

# Consideration of site-specific conditions in the assessment of groundwater pollution potential: An ash disposal case study

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## PREFACE

This study is meant to integrate sound scientific concepts with the law and was inspired by an article titled “*Unintended consequences when the law fails to properly consider scientific concepts and engineering principles – A Case Study from South Africa, where Landfill Regulations attempts to regulate Mining Waste*” by Carin Bosman. I have spent much of my career in water resource management enquiring about the intricacies of the role of scientific concepts, engineering principles, and law in environmental management. This study served as the blueprint of my learnings to date on how these areas can be integrated to enhance decision-making that reduces the risk of unintended consequences while realising the objectives of sustainable development.

I would like to thank my supervisor, Dr Claudine Roos for her responsiveness, contribution and guidance from our first meeting to the final conclusion of the study.

I would like to express my gratitude towards my family for all the support they have provided throughout my life. My beloved wife, Antie, you are the best home remedy that has maintained my well-being.

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I am grateful to a number of friends and colleagues, all of whom never stopped challenging me and helped in my personal and professional development.

I would like to end with the following quote by Jennifer Edwards:

*“The beauty of life is, while we cannot undo what is done, we can see it, understand it, learn from it and change so that every new moment is spent not in regret, guilt, fear or anger but in wisdom, understanding, and love”.*

## ABSTRACT

Groundwater resources, which form an important source of readily available potable water supply, are vulnerable to contamination from land-based activities. One of the potential sources of contamination is waste disposal facilities (WDFs). In South Africa, groundwater pollution potential from WDFs is regulated in terms of the National Water Act (36 of 1998) (NWA) and the National Environmental Management: Waste Act (59 of 2008) (NEM: WA).

These two laws make use of different approaches to determine the groundwater pollution potential, namely, the (1) the Waste Classification Management System (WCMS), currently prescribed for the assessment of waste for landfill disposal under the NEM: WA; and (2) the source-pathway-receptor (SPR) approach recommended in the guidelines giving effect to Water Quality Management Policy developed under the NWA. It was argued that the current application of the WCMS may not consider site-specific conditions associated with groundwater pollution potential from WDFs.

The aim of this study was to understand the extent to which the SPR approach differs from WCMS in terms of consideration of site-specific conditions when assessing potential pollution of groundwater from wet and dry ash disposal facilities (ADFs). SPR is one of the approaches, other than the WCMS, which is believed to make a more suitable provision for site-specific conditions.

A case study method for ash disposal from the power generation processes of Eskom Holdings SOC Ltd was considered. One wet ADF and one dry ADF, located at two different Power Stations, with different site-specific conditions were included. Groundwater quality data, measured quarterly from June 1989 to February 2018 (at Site A) and October 1990 to June 2017 (at Site B) of twenty-two (22) different (source-, pathway- and receptor) boreholes were included for consideration during this study.

Considering the above, it is clear that the WCMS and SPR approaches differ in how they assess groundwater pollution potential of ADFs, as it relates to the source (indicator: leachable concentration), pathway (indicator: NAP and geological structures) and receptor (indicator: thresholds). The fact that the WCMS approach does not provide for site-specific conditions and apply thresholds that do not adequately protect the most sensitive user identified for that catchment, could result in either over- or under-protection of the surrounding environment. It is, therefore, argued that the SPR approach may be a more suitable method for assessing groundwater pollution potential while taking site-specific conditions into consideration.

**Keywords:** groundwater pollution potential, site-specific conditions, ash disposal facility, waste classification management system, source-pathway-receptor approach.

## **ACRONYMS AND ABBREVIATIONS**

AC	ASSIMILATIVE CAPACITY
ADF	ASH DISPOSAL FACILITY
BPG	BEST PRACTICE GUIDELINES
CMS	CATCHMENT MANAGEMENT STRATEGY
DEA	DEPARTMENT OF ENVIRONMENTAL AFFAIRS (now known as DEFF)
DEFF	DEPARTMENT OF ENVIRONMENT, FORESTRY AND FISHERIES
DWS	DEPARTMENT OF WATER AND SANITATION
DWA	DEPARTMENT OF WATER AFFAIRS (now known as DWS)
DWAF	DEPARTMENT OF WATER AFFAIRS AND FORESTRY (now known as DWS)
EPA	ENVIRONMENT PROTECTION AUTHORITY
IWRM	INTEGRATED WATER RESOURCE MANAGEMENT
MDSD	MOST DIFFERENT SYSTEMS DESIGN
NAP	NATURAL ATTENUATION PROCESS
NEMA	NATIONAL ENVIRONMENTAL MANAGEMENT ACT, NO. 107 OF 1998
NEM: WA	NATIONAL ENVIRONMENTAL MANAGEMENT: WASTE ACT, NO. 59 OF 2008
NWA	NATIONAL WATER ACT, NO. 36 OF 1998
NWRS	NATIONAL WATER RESOURCE STRATEGY
RQOs	RESOURCE QUALITY OBJECTIVES
RWQOs	RESOURCE WATER QUALITY OBJECTIVES
SPR	SOURCE-PATHWAY-RECEPTOR
USEPA	UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

WDF	WASTE DISPOSAL FACILITY
WCMS	WASTE CLASSIFICATION MANAGEMENT SYSTEM
WMA	WATER MANAGEMENT AREA
WML	WASTE MANAGEMENT LICENSE
WUL	WATER USE LICENCE

## **DEFINITIONS AND TERMINOLOGIES**

### ***Aquifer***

*Means a geological formation which has structures or textures that hold water or permit appreciable water movement through them.*

**National Water Act (36 of 1998)**

### ***Borehole***

*Includes a well, excavation or any artificially constructed or improved underground cavity which can be used for the purpose of (a) intercepting, collecting or storing water in or removing water from an aquifer; (b) observing and collecting data and information on water in an aquifer; or (c) recharging an aquifer.*

**National Water Act (36 of 1998)**

### ***Catchment***

*In relation to a watercourse or watercourses or part of a watercourse, means the area from which any rainfall will drain into the watercourse or watercourses or part of a watercourse, through the surface flow to a common point or common points.*

**National Water Act (36 of 1998)**

### ***Disposal***

*Means the burial, deposit, discharge, abandoning, dumping, placing or release of any waste into, or onto, any land.*

**National Environmental Management Waste Act (59 of 2008)**

### ***Environment***

*Means the surroundings within which humans exist and that are made up of (i) the land, water and atmosphere of the earth; (ii) micro-organisms, plant and animal life; (iii) any part or combination of (i) and (ii) and the interrelationships among and between them; and (iv) the physical, chemical, aesthetic, and cultural properties and conditions of the foregoing that influence human health and well-being.*

**National Environmental Management Act (107 of 1998)**

**Pollution**

*Means the direct or indirect alteration of the physical, chemical or biological properties of a water resource so as to make it (a) less fit for any beneficial purpose for which it may reasonably be expected to be used; or (b) harmful or potentially harmful (aa) to the welfare, health or safety of human beings; (bb) to any aquatic or non-aquatic organisms; (cc) to the resource quality; or (dd) to property.*

**National Water Act (36 of 1998)**

**Pollution**

*Any change in the environment caused by-(i) substances; (ii) radioactive or other waves; or (iii) noise, odours, dust or heat, emitted from any activity, including the storage or treatment of waste or substances, construction and the provision of services, whether engaged in by any person or an organ of state, where that change has an adverse effect on human health or well-being or on the composition, resilience, and productivity of natural or managed ecosystems, or on materials useful to people, or will have such an effect in the future.*

**National Environmental Management Act (107 of 1998)**

**Protection (in relation to a water resource)**

*Means (a) maintenance of the quality of the water resource to the extent that the water resource may be used in an ecologically sustainable way; (b) prevention of the degradation of the water resource; and (c) the rehabilitation of the water resource.*

**National Water Act (36 of 1998)**

**Reserve**

*Means the quantity and quality of water required (a) to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997 (Act No. 108 of 1997), for people who are now or who will, in the reasonably near future, be (i) relying upon; (ii) taking water from; or (iii) being supplied from, the relevant water resource; and (b) to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource.*

**National Water Act (36 of 1998)**

### **Resource quality**

*Means the quality of all the aspects of a water resource including (a) the quantity, pattern, timing, water level and assurance of instream flow; (b) the water quality, including the physical, chemical and biological characteristics of the water; (c) the character and condition of the instream and riparian habitat; and (d) the characteristics, condition and distribution of the aquatic biota.*

**National Water Act (36 of 1998)**

### **Resource quality objectives**

*Means clear goals relating to the quality of the relevant water resources.*

**National Water Act (36 of 1998)**

### **Waste**

*(a) Any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered; (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered; (iii) where the Minister has, in terms of Section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste.*

**National Environmental Management Waste Act (59 of 2008), as amended**

### **Waste**

*Includes any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted.*

**National Water Act (36 of 1998)**

**Waste assessment**

*Assessment in accordance with the Norms and Standards for Assessment of Waste for Landfill Disposal prior to disposal of waste landfill.*

**GNR 634 of August 2013**

**Waste classification**

*Establishing (a) whether a waste is hazardous based on the nature of its physical, health and environmental hazardous properties (hazard classes); and (b) the degree of severity of hazard posed (hazard categories).*

**GNR 634 of August 2013**

**Waste disposal facility (WDF)**

*Any site or premise used for the accumulation of waste with the purpose of disposing of that waste at that site or on that premise.*

**National Environmental Management Waste Act (59 Of 2008)**

**Water Resource'**

*Water resource includes a watercourse, surface water, estuary or aquifer.*

**National Water Act (36 of 1998)**

**Watercourse**

*Means (a) a river or spring; (b) a natural channel in which water flows regularly or intermittently; (c) a wetland, lake or dam into which, or from which, water flows; and (d) any collection of water which the Minister may, by notice in the Gazette, declare to be a watercourse, and a reference to a watercourse includes, where relevant, its bed and banks.*

**National Water Act (36 of 1998)**

**Water use**

*Water use includes (a) taking water from a water resource; (b) storing water; (c) impeding or diverting the flow of water in a watercourse; (d) engaging in a stream flow reduction activity contemplated in Section 36; (e) engaging in a controlled activity identified as such in Section 37(1)*

*or declared under Section 38(1); (f) discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit; (g) disposing of waste in a manner which may detrimentally impact on a water resource; (h) disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process; (i) altering the bed, banks, course or characteristics of a watercourse; (j) removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people; and (k) using water for recreational purposes.*

**National Water Act (36 of 1998)**

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# CHAPTER 1 INTRODUCTION

## 1.1 Introduction

Groundwater resources, which form an important source of readily available potable water supply, are vulnerable to contamination from land-based activities (WRC, 2014). One of the potential sources of contamination is waste disposal facilities (WDFs) (Chave, 1997). There are many different types of approaches for the assessment of environmental impacts with varying degrees of uncertainties related to the conditions or causes that need to be controlled to protect the environment including groundwater (Dong, 2018). According to the European Food Safety Authority (EFSA) (EFSA, 2016), protection goals in many jurisdictions do not consider site-specific conditions which may influence the outcome of the environmental impact assessments.

In South Africa, groundwater pollution potential from WDFs is regulated in terms of Section 21 of the National Water Act (36 of 1998) (NWA) (RSA, 1998b) and Section 19 of the National Environmental Management: Waste Act (59 of 2008) (NEM: WA) (RSA, 2008). The NEM: WA's mandate is to protect the environment from the impacts of waste disposal, while the NWA focuses on the protection of water resources, which include groundwater (Oelofse, 2008).

These two laws make use of different approaches to determine the potential risk (Bosman, 1999) and consequently the level of protection mechanisms to mitigate such risk (Helmer & Hespanhol, 1997). The NEM: WA follows the *Waste Classification Management System (WCMS)*<sup>1</sup> for the classification and assessment of waste (RSA, 2013a) and the NWA follows a differentiated site-specific approach of the Water Quality Management Policy (RSA, 2017) as implemented by means of source-pathway-receptor (SPR) assessment method (DWS, 2013).

The WCMS approach is similar to the *Minimum Requirements for Waste Disposal by Landfill* (DWAF<sup>2</sup>, 1998, 2005) in respect of assessing groundwater pollution potential by comparing leachate quality against a set of graded standards (thresholds) aimed at protecting the receiving environment (Bredenhann as quoted by Oelofse, 2008). Whilst the thresholds applied across South Africa, the *Minimum Requirements* classification system allowed for deviation in barrier requirements, based on the differences of the site-specific environmental conditions, which involved either an increase in barrier requirements or the relaxation in standards (DWAF, 2005).

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<sup>1</sup> The WCMS promulgated under the NEM:WA, is contained in GN R. 634 (Waste Classification and Management Regulations); GN R. 635 (Norms and Standards for Assessment of Waste for Landfill Disposal); and GN R. 636 (Norms and Standards for Disposal of Waste to Landfill) in GG 36784 of 23 August 2013.

<sup>2</sup> DWAF: Department of Water Affairs and Forestry, now the Department of Water and Sanitation (DWS)

From August 2013, the WCMS, which includes the *Norms and Standards for the Assessment of Waste for Landfill Disposal* (GNR. 635 of August 2013) (RSA, 2013b) is applicable to the assessment of waste for landfill disposal. The outcome of WCMS approach only considers leachate quality and thresholds as the criteria [albeit under different leachate solutions to represent the acidity/alkalinity of the WDF, as explained by Blight *et al.*, (1999)] without assessing the effect of site-specific environmental conditions on groundwater pollution potential (Mor *et al.*, 2006; Oelofse, 2008) based on a differentiated site-specific approach. Whilst the thresholds apply across South Africa (DWS, 2005), exception is provided for mine residue deposits in terms of GN No. 990 where deviation based on the difference in sensitivity of the site-specific environmental conditions could involve either an increase, relaxation in standards (RSA, 2018) or exemption from the requirements in terms of section 74 of the NEM: WA (RSA, 2008). It is argued that the SPR approach, which allows for the consideration of site-specific conditions, may be a more appropriate approach for the assessment of groundwater pollution potential from ADF.

To gain a better understanding of the differences between the WCMS and SPR approaches, this study evaluated the extent to which other conditions under a differentiated site-specific approach are: (1) considered, (2) how they affect groundwater pollution potential from ADFs and (3) the extent to which they influence the outcomes of groundwater pollution potential, when compared to leachate quality. In this respect, the application of discharge standards were proposed by the DWS<sup>3</sup>.

## 1.2 Background to the study

This study focused on the assessment of potential pollution of groundwater from coal ash generated by the South African electricity utility, Eskom. Electricity generation at coal-fired power stations produces ash as the main waste stream. Ash is one of the waste streams that were included in the notice relating to the *Waste Exclusion Regulations* published in GN 535 in GG 42376 of 3 April 2019 (RSA, 2019). However, these exclusions would only be applicable to the beneficial re-use of non-hazardous ash, while the remaining portion of non-reusable ash is generally disposed to land using wet or dry ashing technologies. Wet ashing transports the ash as a slurry to the handling facility where it is allowed to settle and the water is recycled. Dry ashing, on the other hand, involves the placement of “conditioned” ash, which entails dampening with 16 to 20% water (10% at Eskom) before placement, to minimize dust formation (Day & DiNovo, 2013).

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<sup>3</sup> The DWS proposed the use of discharge standards for comparison of the outcome between the WCMS and SPR-approach groundwater pollution potential assessment, based on actual assessments done by Eskom Holdings SOC Ltd for its ADFs.

Coal ash generated by Eskom coal-fired power stations is generally classified as a Type 3 waste (Eskom, 2016), since the concentration of most of the constituents (potentially harmful elements) of the ash is marginally higher than the lowest thresholds provided for the constituents in the GNR 635 (RSA, 2013b; Reynolds-Clausen and Singh, 2016) (refer to **ANNEXURE A**). According to the *National Norms and Standards for the Disposal of Waste to Landfill* (GNR 636), type 3 wastes need to be disposed of at a WDF, which has been designed in terms of Class C liner requirements (RSA, 2013c). The transitional arrangements of the WCMS allowed for existing facilities to be excluded from the requirements which came into effect in August 2013, however, all of the new wet ash disposal facilities (ADFs) (established after August 2013) and subsequent phases of the current dry ADFs will have to meet the barrier requirements of GNR 636 (RSA, 2013a, RSA, 2013c).

A study done by Gitari *et al.* (2009) showed that potentially harmful elements in fly ashes are not easily dissolved due to their low concentrations in the fly ash, and the alkaline nature of fly ash. Different waste compositions (or physico-chemical characteristics) and climatic conditions have an effect on leachate quality that translates into different pollution potentials (Blight *et al.*, 1999). Additionally, geological differences of areas (Mor *et al.*, 2006) also has an effect on the extent of potential groundwater contamination. For instance, the concentrations of toxic substances in leachate may reduce (from its source to its receptor) if a groundwater resource is located deep (increased depth and distance from the source of contamination) (Mor *et al.*, 2006).

The earlier classification system used for disposal of waste to land (*Minimum Requirements for Waste Disposal by Landfill*, DWAF<sup>4</sup>, 1998, 2005) did make provision for site-specific factors and conditions, as explained earlier. The newer WCMS, however, follows a “one size fits all” approach, where thresholds are applied across South Africa, without any consideration of site-specific geological differences. The WCMS process for assessment is uniform in terms of the leaching<sup>5</sup> solution used [which has a very significant effect on the leachability of contaminants as shown by Gitari *et al.* (2009)] and apply uniformly to different types of environments (Thompson, 2006), through the estimation of exposure pathways (Hope, 1995).

Hope (1995) defines an exposure pathway as “*the course a chemical or physical agent takes from a source to an exposed organism*”. He further asserts that for exposure to a chemical contaminant

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<sup>4</sup> DWAF: Department of Water Affairs and Forestry, now the Department of Water and Sanitation (DWS)

<sup>5</sup> Leaching is a natural process by which water soluble substances are washed out from soil or wastes (Chezom *et al.*, 2013).

not to occur (pathway to be generally considered incomplete), any of the following four components need to be *absent*:

- (a) a source and mechanism for contaminant release to the environment,
- (b) an environmental transport medium,
- (c) a point of receptor contact (exposure point) with contaminated media, and
- (d) an exposure route at the exposure point.

Hope (1995) lists eight possible scenarios of exposure pathways depending on the scope of the assessment. In the case of WCMS, the liner (barrier) design is prescribed without due consideration of exposure pathway assessment. Proponents of WCMS may argue that a liner acts as the prevention mechanism for contaminant release to the environment, thus, avoiding the need to assess the absence of the other three components of the exposure pathways, following a precautionary approach.

According to Snowden (2003), uncertainty can either be managed through a 'rule-based' system in which outcomes of the events can be predicted or by further analysis of events through identification of patterns to gain a better understanding of the 'unknowns' and their effect on the outcomes. Currently, the South African legal framework provides for two approaches for the assessment of pollution potential from waste. The NEM: WA provides for the assessment of waste for landfill disposal (in terms of the WCMS), which provides for certain barrier/liner requirements to prevent pollution, while the NWA in its Water Quality Management Policy (RSA, 2017) proposes the source-pathway-receptor (SPR) assessment method for the assessment of pollution potential. The fact that the two approaches are provided for in the South African legal framework, preference for either of the two could create a conflict between the decision-makers and those responsible for the management of waste particularly if outcomes are different. The next section outlines the specific nature of conflict that could arise from the two approaches.

### **1.3 Problem statement**

The NWA (RSA, 1998b) defines pollution as the *direct or indirect alteration of the physical, chemical or biological properties of a water resource so as to make it – (a) less fit for any beneficial purpose for which it may reasonably be expected to be used; or (b) harmful or potentially harmful to the welfare, health or safety of human beings; to any aquatic or non-aquatic organisms; to the resource quality; or to property.*

If the assessment of *pollution* potential is based on whether the activity causes the water to be *less fit* for use (based on the reasonable expectations of the user), or whether the action causes the water to be *harmful or potentially harmful* to people or organisms<sup>6</sup> (Bosman, 1999), then a decision for liner design, or a requirement for installation of a liner based on WCMS may be premature, since it does not take the exposure pathway into consideration. In cases where other pathways exist that can cause groundwater pollution (Bosman, 1999), the WCMS may not be the most appropriate method to identify other pathways and measures to reduce the amount of contaminants to the water resource (Mor *et al.*, 2006).

Therefore, it is argued that the current application of the WCMS (in which the leachable and total concentrations of waste are assessed against the four levels of thresholds to determine the waste type and associated barrier design/liner requirements) lacks the following elements of assessment of groundwater pollution potential from WDFs (and more specifically ADFs):

- (a) The WCMS does not consider site-specific circumstances in the form of the hydrogeological environment and other considerations such as leachate solution and climatic conditions;
- (b) The WCMS does not allow for the determination of the origin of other (surrounding) pollution sources; and
- (c) The inherent prescription of barrier design/liner requirements may not allow for the identification of other scenarios or pollution prevention measures that may not be addressed by means of a liner installation.

Therefore, it is argued that there may be approaches, other than the WCMS, which may make a more suitable provision for site-specific conditions that may influence the pollution potential of WDF. As mentioned earlier, one of the approaches proposed in the *Water Quality Management Policy* (RSA, 2017) for assessing pollution potential, which this dissertation has focused on, includes the source-pathway-receptor (also known as the SPR) approach.

#### **1.4 Aim and objectives of the research**

The aim of this study was to understand the extent to which the SPR approach differs from WCMS in terms of consideration of site-specific conditions when assessing potential pollution of groundwater from wet and dry ADFs by:

- (a) Establishing site-specific conditions applicable to the assessment of groundwater pollution potential of ADFs;

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<sup>6</sup> Refer to the definition of pollution in the National Water Act (36 of 1998)

- (b) Assessing the effects of site-specific conditions on the levels of pollution potential at source, pathway, and the receptor boreholes (within the pathway area); and
- (c) Comparing the outcome of the SPR assessment to the WCMS assessment outcome to determine whether site-specific conditions are significant in groundwater pollution potential assessment.

### 1.5 Delineating the scope of the study

This dissertation focused on establishing the extent to which **site-specific conditions** are considered in the assessment of **groundwater pollution potential**. For this purpose, **ash disposal** from the **power generation processes** of Eskom Holdings SOC Ltd was considered. One **wet ADF** and one **dry ADF**, located (on natural ground without any additional barrier material) at **two different Power Stations**, with **different site-specific conditions** were included. Groundwater quality data from June 1989 to February 2018 (at Site A) and October 1990 to June 2017<sup>7</sup> (at Site B) of **twenty-two (22) different (source-, pathway- and receptor) boreholes** were included for consideration during this study.

The study **considered two approaches** for the assessment of groundwater pollution potential: (1) **the WCMS**, currently prescribed for the assessment of waste for landfill disposal in South Africa in terms of NEM: WA; and (2) the **SPR approach** proposed in the Water Quality Management Policy. **Sulfate concentrations (SO<sub>4</sub>)** are used as an indicator to determine groundwater pollution and groundwater pollution potential.

The study did not include ADFs at other sites in Eskom nor other sectors with similar WDFs.

### 1.6 Research method and design

In addressing these objectives, the first part of the study reviewed the available literature to identify information relevant to site-specific conditions when assessing groundwater pollution potential of ADF. The case study method was then chosen to illustrate the real-world application of the pollution potential assessment method that accounts for site-specific conditions.

A case study research method was based on historical monitoring data for two (one wet and one dry) of Eskom's ADFs. The choice for case study research method was further motivated by its advantage for:

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<sup>7</sup> Data period only reflects the data points with the longest period of monitoring. Some data points would have been established later during the operation as part of the revised monitoring programme.

- using both qualitative (categorical data) and quantitative data (numeric data) as complementary forms of evidence that suits the type of data that will be used for this study;
- method orientation is towards the multiple sources of evidence (e.g., document analysis, and quantitative analysis of archival data) converging on the same set of issues; and
- A groundwater conceptual model and pollution criteria developed from existing literature were used as a template against which to compare the empirical results of the case study (Yin, 2012).

Another feature that distinguishes the case study method from other qualitative and quantitative methods (Yin, 2014) is that it often relies on theoretical concepts to guide design and data collection strategies (Yin, 2012).

Yin (2014) defines these theoretical concepts as a *logic model* and considers the fact that the model provides context as an essential part of defining the case or main unit of analysis. A typical logic model follows a sequence of:

- **Inputs** (i.e. resources used to conduct an activity);
- **Activities** (i.e., the implemented actions believed to produce the outcomes of interest);
- **Outputs** (i.e., the immediate results of the actions); and
- **Outcomes** (i.e., the desired substantive benefits that ultimately justify the activity) (Yin, 2012).

A literature review identified the exposure-pathway or source-pathway-receptor (SPR) approach as relevant to the purpose of assessing groundwater pollution potential from ADF. As a result, the logic model for this case study was based on the SPR approach. Lastly, the Most Different System Design (MDSD) framework (Lor, 2011), was used to compare SPR and WCMS with the aim of identifying the most appropriate assessment method of groundwater pollution potential of ADF that accounts for more site-specific conditions.

### 1.6.1 Limitations of the study

The study made use of existing, available groundwater quality data that may not include all the required contaminant parameters. The study had no control over the sampling, data management and transformation of data into graphical representations that could easily be interpreted. There may be gaps in the data due to weaknesses in maintaining the sampling protocols and data management systems. These limitations could have had a secondary effect on the following:

- Available data might not be sufficient to address all the knowledge gaps;
- Data integrity may have been compromised; and

- Decisions on pollution criteria that represent acceptable protection levels require stakeholder participation. Stakeholder participation was not undertaken as part of this study, due to time and resource constraints.

### **1.6.2 Assumptions**

To test the validity of the argument made in Section 1.3 of this dissertation, regarding WCMS not considering site-specific conditions, it was assumed that consideration of site-specific conditions may not have a significant impact on the outcome of the pollution potential of groundwater from the two ADFs that were studied. Hence, the need to compare the outcomes of the WCMS and the method deemed appropriate to consider site-specific conditions.

In the context that the study made use of water quality data collected by a service provider for Eskom, it was assumed that the quality assurance protocols for data sampling and analysis to ensure data integrity were adhered to. There may have been interference (additional releases of contaminants) from other activities in close proximity to the study area. It was therefore assumed that the data used was representative of the ADF and site-specific conditions within the study area.

This study assumed that the ash from the ADFs is considered to be “waste” in terms of both the definitions of the NEM: WA and the NWA. The exclusion of ash from the definition of waste is provided for in the *Regulations regarding the exclusion of a waste stream or a portion of a waste stream from the definition of waste* (GN. 715 of 18 July 2018) (RSA, 2018), where waste with a beneficial purpose may be excluded from the requirements of NEM: WA, should the application for the exclusion be approved. Ash is one of the waste streams that was included in the notice relating to the *Waste Exclusion Regulations* published in GN 535 in GG 42376 of 3 April 2019 (RSA, 2019). However, these exclusions would only be applicable to the beneficial re-use of non-hazardous ash, while the remaining portion of non-reusable ash is generally disposed to land using wet or dry ashing technologies. Therefore, ash (in the context of this research) is deemed to be “waste” and the legal requirements for the management of waste is deemed to be applicable.

### **1.6.3 Rationale**

The results of this study will assist the industry and the authorities regarding the development of pollution criteria and identification of assessment methods that can provide information on site-specific conditions contributing to pollution. In addition, the study will provide clarity on the extent to which such methods can be applied.

#### **1.6.4 Contribution to research**

There are many studies focusing on the various pollution assessment methods that assist with decision-making in the area of environmental protection. Limited studies have, however, been undertaken to assess ADFs at coal-fired power stations. The study will add to the body of knowledge on how certain assessment methods can aid decision-making with regard to ADFs.

#### **1.7 Structure of the mini-dissertation**

This mini-dissertation comprises five chapters. Chapter 1 provides an introduction to the research study; giving a general overview including a background to the study, the problem statement, objective of the research study, an overview of the research methods and design as well as the scope of the study. Furthermore, the chapter also details the rationale and contribution of the study to current knowledge as well as the structure of the research report.

Chapter 2 provides a background to the concept of groundwater pollution potential of ADF based on scholarly articles, academic publications, and the applicable legal framework. The chapter also identified the following:

- key information required to account for site-specific conditions within the context of the source-pathway-receptor (SPR) assessment approach; and
- Potential limitations of the WCMS as an assessment method.

Chapter 3 provides details of the research methodology used to address the research objectives of this study and motivates the methodological choices made. Included in this chapter is the type of methodology that was used, the unit of analysis, data collection procedures and the process of data analysis.

Chapter 4 presents the findings of this research study in line with the research objectives outlined in Chapter 1. The findings were derived from the analysis of the time-series trends, Piper plots and archival documents guided by the theory presented in Chapter 2 and Chapter 3.

Chapter 5 concludes the research findings presented in Chapter 4 in relation to the research objectives as to the most appropriate pollution potential assessment method to be applied to the ADFs. The chapter also contains conclusions, recommendations on the current constraints and opportunities for further research.

## CHAPTER 2 LITERATURE REVIEW

### 2.1 Introduction

Sustainable use and access to Earth's freshwater resources is increasingly threatened by the impacts of the industry and other sectors which needs water as input and is discharged to the environment as part of their manufacturing processes to meet the economic demands of the world's growing population (Zhang *et al.*, 2013). South Africa is also facing a multi-faceted water challenge, which, if not addressed effectively, has the potential to limit the economic growth potential of the country, especially considering the levels of water scarcity, with frequent droughts, increasing water demands, and deteriorating resource water quality (DWS, 2017).

Experience from the last few decades has shown that groundwater is not unsusceptible to contamination (WRC, 2014), and many people from rural communities and towns throughout South Africa are relying on groundwater as a sole source of water supply (WRC, 2014). Individuals, through the use of groundwater or surface water, may be exposed to contaminants from anthropogenic sources, such as waste disposal facilities (WDFs) (Ikehata & Liu 2011). Environmental protection measures or mechanisms are, therefore, required to protect the environment (which includes humans) from the potential adverse impacts of contaminants.

### 2.2 Environmental protection and sustainable development concept

Achieving a balance between the competing demands of development, environmental protection and sustainable use of natural resources, known as *sustainable development*, remains a challenge for many decision-makers (Dogaru, 2013). In 1987, the World Commission on Environment and Development (the Brundtland Commission) defined sustainable development as "*development that meets the needs of the present without compromising the ability of the future generations to meet their own needs*" (Brundtland Report, 1982).

Seventeen (17) Sustainable Development Goals (SDGs) were developed in January 2015 and adopted by world leaders in September 2015 at the United Nations Summit (UN, 2015). Each of these seventeen goals has specific targets that need to be met by 2030. Many of these goals relate to waste management, prevention of pollution, and protection of water resources (UN, 2015), which are related to the scope of this study. Nationally, strategies have been developed by the Department of Environment, Forestry and Fisheries (DEFF) and the Department of Water and Sanitation (DWS) to address these goals. One such programme is the DWS SDG 6 programme, which amongst others focuses on water resources management (SDG 6.5) and water-related ecosystems (SDG 6.6) (UN, 2015), both with a focus on pollution prevention.

Sustainable development (in the context of pollution prevention) may, however, be interpreted differently by different individuals. According to Beder (2000), those who are pro-development interpret sustainable development to mean that wastes should not be allowed to *exceed the capacity* of the environment to absorb them. This idea is based on the assumption that the environment has the assimilative capacity to transform waste into less harmful substances (e.g. organic wastes that occur naturally, tends to decompose in the environment) (Beder, 2000). On the other hand, the idea of regulating waste/pollution based on assimilative capacity may be seen as a risk to the environment. It is argued that the risk may be reduced, provided that site-specific conditions are taken into consideration (Beder, 2000). Therefore, good scientific information is important as prerequisite for site-specific risk assessments, which incorporates both the principles of a risk-averse and a precautionary approach, where there is *uncertainty* associated with the determination of carrying capacity on a site-specific basis. The NEMA lists both principles in Section 2 as critical to achieve sustainable development in South Africa (RSA, 1998a).

### **2.3 Decision-making in the face of uncertainty**

Klinke and Renn (2002) considered the *risk-based* and *precautionary-based* management approaches as complementary by, firstly, setting risk priorities and, secondly, accounting for any uncertainties through the application of the appropriate management approach. Maxim and Van der Sluijs (2011) argue that most scholarly articles associated *uncertainty* with lack of knowledge. They then developed a framework that allowed them to argue that the socio-economic and regulatory contexts influence the use of available knowledge (e.g. standardised tests, and risk assessment protocols). Therefore, suggesting that lack of knowledge in the regulatory context could have an influence on the choice of adopting a “not fit for purpose” risk-based assessment method which in turn informs precautionary-based management approach (Maxim & Van der Sluijs, 2011).

For instance, assessing pollution potential from WDFs in the South African context, the WCMS requires the application of a management option (in the form of barriers) to protect water resources, based on the amount and composition of leachate generated from the WDF, without consideration of the levels of contamination at exit points (Oelofse, 2008).

