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# Determination of the permeability of seepage flow paths in dams from self-potential measurements

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27 **Abstract.** The flow of the pore water in porous media generates an electrical current known as  
28 the streaming current. This current is due to the drag of the excess of charge contained in the  
29 electrical diffuse layer coating the surface of the grains. This current is associated with an  
30 electric field called the streaming potential field. The fluctuations of this field can be remotely  
31 measured using a set of non-polarizable electrodes located at the ground surface or in wells and  
32 a sensitive voltmeter. The self-potential method (SP) aims at passively measuring the streaming  
33 potential anomalies associated with ground water flow. We present a stochastic numerical  
34 framework for inverting self-potential data in order to localize seepages in dams and  
35 characterize their permeability and Darcy velocity. Our approach is based on the use of Markov  
36 chains Monte Carlo (McMC) method for solving the inverse problem. We performed first a  
37 validation of the method on a synthetic case study and then on large-scale field surveys on three  
38 different dams. Our approach is successful in localizing seepages and determining their  
39 permeability. A sensitivity study is performed on each of these three dams to better define the  
40 hydraulic and electrical parameters influencing the self-potential signal and the uncertainties  
41 associated with the estimation of those parameters. Our results show that the self-potential  
42 method can provide quantitative hydrogeological information for the characterization of  
43 seepages in dams and dikes.

44

45 **Keywords:** Self-potential, forward modeling, inverse modeling, earth dam, seepage  
46 characterization.

47

## 48 **1. Introduction**

49 Earth dams play a vital and indispensable role in our modern societies. They can be  
50 designed to store large volumes of water for domestic and industrial purposes such as supplying  
51 hydroelectric power stations. The flow of the water through a dam can lead to internal erosion  
52 of its inner structure, which may trigger in turn suffusion and subsidence phenomena (e.g.,  
53 Bonelli, 2013; Ferdos et al., 2018; Howard and McLane, 1988; James, 1968). These phenomena  
54 can give rise to dramatic and irreversible consequences leading to the potential collapse or  
55 failure of the dams (e.g., Gutiérrez et al., 2003). Consequently; we need to develop reliable,  
56 efficient, and economically viable remote techniques to monitor dams.

57 Geophysical techniques can be used to non-intrusively probe dams and detect the  
58 occurrence of anomalous seepages within their structure. Ground-Penetrating Radar (e.g.,  
59 Antoine et al., 2015; Di Prinzio et al., 2010; Hui and Haitao, 2011; Li et al., 2018; Xu et al.,  
60 2010) is among these techniques. However, GPR suffers from a major limitation, which is its  
61 small depth of investigation in conductive materials because of the damping of electromagnetic  
62 waves in these conditions. An alternative to GPR is the use of galvanometric geoelectrical  
63 methods (i.e., self-potential, resistivity, and induced polarization methods). The Electrical  
64 Resistivity Tomography (ERT) method is valuable for imaging the foundations of dams and  
65 delineating their seeping zones (e.g., Aina et al., 1996; Bolève et al., 2012; Cho and Yeom,  
66 2007; Panthulu et al., 2001; Sjö Dahl et al., 2008). The induced polarization method is an  
67 extension of the resistivity method as it provides, in addition to the electrical resistivity  
68 distribution, an additional properties characterizing the ability of porous media to store  
69 electrical charges under the application of a primary electrical field. Induced polarization has  
70 recently been applied to detect seepages in Earth dams by monitoring the change in the water  
71 content over time (Abdulsamad et al., 2019). Both resistivity and induced polarization are active  
72 geoelectrical methods for which an electrical current is injected in the ground.

73           The self-potential method is a passive geophysical technique for which we measure the  
74 electric field fluctuations generated by the flow of pore water in porous media. In other words,  
75 the source of current is inside the structure itself and its associated electrical field is measured  
76 remotely. This method is easy to set up and cost-effective (Revil and Jardani, 2013). It has  
77 therefore a considerable potential for the detection of seepages in dams (Rittgers et al., 2015).  
78 Several studies have investigated the effectiveness of using the self-potential method for dam  
79 inspection and monitoring. For instance, Al-Saigh et al. (1994) successfully used self-potential  
80 observations to qualitatively detect water seepages in a dam. Panthulu et al. (2001) combined  
81 the resistivity and self-potential methods to detect seepages in an earth dam built on a  
82 heterogeneous rock mass in India. The self-potential method helped them identify and delineate  
83 the seepage flow paths, which were associated to self-potential amplitudes of 10 to 15 mV.  
84 They concluded that these low self-potential observations are reflective of small seep velocities.  
85 Sheffer and Oldenburg (2007) performed a self-potential survey at an embankment in British  
86 Columbia, Canada and they found a good match between the observed and forward-modeled  
87 self-potential observations. Nevertheless, they stressed the need of developing inverse  
88 modeling strategies for adequately modeling the complex 3D nature of self-potential  
89 observations characteristics. Bolève et al. (2012) applied the self-potential method for  
90 monitoring a dam located in southeastern France, characterized by the presence of downstream  
91 resurgence areas that are visible to the unaided eye. Based on the self-potential observations,  
92 they performed a sensitivity analysis to estimate the magnitude of the permeability of the  
93 hydraulic pattern through which the seepages occur. Recently, Soueid Ahmed et al. (2019)  
94 implemented a 3D forward modeling numerical code for quantitatively simulating self-potential  
95 anomalies of electrokinetic nature in geological systems. They used their code to assess the  
96 effectiveness of employing the self-potential method for detecting seepages in dams by properly  
97 interpreting the self-potential signals measured on an experimental dam designed for

98 geophysical experiments. The aforementioned studies show that the self-potential method is  
99 undoubtedly promising for monitoring seepages in earth dams. That said, the use of the self-  
100 potential method for such applications remains sparse in the literature. In our opinion, the  
101 potential of the self-potential method for dams monitoring has not yet been fully investigated.  
102 Interpretation methodologies need to be developed to answer to the following two scientific  
103 questions: (i) in case of the presence of anomalous seepages in a dam structure, how the self-  
104 potential observations could be used to invert the permeability of the preferential seepage  
105 pathways? (ii) what are the properties of dams or heterogeneous rock masses below the dam to  
106 which the self-potential signals are the most sensitive?

107         To answer these questions, we present a stochastic inverse scheme based on the Markov  
108 chains Monte Carlo methods (McMC) (e.g., Metropolis et al., 1953; Hastings, 1970; Sambridge  
109 and Mosegaard, 2002; Haario et al., 2006). This method is here applied to invert the self-  
110 potential data in order to retrieve the permeability and seepage velocity of the preferential flow  
111 paths. To the best of our knowledge, this is the first time that the permeability of preferential  
112 flow paths of dams is inverted from self-potential measurements. Such study has broad  
113 implications in civil engineering. In order to test the robustness of our approach, we first test  
114 the method on a synthetic case study. Then, we use new self-potential data sets performed on  
115 three different dams in field conditions to further validate the method. The strategy developed  
116 in the current paper is expected to help engineers and geophysicists in efficiently interpreting  
117 self-potential anomalies in a quantitative way to characterize seepage flow path properties in  
118 dams.

119

120

## 121 **2. Geophysical techniques**

### 122 **2.1 The self-potential method**

123 The self-potential method is a passive geophysical technique that measures the natural  
 124 electric potential anomalies that are caused by the flow of pore water in porous media. The self-  
 125 potential measurements are performed using non-polarizing electrodes that can be installed on  
 126 the ground surface, in boreholes, or in water. These electrodes are connected to a voltmeter  
 127 characterized by a high sensitivity ( $\sim 0.1$  mV) and a high input impedance (typically  $>10$   
 128 MOhm). In dams, the self-potential signals have two main causes (i) electrokinetic sources  
 129 generated by fluid flow in porous media, and (ii) electro-redox sources associated with the  
 130 corrosion of metallic objects such as the rebar in concrete or the metallic casing of piezometers  
 131 (see Revil and Jardani, 2013, for specific examples). Within the framework of the current paper,  
 132 we focus our analysis only on the electrokinetic component.

133 The underlying physics of streaming potential is well-established. The literature on this  
 134 subject is extensive (e.g., Ogilvy, 1969; Corwin, 1985; Bolève et al., 2012; Revil et al., 2012;  
 135 Revil and Jardani, 2013). For the sake of completeness, we only recall that the continuity  
 136 equation for electrical charges is given by

$$137 \quad \nabla \cdot \mathbf{j} = 0, \quad (1)$$

138 where  $\mathbf{j}$  ( $\text{A m}^{-2}$ ) denotes the total current density. The electric current density is therefore  
 139 conservative in the absence of sources and sinks in the low-frequency limits of the Maxwell  
 140 equations. The current density is given itself by a constitutive equation as:

$$141 \quad \mathbf{j} = -\sigma \nabla \varphi + \hat{Q}_v \mathbf{u}, \quad (2)$$

142 where  $\sigma$  denotes the electrical conductivity of the porous subsurface (in  $\text{S m}^{-1}$ ),  $\varphi$  (in  
 143 V) denotes the electrical (self-) potential,  $\mathbf{u}$  ( $\text{m s}^{-1}$ ) is the seepage (Darcy) velocity (given by  
 144 Darcy's law, see (Darcy, 1856), and (Richards, 1931)) and  $\hat{Q}_v$  (in  $\text{C m}^{-3}$ ) is the effective excess  
 145 charge density per unit pore volume. The quantity  $\hat{Q}_v$  is related to the permeability  $k$  as  
 146 discussed in (Bolève et al., 2012; Jardani et al., 2006).

147 Combining Equation (1) and Equation (2), we find the elliptic partial differential  
148 equation for the self-potential:

$$149 \quad \nabla \cdot (\sigma \nabla \varphi) = \nabla \cdot (\hat{Q}_v \mathbf{u}). \quad (3)$$

150 The right-hand-side term corresponds to the source of electrical current associated with the flow  
151 of the ground water while the left-hand side corresponds to the causative solution in terms of  
152 electrical (streaming or self-) potential field. The source term is modulated by the distribution  
153 of the charge density  $\hat{Q}_v$  controlled itself by the permeability and the salinity (the influence of  
154 the latter is much weaker than the influence of the permeability, see Jougnot et al., 2019). The  
155 left-hand side of equation (3) is modulated by the electrical conductivity  $\sigma$ . The electrical  
156 conductivity field is therefore an important parameter for modeling the self-potential forward  
157 response of a dam. It can be independently obtained using electrical resistivity tomography.  
158 Furthermore, analyzing the anomalies of the electrical resistivity field may give insights about  
159 the presence of seepage areas in dams as discussed below in section 2.2 (see also (Ikard et al.,  
160 2012)).

