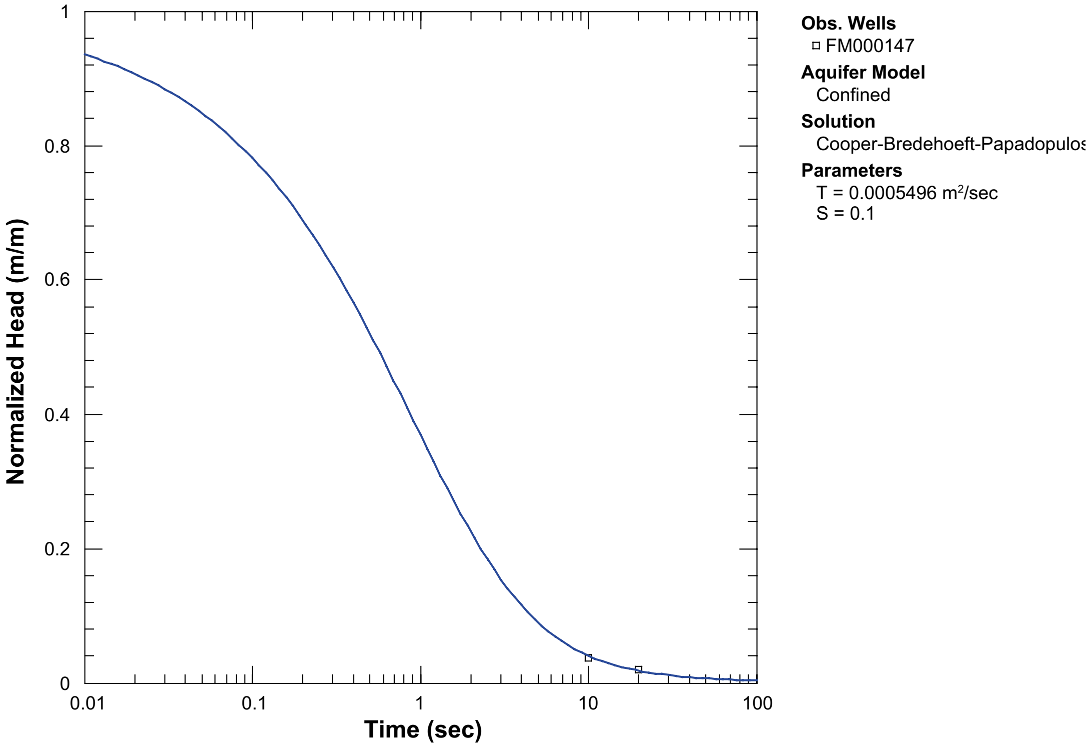


Figure A2-7. *Evaluation of the first (upper plot) and the second (lower plot) falling-head test in well SFM000147.*