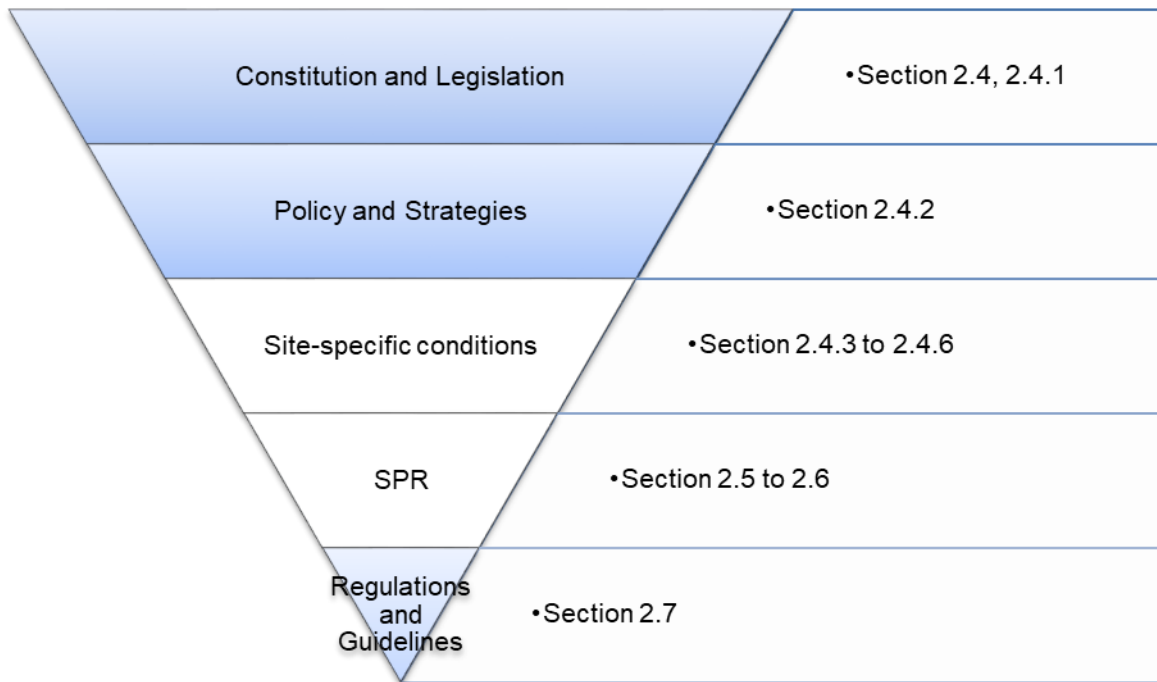
Snowden (2003) uses the Cynefin framework (a conceptual framework used to aid decision-making by considering different contexts/scenarios), to argue that the selection of the appropriate mitigation of risk depends on the society’s understanding of the domain in which lack of knowledge is located. He classifies the domains into “known, knowables, complex and chaotic areas of lack of knowledge”. In the context of this study, these domains have been grouped into ‘known’ (wherein outcomes of events can be predicted) and ‘unknowns’ (where outcomes cannot

be predicted and requires analysis of events, identification of patterns and sometimes learning from mistakes).

The assessment of groundwater pollution potential, based on the WCMS approach, assumes that site-specific conditions informing the risk assessment may have little or no effect on the outcome, compared to the composition and amount of leachate generated. A differentiated site-specific approach that considers additional information in the form of topography, stream flows, water features (i.e. fountains, dams), geology, existing boreholes and wells (Oelofse, 2008) allows for further analysis of the 'unknowns' to determine how outcomes may be influenced differently to inform the best risk mitigation option (e.g. type of liner required). Using the wrong management approach for events with unknown outcomes could lead to unintended consequences (i.e., over-regulation, or under regulation, depending on the site-specific conditions).

Based on the lack of knowledge being associated with: (1) risk assessment method for groundwater pollution potential of ADFs and (2) context of the regulatory framework, the following hierarchical review (outlined in Figure 2.1) was adopted to identify:

- legal provisions for risk-based approaches;
- theory related to indicators of site-specific conditions in the context of the assessment of groundwater pollution potential of ADFs (SPR); and
- the extent to which the site-specific conditions are included in the prescribed (e.g. legislation, regulations and guidelines) assessment methods for ADFs.



**Figure 2-1: Hierarchical review of the South African regulatory framework for the identification of the assessment method that accounts for site-specific conditions**

The next sections (as indicated in Figure 2-1) explore the type of risk-based assessment methods provided for, in the South African regulatory framework.

## **2.4 Strategies for environmental protection and prevention of pollution**

The concept of environmental protection is entrenched in Section 24 of the Constitution of the Republic of South Africa (108 of 1996) (RSA, 1996). It states that: “*Everyone has the right (a) to an environment that is not harmful to their health or well-being; and (b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that – (i) prevent pollution and ecological degradation;(ii) promote conservation; and (iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development.*” To give effect to Section 24 of the Constitution, reasonable legislative and other measures must *define pollution prevention measures* within the context of ecologically sustainable development.

### **2.4.1 Defining *pollution***

The NEMA (RSA, 1998a) defines pollution as *any change in the environment caused by (i) substances; (ii) radioactive or other waves; or (iii) noise, odours, dust or heat emitted from any activity, including the storage or treatment of waste or substances, construction and the provision of services, whether engaged in by any person or an organ of state, where that change has an*

*adverse effect on human health or well-being or on the composition, resilience, and productivity of natural or managed ecosystems, or on materials useful to people, or will have such an effect in the future.*

Whereas the NWA (RSA, 1998b) defines pollution as *the direct or indirect alteration of the physical, chemical or biological properties of a water resource so as to make it – (a) less fit for any beneficial purpose for which it may reasonably be expected to be used; or (b) harmful or potentially harmful to the welfare, health or safety of human beings; to any aquatic or non-aquatic organisms; to the resource quality; or to property.*

Although these two definitions provide the criteria for deciding whether an activity has polluted or is likely to pollute, the NEMA definition was not considered further (in the context of this research) as it broadly applies to every aspect of the environmental medium (e.g., atmosphere, land and water). The more media-specific definition of the NWA, focusing on the water resource, was considered to relate closely to the topic of groundwater pollution, and was the definition deemed to be most relevant to this research.

In terms of Section 2(4)(a)(ii) of the NEMA (RSA, 1998a), pollution and degradation of the environment must either be avoided (prevented), or, where it cannot be altogether avoided, it must be minimized (controlled) and remedied. The consideration of strategies for pollution prevention and/or pollution control, in the context of environmental protection, is, therefore, important.

## **2.4.2 Strategies for water resource pollution control**

Pollution prevention, amongst other objectives of the NWA, is achieved through the implementation of the National Water Resource Strategy (NWRS) (at a national scale) and catchment management strategies (CMS) (at a catchment or regional scale).

### **2.4.2.1 The National Water Resource Strategy (NWRS) and Catchment Management Strategies (CMSs)**

The second edition of the NWRS was published in 2013 (RSA, 2013) and builds on the first version of the strategy which was published in 2004 (RSA, 2004). The purpose of the strategy is to ensure that water resources are protected, used, developed, conserved, managed and controlled in an efficient and sustainable manner towards achieving the country's development priorities in an equitable manner. The NWRS provides a large-scale planning framework on a national level to ensure that water deficits or poor water quality do not arise on a regional basis at the scale of declared water management areas (WMAs) and that international water sharing

obligations are met (RSA, 2004). CMSs applicable to regional WMAs ensure sustainable, equitable and optimal water resource utilization at the catchment scale (RSA, 2004). Both the NWRS and CMSs provide for pollution prevention measures.

Section 9 of the NWA prescribes the minimum components of a CMS and key amongst these is the formulation of the water allocation principles (RSA, 1998b). Intuitively, the allocation may be associated with water quantity, but a significant innovation is found in Section 21 of the NWA where water use is defined very broadly amongst others to include the use of the water resource to dispose of waste (Rossouw *et al.*, 2008). The DWS developed a set of guidelines for the development of the water quality component of a CMS that is based on the resource quality objectives (RQOs) approach (Rossouw *et al.*, 2008) and a Water Quality Management Policy (DWS, 2017). In addition, this policy specifies that a site-specific differentiated approach must be followed in establishing RQOs.

#### **2.4.2.2 Resource Water Quality Objectives (RWQOs)**

Section 1 of the NWA defines RQOs as *clear goals relating to the quality of the water resources* (RSA, 1998b). RQOs are numerical and narrative descriptors of conditions of the water resource (which may be the receptor of pollutants) that need to be met (inclusive of Reserve<sup>8</sup> requirements). Such descriptors relate to:

- quantity, pattern, timing, water level and assurance of instream flow;
- water quality including the physical, chemical, and biological characteristics of the water; character and condition of the instream and riparian habitat; and
- characteristics, condition, and distribution of the aquatic biota (DWS, 2011).

The *water quality* component of the RQOs is the Resource Water Quality Objectives (RWQOs). Chapter 3 of the NWA states that in determining RWQOs a balance must be sought between the need to *protect and sustain* water resources on the one hand, and the need to develop and use them on the other (RSA, 1998b). The water quality allocation framework involves setting of the RWQOs based on the needs expressed by the stakeholders, assessing the catchment water quality status of the variables of concern, assign the difference between the RWQOs and water quality status as the allocatable load and apportion the allocatable load to users who dispose of waste to the water resource (Rossouw *et al.*, 2008).

Bosman (1999) links the notion of RWQOs with pollution and sustainable use by stating that the release of substances (or apportioned allocatable load) at levels where the RWQOs are not

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<sup>8</sup> Refer to definitions and terminologies

exceeded is considered to be "sustainable use or contamination" of the resource. Where apportioned allocatable load is present at levels above RWQOs (or at unacceptable levels), the term *pollution* applies. This notion emphasizes the argument that a complete achievement of zero discharge of pollutants to water bodies is not feasible and usually not cost-effective (Bundschuh *et al.*, 2016) on the basis that steady economic growth and environmental protection are two contradictory goals (Zheng *et al.*, 2015).

The preferred approach is to set limitations on waste disposal discharges for the reasonable protection of human health and the environment (Batlle *et al.*, 2016). Bosman (1999) also associates the concept of RWQOs to the notion of acceptable risk which has a similar meaning to the concept of environmental protection goals since they both (Brown *et al.*, 2017) serve the purpose of the prevention of unacceptable or adverse impacts on biodiversity and ecosystems. Furthermore, principles 9 and 11 of the Integrated Water Quality Management Policy of the DWS advocates for the differentiated risk-based approach of setting RWQOs (DWS, 2017) to account for site-specific conditions.

Having clarified the criteria for pollution and strategies for environmental protection, the next sections deal with how the risk-based approach is implemented to account for site-specific conditions within a framework of the Integrated Water Resource Management (IWRM) approach (Claassen, 2013).

#### **2.4.3 A risk-based approach that accounts for site-specific conditions: IWRM Context**

A comprehensive and objective assessment of the recent publications of the individuals and the institutions that are promoting *integrated water resources management* indicates that different opinions exist about the meaning of the concept in operational terms as well as what is required (Biswas, 2004). According to the different interpretations of the authors, integrated water resources management may mean the *integration* of among other things the following:

- water supply and water demand;
- surface water and groundwater;
- water quantity and water quality; and
- water and land-related issues.

An additional aspect that needs to be considered in risk-based approaches is that contaminants may be introduced into the water resource at any point in the hydrological cycle either through point sources or diffuse (non-point) sources (Potts, 2002). Point sources discharge pollutants directly into environmental media (e.g., air or water) from discrete, identifiable points where discharges can easily be monitored (Shortle & Braden, 2013).

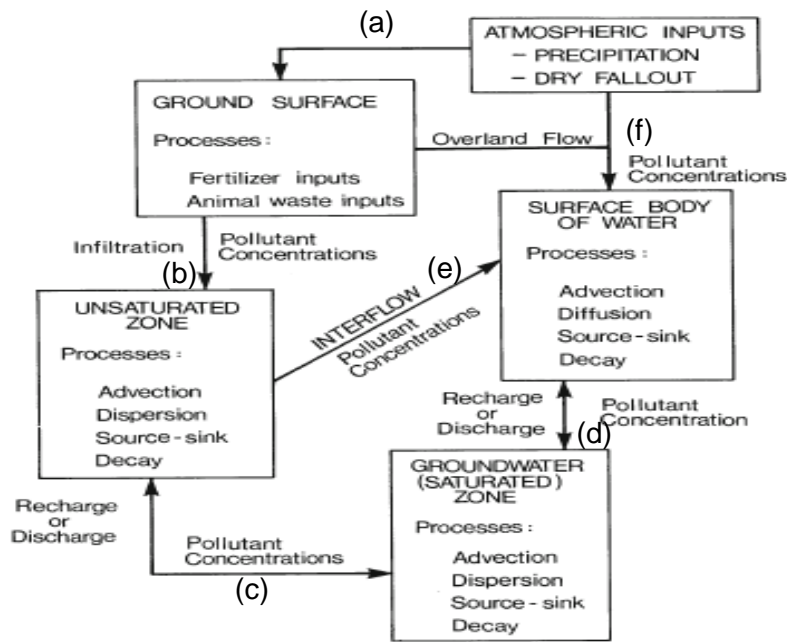
In contrast, contaminants from non-point sources move to environmental media by diffuse, and sometimes very complex, pathways, which may not necessarily be pinpointed accurately (Shortle & Braden, 2013). The diffuse pathways by which non-point pollutants move as well as spatial and temporal variability, make non-point discharges very difficult, expensive and often impractical to monitor accurately and routinely, on a polluter-by-polluter basis (Shortle & Braden, 2013).

One of the scenarios suggested by Hope (1995), by which exposure pathway assessment could be undertaken, considered the potential for contaminants that reach groundwater to be transported to surface waters, if the groundwater has a surface discharge point (e.g., a seep or spring). Similarly, impacts on surface waters could also impact and interact with groundwater. The next section discusses the mechanism by which contaminants move when surface and groundwater interact, as well as how these scenarios could aid the formulation of the mathematical relationship between the RWQOs and discharge standards.

#### **2.4.3.1 Surface and groundwater interaction**

The interaction between surface and groundwater systems (as depicted in Figure 2-2) mostly occurs via the linkages from (a) to (f) (Bobba, 2012). Linkage (a), (b), (c), (d) and (e) mainly represents the surface-groundwater interaction that is more representative of one of the scenarios identified by Hope (1995) for estimation of exposure pathways wherein contaminants that reach groundwater may be transported to surface water, if the groundwater has a surface discharge point (e.g., a seep or spring).

A scenario in which surface and groundwater interaction can form the basis from which site-specific RQOs may be applied to tighten control over point and diffuse pollution potential sources (Enderlein *et al.*, 1997) provided it covers a catchment of a river, its tributaries and any associated groundwater flows (Helmer & Hespanhol, 1997), allows for an integration of site-specific discharge standards and RWQOs (Oelofse *et al.*, 2005). Such a scenario may be represented by the mechanism in which pollutants moves through linkage (a), (b), (c), (d) and (e) (shown in Figure 2-2).



**Figure 2-2 Interaction between surface and groundwater systems (from Bobba, 2012)**

Although no formal linkage has been made in terms of governance of site-specific discharge standards and RWQOs to date (WRC, 2018), Oelofse *et al.* (2005) suggest that the decisions on the amount/level of allowable contaminants (discharge standards) should be dependent on the state of the receiving environment and the RWQOs. If the state of the receiving environment and the RWQOs of a specific area cannot assimilate/absorb the pressures of contaminants in discharges, site-specific interventions such as stricter discharge standards and management action required is supposed to be proportionate to the amount of contaminant that must be reduced (WRC, 2014) (e.g., liner/barrier specifications should be enforced to prevent contaminants from moving from surface to groundwater resources).

To apply the linkage within context of the above scenario, it is necessary to understand the mathematical relationship between the contaminant concentration in the groundwater (from the ADF as the source located on natural ground without additional barrier material), discharge standards and RWQOs.

#### **2.4.3.2 Relationship between RWQOs, discharge standards and contaminant concentration in the groundwater**

Novo (2017) presented a mathematical formula of the description of the concept of assimilative capacity as a ratio between the contaminant concentration in the groundwater ( $C$ , in mass/volume) and the difference between the water quality standard (the maximum acceptable

concentration  $C_{\max}$ , in mass/volume) and the background concentration ( $C_{\text{back}}$ , in mass/volume), as expressed in Equation (1).

$$\text{MAC} = C / (C_{\max} - C_{\text{back}}), \quad (1)$$

Where, MAC = Maximum Assimilative Capacity.

A more direct mathematical relationship for the three variables (e.g. RWQOs, discharge standards and groundwater concentration) can be represented as follows (DWS, 2006):

$$C_{\text{ds}} = [C_{\text{RWQOs}}(\text{MR}+1) - C] / \text{MR}, \quad (2)$$

Where  $C_{\text{ds}}$  = discharge standard,

$$C_{\text{RWQOs}} = \text{RWQOs},$$

$C$  = groundwater concentration,

$\text{MR}$  = mixing ratio, where the mixing ratio is the rate of discharge ( $Q_{\text{ds}}$ ) divided by the rate of streamflow ( $Q$ ).

Equation (2) can further be transformed into:

$$(C_{\text{RWQOs}} - C) = (C_{\text{ds}} - C_{\text{RWQOs}})\text{MR}, \quad (3)$$

Equation (3) can only be valid if the allocatable load is greater than zero (e.g.,  $(C_{\text{RWQOs}} - C) > 0$ ). Wherein,  $(C_{\text{RWQOs}} - C) < 0$ , then  $C_{\text{ds}}$  may have to be reduced (Lee, 2017) to levels equivalent to  $C$ , such that  $C$  will not be above  $C_{\text{RWQOs}}$  (at any point along any pathway mechanisms) before any discharge can be allowed. However, if  $C < C_{\text{RWQOs}}$  after an assessment of the impact, then stricter discharge standards may not have to be applied due to factors such as the natural attenuation process (NAP)<sup>9</sup>. The phenomenon of NAP could explain the temporal and spatial variation of contaminants (Shrestha & Kazama, 2007). The next sections discuss how this variation could influence the risk-based assessment outcome.

#### 2.4.4 Spatial variations in contaminant levels

Chapelle and Bradley (1998) use the boundary-value problem approach to estimate levels to which contaminant concentrations in the source-areas must be lowered (by engineered removal) in order for the NAP (analogous to the concept of AC in surface water systems) of groundwater

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<sup>9</sup> Harter (2002) defines NAP as chemical transformation, biological degradation, or adsorption onto aquifer materials that may reduce the leachate concentrations.

system to achieve acceptable concentration limits or site-specific RWQOs prior to reaching a predetermined regulatory point of compliance. This suggests that where technology cannot sufficiently reduce discharge standards at source, then there is potential for contaminant levels to reduce to no pollution scenario, at some distance away from the source due to NAP.

The UK Environment Agency (2017) describes the regulatory point of compliance as the point along the groundwater flow pathway where the RWQOs (compliance limit or value) must not be exceeded. It means RWQOs may be set anywhere at a specified point along the pathway (for example within the aquifer between the source and receptor (UK Environment Agency, 2017)).

Massmann and Freeze (1987) highlight three critical variables that are associated with the determination of groundwater contamination, namely contaminant structure, hydrogeological environment, and licensing requirements. If licensing requirements refer to site-specific RWQOs representative of the receptor water quality requirements, then the framework proposed by Massmann and Freeze (1987) for contaminant assessment is consistent with the concept of SPR<sup>10</sup> approach (Holdgate, 1979).

Based on the findings of Sankaran *et al.* (2005), if the relative contaminant concentration levels near the source, at pathway, and the receptor are all above or below the RQOs, the results could be interpreted to suggest that there is pollution (or no pollution) and all three elements of the SPR can be regarded as interconnected. In addition, a spatial pattern that shows decreasing pollution levels from source, along the pathway to the receptor could be an indication of strong NAP influence.

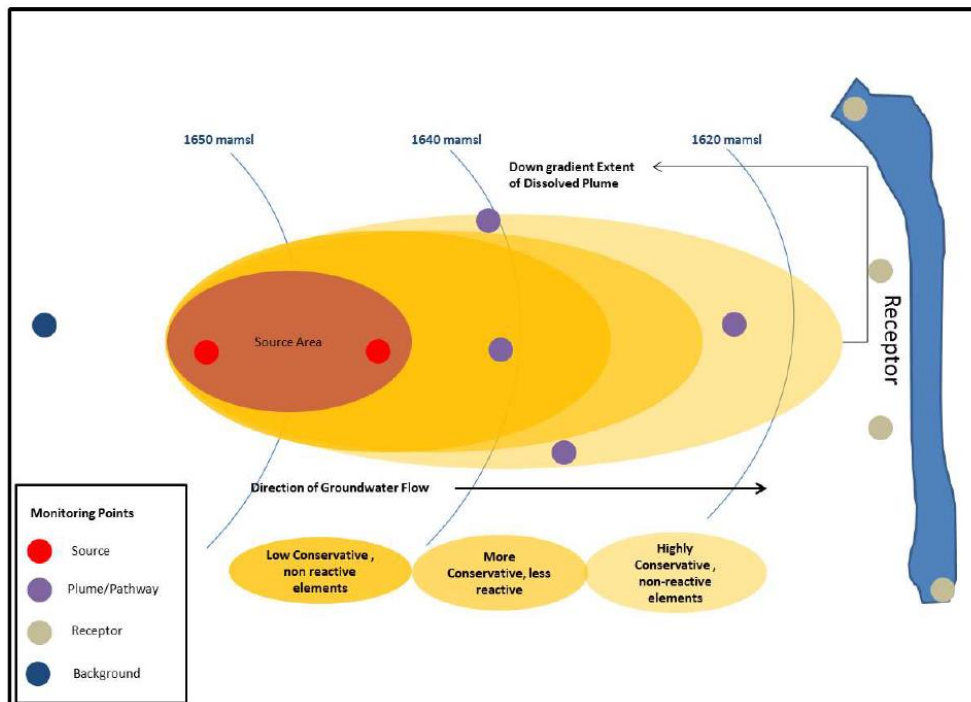
#### **2.4.5 Pollution detection**

Yenigul *et al.* (2013) note that the US Environmental Protection Agency (US EPA) requires at least three down-gradient monitoring boreholes to be placed at locations where they will intersect all possible pathways of contamination and should be as close as possible to the source of pollution so that the contaminants are detected as soon as release occurs (DWAF, 1998). However, they argue that using a limited number of wells could lead to failure to detect contaminant plumes. A real-world case in the Netherlands, described by Yenigul *et al.* (2013) showed that detection of contaminants increases with distance from the contaminant source in less heterogeneous media since the plumes have much more uniform shapes and tend to travel in a direction parallel to the average gradient of groundwater flow.

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<sup>10</sup> Holdgate (1979) suggests that the SPR concept has its origins in environmental engineering to describe the flow of environmental contaminants from a source, through different pathways to potential receptors.

Figure 2-3 shows that the SPR approach allows for the grouping of the plume detection boreholes near the source area, within the pathway and near the receptor (Eskom, 2018d). Furthermore, it can illustrate the influence of the attenuation processes on the extent to which the contaminant (from less to highly conservative contaminants) travels from the source area to the receptor (Eskom, 2018d).



**Figure 2-3 Borehole delineation into Source-Pathway-Receptor plume detection areas (Eskom, 2018d)**

#### 2.4.6 Groundwater contamination scenarios

MacPherson and Townsend (1998) describe conservative elements, such as dissolved contaminants with the tendency to remain in the water phase (hydrophilic elements) which will not participate in chemical reactions that tend to remove contaminants from the groundwater. They assume that these elements move at the same speed as the groundwater, acting as a useful indicator of the groundwater flow rate.

They further state that conservative elements such as sulfate species of weathered ash can be useful indicators of the changes in groundwater potential and describe NAP as representing more than one scenario associated with evaporation, dilution or mixing of different sources of groundwater pollution potential. The following scenarios represented in Table 2-1 describe how the NAP could influence the pollution assessment outcome.

**Table 2-1: Description of natural attenuation scenarios that could influence the pollution assessment outcome**

Scenario	Dominant natural attenuation process	Outcome
1	Evaporation	Sulfate concentration levels at source boreholes are lower than at pathway and receptor boreholes (due to evaporation of water, but not of the contaminant)
2	Dilution	Sulfate concentration levels at source boreholes are higher than pathway boreholes (because of the addition of clean water that dilutes the contaminant)
3	Mixing with another stream of potential pollution sources.	Scenario 1 or 2 outcome depending on whether mixing leads to dilution or concentration of the contaminant

However, considering possible spatial variations of contaminant levels within SPR elements, the above scenarios may not be an exhaustive list for different site-specific conditions. Given that the sub-surface is hidden from view and the complex nature of sub-surface conditions that influence the flow and transport of contaminants, a conceptual model is the most appropriate description of the groundwater system (Anderson & Woessner, 1992).

## 2.5 Source-Pathway-Receptor risk assessment approach

The development of a conceptual model for ground-surface water interaction within a particular site-specific setting enables the understanding of site-specific processes from a contaminant transport perspective (Bobba, 2012). Scenario models are still a common feature in groundwater risk assessment (Chen & Ma, 2006) to simply summarises what is known about the movement of water below the surface (Anderson & Woessner, 1992). This conceptual model can be divided into three interconnected elements of the SPR approach, that is:

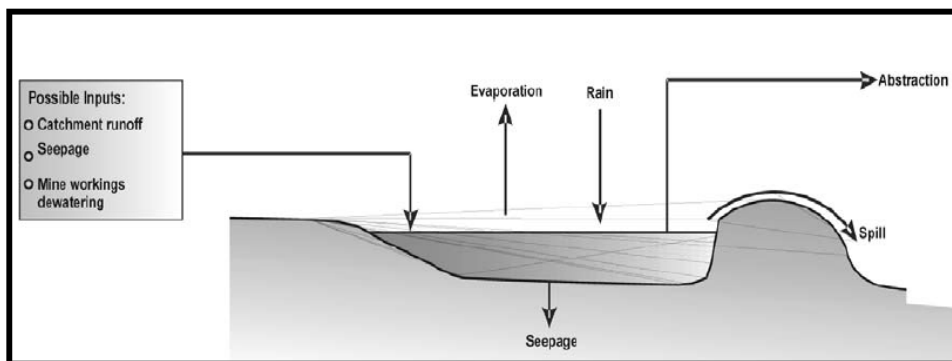
- a) The ADF representing the source of potential pollution;
- b) The pathway described as the area between the ADF to the groundwater discharge point into the surface water; and
- c) The receptor, which is considered as surface water intersection point with the groundwater flow.

The next sections will provide a more detailed description of each of the components of the conceptual model.

### 2.5.1 Contaminant structure: Source of potential pollution (ADF)

Eskom has been operating many of these ADFs for the disposal of ash for an average of 30 years for wet ashing, and 15 years for dry ashing technology. The primary objective of an ADF is for the ash and stored water to remain contained by ensuring safe management of decanting; rainfall-runoff and the management of seepage (EPA, 2017).

Figure 2-4 shows the typical inflows and outflows from ADF (DWS, 2007). By adopting a similar conceptualization of the ADF's water balance, it is evident that pollutants can be released to the environment not only through seepage but also via overflows. However, in terms of NWA Regulations GN 704, overflows must only happen once in a 1: 50-year flood event. Therefore, it makes seepage the only likely mechanism from which contaminants can be released under normal climatic conditions.



**Figure 2-4: Typical inflows and outflows from WDF (Department of Water and Sanitation, 2007)**

A storm water canal runs around the perimeter of the ADF collects some portion of seepage that did not infiltrate to the ground and surface run-off from the ADF from where it is gravity fed to the ash water recovery dams for reuse (e.g. mixing with ash for the slurry formation or ash conditioning) (Eskom, 2016). Therefore, a portion of seepage collected in the storm water perimeter canal may be considered to be leachate since both types of water are characterized by the removal of water-soluble substances from ash (Chezom *et al.*, 2013). The difference is that seepage can be seen as a release into the environment whereas leachate can and should be contained to prevent seepage into the environment.

Field conditions for seepage are generally characterized by oxidation of sulfides from coal combustion (Eskom, 2018) during the electricity generation process and the recirculation of

cooling water concentrates soluble salts such as sulfate ions which are periodically transferred to the ashing system by blowdown (removing a portion of the concentrated cooling water) and diluting the remaining portion with raw water (Loretitsch, 2002). Akinyemi *et al.* (2012) further made observations that chloride and sulfate species of the water-soluble extracts of weathered ash are most likely to leach out over time and become supersaturated at the base of unsaturated weathered ash than other ions. Furthermore, sulfate does not adsorb readily onto clay particles in the soil and does not decay over time (Eskom, 2015).

If the pH of water for ash conditioning or slurry formation is similar to ash composition (or physico-chemical characteristics) and climatic conditions, then seepage quality is likely to be similar (Gitari *et al.*, 2009; Blight *et al.*, 1999). In addition, similar results of leachate qualities based on WCMS for different power stations have shown that comparison of seepage quality or leachate from different power stations may not be adequate to address the main research objective without taking into account other site-specific conditions defined within the SPR assessment method. Hence, leachate or seepage quality as the source element of the SPR will be considered to be similar for different power stations. Differences are, however, foreseen for different power stations, as far as the pathway element of the SPR model is concerned, because site-specific conditions will be different at the power stations.

### **2.5.2 Pathway description**

Harter (2002) describes the *pathway* as an area where natural processes such as chemical transformation, biological degradation, or adsorption onto aquifer materials may reduce the leachate concentrations (from the source) to acceptable levels (within RWQOs) before the water reaches the receptor. It is an area that connects the ADF and the receptor. According to Massmann & Freeze (no date), the pathway is also an area where the monitoring network may be located between the contaminant structure (in this case the ADF) and the receiving environment, to which regulatory compliance requirements may be applicable (Licensing requirement). Borrowing from Yenigul *et al.* (2013) in their description of the regulatory compliance surface (boundary), the pathway could also represent an area between the contaminant sources (WDF) and the final plume size (extent of pollution) at the end of the monitoring period.

According to Burgess and Fletcher (1998), groundwater as the receiving environment refers to the point of abstraction of groundwater (e.g. a well, borehole or boreholes in close proximity) and they termed it as the groundwater source. These sources are connected to portions of land called borehole recharge areas that contribute water by seepage or other means (Harter, 2002). The pathway can be viewed to be an area from the contaminant structure to the nearest point of

abstraction of groundwater or geologic structure between the contaminant structures and where groundwater discharges into surface water. The geological structure can also represent aquifer flow-paths that can determine its ability to lower contaminant concentrations from the contaminant structure to the receptors.

### **2.5.3 Receptor description**

The groundwater itself, points of abstraction, groundwater discharge points into surface water and receiving (surrounding) environment can be considered to be the points of usage and where users' requirements for fitness for use should be set. These points of use will be regarded as receptors.

## **2.6 Assessment method that accounts for site-specific considerations**

The previous sections in this chapter have dealt with information associated with site-specific conditions in the assessment of groundwater pollution potential from the ADF as being related to the following indicators:

- leachate quality from the source;
- dominant NAP within the pathway; and
- site-specific receptor-based thresholds.

These site-specific conditions are inherent in the SPR assessment approach. Continuing with the Maxim and Van der Sluijs (2011) framework that guides areas of lack of knowledge quality or uncertainty in the decision-making processes, the next section reviewed the extent to which current regulatory controls for waste disposal facilities in South Africa covers these site-specific conditions of the SPR assessment method.

## **2.7 Current regulatory controls for waste disposal facilities (WDF) in South Africa**

In South Africa, impacts on groundwater quality from WDFs are regulated in terms of the NWA and NEM: WA. The NEM: WA's mandate is to protect the environment (in general) from waste disposal, while NWA focuses more specifically on the protection of the water resources, which include groundwater (Oelofse, 2008), as explained earlier.

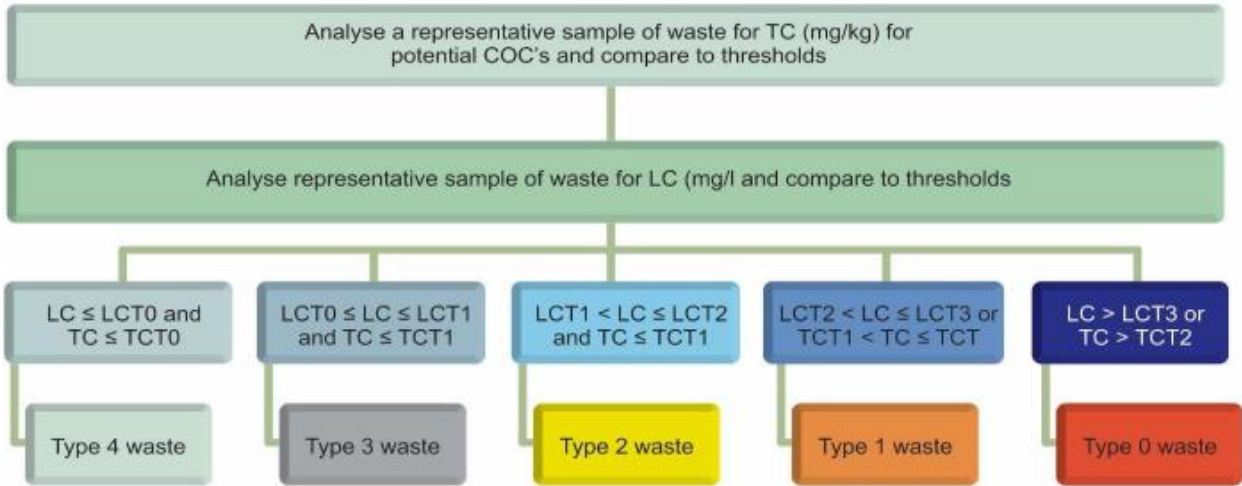
### **2.7.1 Authorization in terms of the NEM: WA**

The disposal of ash on the ADF is considered to be one of the WDFs which qualifies it to be regarded as a listed waste management activity in terms of Category B of GN R. 921. It follows

that ADF required authorization in terms of NEM: WA. As a result, Eskom was issued with waste management licences (WMLs) for the development of the new ADFs and using the Waste Classification Management System (WCMS) to assess the groundwater pollution potential and associated mitigation measures (Eskom, 2018b; Eskom, 2018c & Eskom, 2018e).