161 Solving the self-potential problem consists of first solving the groundwater flow  
162 equation to compute the seepage (Darcy) velocity  $\mathbf{u}$  and then using the distribution of  $\mathbf{u}$  to  
163 compute the right hand-side of the electric potential equation and then the electrical potential  
164 distribution (e.g., Jardani et al., 2006).

165

## 166 **2.2 Electrical resistivity tomography**

167 Electrical resistivity measures the ability of a material to conduct or transmit an electric  
168 current, i.e. the flow of charge carriers. Electrical Resistivity Tomography (ERT) is a  
169 geophysical method that measures the resistivity distribution of the medium (e.g., Loke, 2004).  
170 It consists of injecting an electric current between two electrodes A and B and measuring the  
171 associated electrical field of this medium (i.e., the resulting voltage distribution) between a set



172 of dipoles composed of voltage electrode bipoles M and N (all the electrodes are generally  
 173 stainless steel electrodes). For this goal, we use a network of electrodes and a resistivity meter.  
 174 In an isotropic heterogeneous medium, this forward operator is given by the following field  
 175 equation:

$$176 \quad -\nabla \cdot (\sigma \nabla \varphi) = I \delta(X - X_0), \quad (4)$$

177 where  $\sigma$  (in S m<sup>-1</sup>) is the electrical conductivity (its reverse is the electrical resistivity),  $\varphi$  is  
 178 the electrical potential (voltage in V) and  $I$  (in A) denotes the injected current between the  
 179 current electrodes A and B,  $\delta$  is the Dirac distribution,  $X$  represents the spatial locations and  
 180  $X_0$  represents the spatial coordinates of the current injection electrodes. In essence, equation  
 181 (4) is similar to equation (3) except that the source is here active. In the field, the equipment  
 182 provides the resistance or the apparent resistivity. These quantities are obtained from the  
 183 solution of Equation (4) as:

$$184 \quad R_a = \frac{\Delta \varphi_{MN}}{I}, \quad (5)$$

$$185 \quad \rho_a = GR_a. \quad (6)$$

186 where  $\Delta \varphi_{MN}$  denotes the difference of potential recorded between the electrodes M and N,  $R_a$   
 187 (in  $\Omega$ ) is the measured resistance,  $\rho_a$  (in  $\Omega \cdot m$ ) is the apparent resistivity and  $G$  is the  
 188 geometric factor (which depends on the electrode configuration). Imaging the electrical  
 189 resistivity spatial distribution can be formulated as an inverse problem whose solution is  
 190 obtained through the minimization of an objective function, which reduces the misfit between  
 191 the observed and computed resistances or apparent resistivities plus a regularization term  
 192 introduced to ensure the stability of the inverse problem (Günther et al., 2006; Loke and Barker,  
 193 1996; Soueid Ahmed et al., 2018; Tikhonov, 1943). For more details regarding the underlying  
 194 physics and principle of ERT, the reader is invited to refer to the rich literature on this subject

195 (for instance Daily et al., 2004; Edwards, 1977; Herman, 2001; Revil et al., 2012, just to cite  
196 few references).

197

### 198 **2.3 Hydraulic parameters estimation**

199 Retrieving the permeability field of a preferential groundwater pathway in a dam or its  
200 foundation can be mathematically cast as an inverse problem like for electrical resistivity  
201 tomography. It consists of inferring the permeability values from the self-potential  
202 measurements generally collected upstream and downstream the dam. The inverse problem is  
203 formulated as an optimization problem whose solution is the most optimal permeability model  
204 that reproduces the self-potential observations, knowing the electrical resistivity field. Instead  
205 of using conventional deterministic methods such as the Gauss-Newton method, we use here  
206 an MCMC sampler to solve the inverse problem (e.g., Haario et al., 2006, 2004; Jardani et al.,  
207 2012). Notwithstanding the fact that MCMC samplers require the deployment of intensive  
208 computational resources, we opted for this approach because it does not require assembling  
209 sensitivity matrices and is also more robust for avoiding the inverse algorithm getting trapped  
210 in local minima. In addition, the model solution provided by the MCMC algorithm does not  
211 have a strong dependence on the initial model parameter in contrast to gradient based methods  
212 (e.g., Mosegaard and Tarantola, 1995; Sambridge and Mosegaard, 2002). In this context, we  
213 seek to maximize the conditional probability density  $P(\mathbf{d}|\mathbf{m})$  of  $\mathbf{m}$  given  $\mathbf{d}$ , where  $\mathbf{d}$  ( $n_d \times 1$ )  
214 is the data vector,  $\mathbf{m}$  ( $m_n \times 1$ ) is the unknown vector,  $n_d$  and  $m_n$  are the numbers of  
215 measurements and unknowns, respectively. In our case,  $\mathbf{m}$  is the vector of hydraulic properties  
216 of the preferential flow path (i.e., the permeability and the pressure of the water outlet area).

217 The Bayes formula gives the posteriori probability density of the model parameters  $\mathbf{m}$   
218 given the data vector  $\mathbf{d}$ ,  $\pi(\mathbf{m}|\mathbf{d})$ :

$$219 \pi(\mathbf{m}|\mathbf{d}) \propto P(\mathbf{d}|\mathbf{m})P_0(\mathbf{m}), \quad (7)$$

220 where  $P_0(\mathbf{m})$  denotes the prior probability density of the model parameters  $\mathbf{m}$ .

221 The conditional probability density  $P(\mathbf{d} | \mathbf{m})$  of  $\mathbf{m}$  given  $\mathbf{d}$  is given by:

$$222 \quad P(\mathbf{d} | \mathbf{m}) = \frac{1}{((2\pi)^{n_d} \det \mathbf{R})^{\frac{1}{2}}} \exp\left(-\frac{1}{2}(\mathbf{d} - F_\varphi(\mathbf{m}))^T \mathbf{R}^{-1}(\mathbf{d} - F_\varphi(\mathbf{m}))\right). \quad (8)$$

223 The prior probability density of the model parameters  $\mathbf{m}$  is given by:

$$224 \quad P_0(\mathbf{m}) = \frac{1}{((2\pi)^{m_m} \det \mathbf{C})^{\frac{1}{2}}} \exp\left(-\frac{1}{2}(\mathbf{m} - \mathbf{m}_0)^T \mathbf{C}^{-1}(\mathbf{m} - \mathbf{m}_0)\right), \quad (9)$$

225 where  $F_\varphi(\cdot)$  is the streaming potential forward problem,  $\mathbf{R}$  ( $n_d \times n_d$ ) is the data covariance  
226 matrix,  $\mathbf{C}$  ( $m_m \times m_m$ ) is the model covariance matrix which takes into account the uncertainties  
227 related to the choice of the prior model  $\mathbf{m}_0$ .

228 McMC approaches are iterative processes, which use random walks to sample the values  
229 of the model parameter. At each iteration, the choice of the next state is only based on the  
230 current state. This ensures lower dependence on the initial model. Generally, the starting  
231 realizations are discarded and then the random walker moves toward the regions of high  
232 probability for the model parameters. As indicated by Sternberg (1979), the McMC approaches  
233 are more efficient than Monte Carlo methods (which generate samples independently) because  
234 the chains stay in the regions of high posterior probability of the model parameters space. In  
235 the current work, we use the Metropolis-Hastings (MH) algorithm, which is a variant of the  
236 McMC algorithms. The choice of this algorithm is mainly motivated by its simplicity and  
237 flexibility. It was first introduced by Metropolis et al. (1953) and generalized by Hastings  
238 (1970). The MH algorithm is based on the three following steps:

239 1. Choose an initial model  $\mathbf{m}_0$ .

240 2. Compute the acceptance probability:

241 
$$\alpha(\mathbf{m}^{i-1}, \mathbf{m}^*) = \min\left(1, \frac{\pi(\mathbf{m}^*)}{\pi(\mathbf{m}^{i-1})}\right). \quad (10)$$

242 3. Set  $\mathbf{m}^i = \mathbf{m}^*$  with the probability  $\alpha$  otherwise set  $\mathbf{m}^i = \mathbf{m}^{i-1}$  with the probability  $1 - \alpha$ . The  
 243 index  $i$  denotes the current iteration. Steps 2 and 3 are repeated  $N_t$  times, where  $N_t$  denotes  
 244 the total number of iterations.

245

### 246 **3. Case studies**

#### 247 **3.1. Methodology**

248 In this section, we apply our approach on three case studies. We first wish to validate  
 249 our approach using a synthetic case. Regarding the three case studies discussed below, we  
 250 perform new large scale self-potential surveys. Resistivity measurements were also performed  
 251 to assist the interpretation of the self-potential signals. All the case studies have the same goal,  
 252 i.e. detecting the potential presence of seepage flow paths and retrieving their mean  
 253 permeability. The forward problem is solved using the finite element software Comsol  
 254 Multiphysics and we implement the inverse procedure in Matlab. In our simulation approach,  
 255 each component of the dam (i.e., its core, structure, resistivity of the water of the reservoir,  
 256 foundation geometry and properties) as well as the seepage along a preferential flow path are  
 257 modeled. Each of these components is identified through their electrical property and  
 258 permeability. Geotechnical measurements and resistivity profiles can help estimating these  
 259 properties for the components of the dam. The big challenge resides in finding the permeability  
 260 of the preferential flow path, which can be a pretty difficult task using conventional  
 261 geotechnical techniques.

262 On the other hand, the geometry of the conduit used to simulate the seepage flow path  
 263 has no influence on the self-potential magnitudes and therefore, we do not focus in this paper  
 264 on estimating the exact shape of the seepage flow path. That said, in the last case study, we use

265 an inverse procedure for approximating the shape of the fluid path based on the self-potential  
266 observations.