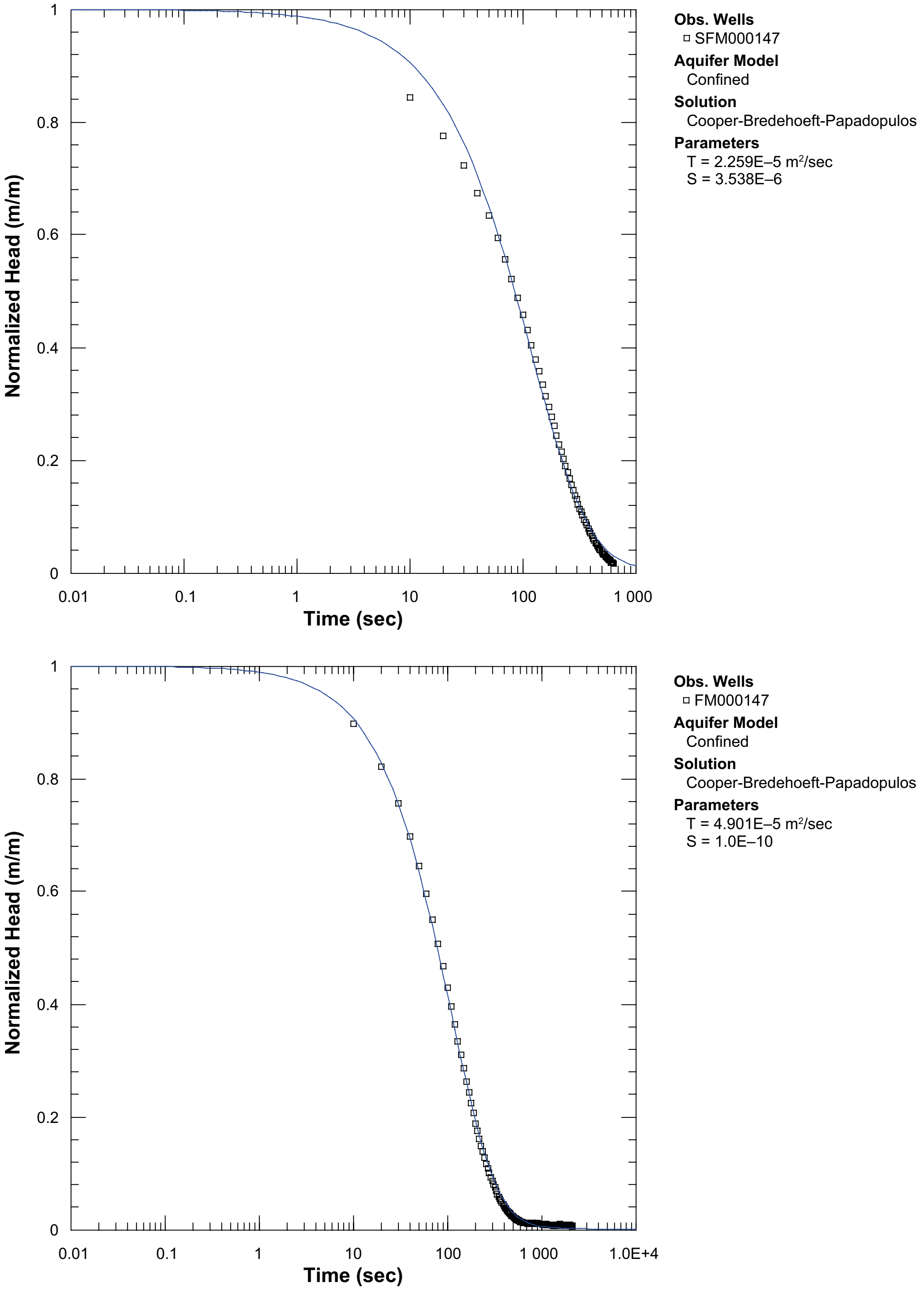


***Figure A2-8.** Evaluation of the first (upper plot) and the second (lower plot) rising-head test in well SFM000147.*

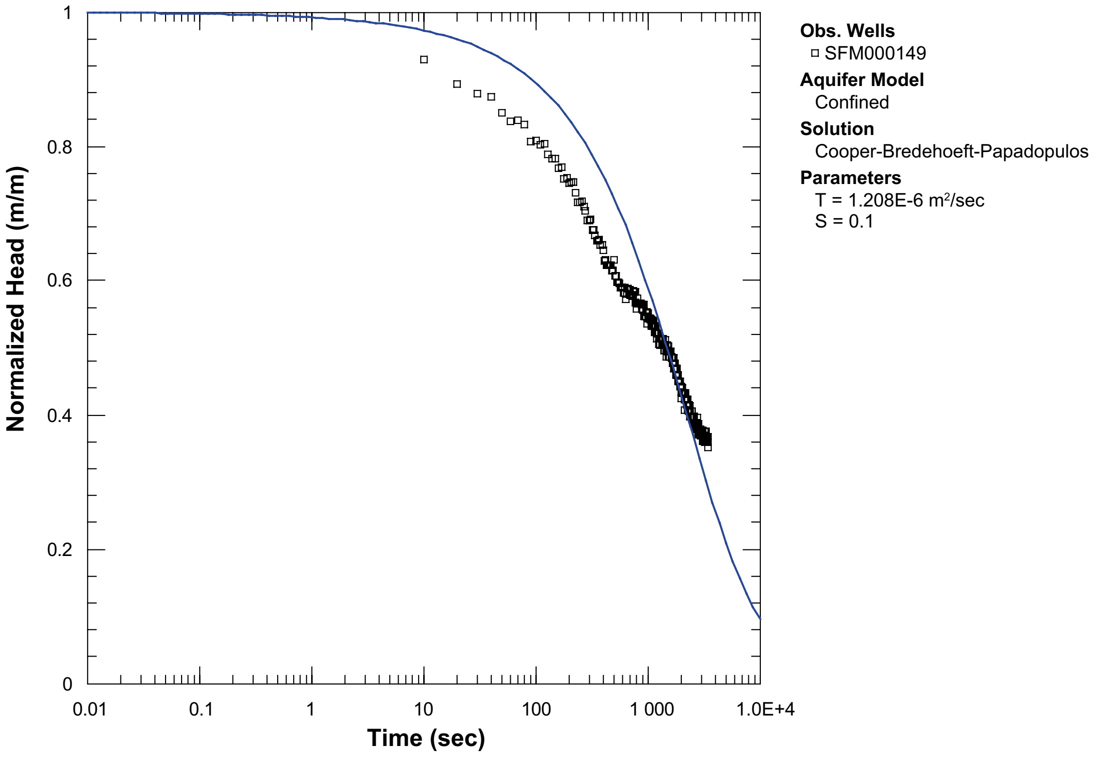


Figure A2-9. *Evaluation of the falling-head test in well SFM000149. There was poor fit to the data from the rising-head test.*