Chapter 2 (Part 2) of the NEM: WA provides for the development of an integrated system of norms and standards, which include the (WCMS), as explained in Chapter 1 of this mini-dissertation. In terms of the GN R.635 (Norms and Standards for the Assessment of Waste for Landfill Disposal) (RSA, 2013b) the potential level of risk associated with the disposal of materials/waste can be determined by following the prescribed and appropriate leach test protocols.

The results must be assessed against the four levels of thresholds for leachable and total concentrations, which in combination, determine the waste type and associated barrier design/liner requirements (as explained in more detail in Chapter 1 of this mini-dissertation). Figure 2-5 shows the flow diagram of the process to be followed to determine the waste type for correct disposal.

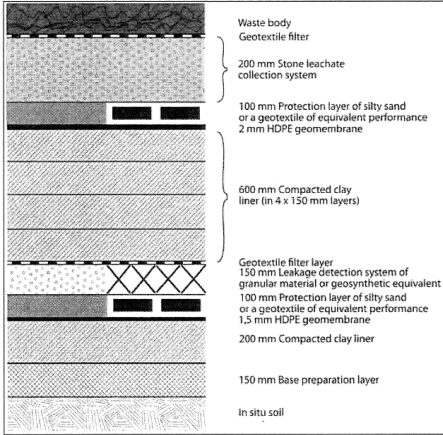
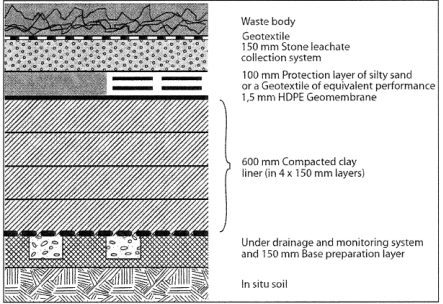
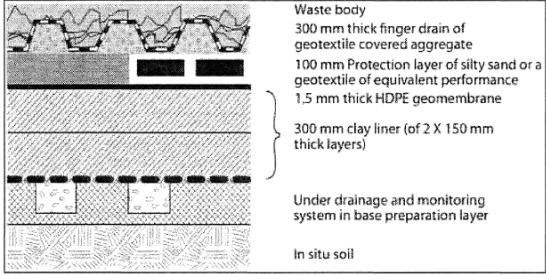
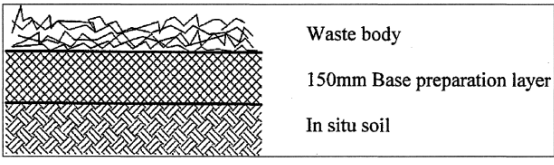


**Figure 2-5: Flow Diagram for Waste Assessment<sup>11</sup>**

Each type of waste (type 0 – 4) requires disposal at a specific WDF (Class A to D), which needs to be designed according to the requisite barrier (liner) requirements prescribed under GN R. 636 (RSA, 2013c), as shown in Table 2-2.

<sup>11</sup> According to the GN R.635. LC = the leachable concentration of a particular contaminant in a waste, expressed as mg/l; TC = the total concentration of a particular contaminant in a waste, expressed as mg/kg; LCT = the leachable concentration thresholds for particular contaminants in a waste (LCT0, LCT1, LCT2, LCT3); and TCT = the total concentration thresholds for particular contaminants in a waste (TCT0, TCT1, TCT2).

**Table 2-2: Waste Disposal Facility Classification System (DEA<sup>12</sup>, 2013c).**

Waste Type	Liner Requirements	WDF
Type 0 <sup>13</sup>	NA	NA
Type 1	 <p>Waste body Geotextile filter 200 mm Stone leachate collection system 100 mm Protection layer of silty sand or a geotextile of equivalent performance 2 mm HDPE geomembrane 600 mm Compacted clay liner (in 4 x 150 mm layers) Geotextile filter layer 150 mm Leakage detection system of granular material or geosynthetic equivalent 100 mm Protection layer of silty sand or a geotextile of equivalent performance 1.5 mm HDPE geomembrane 200 mm Compacted clay liner 150 mm Base preparation layer In situ soil</p>	Class A
Type 2	 <p>Waste body Geotextile 150 mm Stone leachate collection system 100 mm Protection layer of silty sand or a Geotextile of equivalent performance 1.5 mm HDPE Geomembrane 600 mm Compacted clay liner (in 4 x 150 mm layers) Under drainage and monitoring system and 150 mm Base preparation layer In situ soil</p>	Class B
Type 3	 <p>Waste body 300 mm thick finger drain of geotextile covered aggregate 100 mm Protection layer of silty sand or a geotextile of equivalent performance 1.5 mm thick HDPE geomembrane 300 mm clay liner (of 2 X 150 mm thick layers) Under drainage and monitoring system in base preparation layer In situ soil</p>	Class C
Type 4	 <p>Waste body 150mm Base preparation layer In situ soil</p>	Class D

<sup>12</sup> DEA: the Department of Environmental Affairs, now the Department of Environment, Forestry and Fisheries (DEFF)

<sup>13</sup> Disposal of Type 0 waste is not allowed. The waste must be treated and reassessed in terms of the *Norms and Standards for Assessment of Waste for Landfill Disposal*.

## 2.7.2 Authorization in terms of the NWA

The disposal of ash makes the case to be applicable on the basis that the ADF also constitutes a 'water use'<sup>14</sup>, as described in Section 21(g) of the NWA, namely *disposing of waste or water containing waste in a manner that may detrimentally impact on a water resource*", and have been authorized in terms of section 40 of the NWA. It means that ADF requires WML and WUL (if DWS do not dispense of the need in terms of section 22(3) of the NWA) (RSA, 1998b).

## 2.7.3 Best practice requirements in terms of the NWA

In terms of Section 41(2) of the NWA, a responsible authority "(a) may, to the extent that it is reasonable to do so, require the applicant, at the applicant's expense, to obtain and provide it by a given date with (i) other information, in addition to the information contained in the application;(ii) an assessment by a competent person of the likely effect of the proposed licence on the resource quality." (RSA, 1998b). Best Practice Guidelines (BPGs) for pollution control dams, instituted by the DWA (2013) to guide mines on information requirements for water use license applications, also applies to other sectors with Section 21(g) water uses. BPGs for pollution control dams provide information on how to undertake an assessment that accounts for the RQOs for Section 21(g) water uses.

The BPGs state that the purpose of a lining system is to minimize leakage of polluted water from the dam that could result in contamination of groundwater resources (DWA, 2013). Despite differences in liner requirements that might be required between the pollution control dams and the ADFs, same principles and objectives relating to the groundwater pollution potential should apply to the ADFs. BPGs further state that the design of the liner system should be based on the SPR approach, which involves the following:

- Source characterization of the contained polluted water;
- Identification of the various water users within an agreed radius of the dam;
- Identification of the various flow pathways from the dam to the receiving water environment, and
- Quantification of hydraulic conductivities.

The BPGs under the NWA appear to include all the site-specific conditions of the SPR approach while WCMS only highlights the leachate quality and thresholds. An additional difference in the two regulatory controls is that:

- Firstly, the pathway is not a consideration for WCMS; and

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<sup>14</sup> Refer to definitions and terminologies

- Secondly, leachate quality and thresholds do not appear to be based on site-specific conditions.

## **2.8 Concluding statements**

Based on the literature review, the study has established that pollution control measures associated with the precautionary approach are subject to the outcomes of the risk-based assessment approaches. The pollution criteria for risk-based approaches in the South African regulatory framework relevant to groundwater pollution potential assessments are based on acceptable risk represented by RWQOs. Policy principles and guidelines promote a differentiated risk-based approach that requires site-specific conditions to be considered.

An assessment method that considers site-specific conditions in relation to the ADF as the contaminant source was identified to be the SPR. Such site-specific conditions are:

- leachate quality from the source;
- dominant NAP within the pathway; and
- site-specific receptor-based thresholds.

The literature review in this study suggests that the leachate test method adopted in WCMS does not consider other site-specific conditions (e.g., leachate solution, NAP processes within the pathway and receptor-based thresholds) under the SPR method. Hence, the need to test the validity of this argument by applying a case study method to assess the effect of site-specific conditions on the outcomes of the SPR. Then compare the effect of leachate quality on the pollution potential outcomes of the SPR and WCMS using the MDSD method (discussed in detail in Chapter 3 of this mini-dissertation).

The next chapter describes a hybrid of research design methods chosen to address the objectives of this study in relation to data collection strategies and analysis of data.

## CHAPTER 3 RESEARCH METHODOLOGY AND METHODS

### 3.1 Introduction

This chapter provides details pertaining to the research methodology used to address the objectives of this study, and motivate the methodological choices made. Included in this chapter, is the logic model employed to select the design method as well as the description of the unit of analysis, data collection and the data analysis strategies suitable for this study. The limitations and assumptions of the study are outlined in Chapter 1 of this mini-dissertation and will not be repeated in this chapter.

### 3.2 Objectives informing the research methodology

Table 3-1 provides an outline of the research objectives and the methods used to address these objectives.

**Table 3-1: Outline of the research objectives and the methods**

Research objective	Method used	Rationale
Establishing <i>site-specific conditions</i> applicable to the assessment of pollution potential from ADF	A <b>literature review</b> was conducted on pollution criteria and assessment methods that account for site-specific conditions that influence the groundwater pollution levels from ADF	The existing body of research and literature, internationally, informed the indicators for site-specific conditions relevant to ADF. The literature review included various models to provide a holistic overview of the site-specific conditions to be considered. The methodology used to perform the literature review is outlined in Section 3.3, while the information gleaned from the literature review is provided in Chapter 2 (Literature review) of this mini-dissertation.
Assessing the <i>effects of site-specific conditions</i> on the levels of pollution at the source,	The <b>case study method</b> was applied to one wet ADF and one dry ADF from two different Eskom coal-fired power stations, selected as case examples to determine the effects of site-specific conditions on the levels	The case study method allows the development of logic models to be developed from theoretical concepts. Figure 3-1 describes the details relevant to the study of the logic model introduced in Chapter

Research objective	Method used	Rationale
pathway, and the receptor boreholes	of groundwater pollution potential as it relates to the SPR model.	1, Section 1.6 of this mini-dissertation. The logic model adopted the <i>SPR assessment</i> approach to guide the design and data collection strategies.
<p><i>Comparing the outcome of the SPR assessment approach to the WCMS assessment outcome to determine whether site-specific conditions are significant in groundwater pollution potential assessment</i></p>	<p>The framework of <b>most different systems design (MDS)</b> proposed by Lor (2011) was adopted for comparative analysis as shown in Table 4-1 (based on the effect of leachate quality in terms of field data on the outcomes of the WCMS and SPR for one wet ADF and one dry ADF included in the study).</p> <p>To determine whether site-specific conditions are significant in groundwater pollution potential assessment, lessons learned from literature, as well as the results of the comparison will be used.</p>	<p>MDS framework compares cases that share a phenomenon but differ in all except one factor with the same outcome. On the basis that the outcome is the same in spite of the differences in these factors, Lor (2011) suggests that there is a relationship between the outcome and the one factor they have in common. the rival proposition of, the framework could suggest that there is no relationship between the outcome and the one factor the two cases have in common if the outcome is different in spite of the similarities in one common factor.</p>

### 3.3 Research design and method

The literature review (in Chapter 2 of this mini-dissertation) was the basis from which the exposure-pathway approach, in the form of SPR, was selected to provide the theoretical perspective to guide the methodological design for this study. When applied specifically to ADF, the proposition for this study is stated as follows:

For pollution to occur and associated site-specific pollution control measures to be implemented, contaminants should be present at levels above RWQOs, provided that there is interconnection between the following three elements of the SPR approach, that is:

- i. The *ADF* representing the *source*;
- ii. The *pathway* described as the *area between the ADF to the groundwater discharge point into the surface water*; and

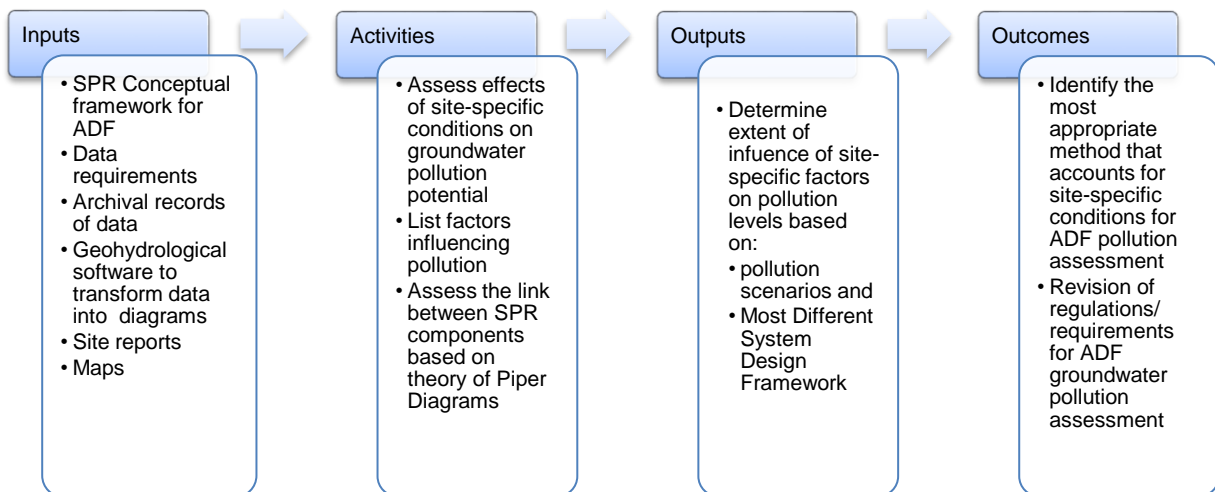
- iii. The *receptor* is considered to be the *surface water intersection point with the groundwater flow*.

It means the test (assessment method) for pollution potential should meet the two (2) requirements, that is:

- a. Contaminant levels should be above the RWQOs at source, pathway and receptor boreholes; and
- b. The three components of the SPR must be interconnected.

The SPR approach in the groundwater pollution assessment gives us information about the unit of analysis and its context, type of data to be collected and how it should be analysed to arrive at a conclusion of whether pollution exists or not. This case study was used as a substitute for experimentation with the intention of testing the above hypotheses (Lor, 2011).

In addition, the theoretical proposition can be represented in the form of a logic model as shown in Figure 3-1 below. Information requirements and resources to undertake the SPR groundwater pollution assessment method can be associated with the inputs to the logic model. Inputs allow the researcher to define activities in the form of the assessment method to be followed to arrive at specific outputs and outcomes (Figure 3-1).



**Figure 3-1: A Logic model for the assessment of the pollution and interconnection of the SPR elements**

As explained earlier, two existing ADFs were used as case examples to address the research objectives (as summarised in Table 3-1). A description of the two ADFs is provided in Section 3.4.

### **3.4 Site selection and description**

Two (2) ADFs were selected (denoted as Site A and Site B) – one wet (Site A) and one dry (Site B) ADF – as case examples for the study. The motivation for selecting the two sites was based on the following:

The Site A ADF is a wet ashing facility, while the Site B ADF is a dry-ashing facility. Both wet and dry ashing technologies are represented, because the type of ashing facility (wet/dry) may have an influence on the pollution assessment outcome;

The two sites of the different power stations are located on natural ground without any additional barrier material, in two different catchments, which could translate into geological and site-specific conditions that are different; and

Long term, historical data is available for both sites, to quantify the existing pollution levels.

### **3.5 Description of source, pathway, and receptor for Site A and Site B**

The logic model based on the SPR approach requires a further definition of the case in terms of contaminant representative of the source, description of the pathway and RWQOs representing pollution criteria. The following descriptions of source, pathway, and receptor for Site A and Site B provide information on the similarities and differences for site-specific conditions that might influence the pollution levels. *The next sections must be read with Section 2.5 of the Literature Review.*

#### **3.5.1 Source characterization**

In Section 2.5.1 of this mini-dissertation, the author assumed that seepage will be the only mechanism from which contaminants can be released based on the conceptualization of the ADF water balance. Section 2.5.1 and 2.4.6 further described the contaminant as identifiable by sulfate species. Therefore, the sulfate ion will be considered to be representative of seepage quality for the SPR assessment.

#### **3.5.2 Pathway characterization**

The pathway description for Site A and B is dominated by horizontal groundwater movement that follows the direction of the topography (based on the correlation curves of groundwater levels vs. surface topography) (Eskom, 2014; Eskom, 2018). The water then reappears on the surface in the streams, at the borders of the study area (Eskom, 2014; Eskom, 2018). This usually happens when the path of the groundwater is obstructed by some barrier (unweathered dolerite) or where

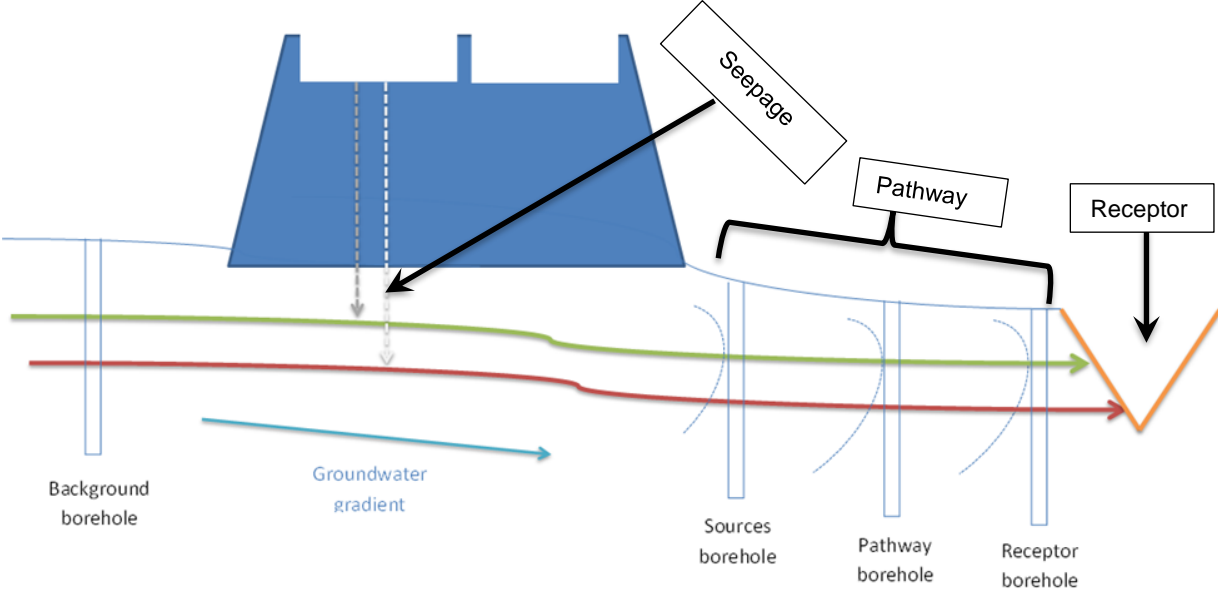
the surface topography, such as a stream, cuts into the water table (Eskom, 2014). This phenomenon is evident in the models that were constructed for the two study areas (also refer to Figure 4-1 and Figure 4-3).

**3.5.3 Receptor**

Information on water users is necessary for the establishment of RWQOs to protect the most sensitive users. However, for purposes of this study and based on available data, drinking water quality standards (SANS 241, 2015) were purposefully selected to represent the RWQOs, since these are, representative of the Reserve for the basic human consumption and generally, stricter than the target water quality ranges proposed for ecological Reserve requirements (DWS, 1996) In addition, the stringent requirements of other water users (e.g. recreation, industrial and agricultural) will not take priority over the Reserve requirements in terms of the hierarchy of water use allocation principle that has been prescribed under NWRS-1 (DWA, 2004) and NWRS-2 (DWS, 2016).

**3.6 SPR Conceptual framework for ADF**

Figure 3-2 can be considered to be representative of the conceptual model of a groundwater system (or SPR conceptual framework) of the sites that were studied.



**Figure 3-2: SPR conceptual framework for Ash Disposal Facility**

The model was used to identify the conditions that influence the sulfate concentration levels from the ADFs along the pathway to the receptor.

### 3.7 Consideration of site-specific conditions within the SPR context

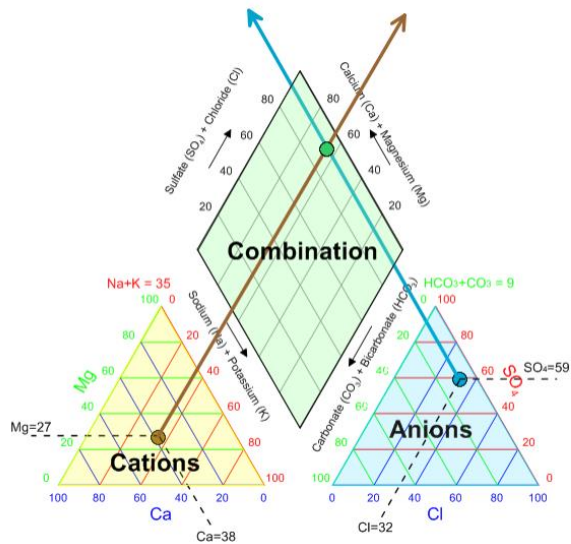
Groundwater pollution assessment can be summarized within the context of the movement of conservative contaminants. These contaminants can be detected from the contaminant source by locating monitoring boreholes near the source, along the pathway and close to the receptor, provided that the contaminant will travel in a direction parallel to the average gradient of groundwater flow as shown in Figure 3-2. The detection of sulfate concentrations based on the SPR approach can provide the following information:

- *Source borehole* concentration levels provide information about the impact of the leachate or seepage quality (contaminant concentration levels) on RWQO (quality of the receptor) before it reaches the *pathway boreholes*; and
- *Pathway boreholes* give an indication of the influence of the natural attenuation process on the contaminant concentration levels from the source to the receptor;
- However, contaminant concentration levels above the RWQOs at *receptor boreholes* do not necessarily indicate any contribution from the source or influence of the natural attenuation process from the pathway.

Hence, an additional assessment tool in a form of Piper plot may be required to provide an indication of either interconnection or no interconnection between the source, pathway and receptor boreholes.

### 3.8 Theoretical description of Piper plots

Piper diagrams are useful in classifying the water type and analysing the distribution of the plots for the type of process that influence the changes in the chemistry of the boreholes at source, pathway, and receptor (Karmegam *et al.*, 2010). Figure 3-3 shows a relative distribution of points in relation to the processes that influence the chemistry of the majority of the boreholes at source, pathway, and receptor (Sadashivaiah *et al.*, 2008). For example, in the diamond diagram, the top quadrant is calcium sulfate waters (gypsum groundwater and mine drainage), the left quadrant is calcium bicarbonate waters (shallow fresh groundwater), the right quadrant is sodium chloride waters (marine and deep ancient groundwater), and the bottom quadrant is sodium bicarbonate waters (deep groundwater influenced by ion exchange). Hence, calcium sulfate waters may not only be representative of pollution from acid mine drainage but also coal-fired power plants.



**Figure 3-3: Example of a Piper plot (Sadashivaiah *et al.*, 2008)**

For instance, the data distribution plot that lies in the top quadrant of the diamond diagram can represent the pollutant sources from the ADFs or any other pollutant source associated with sulfate ion. The distribution plots lying in the remaining quadrants suggest other major ions have higher relative concentrations and are a phenomenon associated with natural attenuation processes.

However, the difference in distribution plots is not always obvious, as described by Karmegam *et al.* (2010). They used Piper diagrams to demonstrate the phenomenon of a certain kind of water mixing with two other kinds of water irrespective of dilution, concentration or chemical modification after mixing. According to Karmegam *et al.* (2010), for mixing to show, the distribution plots for data from the source, pathway and receptor will predominantly lie in one area of the Piper diagram.

### 3.9 Data collection

Purposive convenience sampling was considered desirable for this study on the basis that the characteristic of the unit of analysis is known, it is to be studied intensively and data is easily accessible (Yin, 2012). For purposes of this study, historical water quality data measured on a quarterly basis, from June 1989 to February 2018 (at Site A) and October 1990 to June 2017 (at Site B) of twenty-two (22) different (source, pathway and receptor) boreholes was used to provide sufficient data to draw conclusions from.

An independent qualified contractor used the South African National Accreditation Standards (SANAS) certified laboratory for the analysis of data (for selected ions). Data for major anions ( $\text{CO}_3^{3-}$ ,  $\text{HCO}_3^{3-}$ ,  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ) and cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ ) was used to generate the

Piper plots. As explained in Section 2.4.6 and 2.5.1, the sulfate ion was identified as indicator of pollution from the ADF. Time-series graphs of sulfate concentrations (**Annexure B**) were used to provide sufficient data to draw conclusions from. The data was obtained from Eskom’s electronic database in the form of Excel spreadsheets.

Another source of evidence in the form of monitoring network diagrams found in existing surface and groundwater monitoring reports were used to select the boreholes representative of all the SPR elements. From the monitoring network diagrams, it was deduced that the distribution of monitoring boreholes follows the groundwater gradient (or average flow directions) from the pollution source (which is ADF) to the nearby streams.

### 3.9.1 SPR assessment

Existing monitoring boreholes were used as source, pathway and receptor boreholes. Relative distance (not to scale) from the source to the stream was used to group boreholes into the categories as shown in Table 3-2 and Table 3-3 as below.

**Table 3-2: Site A source, pathway and receptor boreholes**

Drainage Area	Source Borehole	Pathway Borehole	Receptor Boreholes
South-east	KB08, KB62, KB64, KB35, KB65	KB41, KB42, KB19	KB67, KB68, KB29, KB39

**Table 3-3: Site B source, pathway and receptor boreholes**

Drainage Area	Source Borehole	Pathway Borehole	Receptor Boreholes
North-west Drainage	AB01, AB13, AB12	AB01	AB29
North-east Drainage	AB26	AB04, AB36, AB35	AB04

### 3.9.2 Interconnection using Piper diagrams

A geohydrological software package was used to plot Piper diagrams to identify patterns associated with interconnection for source, pathway and receptor boreholes areas (as described in Section 3.10.2).

### 3.9.3 Effect of seepage quality on SPR and WCMS outcome

The author selected the concentration of sulfate ion from storm-water perimeter canals monitoring points as representative of leachate (or seepage) quality based on the description of leachate for ADF in Section 2.5.1. Relative sulfate concentrations from both sites (Sites A and B of two different power stations) were compared to evaluate the effect of seepage quality on the outcomes of the SPR and WCMS assessment method (as per the MDSD framework in Section 3.10.3).

### 3.10 Analysis of data

The author based analysis of data on a number of closely related activities, such as the establishment of pollution scenarios as shown in Table 3-4 below and applying these scenarios to raw data through coding of relative sulfate concentrations at source, pathway and receptor boreholes. In addition, the case study evaluation applied pattern matching between theorized and observed patterns (Yin, 2014) to identify the dominant NAP that could have influenced the changes in the relative sulfate concentrations at source, pathway and receptor boreholes.

#### 3.10.1 Pollution scenarios

The first part of the analysis was based on the pattern matching strategy of time-series graphs for sulfate concentrations at all the boreholes for periods all the data was available as represented by different scenarios, shown in Table 3-4 below.

**Table 3-4: Pollution level scenarios and corresponding natural attenuation process (NAP)**

Scenario	Relative sulfate (SO <sub>4</sub> ) concentrations at source, pathway and receptor boreholes	Description	Pollution from ADF (Yes / No)
			Dominant NAP
1	$C_{\text{source}} = C_{\text{pathway}} = C_{\text{receptor}} = C_{\text{pathway}}$ and $C_{\text{source}} \geq C_{\text{RWQOs}}$ ,	SO <sub>4</sub> contaminant levels exceed RWQOs in all boreholes at source, pathway and receptor	Yes
			No NAP
2	$C_{\text{source}} \leq C_{\text{RWQOs}}$ , $C_{\text{pathway}} \geq C_{\text{RWQOs}}$ , and $C_{\text{receptor}} \geq C_{\text{RWQOs}}$ ,	SO <sub>4</sub> contaminant levels are below the RWQOs in most boreholes at source, and above the RWQOs at pathway and receptor areas	No
			Mixing with other pollutant sources or mineral dissolution is the most dominant NAP
3	$C_{\text{source}} \geq C_{\text{RWQOs}}$ , $C_{\text{pathway}} \leq C_{\text{RWQOs}}$ , and $C_{\text{receptor}} \leq C_{\text{RWQOs}}$ ,	SO <sub>4</sub> contaminant levels exceed the RWQOs in most boreholes	Yes

Scenario	Relative sulfate (SO <sub>4</sub> ) concentrations at source, pathway and receptor boreholes	Description	Pollution from ADF (Yes / No)
			Dominant NAP
		at source and are below at pathway and receptor area	Dilution is the most dominant NAP
4	$C_{\text{source}} = C_{\text{pathway}} = C_{\text{receptor}} = C_{\text{pathway}}$ and or $C_{\text{source}} \leq C_{\text{RWQOs}}$ ,	All the source boreholes have SO <sub>4</sub> contaminant levels that are below the RWQOs	No Dilution is the most dominant NAP

The limited choice of these scenarios assumes a homogeneous system wherein source, pathway and receptor borehole areas represent at most three aquifer systems. Any other scenarios not listed in Table 3-4, the author interpreted such a scenario to represent a heterogeneous system that is not likely to provide information on the interconnection of the SPR elements.

It means that the observations at source, pathway and receptor boreholes should resemble unique water types without interconnection or the same water types with interconnection for a more homogeneous groundwater system. Interconnection could be between the two (2) or three (3) elements of the SPR. In the context of the second part of pollution assessment within the SPR context, interconnection scenarios could suggest mixing two water types forming the third [if they lie in one quadrant of the diamond shape of Piper plot as discussed in Section 3.8].

### 3.10.2 Correlation of contamination levels with borehole locations

In addition, the location of boreholes relative to ADF and other potential pollution sources was used to associate any contaminant levels with the nearest potential pollution sources that could contribute to pollution. The reason for collecting both quantitative and qualitative data was to eliminate bias and find converges across both types of data.

### 3.10.3 Comparative assessment of WCMS and SPR approaches

The second part of the analysis involved a comparative assessment of the outcomes of the WCMS and SPR approaches. Piovani and Krawczyk (2017) argued that two objects can be compared only when they have at least one factor in common. They further state that even before the evaluation of the comparability of two objects, is the question of how they are conceptualized, on the basis of which criteria they are conceived.

The framework of Most Different Systems Design (MDSD) proposed by Lor (2011) was adopted conceptualize the comparability of the outcomes of the SPR and WCMS. The effect of leachate

(seepage quality) on the outcome of the SPR approach (according to the pollution scenarios for the ADFs that were studied for this mini-dissertation) and the outcome of the WCMS were compared based on the MDSD framework. The MDSD framework compares cases that share a phenomenon but differ in all except one factor with the same outcome (Lor, 2011).

### **3.11 Chapter summary**

In summary, the literature review, case study method and MDSD framework were applied to address the research aim on the extent to which groundwater pollution assessment from ADF account for site-specific conditions at Eskom's coal-fired power stations. The three-part research design followed a hierarchical approach:

- Firstly, defining the pollution criteria and identifying the SPR method as relevant to the purpose of accounting for site-specific conditions when assessing groundwater pollution potential from ADF based on literature review;
- The second part adopted a case study approach to illustrate the real-world application of SPR method using sulfate as a representative contaminant of pollution potential of ADF; and
- Lastly, the MDSD framework was used to compare SPR and WCMS with the aim of identifying the extent to which site-specific conditions influence the outcome of the assessment of groundwater pollution potential of ADF.

The next chapter presents the study findings in line with the research questions. Analysis of results was based on Table 3-4, the MDSD framework, as well as analysis of the description of information on the maps.

## CHAPTER 4 RESULTS AND DISCUSSION

### 4.1 Introduction

In this chapter, the results of the study are presented and discussed with reference to the aim of the study, which was to understand the extent to which the SPR approach considers site-specific conditions when assessing potential pollution of groundwater from wet and dry ADFs. For this purpose, one wet ADF and one dry ADF were selected (located within two different catchments) at two different Eskom coal-fired power stations. The research objectives included:

- **Research objective 1:** Establishing site-specific conditions applicable to the assessment of groundwater pollution potential of ADFs;
- **Research objective 2:** Assessing the effects of key indicators for site-specific conditions (associated with SPR) on the levels of groundwater pollution potential from ADF;
- **Research objective 3:** Comparing the outcome of the SPR assessment approach to the WCMS assessment method outcome to determine whether site-specific conditions are significant in groundwater pollution potential assessment.