267 Another issue of interest that is worth noting is the choice of the boundary conditions  
268 for solving the forward model problem. For the electric problem, insulating boundary  
269 conditions are imposed at the dam/air interface (i.e.,  $\hat{\mathbf{n}} \cdot \mathbf{j} = 0$ , where  $\hat{\mathbf{n}}$  is the outward normal  
270 unit vector, and  $\mathbf{j}$  is the total current density). Electric ground boundary conditions are imposed  
271 at the remaining boundaries. For the hydraulic problem, we impose the atmospheric pressure  
272 on the top of the dam, i.e., on all the boundaries that are in contact with the atmosphere. At the  
273 inlet boundary of the preferential flow path, the hydrostatic pressure of the water reservoir is  
274 imposed as a fluid pressure condition. At the outlet, the fluid pressure is unknown and therefore  
275 its value inverted along with the permeability of the seepage flow path. Taking into account  
276 these pressures is necessary for computing the hydraulic gradient which indeed has an important  
277 influence on the magnitude of the self-potential observations. For all the simulations, the  
278 domain of interest is padded with infinite element domains to avoid the influence of the  
279 boundary conditions on the electric potential distribution and the reference electrode has been  
280 placed far away from the from dam.

### 281 **3.2 Synthetic test**

282 We first validate our approach on a synthetic earth dam suffering from a leakage  
283 problem. We use the synthetic self-potential observations computed on the dam (using forward  
284 modeling) to retrieve the permeability of the presumed preferential flow path going through the  
285 dam foundation. The true hydraulic and electric properties of the dam are known (see Table 1)  
286 even though during the inverse process the permeability of the seepage flow path is assumed to  
287 be unknown. The dam has a length of 72 m and a height of 10 m, includes an impermeable clay  
288 core and contains a water reservoir whose level reaches 7 m. Figure 1a illustrates the geometry  
289 of the dam. The true permeability of the preferential flow path is  $10^{-10} \text{ m}^2$  and the seepage

290 velocity within it is  $1.1 \times 10^{-4} \text{ m s}^{-1}$ . We recall that our goal is to retrieve these parameters from  
291 the self-potential measurements observed on the dam. The true self-potential distribution of the  
292 dam obtained using the true hydraulic and electric parameters are shown on Figure 1b. It clearly  
293 reveals the presence of a -27 mV self-potential anomaly at the seepage area and a +20 mV at  
294 the resurgence area. The true data are contaminated with a 2% Gaussian white noise. Using the  
295 proposed McMC inversion approach, we launch 10,000 iterations starting the initial  
296 permeability field at  $10^{-12.5} \text{ m}^2$ . The best permeability estimate is chosen as the mean of the  
297 McMC chain which is  $10^{-10.28} \text{ m}^2$ . The computed velocity within the seepage flow path is  
298  $8.3 \times 10^{-5} \text{ m s}^{-1}$ . These values are close to the true ones, indicating that our methodology is  
299 fairly reliable. Furthermore, the computed self-potential signal reproduces with high fidelity the  
300 true one (see Figure 1 c), showing that the inverse algorithm has converged. The associated  
301 coefficient of correlation is  $R^2 = 0.99$  and the amplitudes of the downstream and upstream  
302 observed self-potential anomalies are well recovered.

303

### 304 **3.3 Case study 1**

305 In this field example, we consider a hydroelectric dam built on a 340 km long river  
306 located in Africa. The priming of this dam was done in 1987 and its reservoir retains  $2 \text{ km}^3$ .  
307 The dam is composed of the following structures: (i) a right bank dyke having a length of 2,780  
308 m and 12 m of height, (ii) a left bank dyke having a length of 1,660 m and 21 m of height. (iii)  
309 A main rockfill dyke with an earth core which is 430 m long and 50 m high. (iv) A moveable  
310 dam including 4 intake openings having a length 56 m and a height of 22 m. (v) A gravity dam  
311 having 2 intake structures and bottom discharge system. This dam is 45 m long and 38 m high.

312 From a geological point of view, the test site is located in the basement rocks of the  
313 Precambrian formation. It contains metamorphic rocks such as gneiss, shales, diorite, and  
314 amphibolite. The two supports of the dam are covered by scree slopes whose thickness

315 approximately varies between 1 m and 3 m. This layer is made up of rock fragments (gneiss  
316 and quartz) as well as clayey materials. Beyond the scree slopes, the rock is severely altered  
317 and takes the form of a sandy-clay loam with some quartzite fragments. In the river bed, the  
318 fresh rock often outcrops and is locally covered by fresh sandy-gravelly alluvium.

319           The main dike contains a lateritic core and is covered by an upstream filter and 2  
320 downstream filters. Its foundation is composed of gneiss and is highly fractured due to the  
321 intrusion of quartz veins and to hydrothermal alteration as well. The foundations of the left bank  
322 and right bank dikes are from lateritic materials. Their cores are made up of a mixture of clay,  
323 silt and sand.

324           Geoelectrical surveys (ERT and SP) have been performed to better characterize the  
325 dam structures and also to inspect the presence of seepages in the dam. The ERT measurements  
326 were performed downstream on a line of 1.4 km along the left bank dike and another line of 2.3  
327 km along the right bank dike. We used a network of 64 electrodes, spaced from each another  
328 by 2.5 m downstream and by 5m at the crest of the dam. This high-resolution array of  
329 measurements at the toe of the dam aims at better detecting and depicting potential seepage  
330 areas in the dam structures. We use the dipole-dipole configuration for acquiring the resistivity  
331 measurements because this protocol is very sensitive to the lateral variations of the resistivity  
332 and thus is useful for detecting resistivity anomalies associated with seepages in dams. The self-  
333 potential profiles were implemented downstream and upstream on the dam. This was done to  
334 be able to localize the seepage areas through their anomalies which are expected to be negative  
335 in the inflow area and positive in the outflow area. Downstream, the self-potential  
336 measurements were collected each 2.5 m (at the same location to the resistivity electrodes) for  
337 a total distance of 8.5 km. Upstream, the self-potential measurements were collected on water  
338 i.e., in the reservoir at approximatively few meters from the bottom of it. We will only consider  
339 the left bank because it is highly suspected to contain seepage flow path due to the presence of

340 visible flood areas at some places at the downstream foot of this dike. Figure 2 shows the  
341 resistivity and self-potential profiles realized on the left bank. These profiles are 1.5 km long  
342 but we only show the parts that exhibit the anomalies of interest. Figure 2 indicates that the  
343 shallow layer of the medium is globally conductive, while the foundation is resistive. Between  
344 the position 1,450 m and 1,490 m we can observe some conductive anomalies (less than 200  
345 Ohm m), which are characteristic of alteration zones that have high permeability and can be  
346 associated with preferential seepage paths. Examining the self-potential observations puts in  
347 evidence a positive peak (+30 to +35mV) that is clearly greater than the average. Interestingly,  
348 this peak is located exactly at the place where the conductive anomalies are observed. In  
349 addition, our self-potential measurements have an excellent reproducibility and thus, we highly  
350 suspect the presence of a seepage area over there. Instead of simply stopping at this stage of  
351 observation, we propose to go further by efficiently interpreting the self-potential observations  
352 that we acquired. We will first perform a sensitivity analysis based on varying the resistivity  
353 and permeability of the components of the dam (i.e., the structure, water of the reservoir, and  
354 the preferential flow path) to see which of them has the most influence on the self-potential  
355 signals measured upstream and downstream. Although this sensitivity analysis is basic and only  
356 consists of only a parametric sweep on the physical parameters' values, it nevertheless gives a  
357 general good understanding on how these parameters influence the self-potential magnitudes.  
358 The dam is modeled as the domain represented in Figure 3.

359           If we suppose that in the conduit (i.e., seepage flow path), the surface conductivity  
360 is negligible (no presence of clayey minerals with high specific surface), Archie's law gives us  
361 a good approximation of the resistivity of the fully saturated porous medium which will be  
362 around 400 Ohm m. In the first sensitivity analysis, we vary the permeability of the conduit and  
363 see which permeability can reproduce the observed self-potential anomalies. We vary the  
364 permeability over the following set of values (expressed in  $m^2$ ):  $\{10^{-10}, 10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}\}$



365  $5, 10^{-4}, 10^{-3}, 10^{-2}$ }. The results of such test are represented in Figure 4a. One can easily see that  
366 the permeability that reproduces the self-potential magnitudes (i.e., - 5 mV upstream and 30 to  
367 35 mV downstream) is comprised between  $10^{-9}$  and  $10^{-8}$  m<sup>2</sup>. We fix the permeability of the  
368 conduit at  $10^{-8}$  m<sup>2</sup> and we vary resistivity of the conduit within the values: {30, 200, 300, 400,  
369 500, 600, 700, 800, 900, 1000} in Ohm m. As illustrated in Figure 4b, an electrical resistivity  
370 of around 400 Ohm m reproduces with high confidence the observed self-potential anomalies.  
371 We also notice that from 400 Ohm m, the self-potential magnitudes do not vary too much.  
372 Another component of interest is the dam structure itself and it is interesting to see to how this  
373 massive part of the dam contributes to the self-potential observation characteristics. We first fix  
374 the resistivity of the structure to 800 Ohm m (this value is taken from the electrical resistivity  
375 profile) then we switch the permeability of the structure in this set of values : { $10^{-20}, 10^{-19}, 10^{-18}, 10^{-17}, 10^{-16}, 10^{-15}, 10^{-14}, 10^{-13}, 10^{-12}$ } in m<sup>2</sup>. Figure 5a illustrates the results of such experiment.  
376 We notice that the self-potential signals vary a little with respect to the variations of the  
377 permeability of the structure. Similarly, we perform a sensitivity analysis on the resistivity of  
378 the structure. Its permeability is fixed at  $10^{-17}$  m<sup>2</sup> and its resistivity varies within this set of  
379 values: {100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200} (in Ohm m). Figure  
380 5b represents the self-potential anomalies obtained with this resistivity set of values. Indeed,  
381 the self-potential amplitudes do not strongly vary unless for conductive media. This sensitivity  
382 analysis tells us that the permeability of the structure does not seem to be the parameter that  
383 influences the most the self-potential magnitudes. The resistivity of the structure has a greater  
384 influence on the observed self-potential signal.

386 We move now to the sensitivity analysis on the salinity (identified by electrical  
387 resistivity) of the water of the reservoir. In fact, the resistivity of the water was measured during  
388 the field campaign, and was found to be around 50 Ohm m. The purpose of this sensitivity  
389 analysis is to make sure that this value is plausible and to see the influence of the resistivity of

390 the water on the self-potential signal. We vary the resistivity of the water in the following set  
391 of values: {10, 12.5, 16.7, 25, 50, 100, 200, 1000} Ohm m. Figure 6 shows that the observed  
392 self-potential magnitudes are retrieved with a resistivity ranging from 50 to 100 Ohm m which  
393 indicates the correctness of the magnitude of the measured resistivity.