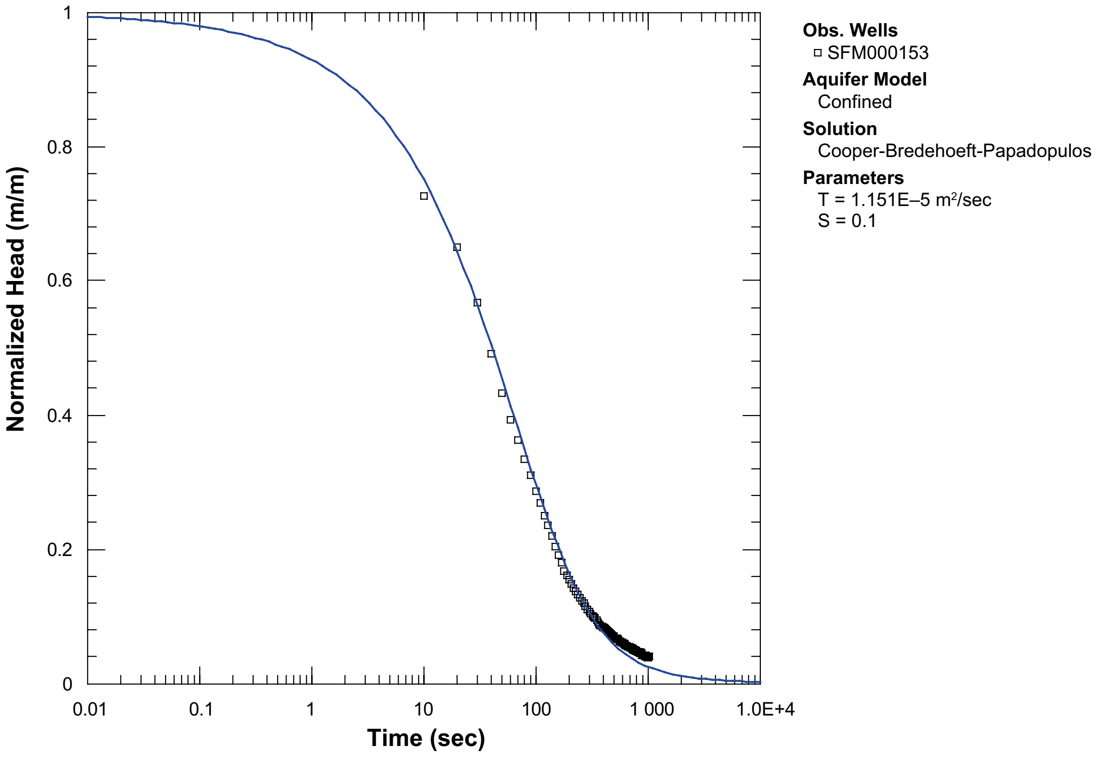


Figure A2-10. *Evaluation of the rising-head test in well SFM000153. There was poor fit to the data from the falling-head test.*

Table A2-4. List of raw data files, converted files and AQTESOLV® files.

Well id	Raw data files	Converted files (Win-Situ® and Microsoft Excel® software)	AQTESOLV® files (.aqt)
SFM0077	sfm0077-slugg 2016-11-24 15.46.43.wsl	sfm0077-slugg 2016-11-24 15.46.43.txt, xlsx	SFM0077_falling_test
SFM0078	sfm0078-slugg 2016-11-24 15.10.36.wsl	sfm0078-slugg 2016-11-24 15.10.36.txt, xlsx	SFM0078_falling_test SFM0078_rising_test
SFM0079	SN16517 2016-11-24 121423 sfm0079-slugg.bin	sfm0079.txt, xlsx	SFM0079_falling_test SFM0079_rising_test
SFM000122	SN16517 2016-12-07 132130 sfm00122-slugg.bin	sfm00122.txt, xlsx	SFM000122_falling_test SFM000122_rising_test
SFM000139	SN11237 2016-11-24 125705 sfm00139-slugg.bin	sfm00139.txt, xlsx	SFM000139_falling_test SFM000139_rising_test
SFM000143	SN16517 2016-11-28 082720 sfm00143-slugg.bin	sfm00143.txt, xlsx	SFM000143_falling_test SFM000143_rising_test
SFM000144	SN11237 2016-11-28 105025 sfm00144-slugg.bin	sfm00144.txt, xlsx	SFM000144_falling_test SFM000144_rising_test
SFM000145	SN16517 2016-12-02 094937 sfm00145-slugg.bin	sfm00145.txt, xlsx	SFM000145_falling_test SFM000145_rising_test
SFM000146	SN16517 2016-12-05 102711 sfm00146-slugg.bin	sfm00146.txt, xlsx	SFM000146_falling_test SFM000146_rising_test
SFM000147	SN11237 2016-11-25 082543 sfm00147-slugg.bin	sfm00147.txt, xlsx	SFM000147_falling_1_test SFM000147_falling_2_test SFM000147_rising_1_test SFM000147_rising_2_test
SFM000149	N16517 2016-11-30 115717 sfm00149-slugg.bin	sfm00149.txt, xlsx	SFM000149_falling_test SFM000149_rising_test
SFM000153	SN11237 2016-11-25 123233 sfm00153-slugg.bin	sfm00153.txt, xlsx	SFM000153_falling_test SFM000153_rising_test

Arkitektkopia AB, Bromma, 2018

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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