Research objective 1 was mainly addressed through the literature review section. Results of research objectives 2 and 3 are dealt with in this chapter.

### 4.2 Establishing site-specific conditions applicable to the assessment of groundwater pollution potential of ADFs (Research objective 1)

Although Section 24 of the Constitution and NEMA provide a broad definition of pollution, the NWA definition of pollution was chosen to be the most appropriate in the evaluation of the methods that consider site-specific conditions when assessing groundwater pollution from the ADFs. The approach of choice considered to be appropriate to provide the information relevant for the purpose of assessing groundwater pollution from the ADFs was the SPR model. However, the SPR approach extends the pollution criteria of the NWA (RSA, 1998b) by incorporating some of the concepts of the NWA strategies (RWQOs) and aspects of Hope (1995) criteria on the exposure pathway.

Although the characteristics of the “*source*” in both the WCMS and SPR approaches may be similar in terms of its physicochemical characteristics (which includes physical, health and environmental hazards, including parameters, such as pH, mineral and metal content, toxicity, etc.,) and leachability (in terms of total concentration and leachable concentration), it is argued

that the WCMS approach does not consider site-specific considerations, applicable to the “pathway” and the “receptor”.

Site-specific considerations (represented by the dominant NAP in this study) applicable to the “pathway”, which may cause variability in pollution potential at different “sites” or areas, may include:

- Differences in the geology of the area, i.e. heterogeneous versus homogeneous systems;
- Climatic conditions;
- Depth of the groundwater resource; and
- The chemistry of the host rock.

Site-specific considerations applicable to the “receptor” may include:

- Current water quality status of the nearby stream; and
- Water quality requirements of the most sensitive user at the nearby stream.

The pollution criteria based on the SPR approach was then used to develop the following proposition:

For pollution to exist and associated site-specific pollution control measures to be implemented, contaminants should be present at levels above RWQOs, provided that there is interconnection between the following three elements of the SPR approach, that is:

- i. The *ADF* representing the *source*;
- ii. The *pathway* described as the *area between the ADF to the groundwater discharge point into the surface water*, and
- iii. The *receptor* is considered to be the *surface water intersection point with the groundwater flow*.

Wherein, interconnection can be represented by either pollution pattern scenarios 1 and 4 in Table 3-4 or distribution of relative concentrations of major ions in the source, pathway and receptor boreholes lying in one quadrant of the diamond shape of Piper plot as discussed in Section 3.8.

#### **4.3 Assessing the effects of site-specific conditions on pollution at source, along the pathway, and at the receptor (Research objective 2)**

Having established the criteria of groundwater pollution within the context of the SPR approach, assessing the effects of site-specific conditions required a detailed discussion of the following:

- Site description;
- borehole distribution and delineation into SPR elements;
- pollution distribution pattern and analysis of dominant NAP; as well as
- Interconnection.

A list of data with time-series trends is presented in **Annexure B** and was used to identify distribution patterns for sulfate concentrations as well as interconnection based on Piper diagrams. Archival analysis of exceptions to scenarios in Table 3-4 was undertaken by correlating the observations with information from the existing reports and site maps.

#### **4.3.1 Assessing the effects of site-specific conditions at Site A**

##### **4.3.1.1 Site A description**

Figure 4-1 shows Site A, a wet ADF. Site A is a coal-fired power station designed to produce approximately 3000 MW of electricity to the national grid. The ADF has been operational since 1979 and is made up of three adjacent ash dams that cover a total area of approximately 300 hectares (300 Ha). Initially comprising Dam 1 and Dam 2 with the construction of Dam 3 commencing in 1985. Ash is pumped to the sites via a network large-diameter steel pipes several kilometres long.

##### **4.3.1.2 Site A SPR borehole distribution analysis**

Borehole delineation at Site A was represented by orange, purple and blue-coloured circles in Figure 4-1 based on relative distance from the ADF. Source boreholes within the orange circle were identified to be the nearest boreholes along the perimeter channel that is situated south of the ADF. The second set of boreholes (purple circle) representing the pathway, is located between the source boreholes and the last set of boreholes (representing the receptor in blue circle) closest to the Spruit A stream (south-west of the ADF). Pathway boreholes are mainly within the mine spoils which could influence the results. Receptor boreholes are not only close to the stream but are also on the edge of the mine spoils boundary. The sulfate concentration levels of the pathway and receptor boreholes are not expected to be significantly different when compared to the source boreholes.

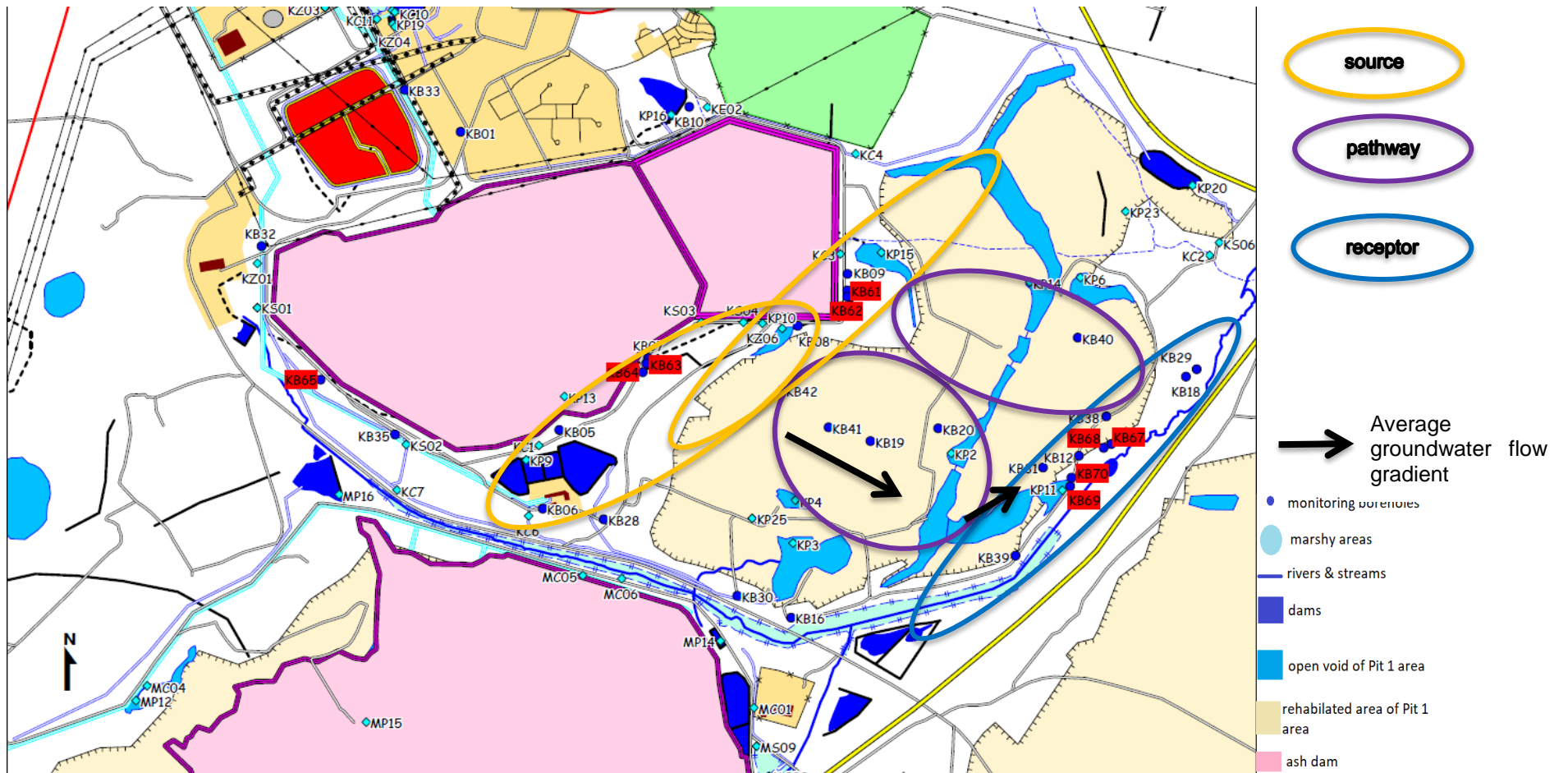


Figure 4-1: Site A layout map with the distribution of monitoring points relative to the infrastructure

#### 4.3.1.3 Site A Pollution distribution and observed NAP

Borehole KB08 at the source area has a long history of data from 1989 to 2018 (it was the only borehole analysed until 2010 from the selected source boreholes). Starting from 2014 until 2018 is a period in which data is available for all the selected boreholes to allow for comparison in sulfate concentrations trends. All the boreholes have been ranging below the thresholds limit of 500 mg/l of sulfate except at KB08 which has shown steady increases from over 600 mg/l to 700 mg/l of sulfate for the same period.

For the same period, the entire pathway boreholes have mainly been trending over 500 mg/l. however, receptor boreholes show varying trends with some consistently above the limit whilst results from other boreholes fluctuate below and above the limit.

Scenarios presented in Table 3-4 assume the boreholes within the same areas (e.g., source, pathway or receptor) should all show the same outcomes of the pollution levels when compared to the RWQOs to indicate that groundwater flow in any of one of these areas is homogeneous. Contrary to the presumed outcomes, the observed unique results at source borehole KB08, where sulfate concentrations exceed the RWQOs (when compared to other source boreholes) may suggest that the groundwater system is not homogenous in that area.

However, the time-series graph (**Annexure B**) for KB08 from 1989 to 2002 shows sulfate concentrations were at similar levels to observations at other boreholes. Hence, further indicating that ADF may have started to release contaminants after 2002 in an area close to KB08 without necessarily affecting the entire source area. Therefore, suggesting that the source area is heterogeneous. A geological map in **Annexure C** of the report shows that the ADF at Site A is underlaid by impervious rock (known as dolerite sill) and the southern part of the ADF perimeter wall along the source boreholes is bordered by another continuous impermeable structure (typical of a dyke) (Eskom, 2018).

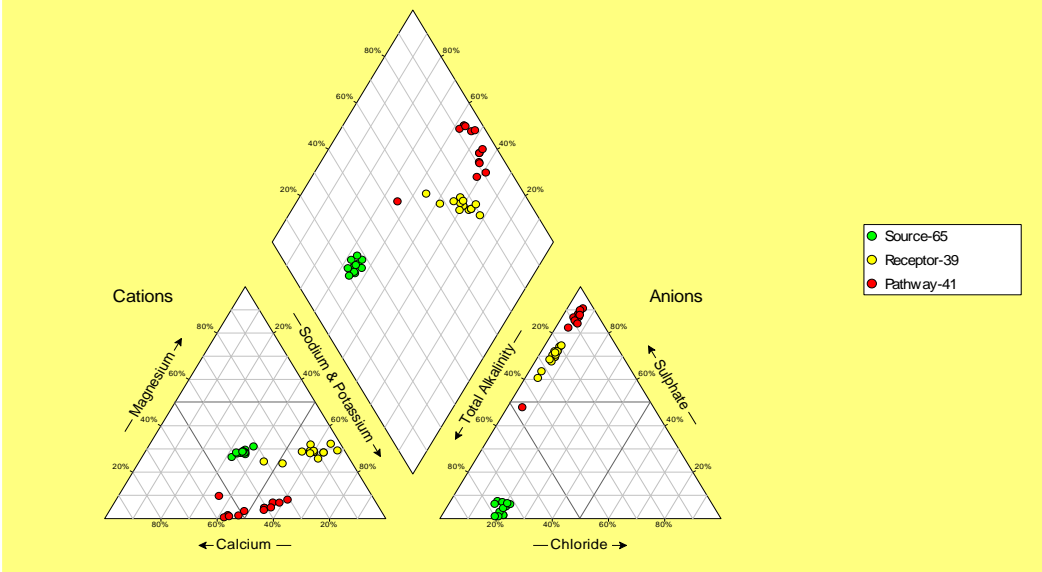
Dolerite sill promotes horizontal movement of groundwater while a dyke prevents it (by redirecting it either upwards or downwards depending on how it developed) (Eskom, 2018). Despite the presence of these structures, only KB08 among other source boreholes appears to have increased sulfate concentrations. Hence, borehole KB08 quality could have been affected by a combination of the presence of these structures and a nearby possible crack on the concrete channel. Despite the unique qualities at KB08 from other source boreholes, the outcome of the majority of the boreholes at source, pathway and receptor areas showed results that can be represented as follows:

$$C_{\text{source}} < C_{\text{pathway}}, C_{\text{receptor}} = C_{\text{pathway}} \text{ and } C_{\text{source}} < C_{\text{RWQOs}},$$

The observed scenario appears to be more associated with scenario 2 in Table 3-4. It means that there is no pollution from the ADF (except at borehole KB08) with mineral dissolution as the dominant NAP. In addition, for ADF pollution to move from KB08, then there must be an interconnection between the source, pathway, and receptor.

**4.3.1.4 Interconnection at Site A**

Piper diagrams (Figure 4-2) show green dots representing source boreholes ion distribution, red dots as an indicator of pathway boreholes ions distribution and yellow dots represent receptor boreholes ions distribution. The bicarbonate type dominates water type at the source. Pathway and Receptor are both sulfate dominated. The results suggest distinct hydrochemical signatures exist for the source area with pathways and receptors having similar water types. It indicates that spatially, source area is not interconnected with pathway and receptor areas. This indicates that it is unlikely that pollution from ADF (at KB08) is the biggest contributor to pollution at the pathway. Therefore, pathway area might have another source that contributes to pollution.



**Figure 4-2: Site A Piper Plot**

The assessment of site A lay-out map and other geologic maps shows that pathway is an area where mining previously took place. Hence, the mining activity could be the main contributor to sulfate in the pathway and receptor areas.

## **4.3.2 Assessing the effects of site-specific conditions at Site B**

### **4.3.2.1 Description of Site B**

Figure 4-3 shows Site B, a dry ADF. Site B is a coal-fired power station designed to produce approximately 4 110 MW of electricity for the national grid. The construction of Site B power station commenced on September 1983 and the first unit went online on 1 April 1996. Construction of Site B Power Station was completed on 1 April 2001. The ADF has been operational for 23 years. The current footprint of the ash stack covers an area of approximately 92.5 hectares and the design caters for at least the next 37 years. Ash is dumped onto the ash dump and sprayed with excess process water for dust suppression. Water is lost only by evaporation and seepage through an unlined ADF facility. Some of the seepage flow collects to surface and toe drains channelled to one of three ash return-water dams (referred to as Ash Dams West, North, and East on the map). Typical ash water quality from the ADF and associated infrastructure (canal and pollution control dams) range from 700 mg/l to 1400 mg/l of sulfate.

Impacts upon the Spruit Ba (north-west of the ADF) would mainly originate from the ashing area, which is located to the south-east of the stream. Impacts upon the Spruit Bb (north-east of the ADF) would mainly originate from the south-western part of the ash facility. Drainage from the area identified for ash disposal facility is mainly in a north-easterly and north-westerly direction.

### **4.3.2.2 Site B SPR borehole distribution analysis**

Borehole delineation into the source (orange circle), pathway (purple circle) and receptor (blue circle) at Site B in Figure 4-3 have borehole AB01 located in an area where source and pathway areas overlap. The reason being that it is the most down-gradient borehole (before the receptor borehole AB29) when compared to other source boreholes on the north-west drainage side. Another dual appearance was found for borehole AB04 acting as borehole that detect pollution levels at pathway and receptor due to its location as the most down-gradient of the pathway boreholes and being close to the receptor. Borehole AB26 appears as a source borehole for North-West and North-East drainage regions due to its location that appears to be within a catchment divide.

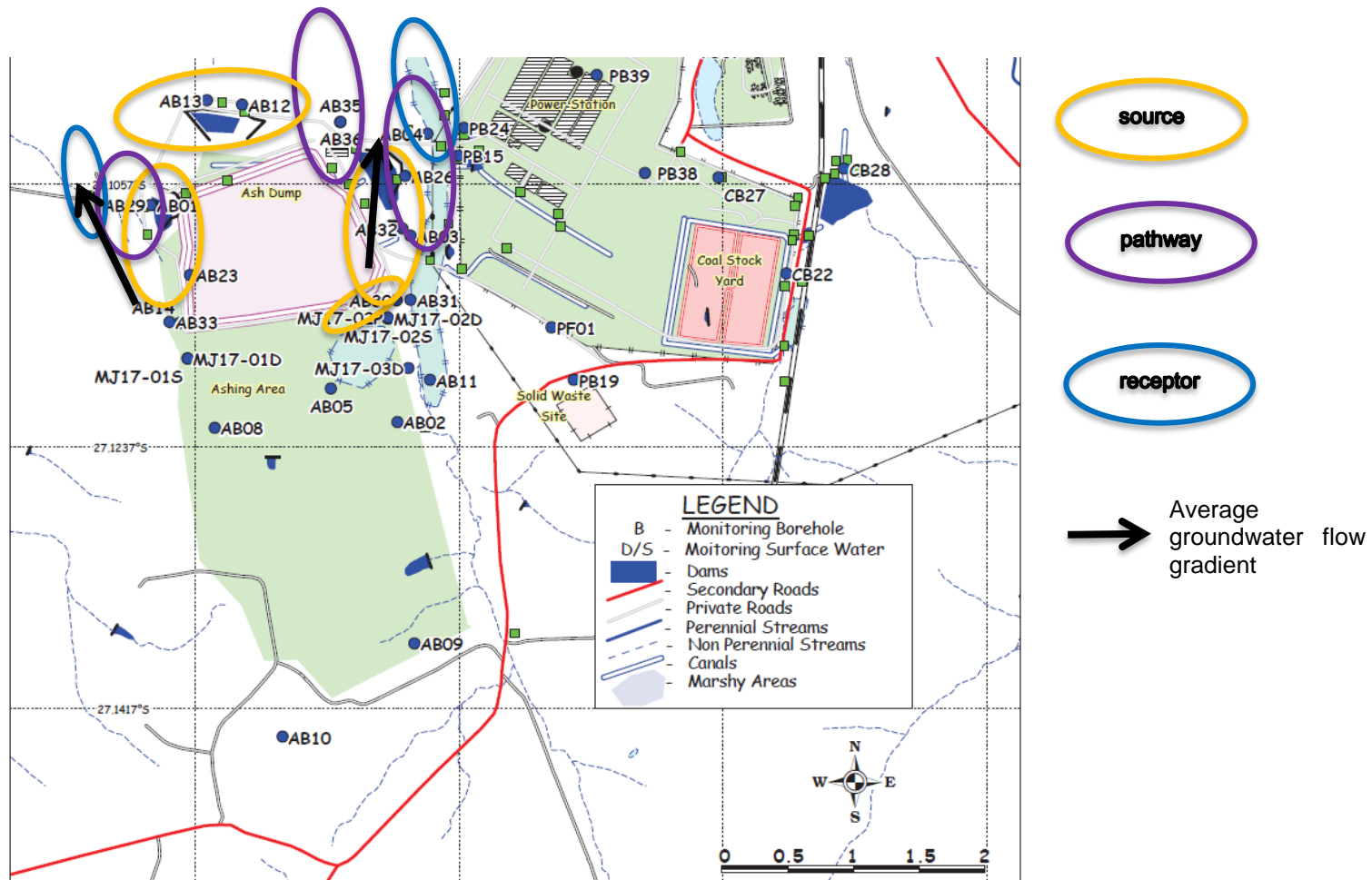


Figure 4-3: Site B layout map with the distribution of monitoring points relative to the infrastructure

Site B borehole locations for AB01 and AB04 cannot distinctively be associated with a single element of SPR. While AB26 may be detecting pollution from both or either one of the drainage areas. Data for these boreholes were interpreted as follows:

- If any of the boreholes AB01 and AB04 show sulfate levels above (or below) RWQOs in one element of the SPR, it should show the same levels of sulfate in another element of the SPR; and
- Exceedance of RWQOs in Borehole AB26 may indicate the release of contaminants from the ADF without knowledge of which side of the drainage is likely to contaminate.

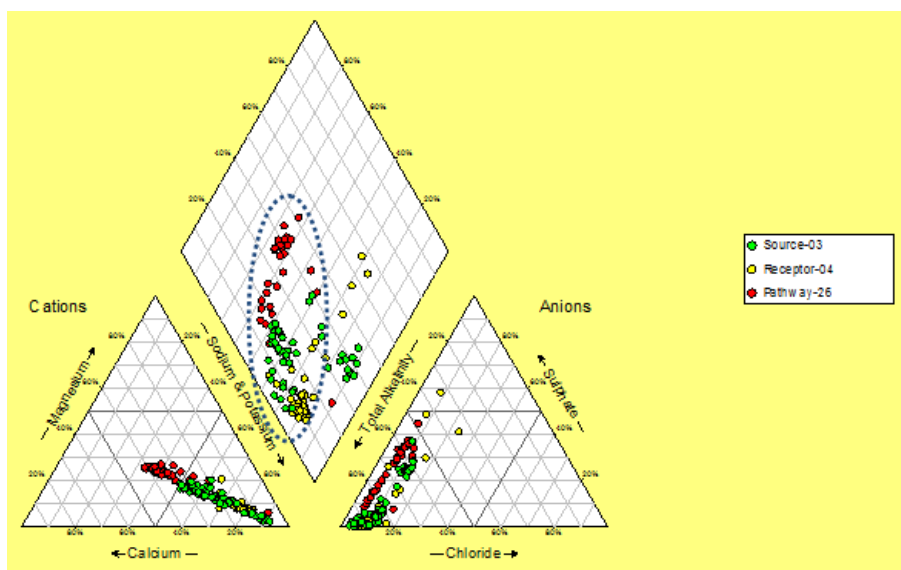
#### **4.3.2.3 Site B Pollution distribution and observed NAP**

Time-series graphs show that the first monitoring started in 1990 at source boreholes AB13 and AB04 (Annexure A). Other boreholes were phased in from 1994 (AB12) to 2012 (AB36 and AB35). The period starting from 1990 to 2017 (the last date of monitoring data), was used to undertake a comparative analysis of the boreholes at all the SPR elements. Time-series graphs show that all the sulfate concentrations at source, pathway and receptor boreholes ranged between (3 to 183 mg/l of sulfate) and are well below the RWQOs (threshold of 500 mg/l of sulfate concentrations).

Observations at Site B are representative of scenario 4 (Table 3-4), which implies that no contaminant is released from the ash ADF. If it is released, the dominant NAP associated with scenario 4 is dilution from rainfall and mixing with other groundwater sources.

#### **4.3.2.4 Interconnection at Site B**

Piper diagram (Figure 4-4) shows green dots representing source boreholes ion distribution, red dots as an indicator of pathway boreholes ions distribution and yellow dots represent receptor boreholes ions distribution. Site B Piper plot shows that water type at source is dominated by the bicarbonate type. A straight-line pattern for both cations and anions positions is related to the mixing pattern described by Karmegam (2010) and others. A mixing line on the central field highlighted by the blue dotted oval shape was observed. It indicates that spatially, the source area is interconnected with pathway and receptor areas. The bottom quadrant is sodium bicarbonate waters typical of deep groundwater influenced by ion exchange.



**Figure 4-4: Site B Piper Plot**

#### 4.4 Comparing the outcomes of SPR and WCMS assessments (Research objective 3)

Leachate test method adopted in WCMS classified ash as a Type 3 waste (Eskom, 2016) based on contaminants other than the sulfate (72 mg/l of sulfate for Site A, and 96 mg/l of sulfate for Site B were below the thresholds for Type 3 waste). In Section 2.5.1 it was argued that the leachate test method may not have considered other site-specific conditions (e.g., leachate solution from concentrated cooling water (Loretitsch, 2002) and longer contact time (based on ash deposition period) of leachate solution with weathered ash (Akinyemi *et al.*, 2012).

In contrast, field data appeared to be more representative of conditions that promote the leachability of sulfate due to the above thresholds levels of 1400 mg/l of sulfate for Site A, and 1500 mg/l of sulfate for Site B. It shows that replacement of field data with the results of leachate test method, would classify ash as a Type 3 waste in terms of the sulfate concentration. It further shows that there is a correlation between the leachate quality and conditions that promote the leachability of sulfate. Therefore, it can be argued that similar leachate quality at Site A and Site B, will classify ash as a Type 3 waste irrespective of other conditions within the *pathway* element of the SPR approach.

According to the MDSD framework proposed by Lor (2011), the characteristics of leachate (from the source) can be considered as the main factor that influences groundwater pollution potential, if the outcome is the same for the two sites.

If not, then other *site-specific conditions* associated with pathway mechanisms as indicated by NAP are deemed to have a significant impact on groundwater pollution potential, which could, in turn, suggest that the characteristics of the ash (source) (Physico-chemical properties, total

concentration, and leachable concentration) are not the main contributor/factor that needs to be considered when pollution prevention and mitigation measures (such as waste barriers) are considered.

Having observed pollution scenarios at Site A and B within the context of the SPR approach as well as knowing seepage qualities from the respective sites, Table 4-1 was populated to provide the following results from which comparative assessment can be undertaken.

Table 4-1 clearly indicates that, although the leachable concentrations of  $\text{SO}_4$  of the ash at Site A and Site B are similar, the concentrations of  $\text{SO}_4$  at source, pathway and receptor boreholes of Site A and B vary greatly. This means that, although the WCMS results indicate that ash from both sites belongs to type 3 and that the proposed barrier design requirements would be similar, the groundwater pollution potential of ash at the two sites differ. This indicates that factors other than merely the total concentration (TC) and leachable concentration (LC) of the ash influence groundwater pollution potential. Site-specific considerations such as other surrounding sources of pollution (e.g. mine spoils at Site A and localized seepage associated with operational and maintenance deficiencies), geological formations (e.g. rock chemistry, water table, sills and dykes at Site A and B) and climatic conditions (e.g. rainfall recharge at Site A and B) seem to play a more significant role in groundwater pollution potential.

**Table 4-1: Comparison of sulfate concentrations of ash and source, pathway and receptor boreholes**

Site	Maximum Leachable Concentration of SO <sub>4</sub> for field data (mg/l)	Outcome of WCMS (Waste type)	Range of SO <sub>4</sub> concentration at <i>source</i> boreholes (average of min - average of max) (mg/l)	Range of SO <sub>4</sub> concentration at <i>pathway</i> boreholes (average of min - average of max) (mg/l)	Range of SO <sub>4</sub> concentration at <i>receptor</i> boreholes (mg/l) (average of min - average of max)	Pollution level scenarios (outlined in Table 3-4) based on levels at source, pathway and receptor boreholes
A	1500	Type 3	14 – 138	223 – 1567	157 – 999	Scenario 2: $C_{source} \leq C_{RWQOs}$ and $C_{pathway} \geq C_{RWQOs}$ , and $C_{receptor} \geq C_{RWQOs}$ (despite leachate concentration being below the RWQOs, SO <sub>4</sub> levels were above the RWQOs at pathway and receptor boreholes and at the source boreholes)
B	1400	Type 3	3,5 – 247	0,1 - 162	16 - 243	Scenario 4: $C_{source} = C_{pathway} = C_{receptor} = C_{RWQOs}$ (All boreholes have SO <sub>4</sub> levels below the RWQOs)

## CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

### 5.1 Introduction

This chapter provides the final conclusions on the research objectives of the study, namely:

- Research objective 1: Establishing site-specific conditions applicable to the assessment of groundwater pollution potential of ADFs;
- Research objective 2: Assessing the effects of key indicators for site-specific conditions (associated with SPR) on the levels of pollution from ADF;
- Research objective 3: Comparing the outcome of the SPR assessment approach to the WCMS assessment method outcome to determine whether site-specific conditions have more influence in groundwater pollution potential assessment.

### 5.2 Conclusions

The literature review chapter (Chapter 2) provided an overview of the site-specific conditions applicable to the assessment of groundwater pollution (*Research objective 1*) and discussed the indicators (*Research objective 2*) to assess whether site-specific conditions play a significant role in groundwater pollution potential assessment. Based on the literature review, the study has established that pollution control measures associated with the precautionary approach are subject to the outcomes of the risk-based assessment approaches. The pollution criteria for risk-based approaches in the South African regulatory framework relevant to groundwater pollution potential assessments are based on acceptable risk represented by RWQOs. Policy principles and guidelines promote a differentiated risk-based approach that requires site-specific conditions to be considered.

An assessment method that considers site-specific conditions in relation to the ADF as the contaminant source was identified to be the SPR. Such site-specific conditions are:

- leachate quality from the source;
- dominant NAP within the pathway; and
- site-specific receptor-based thresholds.

This study could not find any evidence that the WCMS approach accounts for any site-specific considerations when determining the waste type to inform barrier designs. An extensive

amount of literature and data are, however, available regarding pollution potential assessment related to the pathway variables, as part of the SPR approach.

The study assessed the effects of key indicators for site-specific conditions on the levels of pollution (*Research objective 2*) at source, pathway, and receptor boreholes at two sites (Site A and Site B), following the SPR approach.

As far as research objective 3 was concerned, the results revealed that, although the leachable concentration of sulfate at both sites were similar, the sulfate levels varied greatly at source, pathway and receptor boreholes, which indicates that factors other than merely the concentration of pollutants in the ash influence groundwater pollution potential. Site-specific considerations such as other surrounding sources of pollution, geological formations, climatic conditions, and other factors seem to play a significant role in groundwater pollution potential. During this study, it was found that, for the two sites investigated, the key variables that influence groundwater pollution potential are NAP and geological structures for each case. In some instances exceedance of thresholds could be associated with sources or pathways other than leachate from ADF based on the relative location of activities with borehole location.

The study showed that the WCMS and SPR approaches consider leachate concentrations to varying degrees and use the information for different purposes, whereas leachable contaminants that exceed the thresholds (Eskom, 2016) for WCMS are not contaminants that are representative of the source. For instance, sulfate concentrations measured at the source may be above the thresholds of WCMS as opposed to the outcome based on conditions of the leachate test.

Considering the above, it is clear that the WCMS and SPR approaches differ in how they assess groundwater pollution potential of ADFs, as it relates to the source (indicator: leachable concentration), pathway (indicator: NAP and geological structures) and receptor (indicator: thresholds). The fact that the WCMS approach does not provide for site-specific conditions and apply thresholds that do not adequately protect the most sensitive user identified for that catchment, could result in either over or under-protection of the surrounding environment (e.g. sulfate threshold for WCMS is 250ppm half that of the SANS drinking water quality standards representing the human consumption component of the Reserve as the priority water user (DWA, 2004) for the SPR approach).

The learning from applying the research methodology and methods in the context of groundwater pollution potential is that there are existing theories and analytical tools (e.g NAP, geologic conditions, time-series graphs and Piper diagrams) that can be used to select a contaminant

representative of the source, estimations of groundwater flow directions and possible NAP processes that influence the spatial and temporal variation of the contaminant to establish the corresponding conditions that influence the changes in the contaminant levels.

### **5.3 Recommendations**

Based on the conclusions of the study, it is recommended that site-specific conditions, as provided for in the SPR approach, be taken into consideration during groundwater pollution potential assessment.

The study has identified some constraints and opportunities that may have to be considered for further work. The study did not review the extent to which other sites in Eskom and other sectors with similar WDFs considered site-specific conditions (Bhattacharjee, 2012). Such a review may validate the findings of this study in terms of the following:

- Consistency of variables associated with the site-specific conditions;
- Replicating the study with other conservative contaminants representative of different types of WDF; and
- Using other evidence sources to triangulate or statistical analysis based on multi-case studies (Bhattacharjee, 2012).

Research methodology and methods applied in this study could be used to identify the knowledge gaps with regard to data related to site-specific conditions for the assessment of groundwater pollution potential of ADF. In addition, outcome of identification of knowledge gaps from applying this research methodology and methods may be input into the decision-making process of selecting the appropriate mitigation options that will ensure the balance between the protection and sustainable use of the water resource is achieved.