394           The estimation of the hydraulic properties of the preferential flow path is done via  
395 inverse modeling as explained in section 2. The sensitivity analysis has established that the  
396 permeability of the conduit should be between  $10^{-9} \text{ m}^2$  and  $10^{-8} \text{ m}^2$ . We propose to invert for the  
397 value of the permeability from self-potential measurements and to see how well it compares  
398 with the range of magnitudes given by the sensitivity analysis. Since the resolution of the  
399 forward problem requires the knowledge of the pressure at the resurgence area (set as a  
400 boundary condition), we invert for the value of this pressure along with the permeability. The  
401 inverse problem ran during 12 h on a 32 cores desktop, using a total number of 30,000 iterations.  
402 This means that the forward problem needs to be solved 30,000 times. The best solution is  
403 chosen as the mean of the Markov chains associated to the permeability and pressure values.  
404 We obtain  $5 \times 10^{-9} \text{ m}^2$  for the permeability of the conduit and a pressure of 4500 Pa at its outlet.  
405 This permeability value indeed falls within the range of magnitudes obtained by the sensitivity  
406 analysis.

407           Furthermore, the reconstructed permeability and pressure reproduce the observed  
408 self-potential anomalies with high fidelity. Indeed, the simulated self-potential magnitude in  
409 the reservoir is around -5 mV at 1 m from the bottom of the reservoir while the simulated is  
410 anomaly is around 30 mV downstream (see Figure 7a). The coefficient of correlation of the  
411 observed self-potential data versus the true ones is 0.9 which indicates an excellent match  
412 between them, as indicated by Figure 7b. Once the hydraulic properties of the dam have been  
413 evaluated, one can compute an important parameter that is, the seepage velocity. In our case  
414 study, this seepage velocity is 0.019 m/s.

415

### 416 **3.4 Case study 2**

417           The second case deals with a hydroelectric dam located in west Africa. This dam  
418 was first operated in the 80's. It is 3615 m long and its water reservoir has an impounding  
419 capacity of 8.4 billion m<sup>3</sup>. The dam is composed of the following facilities: (i) a 3615 m long  
420 main dike that is 37 m high above the river bed, (ii) a secondary dike having a length of 1985  
421 m and a maximum height of 20 m, (iii) a closing pass dike. (iv) A 3480 m tailrace, excavated  
422 with rocky formations.

423           The site is located in a region that is globally very eroded and severely weathered.  
424 The dam itself (i.e., main and secondary dikes) is built on a very heterogonous rocky  
425 substratum, distributed as follows: (i) right bank of the main dike: shale formation composed  
426 of schists and micaschists, called « upstream formation », (ii) River bed (main dike): called the  
427 « transition formation », it is the formation of composed amphibolites, aplite rodes and very hard  
428 lepptynite, (iii) left bank of the main dike and secondary dike: granite with two micas (biotite  
429 and muscovite) with ferromagnesian mineral enclaves, (iv) edge of the left bank of the  
430 secondary dike: formation of shales, called the « downstream formation ».

431           A seepage area has been identified in the right bank of the main dike and unintended  
432 water puddles are clearly visible at the bottom of the dike. Self-potential measurements were  
433 collected upstream (i.e., in the water reservoir) on a distance of 1.5km and downstream on a  
434 1.5km profile long and 5m between each electrode. A total of 2,000 self-potential  
435 measurements were collected. 1,800 resistivity measurements were performed on a 1.5km  
436 profile. We used a dipole-dipole protocol with an electrode interval of 5m. The self-potential  
437 measurements are represented in Figure 8.

438           Similar to the previous case studies, we performed a sensitivity analysis on the  
439 electrical properties of the different components of the dam. The geometry used for the

440 numerical simulations is represented in Figure 9. The water reservoir level reaches 20 m. The  
441 observed self-potential magnitudes are around -15 mV at the seepage area (i.e., in the reservoir)  
442 and +50 mV downstream at the resurgence area. The first sensitivity analysis consisted in fixing  
443 the resistivity of the preferential flow path at 150 Ohm m (this value is deduced from the  
444 resistivity profile) and then we switch the permeability values in the set  $\{10^{-10}, 10^{-9}, 10^{-8}, 10^{-7},$   
445  $10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}\}$  expressed in  $m^2$ . The results of such test are reported in Figure 10a.  
446 One can notice that the downstream and upstream self-potential magnitudes are reproduced  
447 with a permeability interval of  $[10^{-9}, 10^{-8}]$ . We will perform the inversion of the permeability  
448 of the conduit later on to validate this permeability range. We now fix the permeability of the  
449 conduit at  $10^{-9} m^2$  and vary the electrical resistivity within these values: {30, 200, 300, 400,  
450 500, 600, 700, 800, 900, 1000} in Ohm m. As illustrated in Figure 10b, an electrical resistivity  
451 of 100-150 Ohm m allows for reconstructing the observed self-potential amplitudes. In addition,  
452 this value is in well accordance with the resistivity tomogram which shows a 150 Ohm m  
453 anomaly. We presently move on to the sensitivity analysis on the properties of the main  
454 structure of the dam. We assigned a resistivity of 2000 Ohm m to the main structure of the dam.  
455 This value is suitable for this type of material and is confirmed by the ERT. Then the  
456 permeability of the structure is switched within the following values (expressed in  $m^2$ ):  $\{10^{-20}, 10^{-19}, 10^{-18}, 10^{-17}, 10^{-16}, 10^{-15}, 10^{-14}, 10^{-13}, 10^{-12}\}$ . As illustrated in Figure 11a, the permeability of  
457 the structure does not have a major impact on the self-potential signal, which remains quite  
458 constant despite the wide range of permeability that we used. The resistivity sensitivity analysis  
459 is performed by fixing the permeability at  $10^{-15} m^2$  (see Table 1).  
460

461           The resistivity is varied within this set of magnitudes: {100, 200, 300, 400, 500, 600,  
462 700, 800, 900, 1000, 1100, 1200} in Ohm m. Figure 11b shows the downstream and upstream  
463 generated self-potential anomalies. Indeed, unless we are in the presence of very conductive  
464 media, the magnitudes of self-potential anomalies do not vary significantly and are almost

465 constant. This suggests that the resistivity of the dam structure does not need to be known with  
466 high precision, and having relatively wide but reasonable resistivity range will not affect the  
467 numerical modeling of the self-potential signatures.

468 We discuss now the effect of the water resistivity on the self-potential signal  
469 measured on the dam. This water sensitivity analysis on the resistivity parameter was important  
470 for approximating the resistivity that should be assigned to the reservoir in our modeling. The  
471 water resistivity is varied within the following set of values: {10, 12.5, 16.7, 25, 50, 100, 200,  
472 1000} in Ohm m. As illustrated in Figure 12, one can notice that the observed self-potential  
473 anomalies (i.e., -15 mV upstream and +50 mV) are well reproduced for resistivity ranging from  
474 12.5 to 100 Ohm m. In the field, the measured resistivity was 100 Ohm m, therefore this value  
475 seems quite reasonable for modeling the effect of water salinity on the self-potential signal.

476 Once the sensitivity analysis has been performed, we move on to the estimation of  
477 the hydraulic properties of the preferential flow path. The sensitivity analysis has established  
478 that the likely value of the permeability is between  $10^{-9} \text{ m}^2$  and  $10^{-8} \text{ m}^2$ . The inversion that we  
479 run is performed to check by another means the accuracy of this estimation. We ran 30,000  
480 McMC simulations to reach the convergence of the inverse algorithm. The algorithm gives 2.5  
481  $10^{-9} \text{ m}^2$  for the permeability of the seepage flow path and 2843.9 Pa at its exit. These values  
482 indeed allow for reproducing the values of the observed anomalies i.e. -15 mV in the vicinity  
483 of the bottom of the water reservoir and +50 to +60 mV downstream, at the resurgence area  
484 (see Figure 13a). This is in accordance with the physics behind the self-potential method.  
485 Indeed, the self-potential anomalies are expected to be negative upstream around the seepage  
486 area and positive upstream around the resurgence area.

487 The comparison of the observed self-potential signal against the simulated one  
488 obtained using the best hydraulic properties given by the inverse modeling, shows a very good  
489 match between both signals (see Figure 13b). The corresponding coefficient of correlation is

490  $R^2 = 0.99$ . The computed velocity within the seepage flow path is obtained from the inverted  
491 hydraulic properties and is estimated to be  $1.5 \cdot 10^{-3} \text{ m.s}^{-1}$ .

492

### 493 **3.5 Case study 3**

494           The third dam that we are working on in this case study is located in West Africa as  
495 well. It was built in 1980. Its reservoir has a volume of 38.5 billion  $\text{m}^3$  and the water level within  
496 it reaches 15 m. The earth dam consists on homogeneous backfill bank and rockfill on upstream  
497 side. The total length of the dam is 1,164 m for a maximum high of 31m above foundation.  
498 Geological structure of the site contains four main geological units from the top to the bottom:  
499 (i) lateritic cuirass (it is a very hard rock partly constituting the dam foundation), (ii) lateritic  
500 carapace (composed of gravel with clay matrix or lateritic clays). The cumulative thickness of  
501 these two units is less than 10 m, (iii) dolerite arena (predominantly sandy-clay. It is thicker on  
502 the left bank where it can reach 25 m thick against 10 m) on the right shore, (iv) dolerite appears  
503 progressively less weathered with depth or directly healthy under the dolerite arena. Its roof is  
504 not uniform and presents locally faulted passages. The Lateritic cuirass and carapace units are  
505 both porous in the form of canaliculi whose diameter, according to information provided, can  
506 reach centimeters to decimeters. Constituting the upstream and downstream foundation of the  
507 dam (located in contact with the clay core of the dam as well), we can assume that these two  
508 units are responsible of preferential seeps.

509           In order to model the dam environment, we geometrically represent each of the  
510 geological formations of the dam site (see Figure 14) and we assign to each of them its physical  
511 properties as reported in Table 2. The self-potential measurements performed on the dam  
512 revealed the presence of a seepage area characterized by negative self-potential anomalies  
513 upstream of the dam, reaching -40 to -50 mV and +150 mV self-potential anomalies observed  
514 downstream of the dam (see Figure 15).