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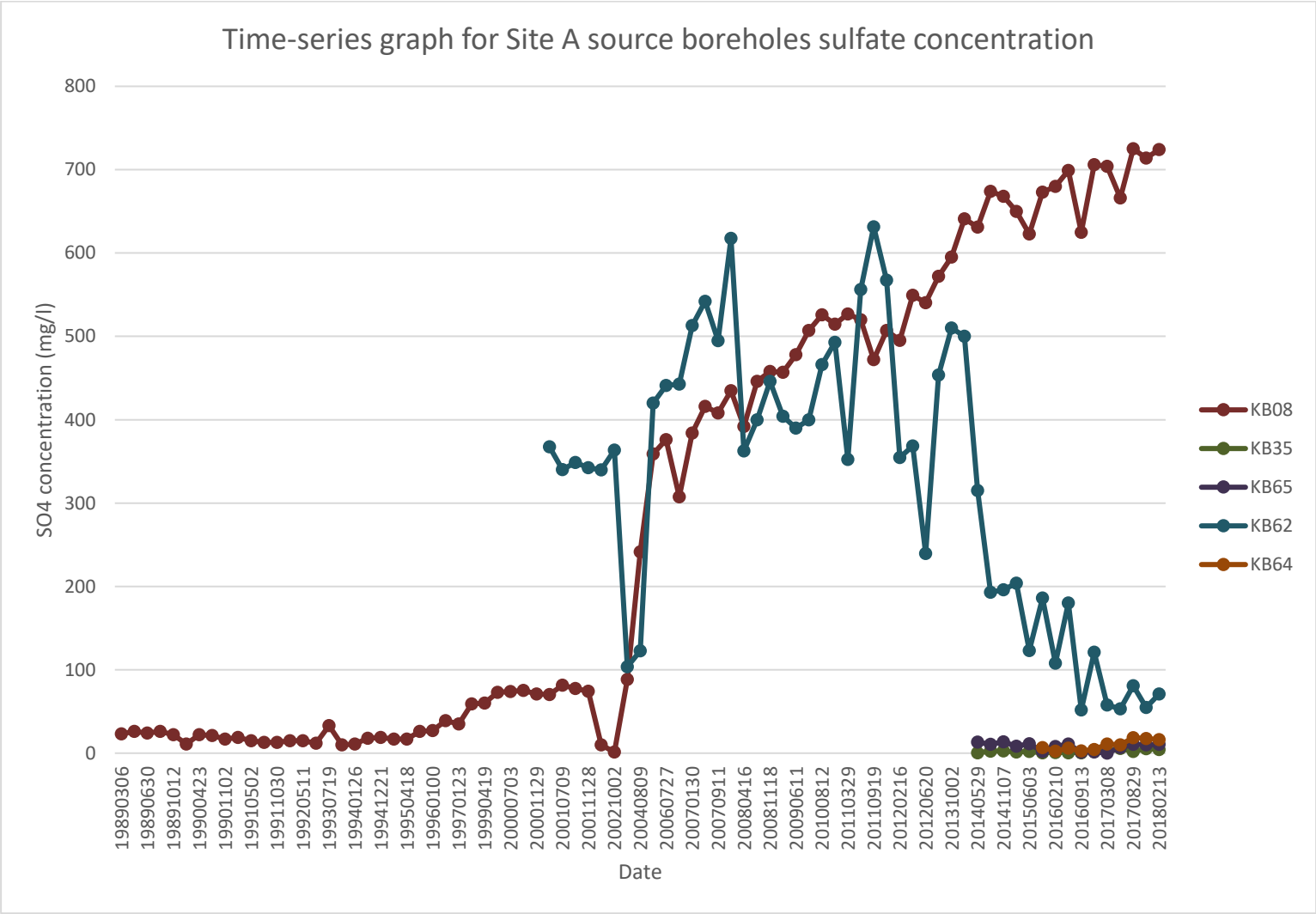
## ANNEXURE A: LEACHABLE CONCENTRATIONS OF VARIOUS ELEMENTS AT SITE A AND B, IN OTHER ESKOM ASHES AND ACTUAL FIELD (SEEPAGE) DATA

ELEMENT	LCT0 mg/l	LCT1 mg/l	LCT2 mg/l	SITE A	SITE B	1	2	3	4	5	Seepage Data
				LC mg/l	LC mg/l	LC mg/l	LC mg/l	LC mg/l	LC mg/l	LC mg/l	
As	0.01	0.5	1	0.010	0.004	0.39	0.13	0.02	0.007	0.08	0.007
B	0.5	25	50	0.518	0.13	10	3.5	0.637	0.11	0.1	0.549
Ba	0.7	35	70	0.048	0.37	0.14	0.32	0.23	0.27	0.19	NA
Cd	0.005	0.25	0.5	0.003	0.0004	0.02	<0.002	0.003	0.003	0.003	NA
Co	0.5	25	50	0.025	<0.001	0.005	0.007	0.02	0.02	0.02	NA
Cr	0.05	5	10	0.240	0.19	0.077	0.05	0.09	0.01	0.01	NA
Cr <sup>6+</sup>	0.05	2.5	5	0.029	0.17	0.069	0.02	0.09	<0.05	<0.02	0.003
Hg	0.006	0.3	0.6	0.001	0.0007	0.003	0.004	0.003	0.004	0.004	NA
Cu	2	100	200	0.025	0.0144	0.001	0.01	0.01	0.05	0.07	0.002
Mn	0.5	25	50	0.025	0.0093	0.003	0.54	0.13	1.67	0.91	0.524
Mo	0.07	3.5	7	0.026	0.0382	0.015	0.06	0.085	0.003	0.003	NA
Ni	0.07	3.5	7	0.025	0.0009	0.003	0.04	0.002	0.09	0.07	NA
Pb	0.01	0.5	1	0.010	0.0425	<0.001	<0.005	<0.005	0.005	<0.005	NA
Sb	0.02	1	2	0.010	0.0024	<0.02	<0.02	<0.02	0.06	<0.02	NA
Se	0.01	0.5	1	0.010	0.039	0.014	0.016	0.016	0.01	0.013	NA
V	0.2	10	20	0.037	0.027	0.08	0.114	0.12	0.012	0.013	NA
Zn	5	250	500	0.025	0.117	0.02	0.04	0.07	0.03	0.12	0.002
TDS	1000	12500	25000	222	292	420	196	213	114	90	2059
Chloride	300	15000	30000	<5	1.96	0.27	6	<5	3.7	<5	80
NO <sub>3</sub> <sup>-</sup>	11	550	1100	0.2	0.2115	<0.1	0.84	0.2	0.9	0.2	0.097
Cyanide	1.5	75	150	<0.05	<0.01	NA	<0.01	<0.01	0.02	0.01	NA
Sulphate	250	12500	25000	72	96	17.8	72.7	130	9	7	1005

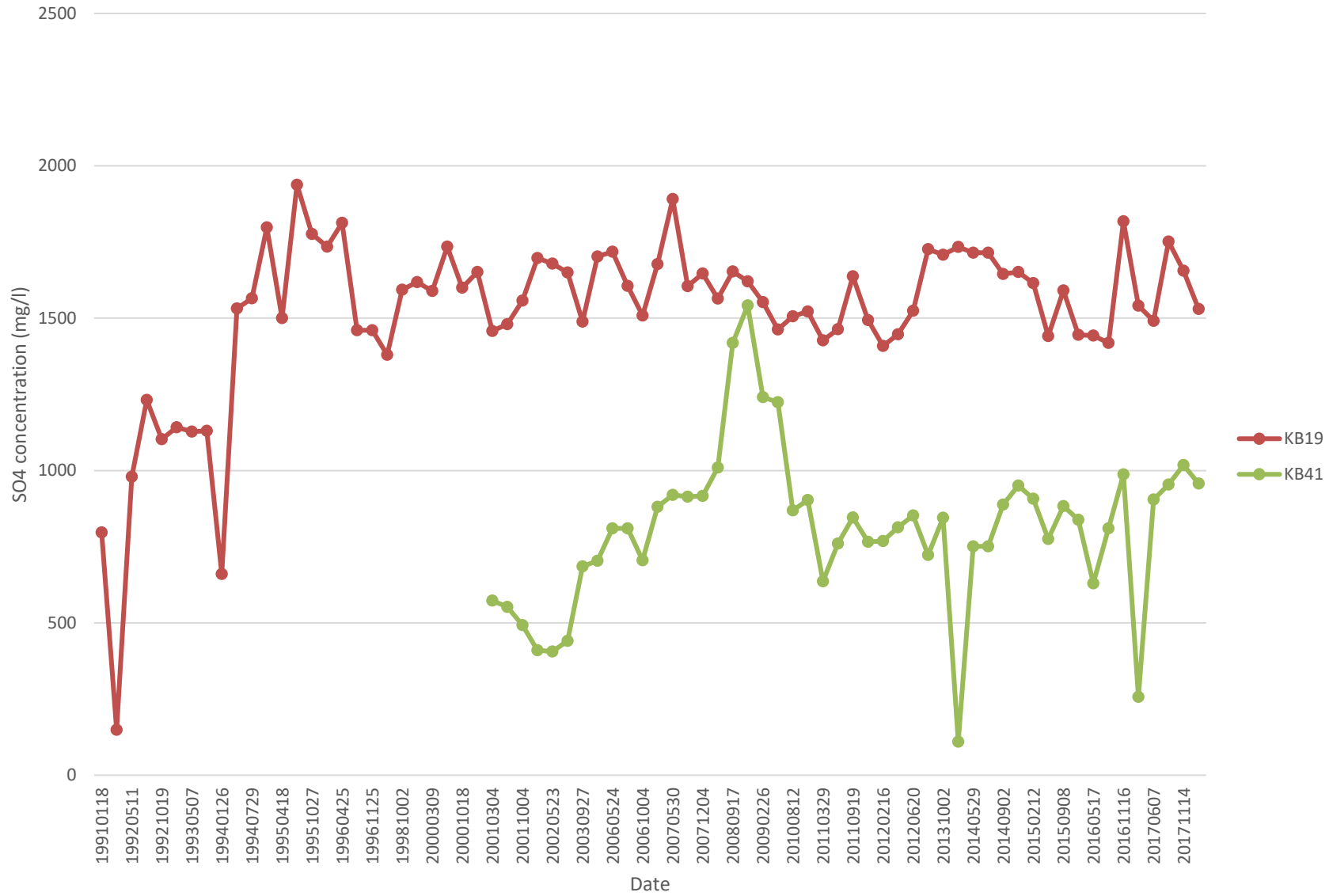
	Below or equal to LCT 0
	Above LCT 0, below LCT 1
	Above LCT 1, below LCT 2
	Above LCT 2

NA – Not analyzed

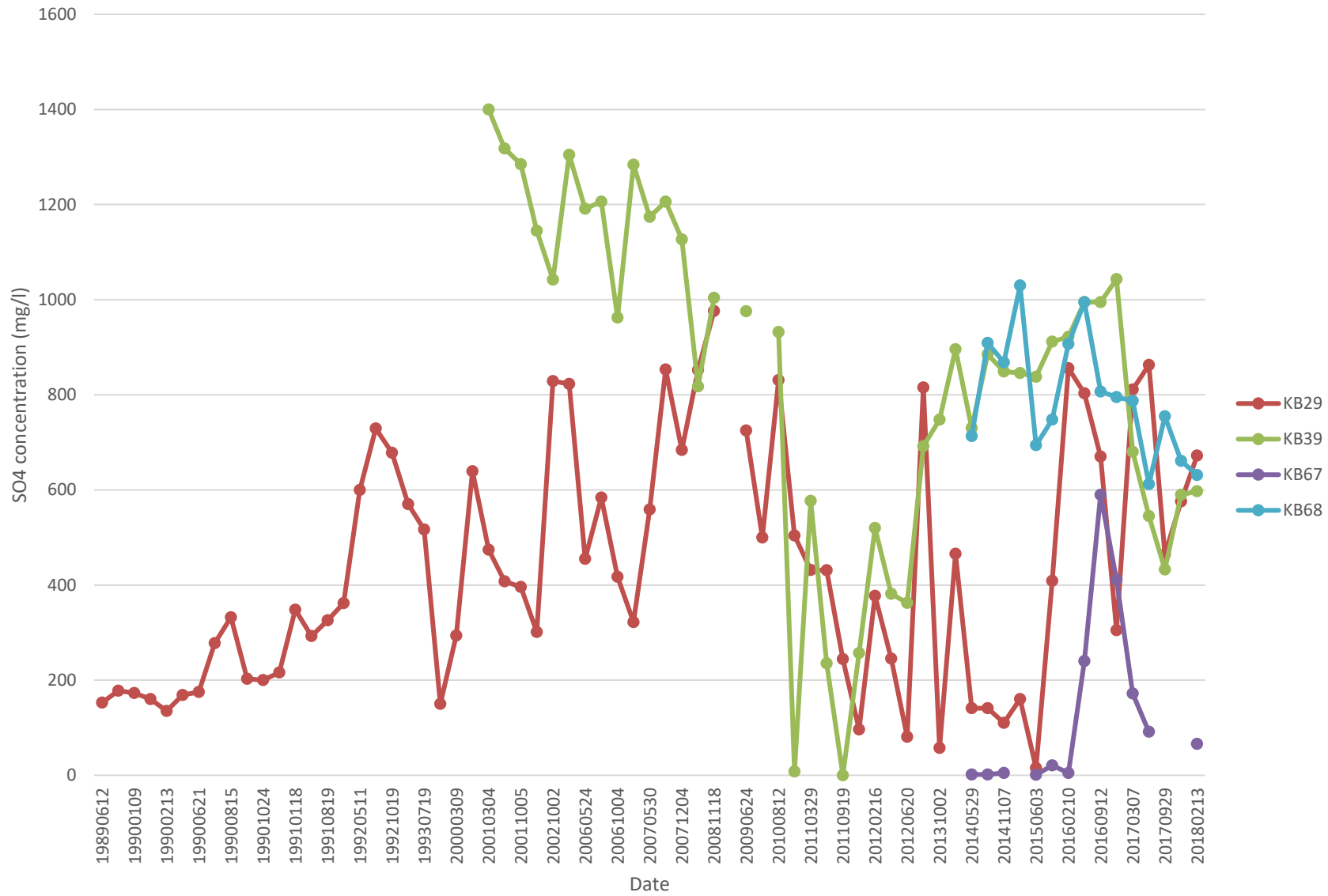
# ANNEXURE B1: SULFATE DATA AND TIME-SERIES GRAPHS FOR SITE A



Time-series graph for Site A pathway boreholes sulfate concentration



Time-series graph for Site A receptor boreholes sulfate concentration

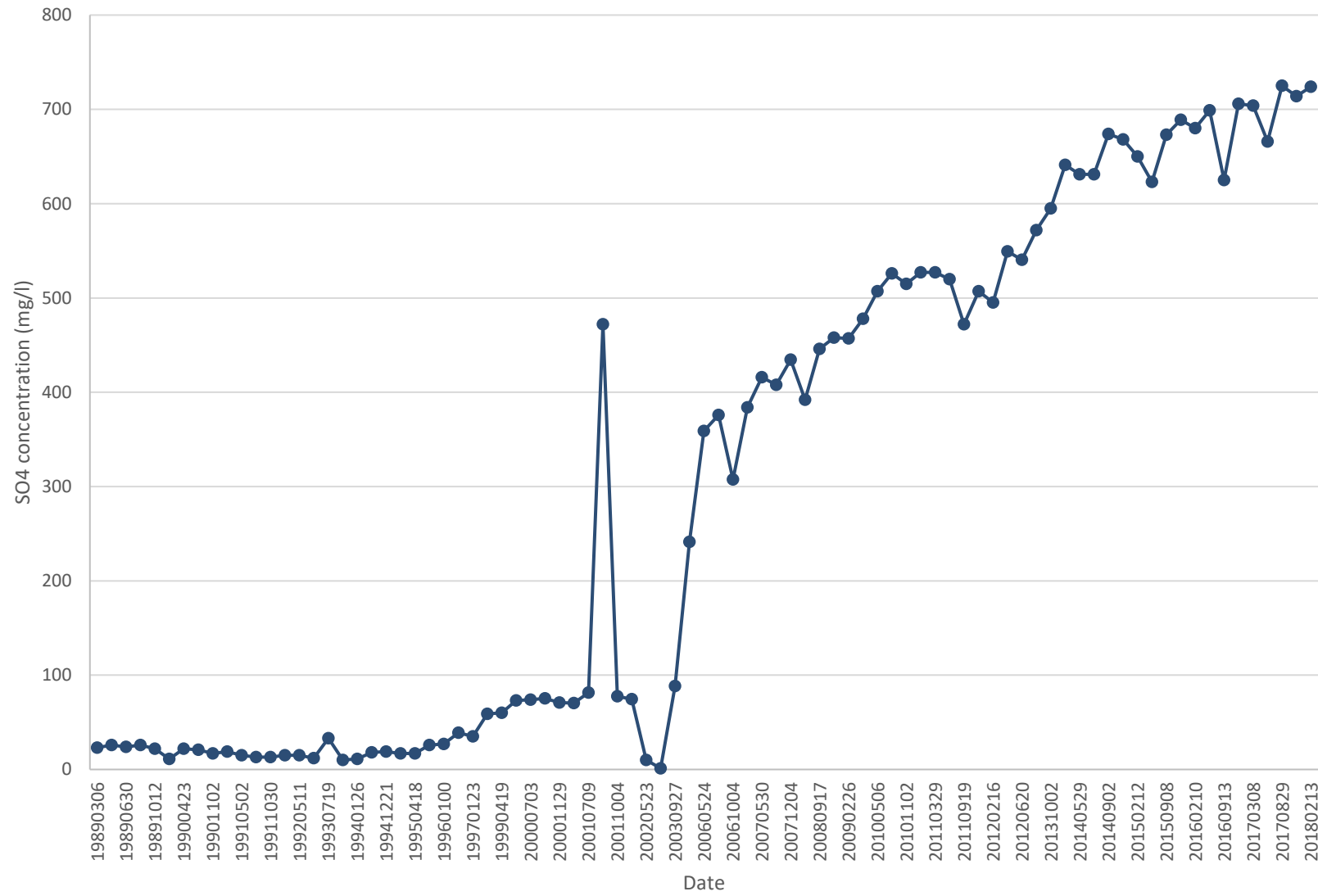


Site A source boreholes: KB08 Sulfate concentration

Borehole description	Date (yymmdd)	Concentration (mg/l)
KB08D	19890306	23
KB08D	19890523	26
KB08D	19890630	24
KB08D	19890815	26
KB08D	19891012	22
KB08D	19900109	11
KB08D	19900423	22
KB08D	19900621	21
KB08D	19901102	17
KB08D	19910118	19
KB08D	19910502	15
KB08D	19910819	13
KB08D	19911030	13
KB08D	19920120	15
KB08D	19920511	15
KB08D	19930225	12
KB08D	19930719	33
KB08D	19931108	10
KB08D	19940126	11
KB08D	19940729	18
KB08D	19941221	19
KB08D	19950301	17
KB08D	19950418	17
KB08D	19950728	26
KB08D	19960100	27
KB08D	19960425	39
KB08D	19970123	35
KB08D	19981002	59
KB08D	19990419	60
KB08D	20000309	73
KB08D	20000703	74
KB08D	20001018	75,4
KB08D	20001129	71
KB08D	20010304	70,3
KB08D	20010709	81,4
KB08D	20010919	472,15
KB08D	20011004	77,7
KB08D	20011128	74,4
KB08D	20020523	9,9
KB08D	20021002	1,2
KB08D	20030927	88,31
KB08D	20040809	241,44
KB08D	20060524	359

Borehole description	Date (yymmdd)	Concentration (mg/l)
KB08D	20060727	376
KB08D	20061004	307,57
KB08D	20070130	384
KB08D	20070530	416
KB08D	20070911	408
KB08D	20071204	434,68
KB08D	20080416	391,96
KB08D	20080917	446
KB08D	20081118	457,99
KB08D	20090226	457
KB08D	20090611	478
KB08D	20100506	507
KB08D	20100812	526
KB08D	20101102	514,78
KB08D	20110329	527
KB08D	20110329	527
KB08D	20110620	520
KB08D	20110919	472,15
KB08D	20111117	507,06
KB08D	20120216	495,16
KB08D	20120425	549,25
KB08D	20120620	540,55
KB08D	20120926	571,92
KB08D	20131002	595
KB08D	20140318	641
KB08D	20140529	631
KB08D	20140529	631
KB08D	20140902	674
KB08D	20141107	668
KB08D	20150212	650
KB08D	20150603	623
KB08D	20150908	673
KB08D	20151111	689
KB08D	20160210	680
KB08D	20160517	699
KB08D	20160913	625
KB08D	20161115	706
KB08D	20170308	704
KB08D	20170607	666
KB08D	20170829	725
KB08D	20171114	714
KB08D	20180213	724

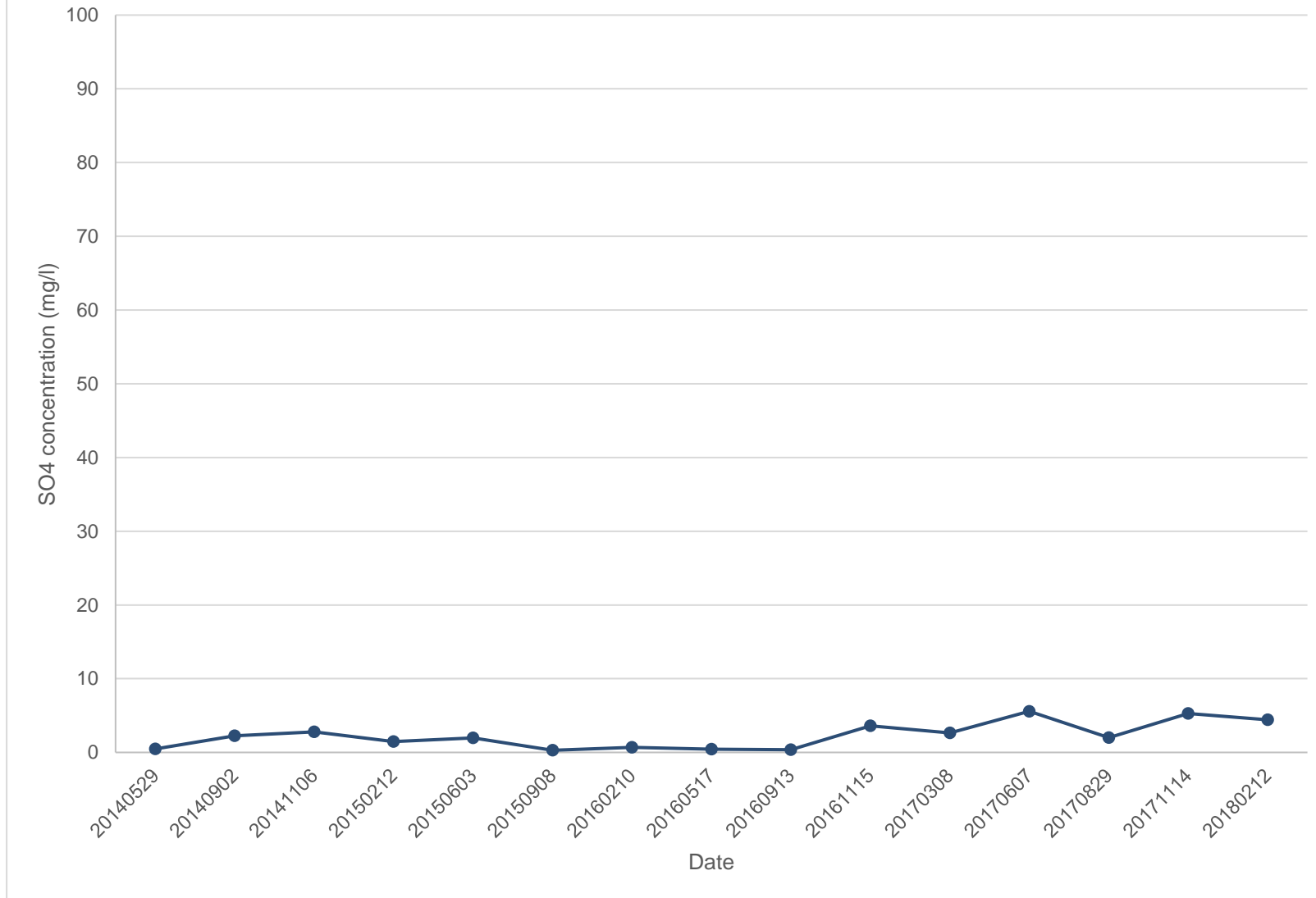
Time-series graph for borehole KB08 sulfate concentration



**Site A source boreholes: KB62 sulfate concentrations (mg/l)**

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Sulfate Concentration (mg/l)</b>
KB62	20140529	0,49
KB62	20140902	2,24
KB62	20141106	2,8
KB62	20150212	1,47
KB62	20150603	1,97
KB62	20150908	0,29
KB62	20160210	0,694
KB62	20160517	0,445
KB62	20160913	0,364
KB62	20161115	3,59
KB62	20170308	2,64
KB62	20170607	5,58
KB62	20170829	2
KB62	20171114	5,28
KB62	20180212	4,41

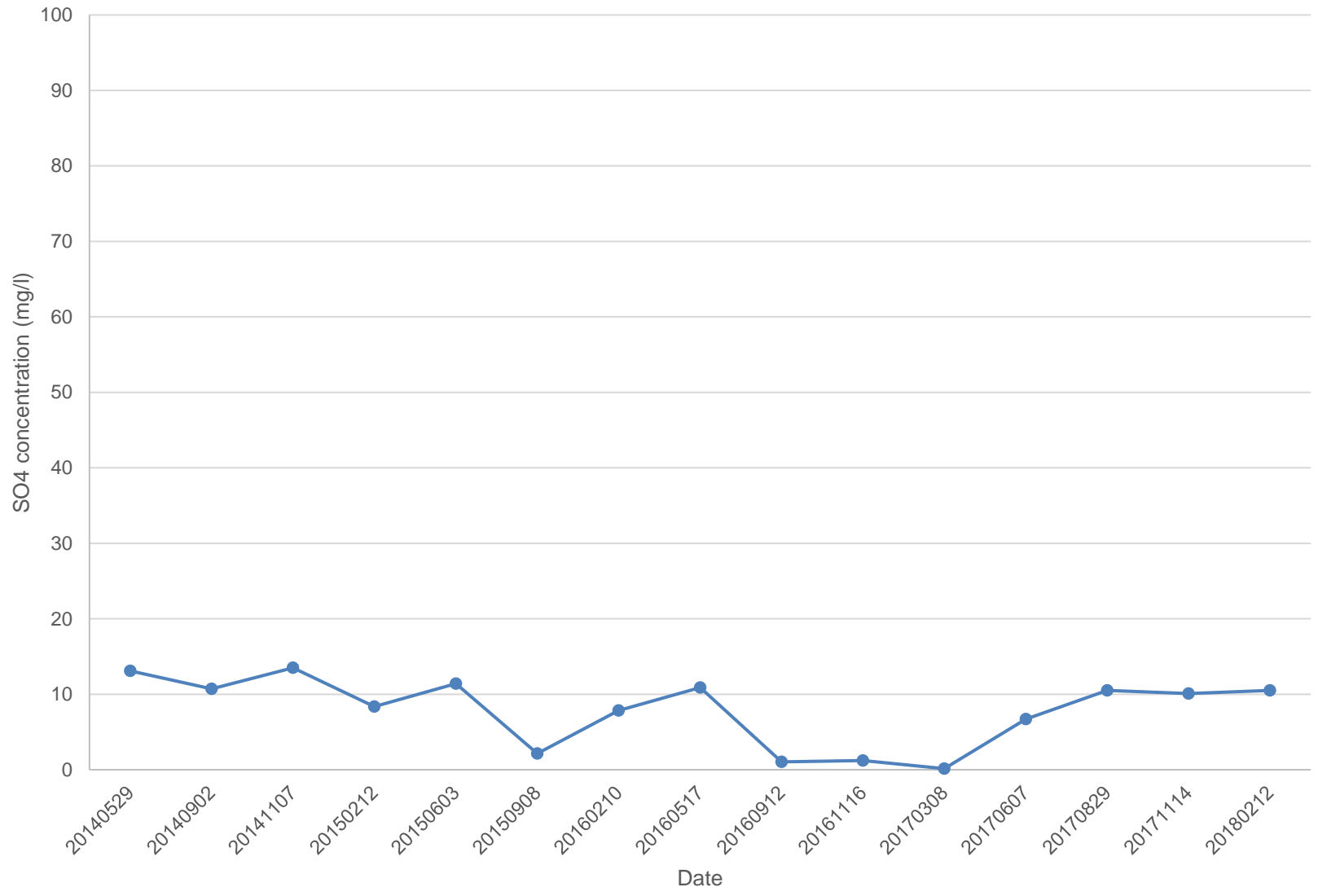
Time-series graph for borehole KB62 sulfate concentration



**Site A source boreholes: KB65 sulfate concentrations (mg/l)**

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Sulfate Concentration (mg/l)</b>
KB65	20140529	13,1
KB65	20140902	10,7
KB65	20141107	13,5
KB65	20150212	8,35
KB65	20150603	11,4
KB65	20150908	2,15
KB65	20160210	7,85
KB65	20160517	10,9
KB65	20160912	1,04
KB65	20161116	1,23
KB65	20170308	0,141
KB65	20170607	6,7
KB65	20170829	10,5
KB65	20171114	10,1
KB65	20180212	10,5

Time-series graph for borehole KB65 sulfate concontration

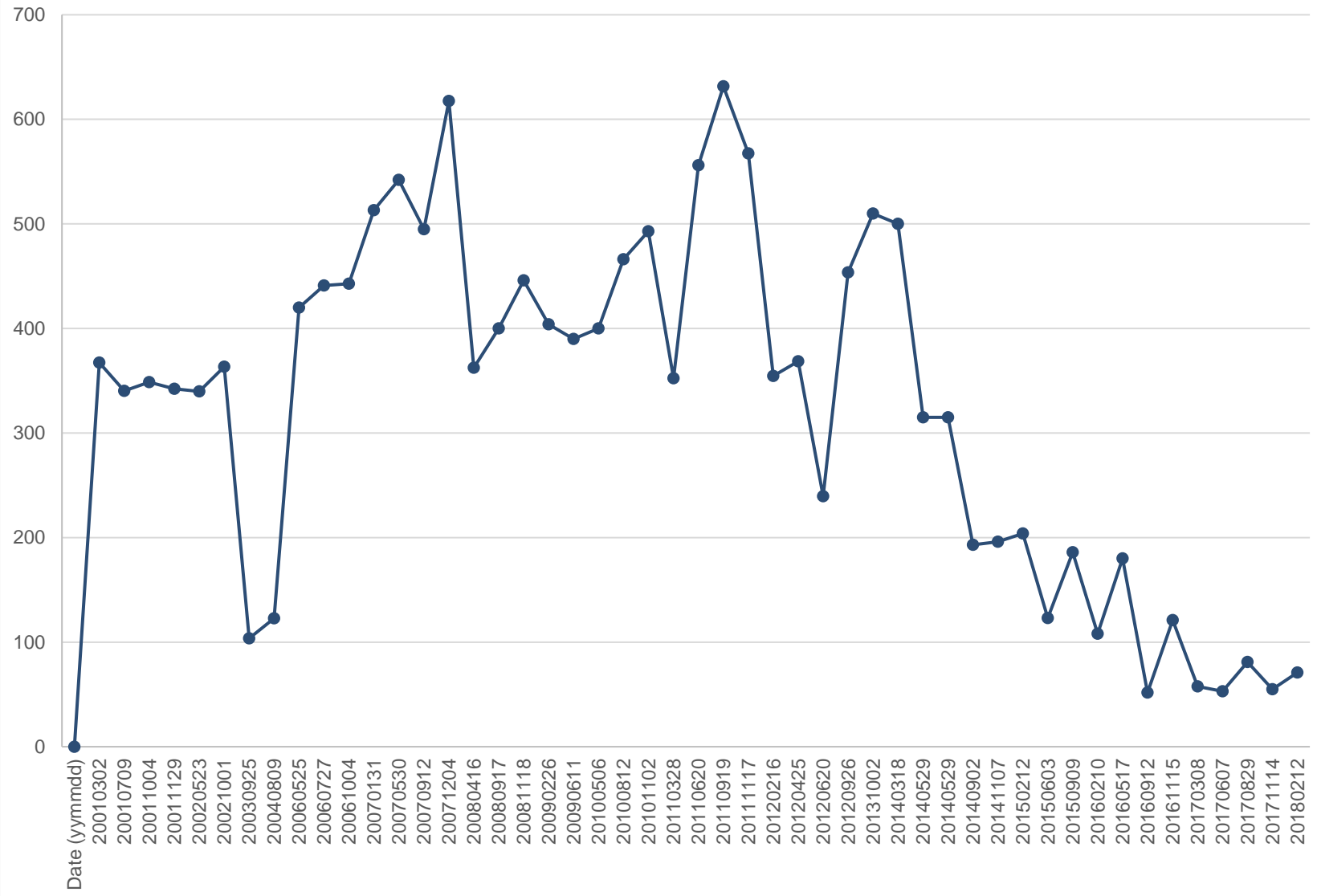


Site A source boreholes: KB35 sulfate concentrations (mg/l)

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
KB35	20010302	367,37
KB35	20010709	340,2
KB35	20011004	348,7
KB35	20011129	342,3
KB35	20020523	339,9
KB35	20021001	363,5
KB35	20030925	103,58
KB35	20040809	122,9
KB35	20060525	420
KB35	20060727	441
KB35	20061004	442,85
KB35	20070131	513
KB35	20070530	542
KB35	20070912	495
KB35	20071204	617,64
KB35	20080416	362,49
KB35	20080917	400
KB35	20081118	445,93
KB35	20090226	404
KB35	20090611	390
KB35	20100506	400
KB35	20100812	466,26
KB35	20101102	493
KB35	20110328	352,36
KB35	20110620	556,1
KB35	20110919	631,6
KB35	20111117	567,32
KB35	20120216	354,54
KB35	20120425	368,6
KB35	20120620	239,61
KB35	20120926	453,57
KB35	20131002	510
KB35	20140318	500
KB35	20140529	315
KB35	20140529	315
KB35	20140902	193
KB35	20141107	196
KB35	20150212	204
KB35	20150603	123
KB35	20150909	186
KB35	20160210	108

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Sulfate Concentration (mg/l)</b>
KB35	20160517	180
KB35	20160912	51,8
KB35	20161115	121
KB35	20170308	57,7
KB35	20170607	53,1
KB35	20170829	81
KB35	20171114	54,9
KB35	20180212	70,9

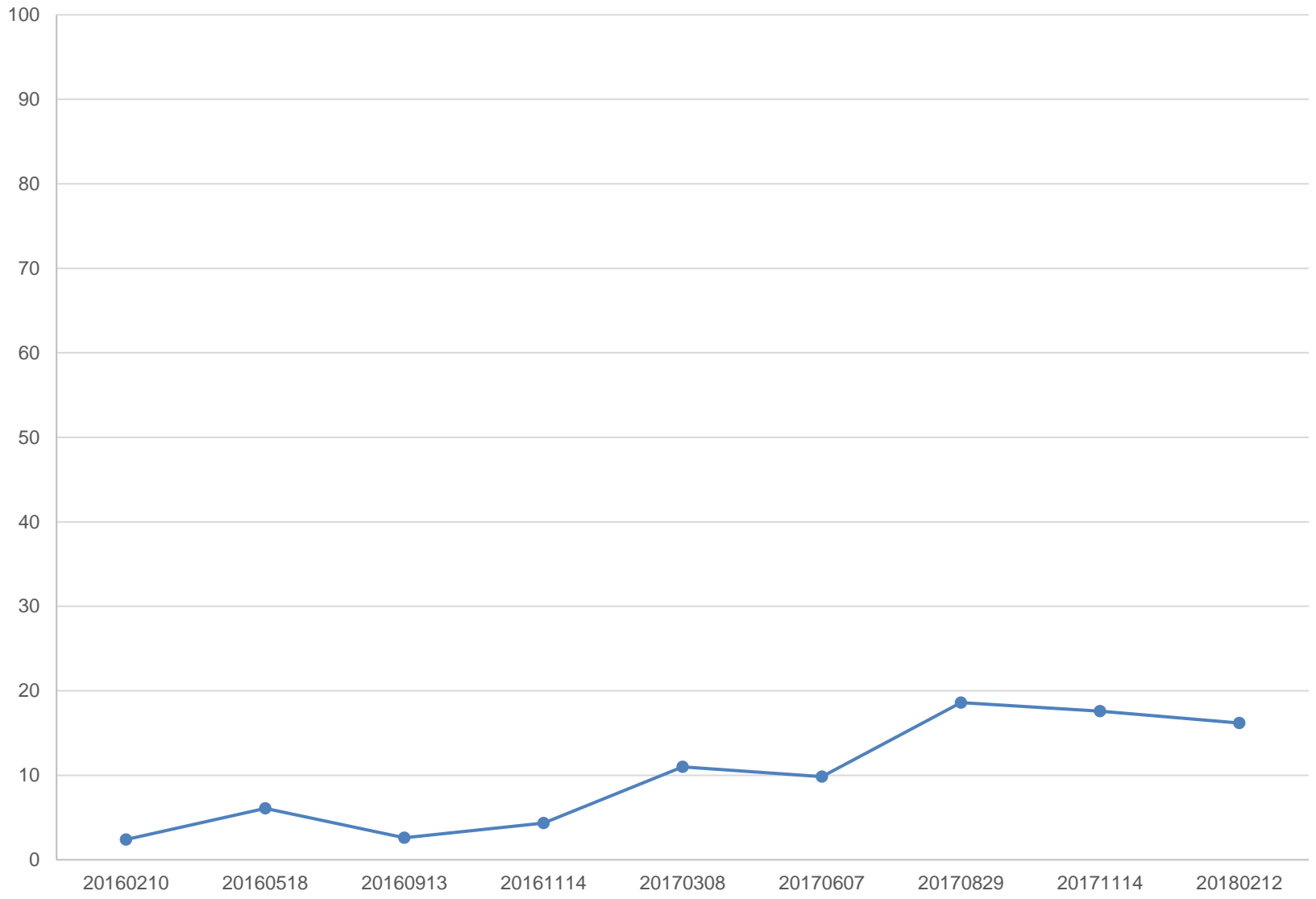
Time-series graph for borehole KB35 sulfate concentration (mg/l)



**Site A source boreholes: KB64 sulfate concentrations (mg/l)**

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Concentration (mg/l)</b>
KB64	20150908	6,64
KB64	20160210	2,4
KB64	20160518	6,07
KB64	20160913	2,61
KB64	20161114	4,34
KB64	20170308	11
KB64	20170607	9,84
KB64	20170829	18,6
KB64	20171114	17,6
KB64	20180212	16,2

Time-series graph for borehole KB64 sulfate concentration (mg/l)

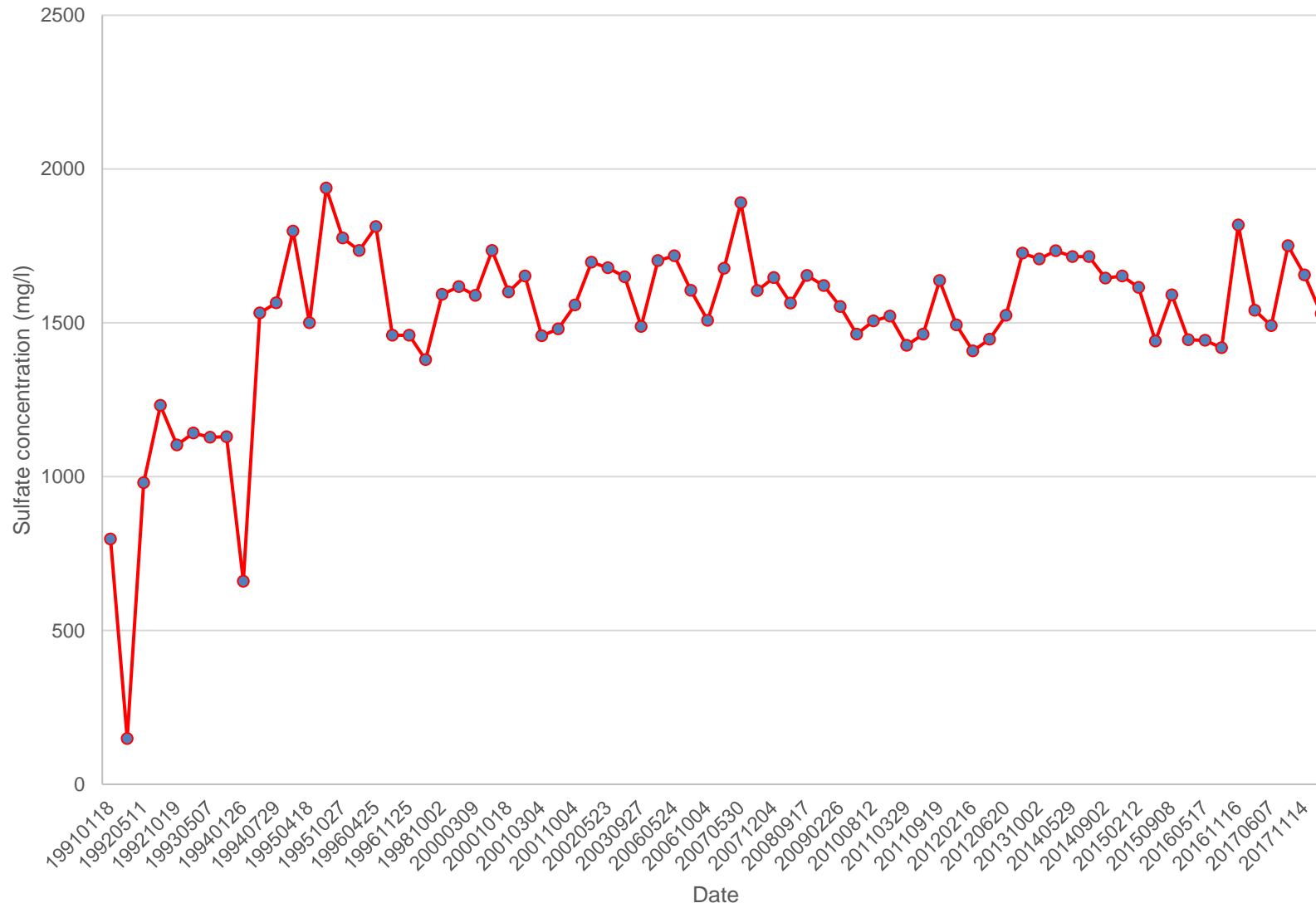


Site A Pathway Borehole: KB19 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
KB19	19910118	797
KB19	19920120	149
KB19	19920511	980
KB19	19920727	1232
KB19	19921019	1103
KB19	19930225	1142
KB19	19930507	1128
KB19	19930719	1130
KB19	19940126	660
KB19	19940503	1532
KB19	19940729	1565
KB19	19950301	1798
KB19	19950418	1500
KB19	19950728	1938
KB19	19951027	1776
KB19	19960100	1735
KB19	19960425	1813
KB19	19961016	1460
KB19	19961125	1460
KB19	19970123	1380
KB19	19981002	1593
KB19	19990419	1618
KB19	20000309	1589
KB19	20000703	1735
KB19	20001018	1600,1
KB19	20001129	1652
KB19	20010304	1458,2
KB19	20010709	1480,3
KB19	20011004	1558
KB19	20011128	1697
KB19	20020523	1679
KB19	20021001	1650
KB19	20030927	1488,52
KB19	20040810	1702,2
KB19	20060524	1718
KB19	20060727	1606
KB19	20061004	1508,24
KB19	20070131	1677
KB19	20070530	1891
KB19	20070911	1605,2
KB19	20071204	1647,03

Borehole description	Date (yyymmdd)	Sulfate Concentration (mg/l)
KB19	20080416	1563,99
KB19	20080917	1653,66
KB19	20081118	1621
KB19	20090226	1552,78
KB19	20090611	1463
KB19	20100812	1506
KB19	20101102	1522
KB19	20110329	1426,74
KB19	20110620	1463,6
KB19	20110919	1637,59
KB19	20111117	1493,49
KB19	20120216	1408,7
KB19	20120425	1446,7
KB19	20120620	1524,56
KB19	20120926	1726,32
KB19	20131002	1708
KB19	20140318	1734
KB19	20140529	1715
KB19	20140529	1715
KB19	20140902	1645
KB19	20141107	1652
KB19	20150212	1615
KB19	20150602	1441
KB19	20150908	1591
KB19	20160210	1445
KB19	20160517	1443
KB19	20160913	1419
KB19	20161116	1818
KB19	20170307	1541
KB19	20170607	1491
KB19	20170829	1751
KB19	20171114	1656
KB19	20180213	1530

Time-series graph of borehole KB19 sulfate concentration

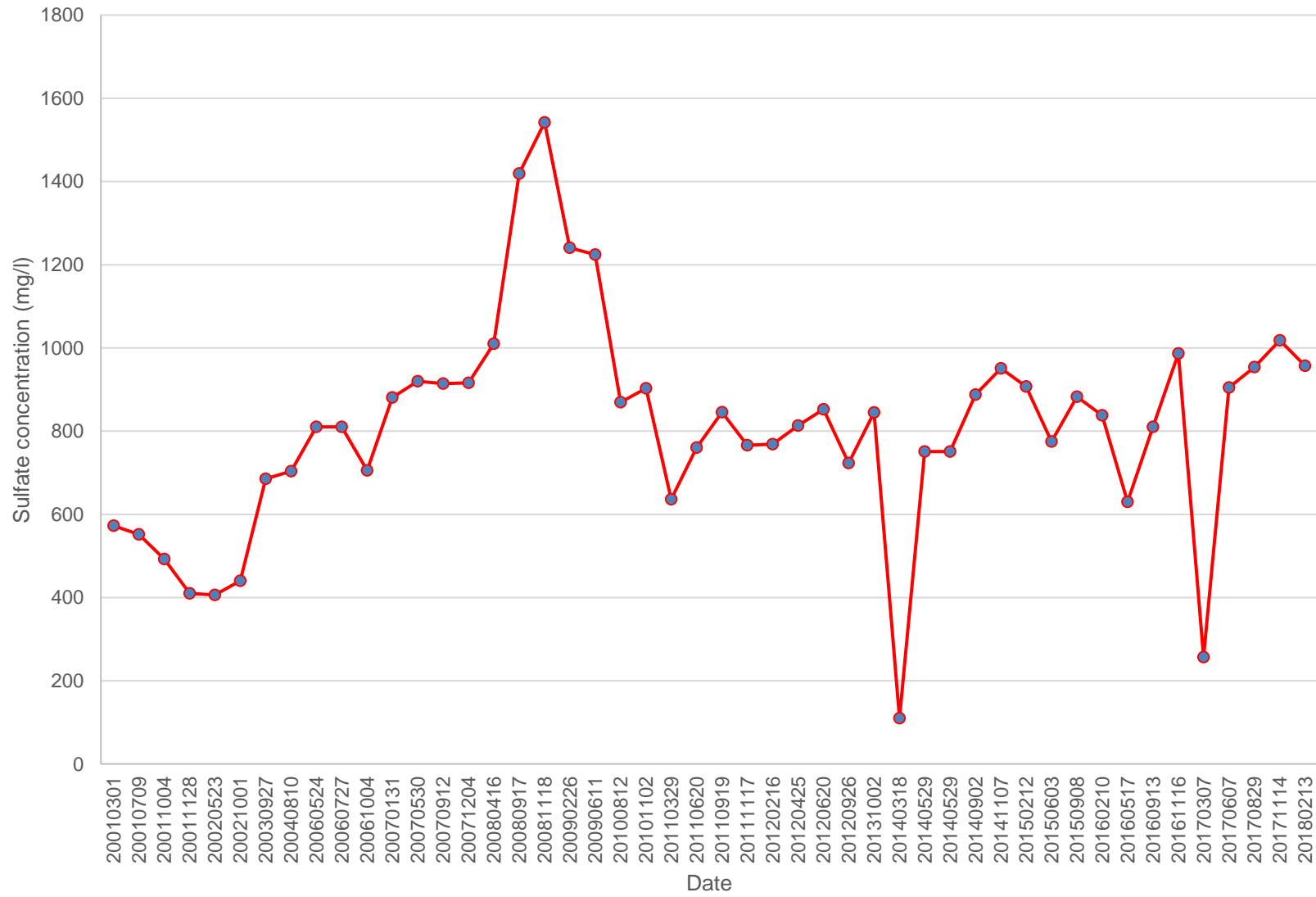


Site A Pathway Borehole: KB41 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
KB41	20010301	572,78
KB41	20010709	551,9
KB41	20011004	492,3
KB41	20011128	409,8
KB41	20020523	406
KB41	20021001	440,5
KB41	20030927	685,56
KB41	20040810	703,62
KB41	20060524	810
KB41	20060727	810
KB41	20061004	705,59
KB41	20070131	881
KB41	20070530	919,8
KB41	20070912	914,2
KB41	20071204	916,35
KB41	20080416	1010
KB41	20080917	1419,18
KB41	20081118	1542
KB41	20090226	1240,7
KB41	20090611	1224
KB41	20100812	869,21
KB41	20101102	903
KB41	20110329	636,14
KB41	20110620	760,5
KB41	20110919	845,69
KB41	20111117	765,84
KB41	20120216	768,49
KB41	20120425	813,63
KB41	20120620	852,46
KB41	20120926	723,04
KB41	20131002	845
KB41	20140318	110
KB41	20140529	751
KB41	20140529	751
KB41	20140902	888
KB41	20141107	951
KB41	20150212	907
KB41	20150603	775
KB41	20150908	883
KB41	20160210	838
KB41	20160517	630

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Sulfate Concentration (mg/l)</b>
KB41	20160913	810
KB41	20161116	987
KB41	20170307	257
KB41	20170607	905
KB41	20170829	954
KB41	20171114	1018
KB41	20180213	957

Time-series graph for borehole BK41 sulfate concentration

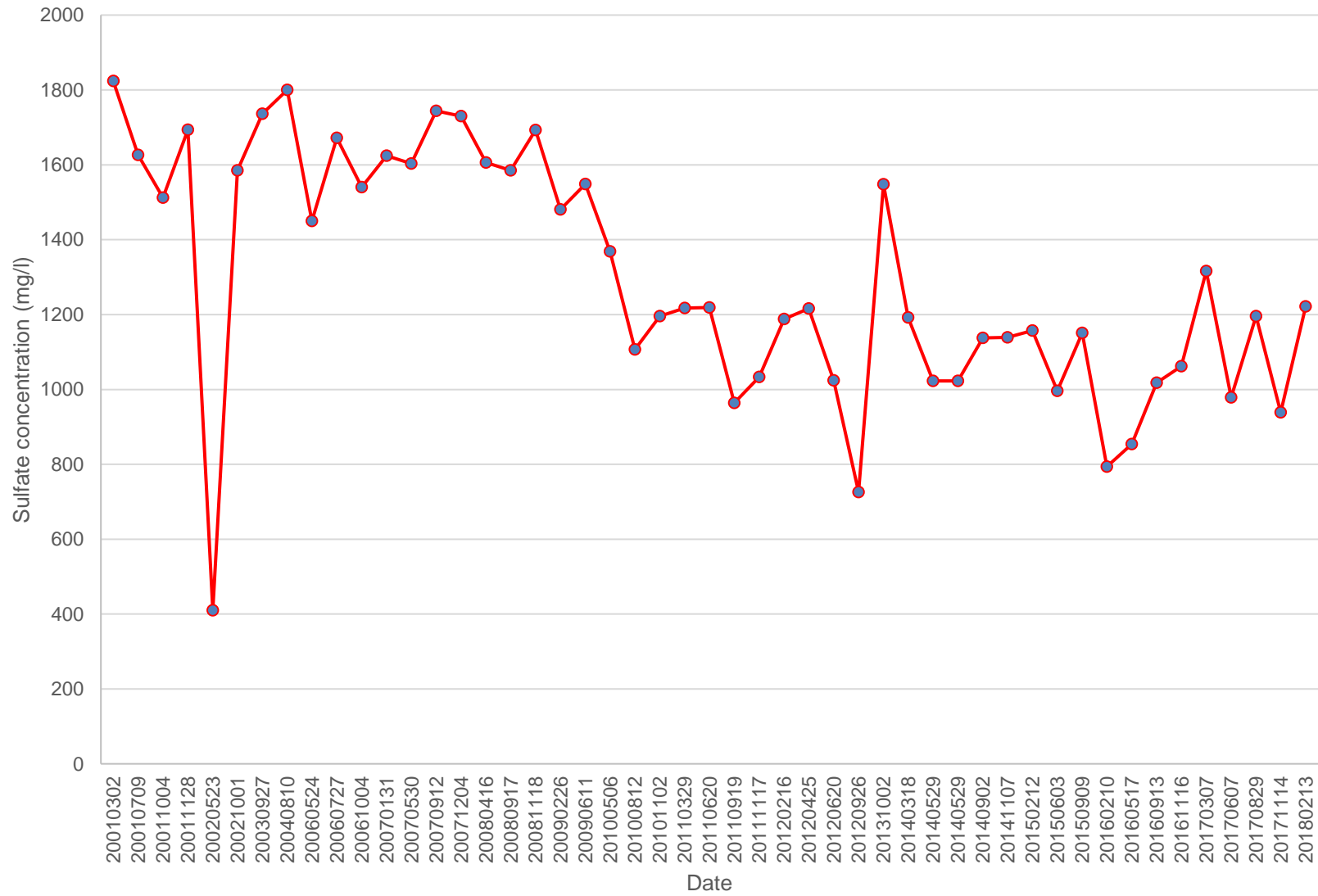


Site A Pathway Borehole: KB42 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
KB42	20010302	1823,57
KB42	20010709	1626,2
KB42	20011004	1512
KB42	20011128	1694
KB42	20020523	409,9
KB42	20021001	1585
KB42	20030927	1736,25
KB42	20040810	1799,79
KB42	20060524	1450
KB42	20060727	1671,66
KB42	20061004	1540,02
KB42	20070131	1624
KB42	20070530	1603
KB42	20070912	1744,3
KB42	20071204	1730
KB42	20080416	1605,89
KB42	20080917	1585,4
KB42	20081118	1693,22
KB42	20090226	1481
KB42	20090611	1549
KB42	20100506	1369
KB42	20100812	1107
KB42	20101102	1196
KB42	20110329	1217,73
KB42	20110620	1219
KB42	20110919	963,93
KB42	20111117	1033,39
KB42	20120216	1188,2
KB42	20120425	1215,8
KB42	20120620	1024,46
KB42	20120926	726,15
KB42	20131002	1548
KB42	20140318	1192
KB42	20140529	1023
KB42	20140529	1023
KB42	20140902	1138
KB42	20141107	1139
KB42	20150212	1157
KB42	20150603	996
KB42	20150909	1151
KB42	20160210	794

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Sulfate Concentration (mg/l)</b>
KB42	20160517	854
KB42	20160913	1018
KB42	20161116	1062
KB42	20170307	1316
KB42	20170607	979
KB42	20170829	1196
KB42	20171114	939
KB42	20180213	1222

Time-series graph for borehole KB42 sulfate concentration

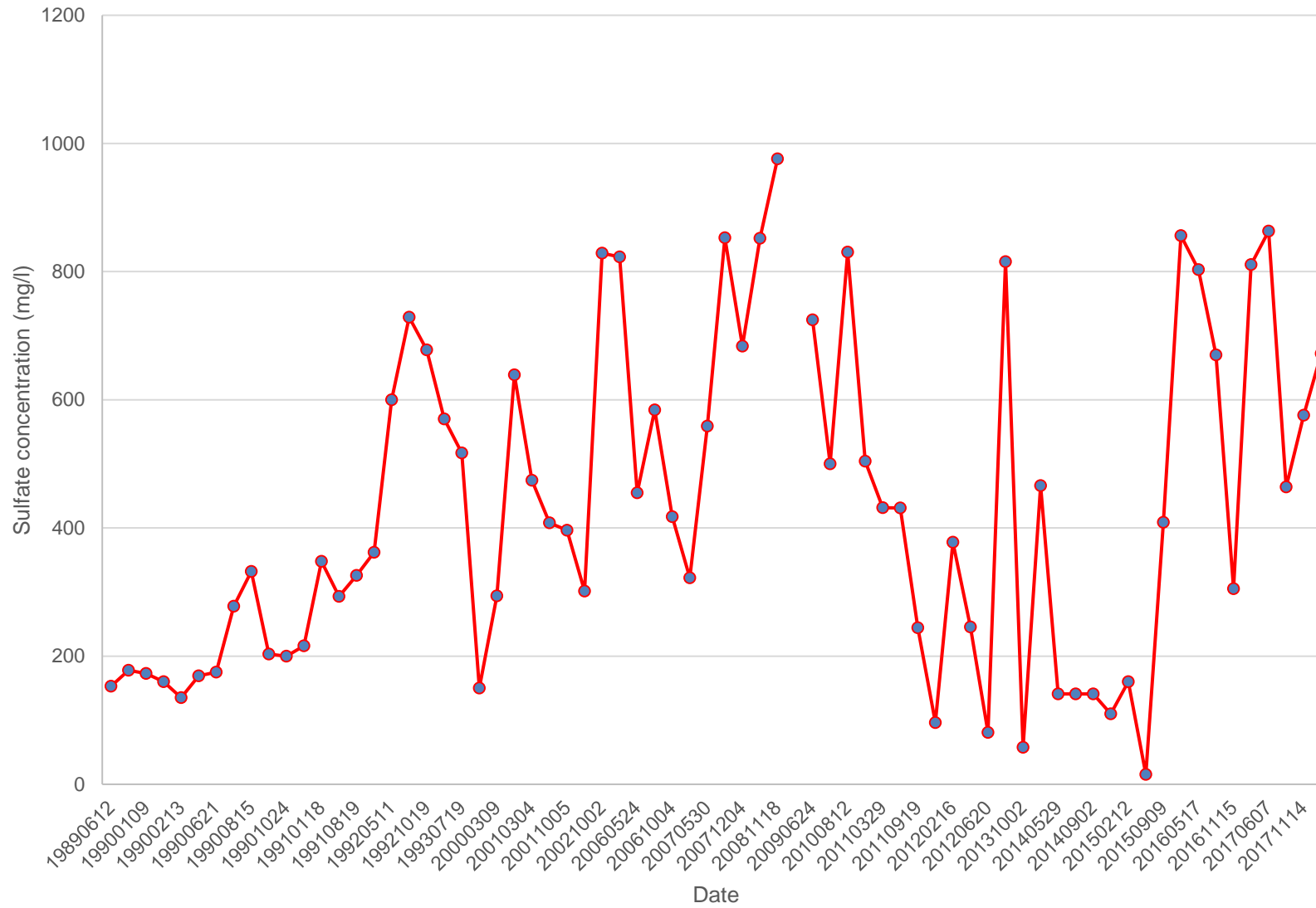


Site A Receptor Borehole: KB29 sulfate concentration

Borehole description	Date (yymmdd)	Concentration (mg/l)
KB29	19890612	153
KB29	19890612	178
KB29	19900109	173
KB29	19900213	160
KB29	19900213	135
KB29	19900423	169
KB29	19900621	175
KB29	19900815	278
KB29	19900815	332
KB29	19901024	203
KB29	19901024	200
KB29	19901102	216
KB29	19910118	348
KB29	19910502	293
KB29	19910819	326
KB29	19911030	362
KB29	19920511	600
KB29	19920727	729
KB29	19921019	678
KB29	19930225	570
KB29	19930719	517
KB29	19940126	150
KB29	20000309	294
KB29	20000704	639
KB29	20010304	474,3
KB29	20010709	408
KB29	20011005	396,2
KB29	20020523	301,3
KB29	20021002	828,9
KB29	20040810	823,09
KB29	20060524	455
KB29	20060727	584
KB29	20061004	417,37
KB29	20070131	322
KB29	20070530	559
KB29	20070912	853
KB29	20071204	683,77
KB29	20080917	852
KB29	20081118	976,05
KB29	20081216	
KB29	20090624	724,9

Borehole description	Date (yymmdd)	Concentration (mg/l)
KB29	20100506	500
KB29	20100812	830,6
KB29	20101102	504
KB29	20110329	431,78
KB29	20110620	431
KB29	20110919	244,29
KB29	20111117	96,14
KB29	20120216	377,52
KB29	20120425	245,6
KB29	20120620	80,91
KB29	20120926	815,54
KB29	20131002	57,8
KB29	20140318	466
KB29	20140529	141
KB29	20140529	141
KB29	20140902	141
KB29	20141107	110
KB29	20150212	160
KB29	20150603	15,4
KB29	20150909	409
KB29	20160210	856
KB29	20160517	803
KB29	20160912	670
KB29	20161115	305
KB29	20170307	811
KB29	20170607	863
KB29	20170929	464
KB29	20171114	576
KB29	20180213	672

Time-series graph for borehole KB29 sulfate concentration

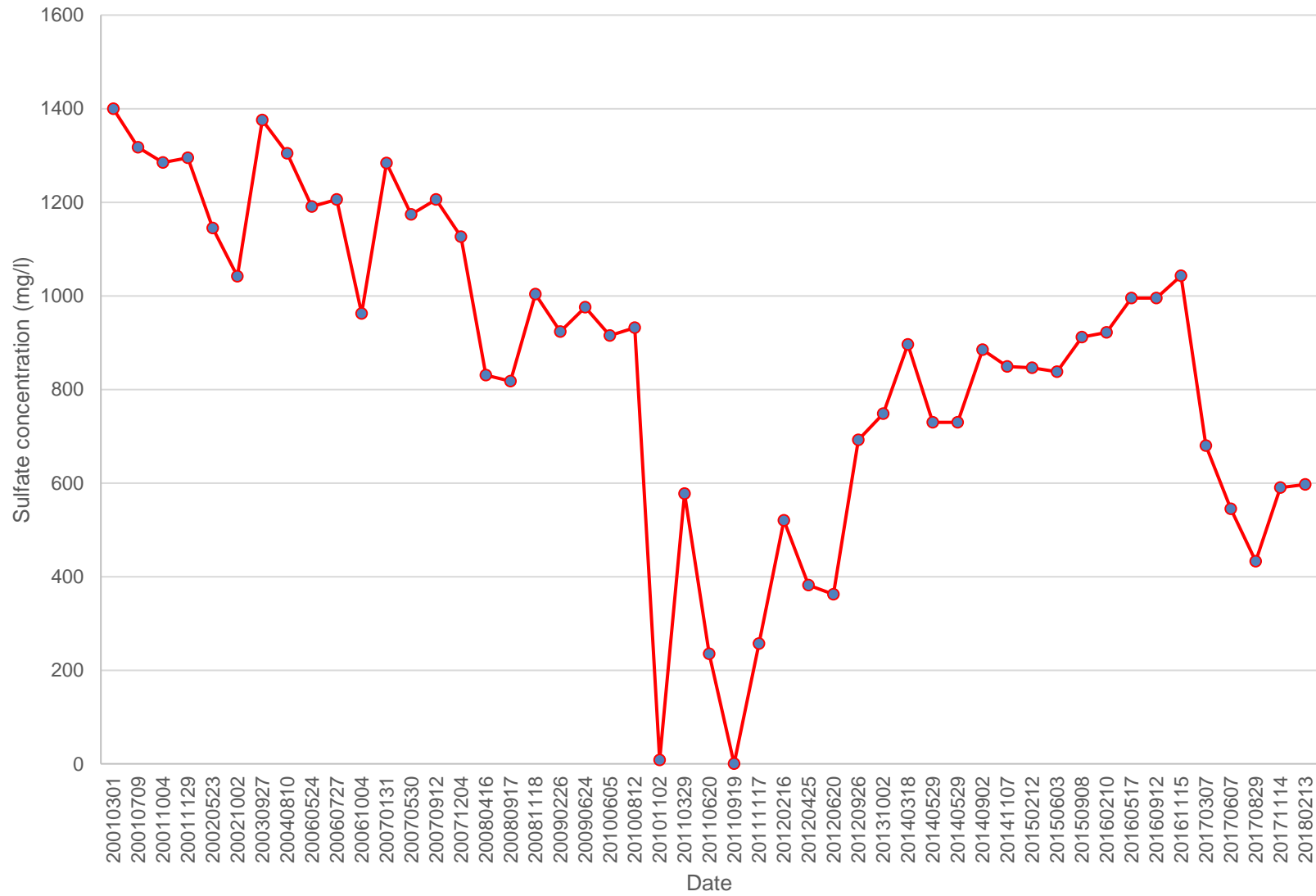


Site A Receptor Borehole: KB39 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
KB39	20010301	1399,9
KB39	20010709	1317,6
KB39	20011004	1285
KB39	20011129	1295
KB39	20020523	1144,6
KB39	20021002	1042
KB39	20030927	1375,6
KB39	20040810	1304,31
KB39	20060524	1191
KB39	20060727	1206
KB39	20061004	962,42
KB39	20070131	1284
KB39	20070530	1174
KB39	20070912	1206
KB39	20071204	1126,52
KB39	20080416	830,62
KB39	20080917	817,74
KB39	20081118	1003,62
KB39	20090226	923,49
KB39	20090624	975,7
KB39	20100605	915
KB39	20100812	932,15
KB39	20101102	8,01
KB39	20110329	577,08
KB39	20110620	235,1
KB39	20110919	0,11
KB39	20111117	256,88
KB39	20120216	520,19
KB39	20120425	381,58
KB39	20120620	362,48
KB39	20120926	691,97
KB39	20131002	748
KB39	20140318	896
KB39	20140529	730
KB39	20140529	730
KB39	20140902	885
KB39	20141107	849
KB39	20150212	846
KB39	20150603	838
KB39	20150908	912
KB39	20160210	922

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Sulfate Concentration (mg/l)</b>
KB39	20160517	995
KB39	20160912	995
KB39	20161115	1043
KB39	20170307	680
KB39	20170607	545
KB39	20170829	433
KB39	20171114	590
KB39	20180213	597