515 In this case study, we adopt a different strategy as we approximate the shape of the  
516 seepage fluid path. We first compute the source current density  $\mathbf{j}_s$  from the self-potential  
517 observations by solving an inverse problem. This inverse problem is linear and can be readily  
518 solved as its resolution does not require the use of any interactive process. For the sake of  
519 brevity, we will not discuss here the algorithm used for the linear inversion. The reader who  
520 desires more details about this inverse strategy is invited to refer to Soueid Ahmed et al. (2013).  
521 The estimation of the current density is represented in Figure 15b. One can notice that this  
522 current density distribution shows an area of high magnitude which presumably corresponds to  
523 the area where the anomalous seepage occurs. Therefore, this gives the possibility of delineating  
524 the seepage flow path.

525 As for the previous case studies, we will do a sensitivity analysis on the properties  
526 of the dam. We underline that this dam has a homogenous structure (i.e., it does not contain a  
527 low permeability core) which is well characterized (see Table 3) so we did not see a rationale  
528 for performing a sensitivity analysis on its structure as done for the previous studied dams. The  
529 sensitivity analysis is restricted to the seepage flow path and water properties. The resistivity  
530 tomogram identified an anomaly of around 800 Ohm m, thus we chose it to be the resistivity of  
531 the seepage preferential flow path. The permeability (expressed in  $\text{m}^2$ ) is varied with the  
532 following set of values:  $\{10^{-10}, 10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}\}$ . The results of such  
533 sensitivity analysis are illustrated in Figure 16a. One can see that the observed self-potential  
534 anomalies can be reproduced by a permeability ranging between  $10^{-10} \text{ m}^2$  and  $10^{-9} \text{ m}^2$ . Let us  
535 now fix this permeability at  $10^{-9} \text{ m}^2$  for the sake of performing a sensitivity analysis on the  
536 resistivity of the preferential flow path. We vary the resistivity within the set of values:  $\{30,$   
537  $200, 300, 400, 500, 600, 700, 800, 900, 1000\}$  in Ohm m. As expected, a resistivity comprised  
538 between 600 Ohm m and 900 Ohm m satisfactorily reproduced the observed self-potential  
539 anomalies, that is -10 to -15 mV upstream and 50 mV downstream (see Figure 16b). Then we

540 performed a sensitivity analysis on the resistivity of the water of the reservoir. We vary the  
541 resistivity of the pore water within the set of values given by: {10, 12.5, 16.7, 25, 50, 100, 200,  
542 1000} (in Ohm m). As shown in Figure 16c, the downstream and upstream self-potential  
543 anomalies are reproduced with a resistivity ranging from  $10^{2.4}$  to  $10^3$  Ohm m, or equivalently  
544 from 251 to 1000 Ohm m. We consider now the estimation of the permeability of the  
545 preferential flow path. The sensitivity study has shown that the value of the permeability is  
546 likely comprised between  $10^{-10}$  m<sup>2</sup> and  $10^{-9}$  m<sup>2</sup>. After 30,000 simulations, the MCMC algorithm  
547 converged towards a permeability of  $5 \cdot 10^{-10}$  m<sup>2</sup> and an outlet pressure of 2946 Pa. As illustrated  
548 in Figure 17a and 17b, the recovered permeability field reconstructs with high fidelity the  
549 observed self-potential anomalies. The coefficient of correlation between the observed and  
550 simulated self-potential signals is  $R^2 = 0.996$ . The computed self-potential distribution clearly  
551 reveals a negative upstream anomaly and a positive downstream one, which are reflective of  
552 the presence of a seepage flow path. The flow velocity within the seepage flow path is  $4.6 \cdot 10^{-4}$   
553 m.s<sup>-1</sup>.

554 The sensitivity analysis that we performed on the three dams gave us insights about the  
555 characteristics of self-potential signals in dams. From the three studied dams, we conclude that  
556 estimating the permeability of the seepage flow path needs to be done with high accuracy as  
557 this factor directly affects the magnitudes of the self-potential anomalies. In contrast to the  
558 narrow range of permeability, a relatively wide range of resistivity values reproduces well the  
559 observed self-potential anomalies. Indeed, the resistivity magnitudes revealed by the resistivity  
560 for the seepage areas give accurate estimation of the observed self-potential magnitudes. This  
561 suggests that using the resistivity field given by the resistivity as input in the self-potential  
562 simulations is acceptable and will not lead to significant errors in the simulation of the self-  
563 potential signal. On the other hand, the permeability of the main structure of the dam does not  
564 seem to have a strong impact on the self-potential signals while its resistivity has a stronger



565 impact on the self-potential signal, especially when this resistivity is underestimated. In this  
566 case, the self-potential signal becomes weak and the computed signal does not match well with  
567 the observed one. The sensitivity analysis has (besides checking the accuracy of the water  
568 resistivity measured in the field), underlined the importance of having reliable measures of this  
569 property for a more accurate approximation of the self-potential signatures.

570 As a final note, we underline the fact that we have computed the Reynolds number for  
571 the three case studies to see under which regime flow we are working. The Reynolds number  
572 is, 0.3, 0.19 and 0.3 for the three cases, respectively. Indeed, these low values of the Reynolds  
573 number suggest that we are under the laminar flow regime and therefore the Reynolds number  
574 has a very weak influence on the self-potential signatures and can be neglected.

575 The case studies presented above show the effectiveness of the SP method as an efficient  
576 nondestructive and passive technique for dams' prospection, which has the twofold advantage  
577 of being straightforward to set up and financially cheap. Indeed, thanks to its high sensitivity to  
578 the groundwater flow, the SP method can provide valuable information regarding the hydraulic  
579 texture of the subsurface and the behavior of the water flow within it. That said, the literature  
580 on the use of the SP method for dams investigations, is mostly restricted to quantitative studies  
581 in which the SP method is simply used as an indicator of the presence of seeps in the structure  
582 of the dam. The current work helps filling this interpretation gap by providing more powerful  
583 numerical approaches for taking full advantage of the SP data and though obtaining key  
584 information such as accurate delimitation of the seepage area, the velocity of the seepage flow  
585 as well as the permeability of the seepage flow path. Therefore, the methodology that we have  
586 developed is of high interest especially for the engineers working on the prospection and  
587 surveillance of hydraulic structures such as dams and embankments.

588

#### 589 **4. Conclusion**

590 The self-potential method appears as a suitable method for large-scale investigation of  
591 earth dams. We have developed a strategy for interpreting quantitatively self-potential  
592 observations in achieving a two-fold objective: (i) putting in evidence the presence of an  
593 anomalous seepage in the structure or foundation of a given dam, (ii) estimating the  
594 permeability of the seepage flow paths and the flow velocity within them. Being able to evaluate  
595 such properties is of paramount importance for dam managers to evaluate suffusion phenomena.  
596 The inverse methodology that we propose is based on the MCMC approach that has the  
597 advantage of not requiring assembly of the sensitivity matrix, which is a daunting task  
598 especially when working on large-scale applications. We have validated the effectiveness and  
599 robustness of our inverse scheme on a synthetic test and several real field applications in which  
600 the self-potential method clearly exhibits the seepage areas and successfully allows for the  
601 estimation of the hydraulic properties of the seepage flow paths. Our study shows also the  
602 importance of jointly using other techniques in addition to the self-potential method to  
603 strengthen the interpretation of self-potential anomalies. In our case, the resistivity tomography  
604 method was used to connect the resistivity anomalies associated to the presence of seepages to  
605 the self-potential signatures and to provide the electrical resistivity field, which is an input for  
606 the forward modeling. Future works should be geared towards the combination of the self-  
607 potential and induced polarization methods. The latter could be used to infer water content and  
608 saturation through the dam structure. We also see an opportunity for using deep learning  
609 algorithms for better delineation of the seepage flow paths.

610

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621

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## Tables

733 **Table 1. Synthetic test: Physical properties of the different components of the dam.**

	Water	Foundation	Seepage flow path	Core	Structure
Permeability (m <sup>2</sup> )	0.1	10 <sup>-16</sup>	10 <sup>-10</sup>	10 <sup>-18</sup>	10 <sup>-15</sup>
Resistivity (Ohm m)	600	1,000	300	100	2,000

734

735 **Table 2. Field study 1: Physical properties of the different components of the dam.**

	Water	Foundation	Seepage flow path	Core	Structure
Permeability (m <sup>2</sup> )	0.1	10 <sup>-18</sup>	5 10 <sup>-9</sup>	10 <sup>-20</sup>	10 <sup>-17</sup>
Resistivity (Ohm m)	100	1,000	400	400	800

736

737 **Table 3. Field study 2: Physical properties of the different components of the dam.**

	Water	Foundation	Seepage flow path	Core	Structure
Permeability (m <sup>2</sup> )	0.1	10 <sup>-18</sup>	2.5 10 <sup>-9</sup>	10 <sup>-17</sup>	10 <sup>-15</sup>
Resistivity (Ohm m)	130	1,000	100	100	2,000