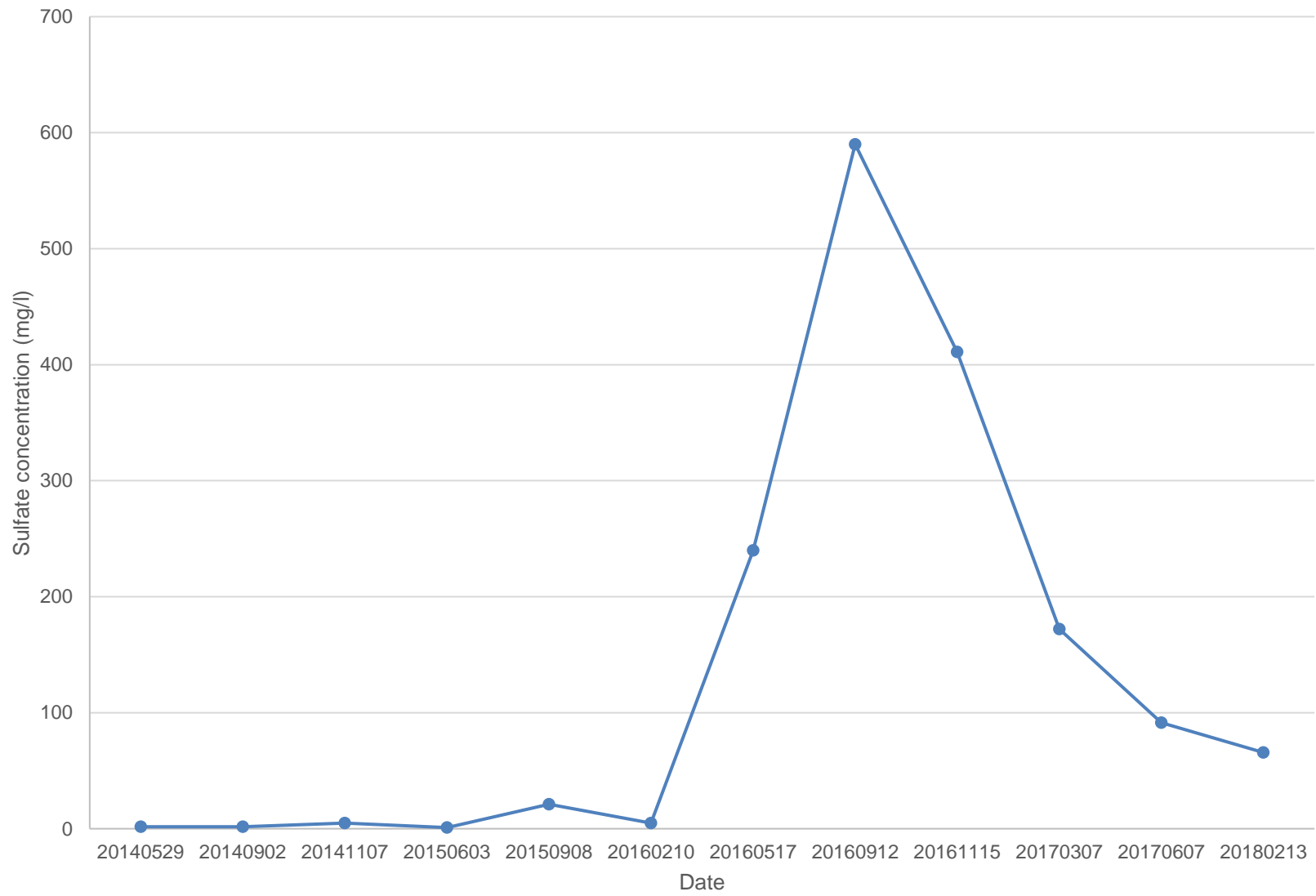
Time-series graph for borehole KB39 sulfate concentration



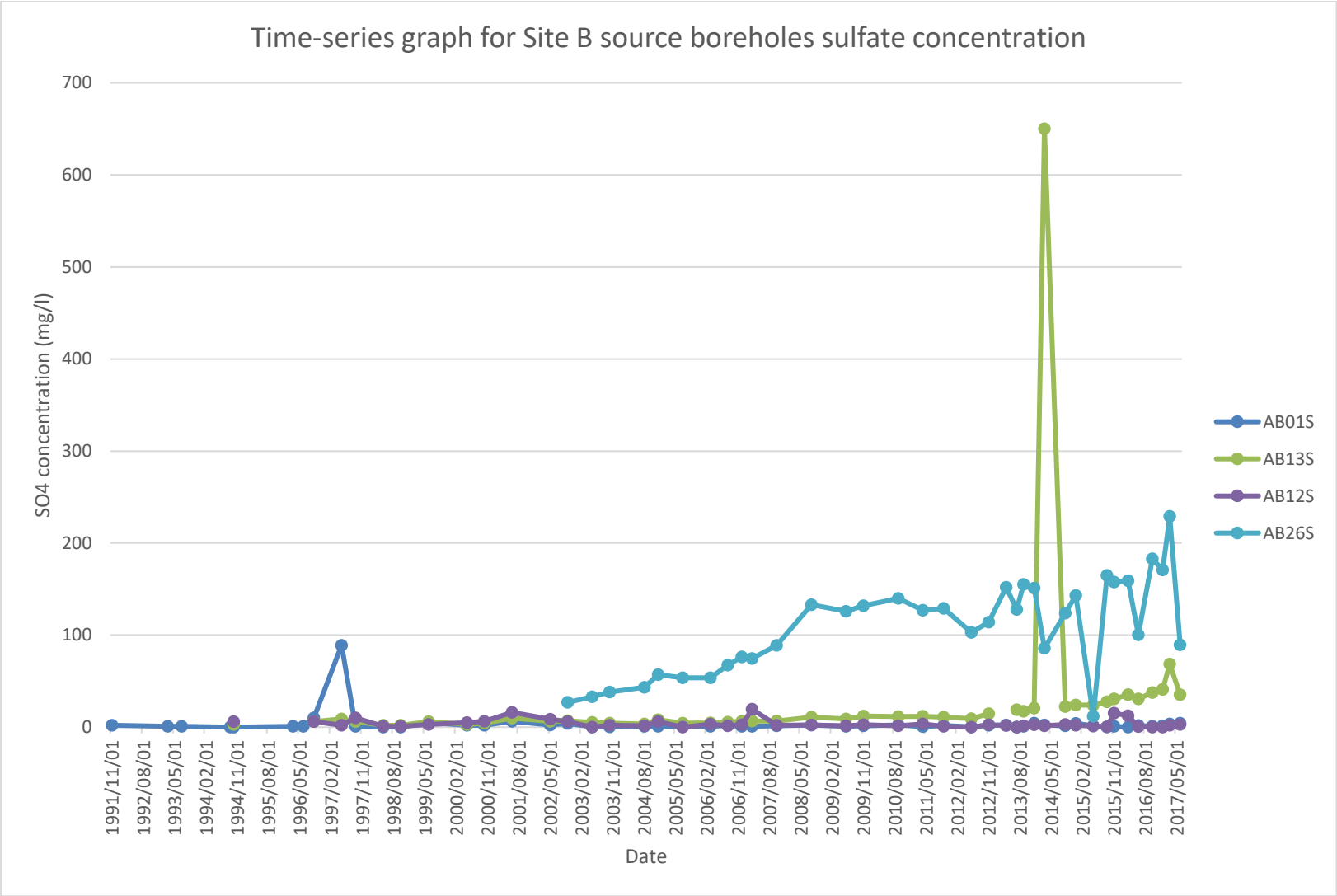
**Site A Receptor Borehole: KB67 sulfate concentration**

<b>Borehole description</b>	<b>Date (yymmdd)</b>	<b>Sulfate Concentration (mg/l)</b>
KB67	20140529	1,73
KB67	20140902	1,74
KB67	20141107	4,75
KB67	20150603	0,98
KB67	20150908	21
KB67	20160210	4,92
KB67	20160517	240
KB67	20160912	590
KB67	20161115	411
KB67	20170307	172
KB67	20170607	91,4
KB67	20180213	65,8

Time-series graph for borehole KB67 sulfate concentration

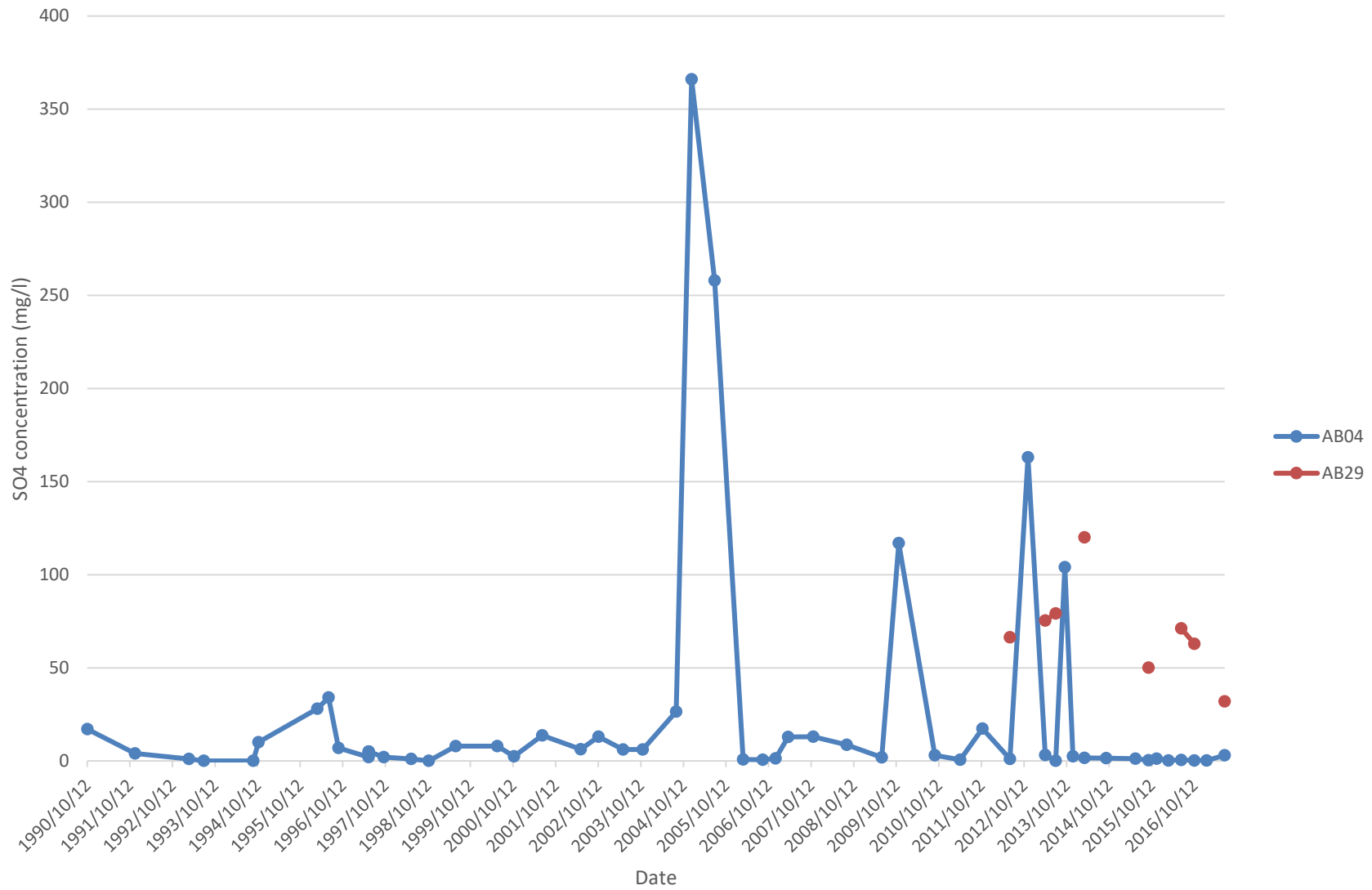


**ANNEXURE B2: SULFATE DATA AND TIME-SERIES GRAPHS FOR SITE B**





Time-series graph for Site B  
receptor boreholes sulfate concentration



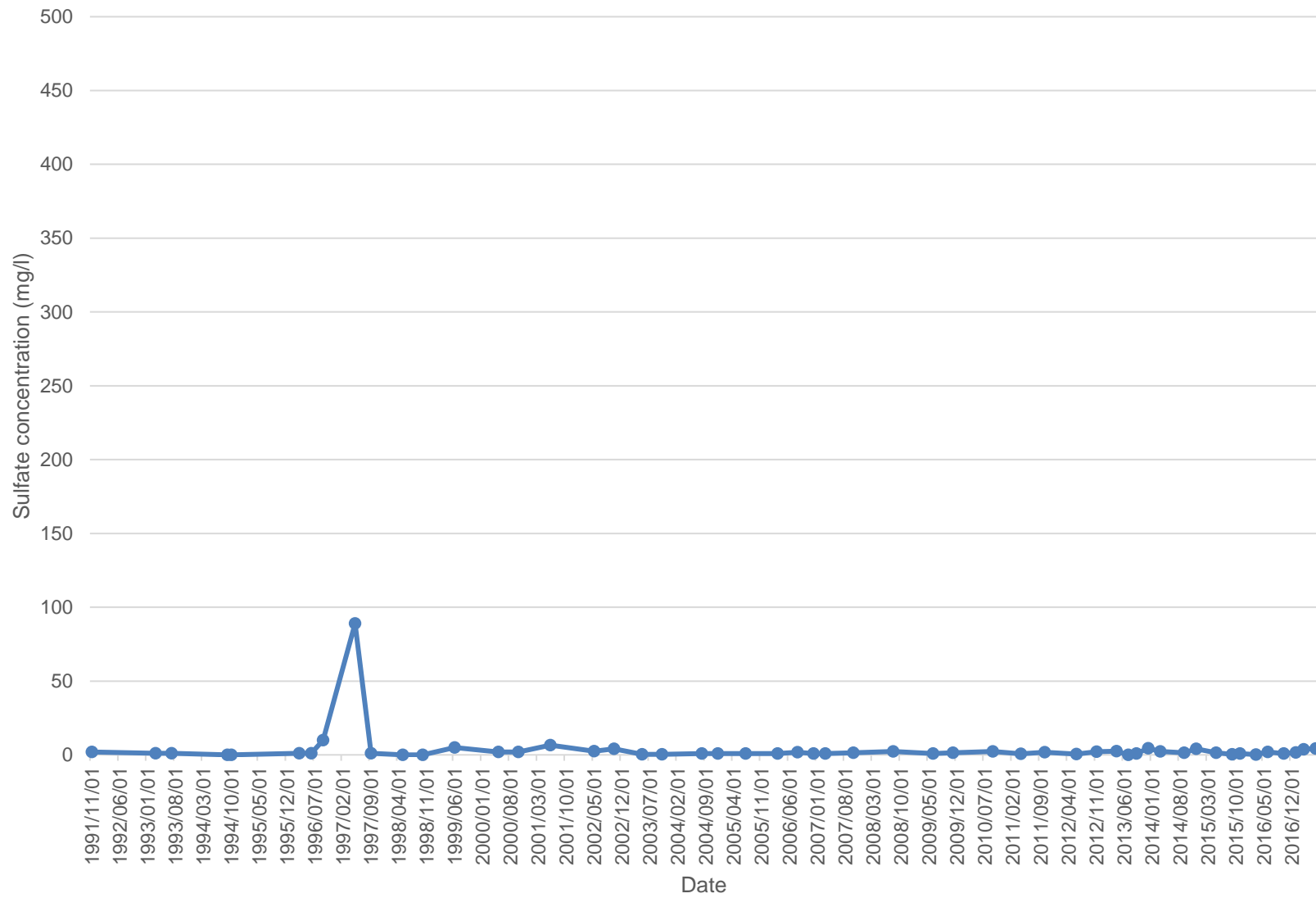
Site B Source Boreholes: AB01 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB01	1991/11/26	2
AB01	1993/03/02	1
AB01	1993/07/08	1
AB01	1994/09/15	0
AB01	1994/10/19	0
AB01	1996/03/07	1
AB01	1996/06/11	1
AB01	1996/09/05	10
AB01	1997/05/21	89
AB01	1997/09/28	1
AB01	1998/05/22	0
AB01	1998/10/20	0
AB01	1999/06/07	5
AB01	2000/05/29	2
AB01	2000/10/19	2
AB01	2001/06/19	6,5
AB01	2002/05/15	2,4
AB01	2002/10/15	4
AB01	2003/05/13	0,4
AB01	2003/10/29	0,4
AB01	2004/08/11	0,8
AB01	2004/12/21	0,9
AB01	2005/07/06	0,9
AB01	2006/03/07	0,8
AB01	2006/08/23	1,8

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB01	2006/12/13	0,8
AB01	2007/03/28	0,9
AB01	2007/10/30	1,4
AB01	2008/08/13	2,3
AB01	2009/06/10	0,95
AB01	2009/11/02	1,44
AB01	2010/09/07	2,38
AB01	2011/04/13	0,62
AB01	2011/10/21	1,79
AB01	2012/06/12	0,46
AB01	2012/11/15	2,15
AB01	2013/04/11	2,43
AB01	2013/07/09	0,04
AB01	2013/09/26	0,89
AB01	2013/12/06	4,41
AB01	2014/03/16	2,34
AB01	2014/09/17	1,44
AB01	2014/12/09	4,01
AB01	2015/05/25	1,49
AB01	2015/09/15	0,287
AB01	2015/11/24	0,86
AB01	2016/03/02	0,162
AB01	2016/06/22	1,87
AB01	2016/10/11	0,955
AB01	2017/01/24	1,55

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB01	2017/03/29	3,64
AB01	2017/06/28	4,33

Time-series graph at source-pathway borehole AB01 for sulfate concentration

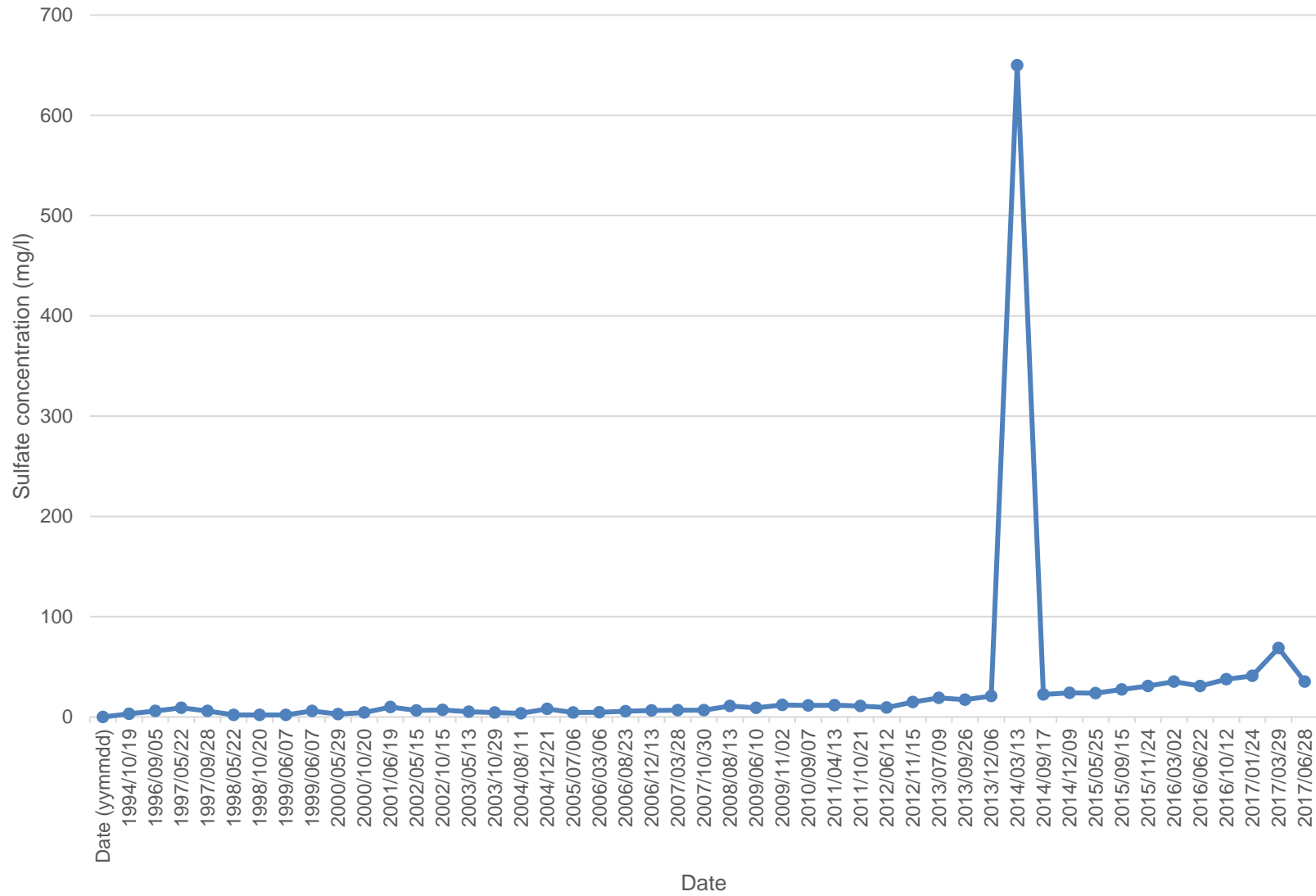


Site B Source Borehole: AB13S sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB13	1994/10/19	3
AB13	1996/09/05	6
AB13	1997/05/22	9
AB13	1997/09/28	6
AB13	1998/05/22	2
AB13	1998/10/20	2
AB13	1999/06/07	2
AB13	1999/06/07	6
AB13	2000/05/29	2,8
AB13	2000/10/20	4,5
AB13	2001/06/19	9,8
AB13	2002/05/15	6,5
AB13	2002/10/15	7
AB13	2003/05/13	5,1
AB13	2003/10/29	4,5
AB13	2004/08/11	3,5
AB13	2004/12/21	8
AB13	2005/07/06	4,5
AB13	2006/03/06	4,7
AB13	2006/08/23	5,6
AB13	2006/12/13	6,4
AB13	2007/03/28	6,7
AB13	2007/10/30	6,7
AB13	2008/08/13	11
AB13	2009/06/10	9,06

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB13	2009/11/02	12
AB13	2010/09/07	11,52
AB13	2011/04/13	11,72
AB13	2011/10/21	10,99
AB13	2012/06/12	9,35
AB13	2012/11/15	14,8
AB13	2013/07/09	19,1
AB13	2013/09/26	17,2
AB13	2013/12/06	20,8
AB13	2014/03/13	650
AB13	2014/09/17	22,3
AB13	2014/12/09	24
AB13	2015/05/25	23,8
AB13	2015/09/15	27,5
AB13	2015/11/24	30,74
AB13	2016/03/02	35,2
AB13	2016/06/22	30,74
AB13	2016/10/12	37,6
AB13	2017/01/24	41,1
AB13	2017/03/29	68,7
AB13	2017/06/28	35,2

Time-series graph at source borehole AB13 for sulfate concentration

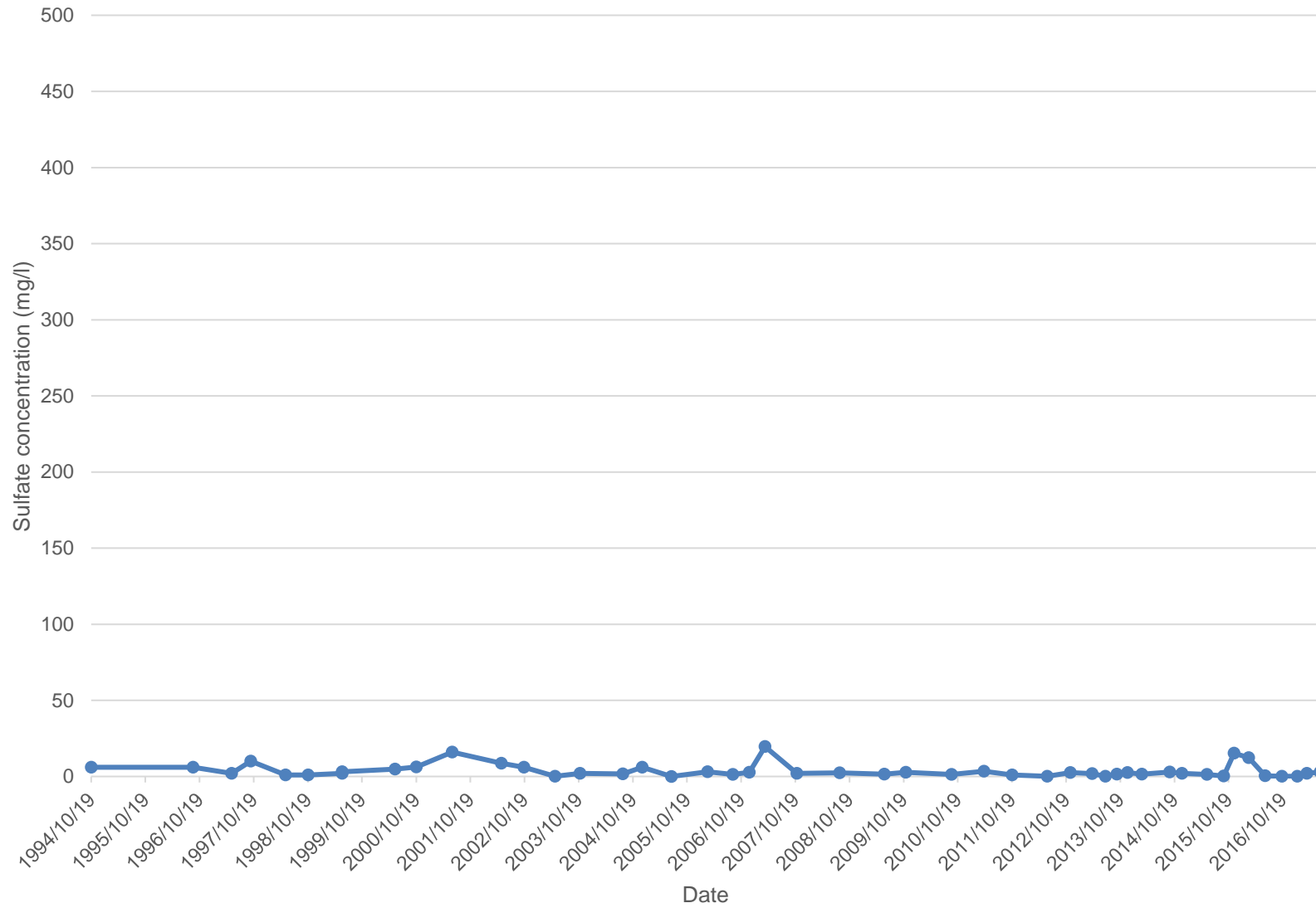


Site B Source Borehole: AB12S sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB12	1994/10/19	6
AB12	1996/09/05	6
AB12	1997/05/22	2
AB12	1997/09/28	10
AB12	1998/05/22	1
AB12	1998/10/20	1
AB12	1999/06/07	2
AB12	1999/06/07	3
AB12	2000/05/29	4,8
AB12	2000/10/20	6,3
AB12	2001/06/19	16
AB12	2002/05/15	8,6
AB12	2002/10/15	6
AB12	2003/05/13	0,2
AB12	2003/10/29	2,1
AB12	2004/08/11	1,6
AB12	2004/12/21	6,1
AB12	2005/07/06	0
AB12	2006/03/06	3,1
AB12	2006/08/23	1,4
AB12	2006/12/13	2,7
AB12	2007/03/28	19,6
AB12	2007/10/30	2,1
AB12	2008/08/13	2,4
AB12	2009/06/10	1,48

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB12	2009/11/02	2,7
AB12	2010/09/07	1,37
AB12	2011/04/13	3,38
AB12	2011/10/21	1
AB12	2012/06/12	0,13
AB12	2012/11/15	2,52
AB12	2013/04/11	1,81
AB12	2013/07/10	0,04
AB12	2013/09/26	1,48
AB12	2013/12/06	2,61
AB12	2014/03/13	1,56
AB12	2014/09/17	2,88
AB12	2014/12/09	2,08
AB12	2015/05/25	1,29
AB12	2015/09/15	0,287
AB12	2015/11/24	15,21
AB12	2016/03/02	12,3
AB12	2016/06/22	0,5
AB12	2016/10/12	0,141
AB12	2017/01/24	0,141
AB12	2017/03/29	2,07
AB12	2017/06/28	2,89

Time-series graph at source borehole AB12S for sulfate concentration

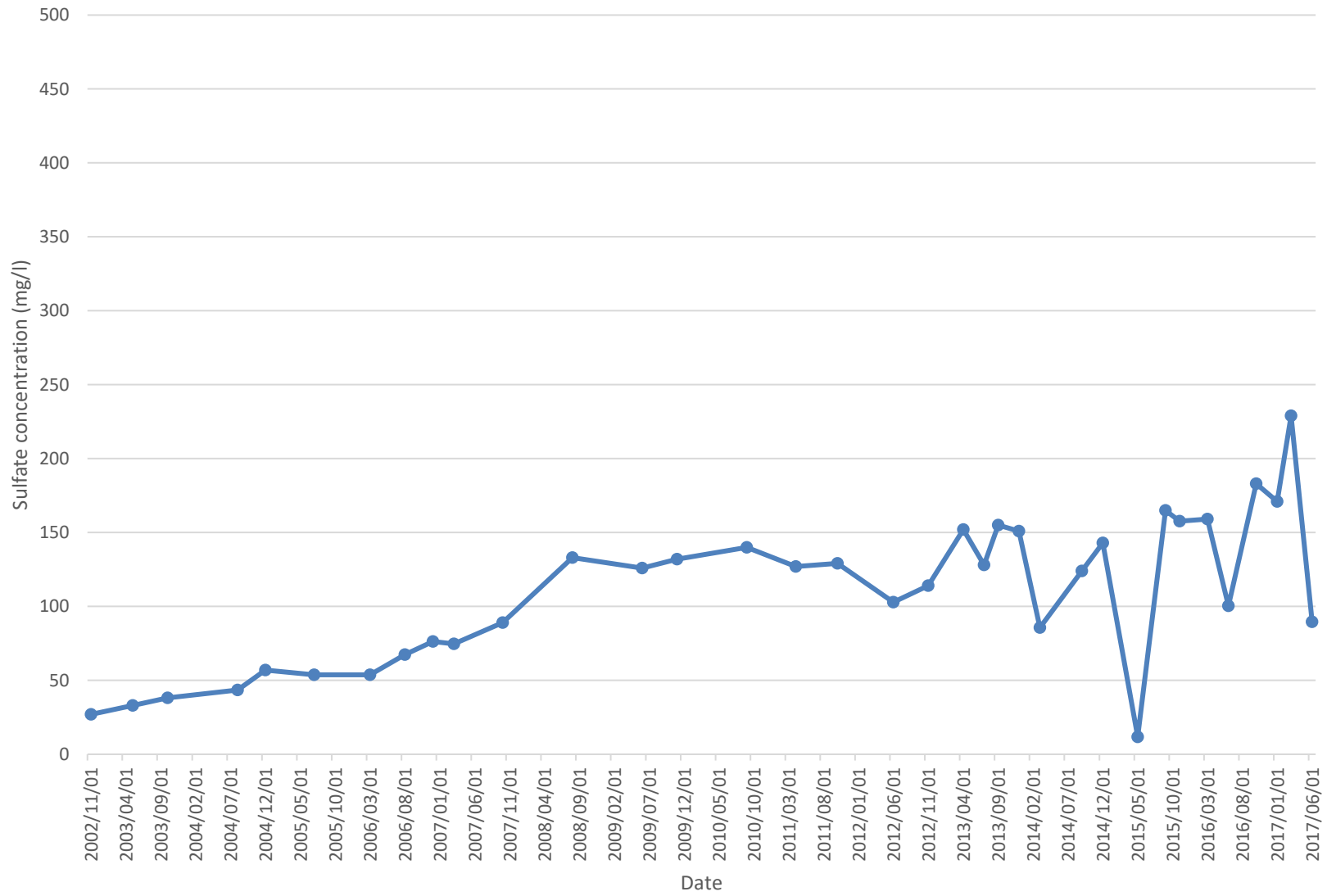


Site B Source Borehole: AB26S for sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB26	2002/11/17	27
AB26	2003/05/13	33
AB26	2003/10/29	38,2
AB26	2004/08/12	43,4
AB26	2004/12/22	57
AB26	2005/07/06	53,8
AB26	2006/03/06	53,8
AB26	2006/08/23	67,4
AB26	2006/12/12	76,3
AB26	2007/03/28	74,7
AB26	2007/10/30	89
AB26	2008/08/13	133
AB26	2009/06/10	126
AB26	2009/11/02	132
AB26	2010/09/07	140
AB26	2011/04/13	127
AB26	2011/10/21	129,11
AB26	2012/06/12	102,96
AB26	2012/11/15	114
AB26	2013/04/11	152
AB26	2013/07/09	128
AB26	2013/09/26	155
AB26	2013/12/06	151
AB26	2014/03/13	85,7
AB26	2014/09/17	124

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB26	2014/12/09	143
AB26	2015/05/25	11,8
AB26	2015/09/15	165
AB26	2015/11/24	157,6
AB26	2016/03/02	159
AB26	2016/06/22	100,4
AB26	2016/10/12	183
AB26	2017/01/25	171
AB26	2017/03/30	229
AB26	2017/06/28	89,6

Time-series graph at source borehole AB26 for sulfate concentration



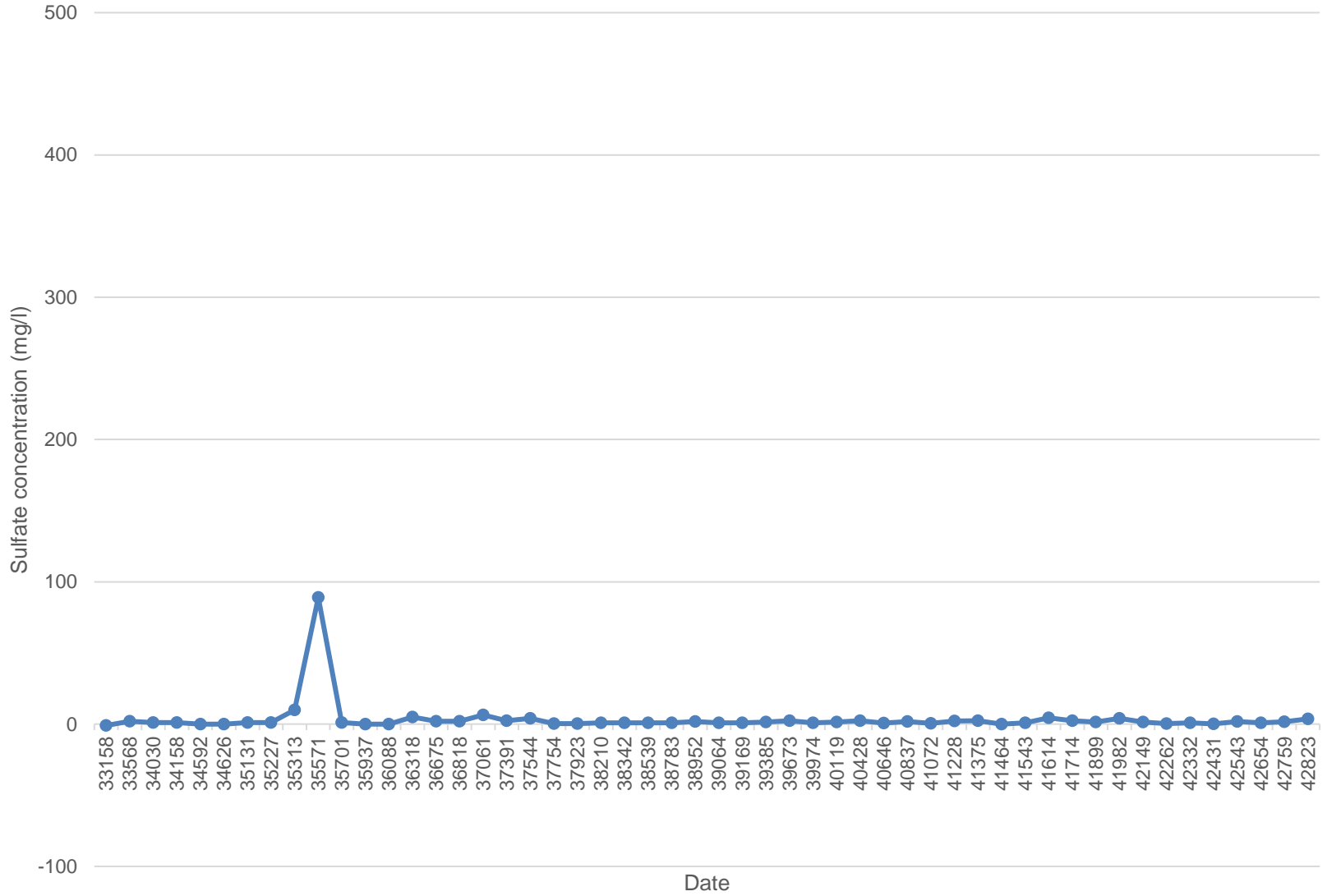
Site B Pathway Borehole: AB01S sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB01	1991/11/26	2
AB01	1993/03/02	1
AB01	1993/07/08	1
AB01	1994/09/15	0
AB01	1994/10/19	0
AB01	1996/03/07	1
AB01	1996/06/11	1
AB01	1996/09/05	10
AB01	1997/05/21	89
AB01	1997/09/28	1
AB01	1998/05/22	0
AB01	1998/10/20	0
AB01	1999/06/07	5
AB01	2000/05/29	2
AB01	2000/10/19	2
AB01	2001/06/19	6,5
AB01	2002/05/15	2,4
AB01	2002/10/15	4
AB01	2003/05/13	0,4
AB01	2003/10/29	0,4
AB01	2004/08/11	0,8
AB01	2004/12/21	0,9
AB01	2005/07/06	0,9
AB01	2006/03/07	0,8
AB01	2006/08/23	1,8

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB01	2006/12/13	0,8
AB01	2007/03/28	0,9
AB01	2007/10/30	1,4
AB01	2008/08/13	2,3
AB01	2009/06/10	0,95
AB01	2009/11/02	1,44
AB01	2010/09/07	2,38
AB01	2011/04/13	0,62
AB01	2011/10/21	1,79
AB01	2012/06/12	0,46
AB01	2012/11/15	2,15
AB01	2013/04/11	2,43
AB01	2013/07/09	0,04
AB01	2013/09/26	0,89
AB01	2013/12/06	4,41
AB01	2014/03/16	2,34
AB01	2014/09/17	1,44
AB01	2014/12/09	4,01
AB01	2015/05/25	1,49
AB01	2015/09/15	0,287
AB01	2015/11/24	0,86
AB01	2016/03/02	0,162
AB01	2016/06/22	1,87
AB01	2016/10/11	0,955
AB01	2017/01/24	1,55

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB01	2017/03/29	3,64
AB01	2017/06/28	4,33

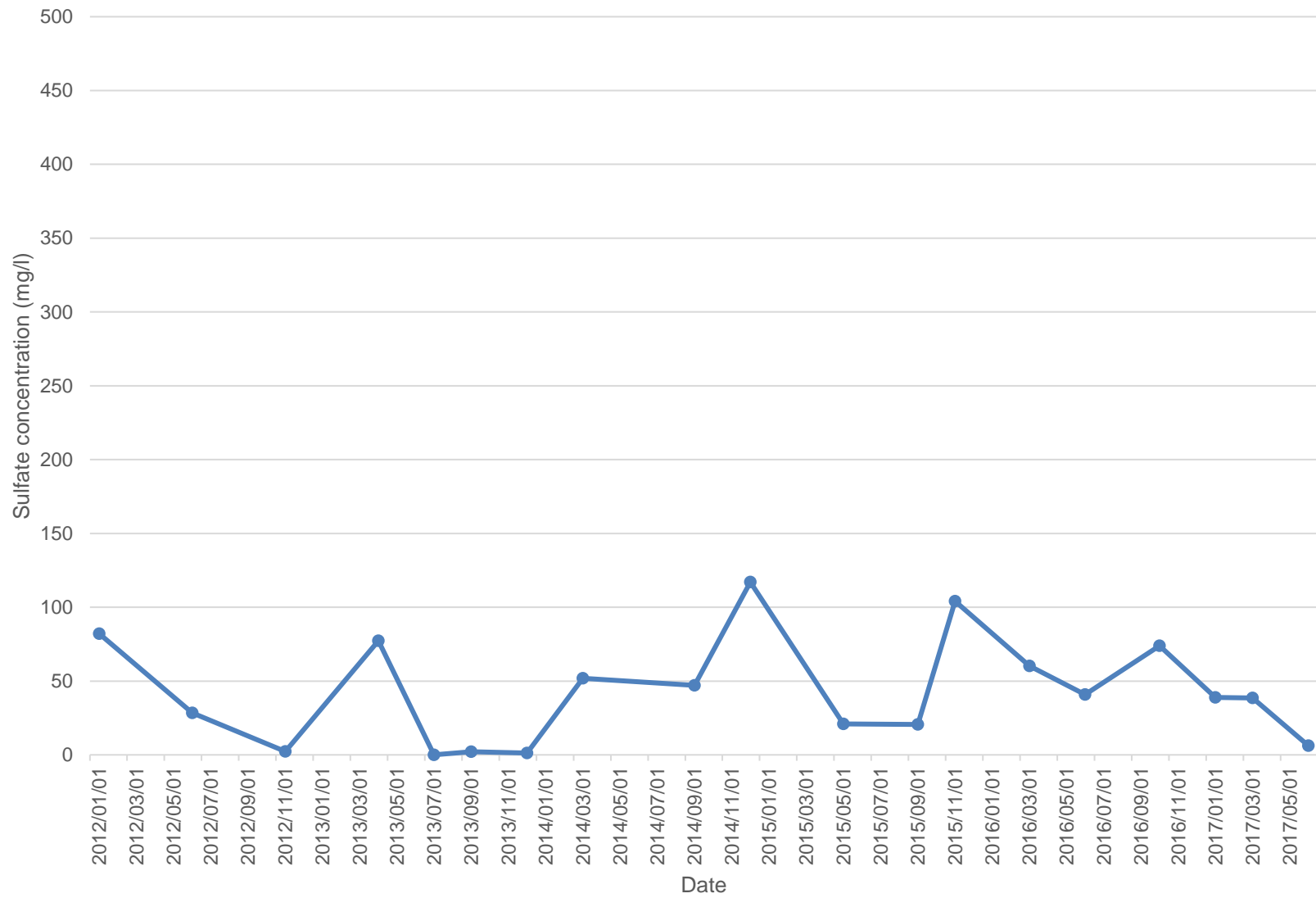
Time-series graph at pathway borehole AB01 for sulfate concentration



Site B Pathway Borehole: AB36 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB36	2012/01/26	82
AB36	2012/06/12	28,44
AB36	2012/11/15	2,36
AB36	2013/04/11	77,3
AB36	2013/07/09	0,04
AB36	2013/09/26	2,05
AB36	2013/12/05	1,18
AB36	2014/03/13	51,9
AB36	2014/09/17	47,1
AB36	2014/12/09	117
AB36	2015/05/25	21
AB36	2015/09/15	20,6
AB36	2015/11/24	104,1
AB36	2016/03/02	60,3
AB36	2016/06/22	40,9
AB36	2016/10/12	73,9
AB36	2017/01/24	38,9
AB36	2017/03/29	38,5
AB36	2017/06/28	6,22

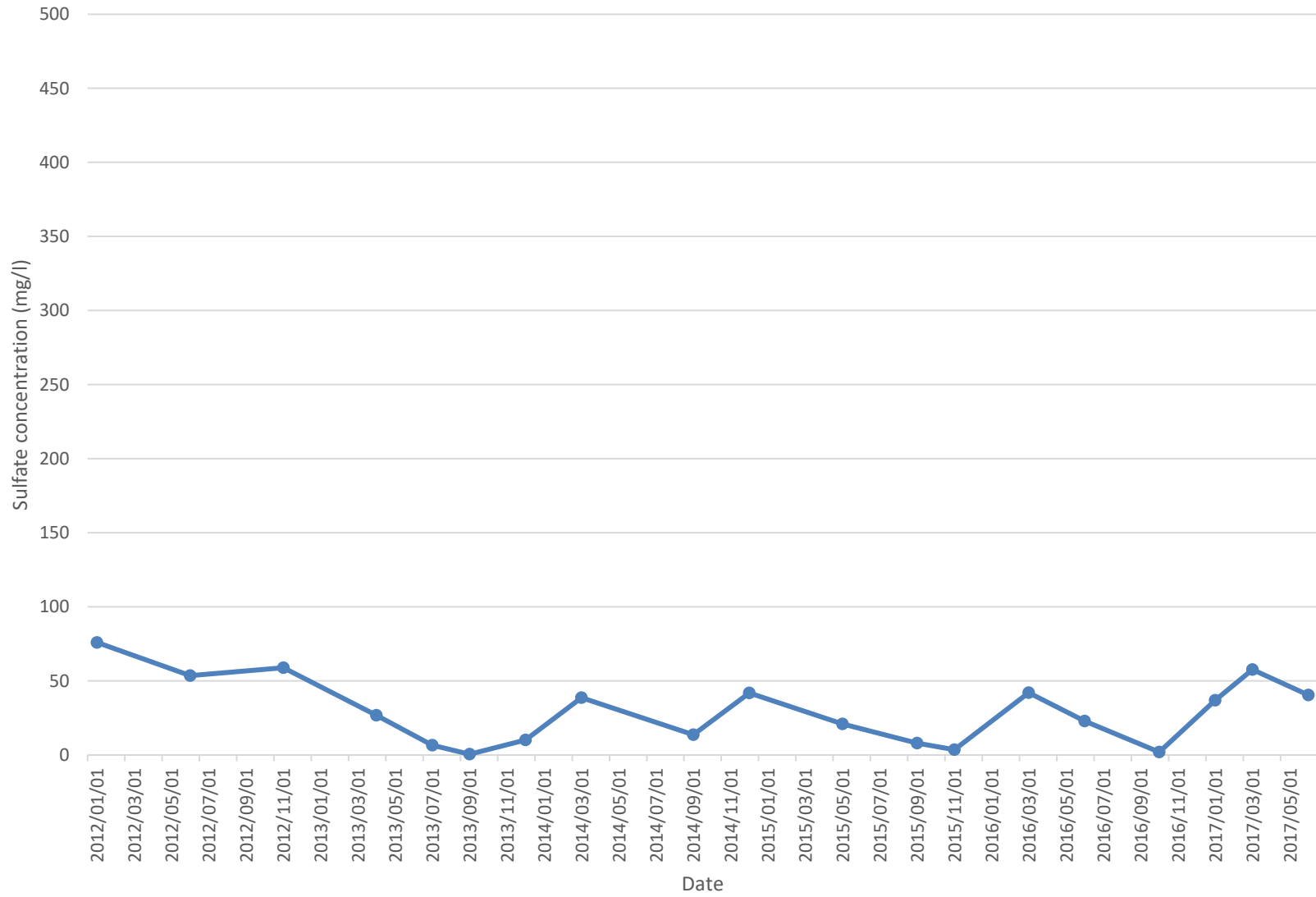
Time-series graph at pathway borehole AB36 for sulfate concentration



Site B Pathway Borehole: AB35 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB35	2012/01/26	76
AB35	2012/06/12	53,65
AB35	2012/11/15	58,9
AB35	2013/04/11	26,8
AB35	2013/07/09	6,62
AB35	2013/09/26	0,51
AB35	2013/12/05	10,1
AB35	2014/03/14	38,6
AB35	2014/09/17	13,6
AB35	2014/12/09	41,8
AB35	2015/05/25	20,9
AB35	2015/09/15	8,02
AB35	2015/11/24	3,64
AB35	2016/03/02	42
AB35	2016/06/22	22,83
AB35	2016/10/12	1,98
AB35	2017/01/24	36,9
AB35	2017/03/29	57,7
AB35	2017/06/28	40,5

Time-series graph at pathway borehole AB35 for sulfate concentration



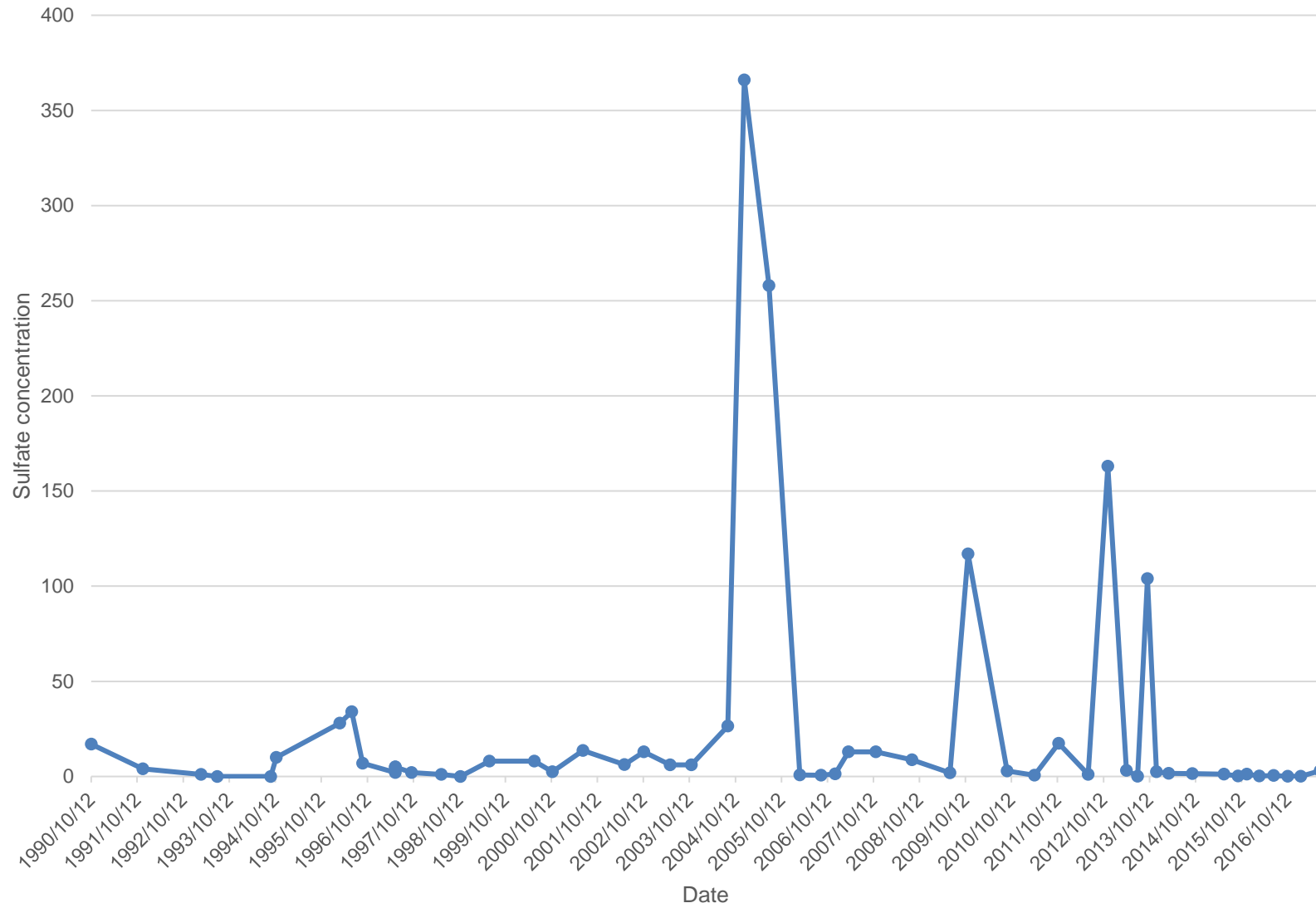
Site B Pathway Borehole: AB04 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB04	1990/10/12	17
AB04	1991/11/26	4
AB04	1993/03/02	1
AB04	1993/07/08	0
AB04	1994/09/05	0
AB04	1994/10/19	10
AB04	1996/03/07	28
AB04	1996/06/11	34
AB04	1996/09/05	7
AB04	1997/05/22	2
AB04	1997/05/22	5
AB04	1997/05/23	5
AB04	1997/09/28	2
AB04	1998/05/22	1
AB04	1998/10/20	0
AB04	1999/06/07	8
AB04	2000/05/29	8
AB04	2000/10/20	2,5
AB04	2001/06/19	13,7
AB04	2002/05/15	6,3
AB04	2002/10/15	13
AB04	2003/05/13	6,1
AB04	2003/10/29	6,1
AB04	2004/08/11	26,5
AB04	2004/12/21	366

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB04	2005/07/06	258
AB04	2006/03/07	0,8
AB04	2006/08/23	0,6
AB04	2006/12/12	1,3
AB04	2007/03/28	12,9
AB04	2007/10/30	13
AB04	2008/08/13	8,7
AB04	2009/06/10	1,96
AB04	2009/11/02	117
AB04	2010/09/07	2,95
AB04	2011/04/13	0,66
AB04	2011/10/21	17,41
AB04	2012/06/12	1,04
AB04	2012/11/15	163
AB04	2013/04/11	3,15
AB04	2013/07/09	0,04
AB04	2013/09/26	104
AB04	2013/12/05	2,5
AB04	2014/03/13	1,61
AB04	2014/09/17	1,42
AB04	2015/05/25	1,16
AB04	2015/09/15	0,287
AB04	2015/11/24	1,23
AB04	2016/03/02	0,162
AB04	2016/06/22	0,5
AB04	2016/10/12	0,141

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB04	2017/01/25	0,141
AB04	2017/06/28	3,08

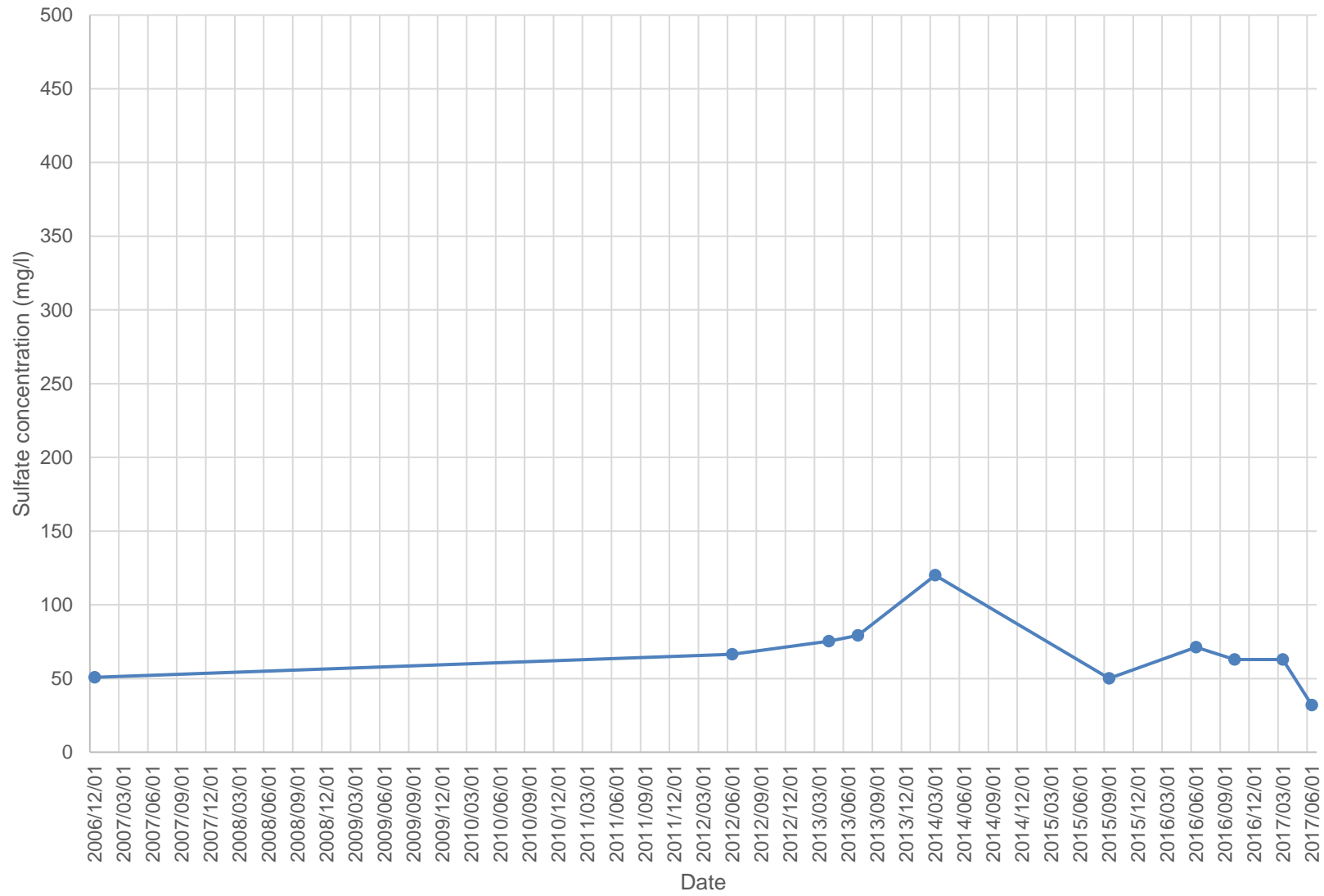
Time-series graph at pathway borehole AB04 for sulfate concentration



Site B Receptor Borehole: AB29 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB29	2006/12/12	50,8
AB29	2012/06/12	66,44
AB29	2013/04/11	75,3
AB29	2013/07/09	79,2
AB29	2014/03/13	120
AB29	2015/09/15	50,1
AB29	2016/06/22	71,2
AB29	2016/10/12	62,9
AB29	2017/03/29	62,8
AB29	2017/06/28	31,9

Time-series graph at receptor borehole AB29 for sulfate concentration



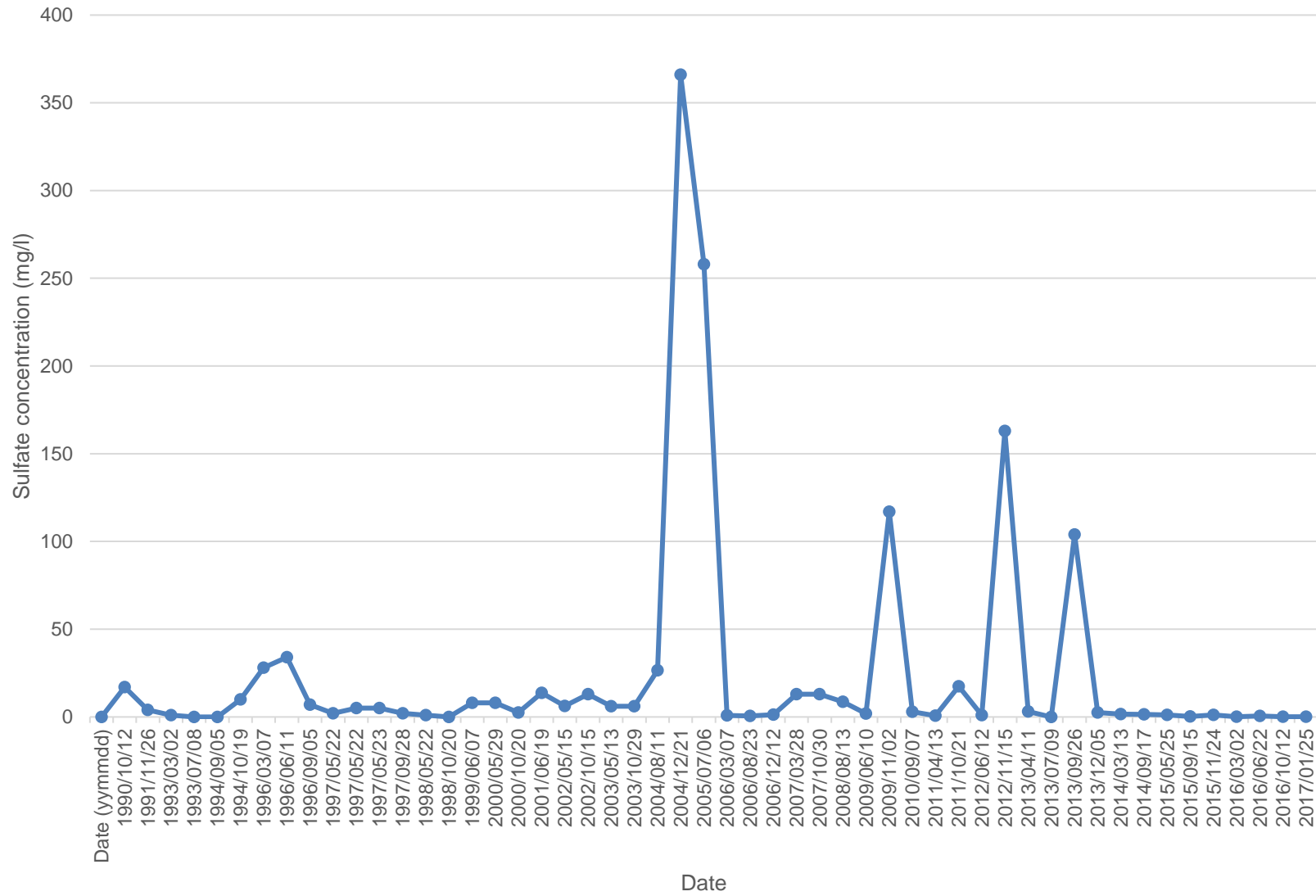
Site B Receptor Borehole: AB04 sulfate concentration

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB04	1990/10/12	17
AB04	1991/11/26	4
AB04	1993/03/02	1
AB04	1993/07/08	0
AB04	1994/09/05	0
AB04	1994/10/19	10
AB04	1996/03/07	28
AB04	1996/06/11	34
AB04	1996/09/05	7
AB04	1997/05/22	2
AB04	1997/05/22	5
AB04	1997/05/23	5
AB04	1997/09/28	2
AB04	1998/05/22	1
AB04	1998/10/20	0
AB04	1999/06/07	8
AB04	2000/05/29	8
AB04	2000/10/20	2,5
AB04	2001/06/19	13,7
AB04	2002/05/15	6,3
AB04	2002/10/15	13
AB04	2003/05/13	6,1
AB04	2003/10/29	6,1
AB04	2004/08/11	26,5
AB04	2004/12/21	366

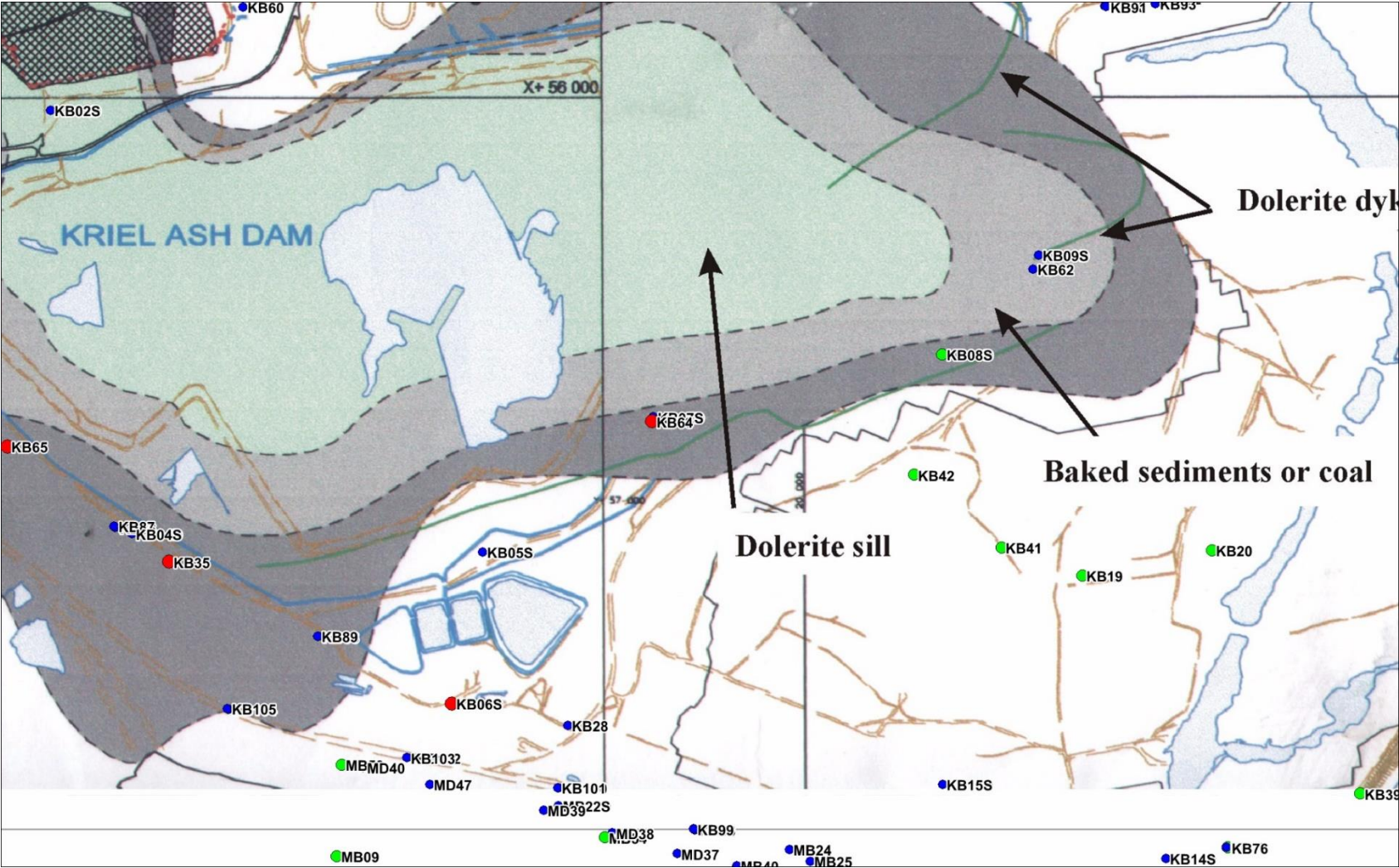
Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB04	2005/07/06	258
AB04	2006/03/07	0,8
AB04	2006/08/23	0,6
AB04	2006/12/12	1,3
AB04	2007/03/28	12,9
AB04	2007/10/30	13
AB04	2008/08/13	8,7
AB04	2009/06/10	1,96
AB04	2009/11/02	117
AB04	2010/09/07	2,95
AB04	2011/04/13	0,66
AB04	2011/10/21	17,41
AB04	2012/06/12	1,04
AB04	2012/11/15	163
AB04	2013/04/11	3,15
AB04	2013/07/09	0,04
AB04	2013/09/26	104
AB04	2013/12/05	2,5
AB04	2014/03/13	1,61
AB04	2014/09/17	1,42
AB04	2015/05/25	1,16
AB04	2015/09/15	0,287
AB04	2015/11/24	1,23
AB04	2016/03/02	0,162
AB04	2016/06/22	0,5
AB04	2016/10/12	0,141

Borehole description	Date (yymmdd)	Sulfate Concentration (mg/l)
AB04	2017/01/25	0,141
AB04	2017/06/28	3,08

Time-series graph at receptor borehole AB04 for sulfate concentration



**ANNEXURE C: SITE A GEOLOGICAL MAP OF DOLERITE SILL AND DYKE NEAR BOREHOLE KB08**





## *Declaration*

*This is to declare that I, Annette L Combrink, accredited language editor and translator of the South African Translators' Institute, have language-edited the mini-dissertation with the title*

# **Consideration of site-specific conditions in the assessment of groundwater pollution potential: An ash disposal case study**

by

**TR Chabedi**



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Date: 18 November 2019*