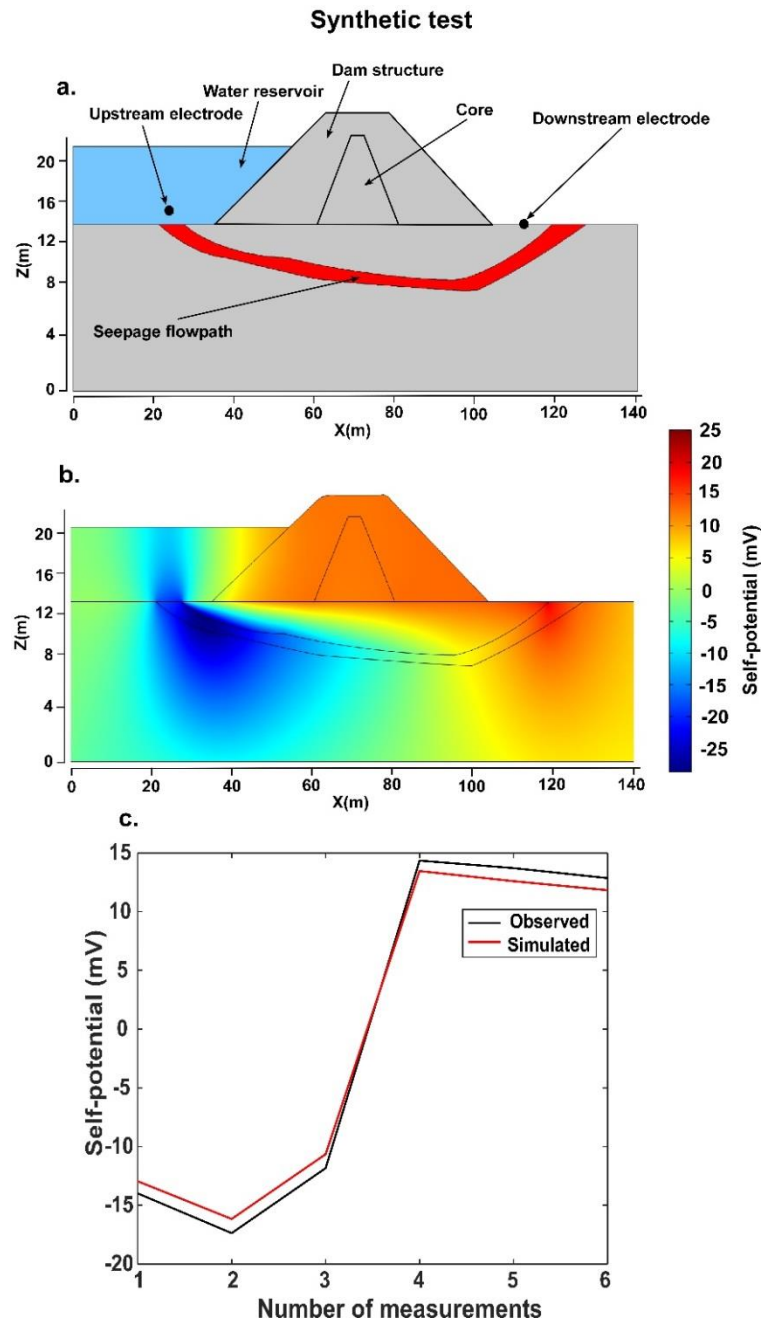
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739 **Table 4. Field study 3: physical properties of the different components of the dam.**

	water	dam	Lateritic material	Lateritic clay	Doleritic sand	Fresh Dolerite
Permeability (m <sup>2</sup> )	0.1	10 <sup>-16</sup>	10 <sup>-14</sup>	1.4 10 <sup>-14</sup>	910 <sup>-13</sup> – 910 <sup>-15</sup>	910 <sup>-16</sup> – 910 <sup>-17</sup>
Resistivity (Ohm m)	400	600	1,000 – 1,500	200 – 600	100 – 200	2,000 – 4,500

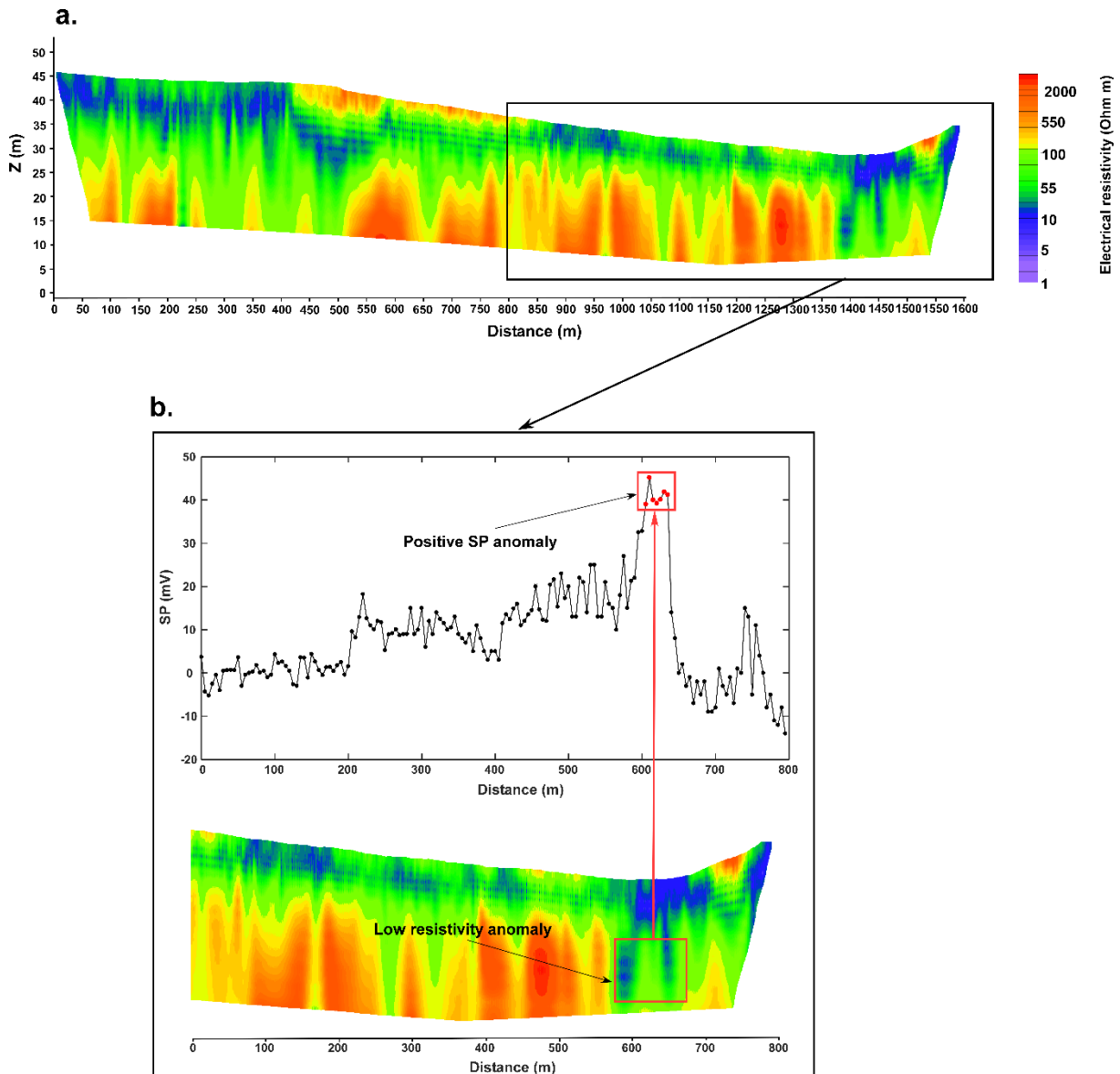
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## Figures



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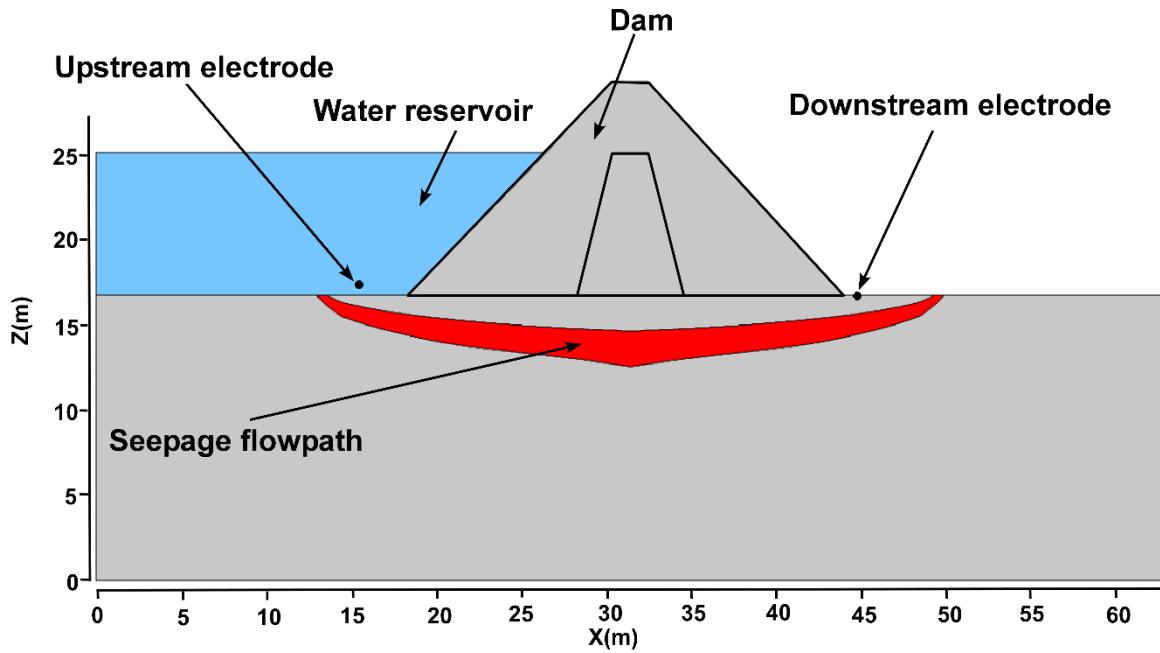
743 **Figure 1.** Synthetic test. **a.** Geometry of the synthetic dam. The measurements are collected on  
 744 two electrodes, one located upstream and the other downstream. The hypothetical seepage flow  
 745 path is highlighted in red. **b.** The true self-potential distribution observed across the dam. The  
 746 reference electrode is placed far away from the region of interest. Its potential is negligible. A  
 747 positive anomaly can be observed downstream while a negative one is visible upstream at the  
 748 vicinity of the seepage area. **c.** Observed and computed self-potential signals. The self-potential  
 749 signal generated using the best permeability estimate, reproduces well the exact self-potential  
 750 signal.



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753 **Figure 2.** Field study 1: Geoelectrical measurements collected on the left bank dike.  
 754 **a.** Downstream electrical resistivity profile. The foundation of the dam is located in a globally  
 755 highly resistive gneiss rock except between the abscissas 1440m and 1490m where conductive  
 756 anomalies are observed. The self-potential measurements show a peak at the same location. **b.**  
 757 Zoom on the suspected seepage area. The conductive resistivity anomalies coincide with the  
 758 location of a +30 to +35 mV self-potential anomaly (red points on the curve) that is reflective  
 759 of the presence of a preferential flow path in the dam structure. The resistivity profile is 1180  
 760 m long but we only show the part of the profile that contains the low resistivity anomaly  
 761 associated with the seepage area. Some shallow low resistivity anomalies associated with the  
 762 conductive nature of terrain are observed as well.  
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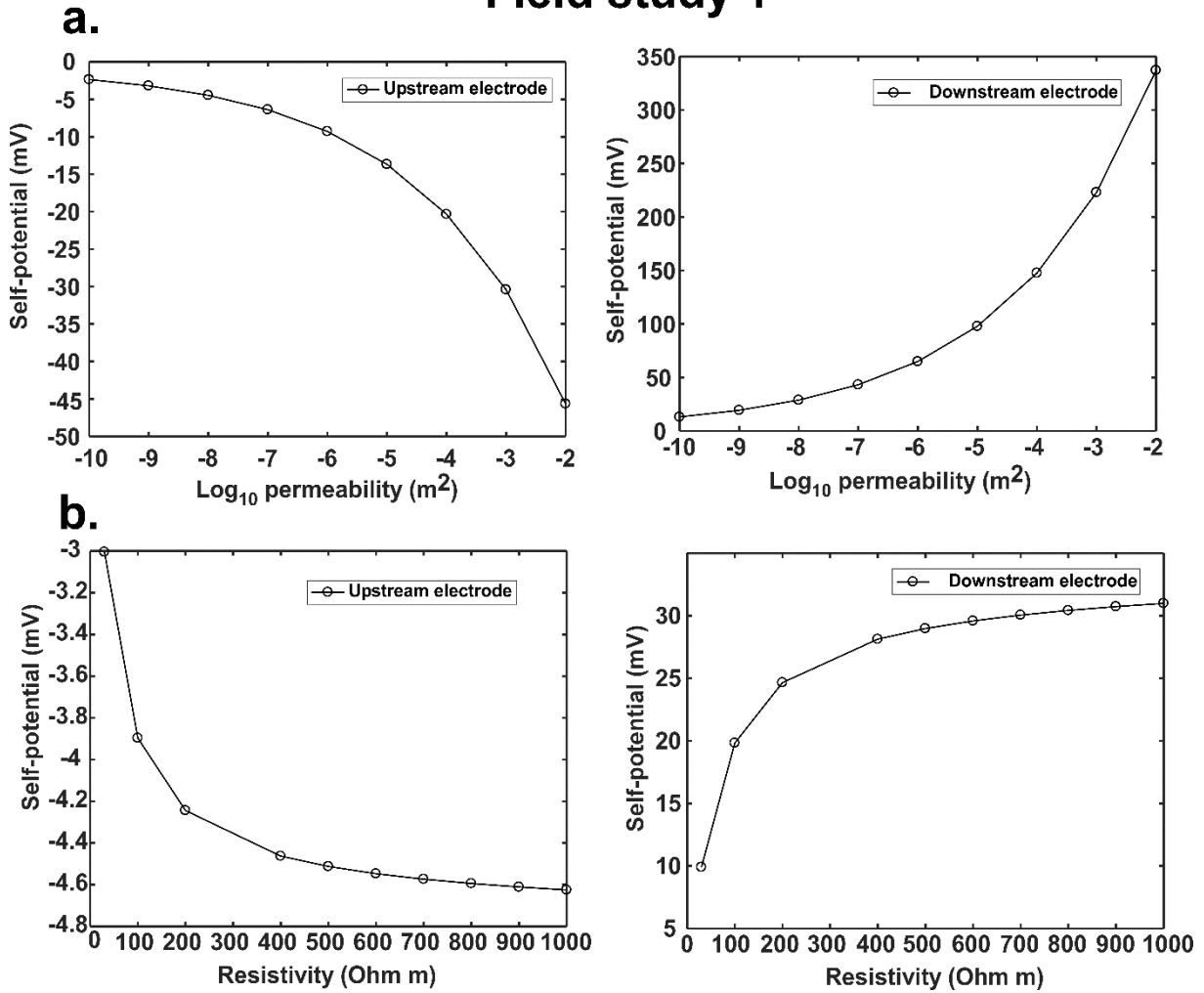
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767 **Figure 3.** Field study 1: Simulation domain geometry. The different components of the dam  
768 that are modeled are represented. Two electrodes, one located at 1 m from the bottom of the  
769 reservoir and the other located upstream at 2.5 m from the bottom of the dam, are used to  
770 measure the self-potential signals.

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## Field study 1



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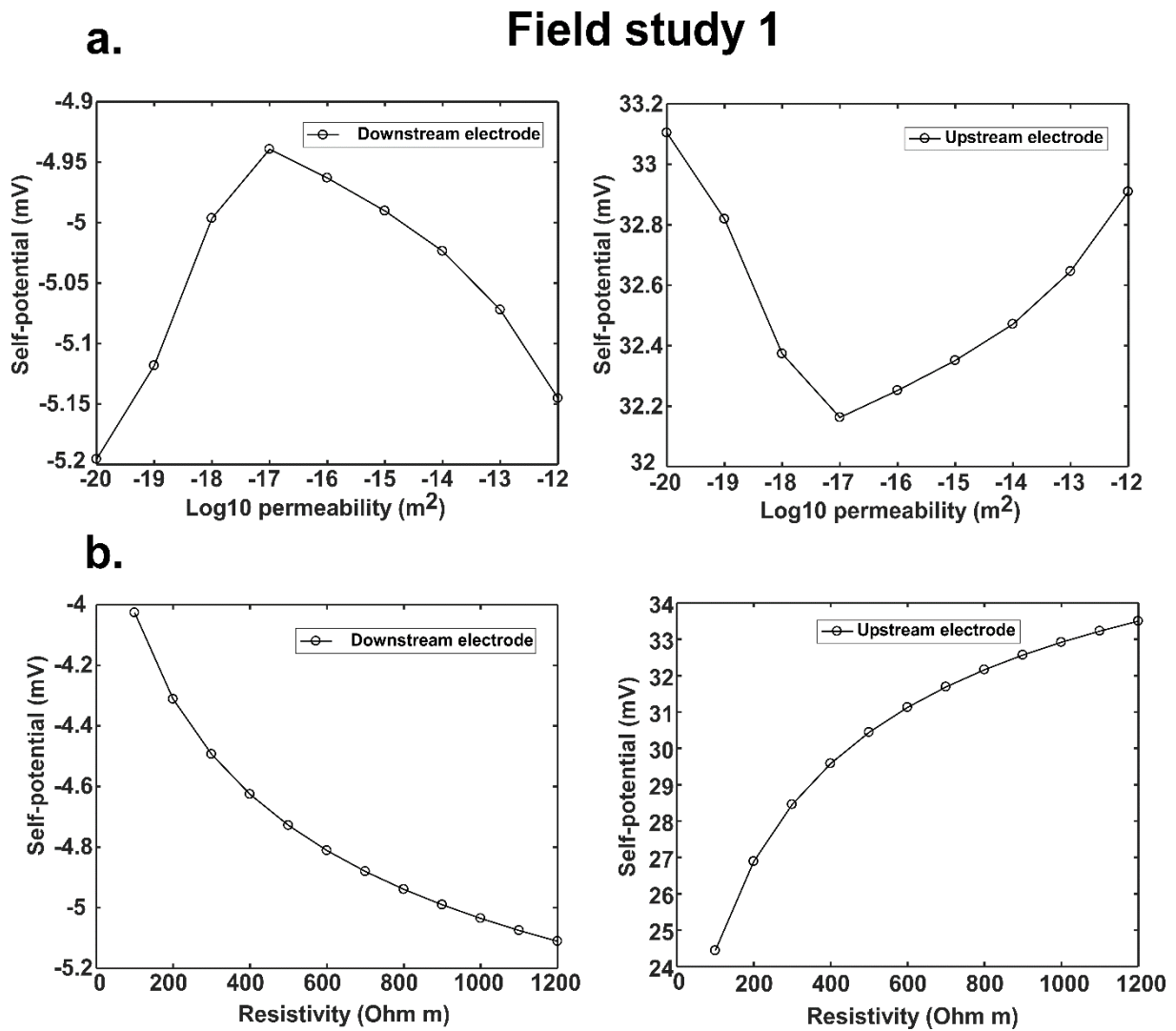
775 **Figure 4.** Field study 1: Sensitivity analysis on the seepage flow path properties. **a.** Permeability  
 776 of the seepage flow path. **b.** Resistivity of the seepage flow path. The permeability and the  
 777 resistivity of the seepage flow path are varied to find the orders-of-magnitude of these properties  
 778 that enable simulation of the observed self-potential anomalies. A permeability comprised  
 779 between  $10^{-9}$  and  $10^{-8}$  m<sup>2</sup> and a resistivity of around 400 Ohm m approximates the observed  
 780 self-potential amplitudes downstream and upstream.

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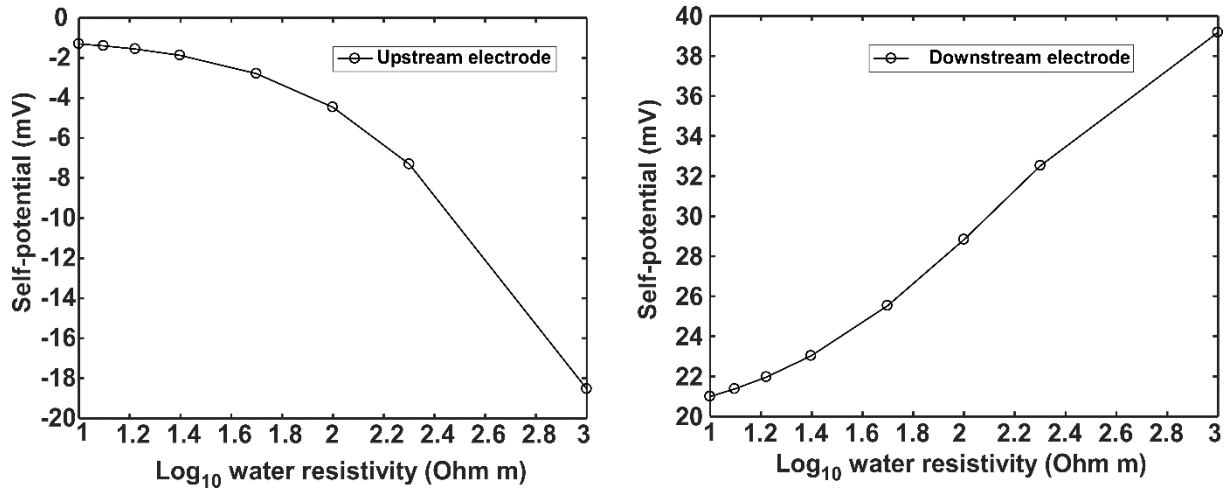
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787 **Figure 5.** Field study 1: Sensitivity analysis on the dam structure properties. **a.** Permeability of  
 788 the dam structure. The permeability of the structure has a weak influence on the observed self-  
 789 self-potential amplitudes. The permeability of the structure has a weak influence on the observed  
 790 self-potential, which change roughly 0.2 to 0.8 mV over 10 orders of magnitude of permeability.  
 791 As one can see, varying the permeability of the dam structure only results in a very slight  
 792 variation of the self-potential signal. **b.** Resistivity of the dam structure. The self-potential signal  
 793 seems to not significantly vary with the resistivity of the structure unless for the low resistivity  
 794 environments.

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## Field study 1



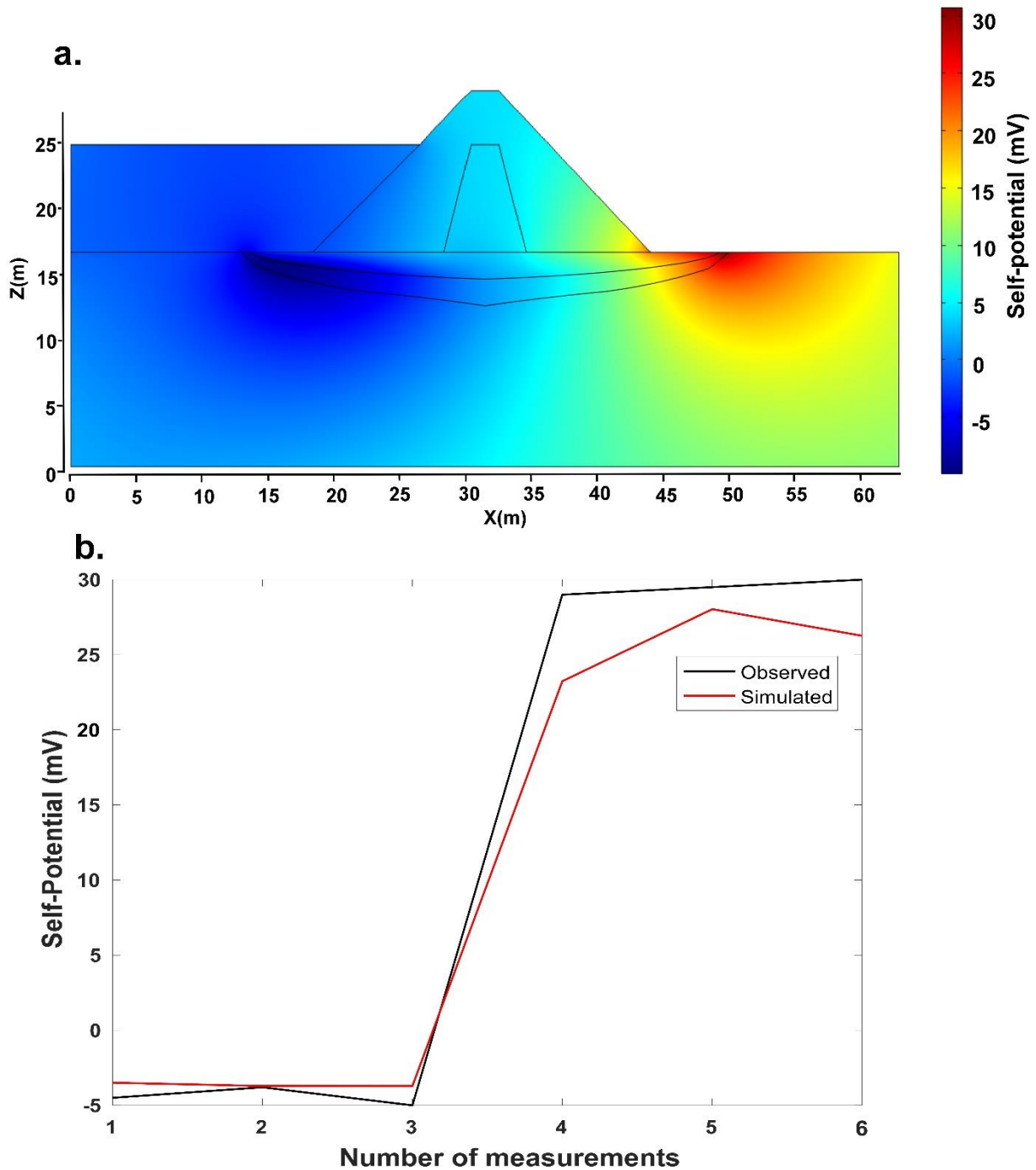
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800 **Figure 6.** Field study 1: Sensitivity analysis on the resistivity of the water of the reservoir. The  
 801 observed self-potential magnitudes are retrieved with a resistivity ranging from 50 to 100 Ohm  
 802 m. This is in accordance with the measurement of the resistivity of the water on the field which  
 803 was found to be 50 Ohm m.

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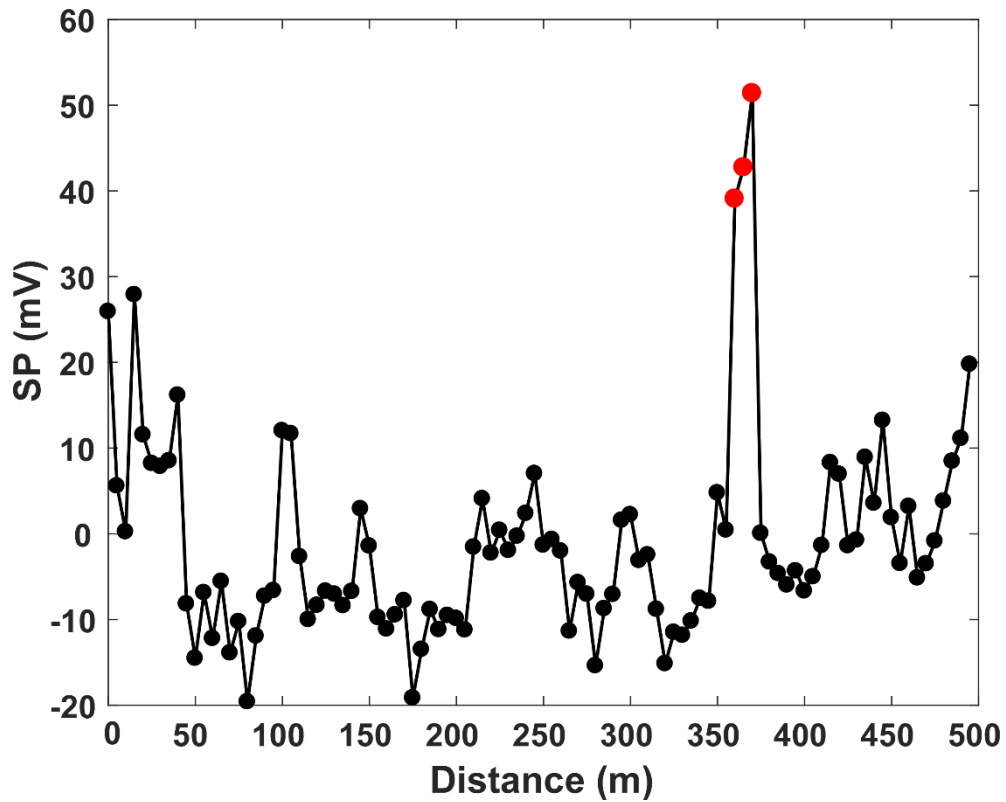


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809 **Figure 7.** Field study 1: self-potential signal: **a.** Simulated self-potential distribution. **b.**  
810 Observed against simulated self-potential signal. There is a very good match between the  
811 observed and self-potential signal. The self-potential distribution clearly shows regions of  
812 negative and positive self-potential anomalies at the ends of the preferential flow path.  
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817 **Figure 8.** Field study 2: self-potential measurements collected on the right side of the dike. This  
818 self-potential profile was measured on the bottom of the right bank in a region where water was  
819 emerging. A positive anomaly with an amplitude of 40 to 50 mV (represented by the red points)  
820 is observed at the vicinity of this resurgence area. The self-potential electrodes have a 5 m  
821 interval.

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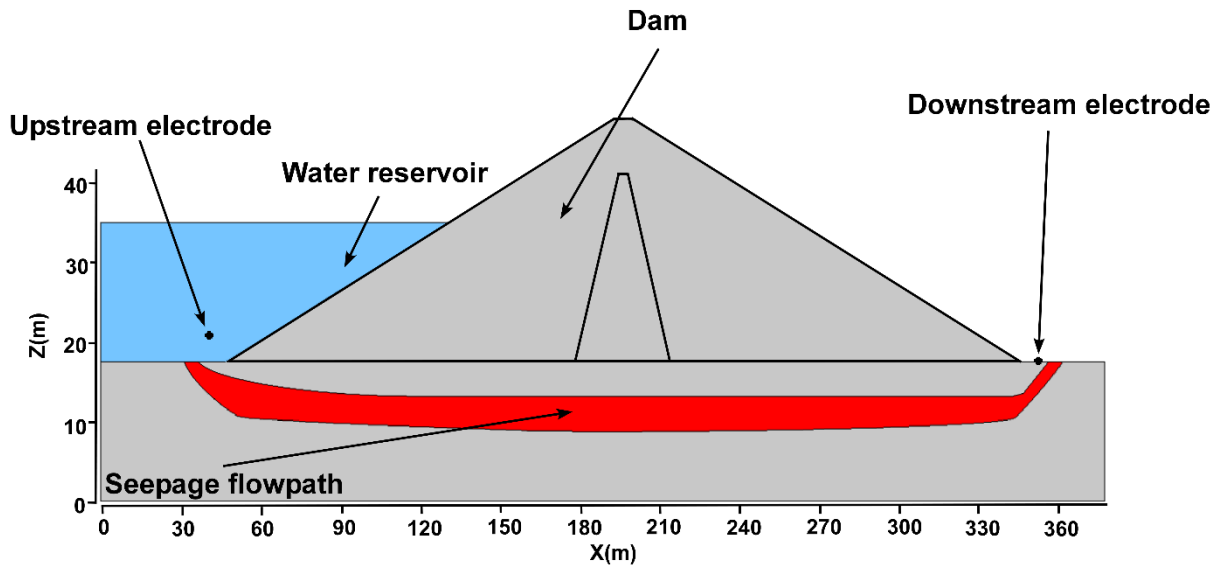
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829 **Figure 9.** Simulation domain geometry for the field study 2. The different components of the  
830 dam that are modelled are represented. The self-potential simulated signal is collected at an  
831 electrode located at one 1 m from the bottom of the reservoir and Another electrode located  
832 upstream at 2 m from the bottom of the dam.

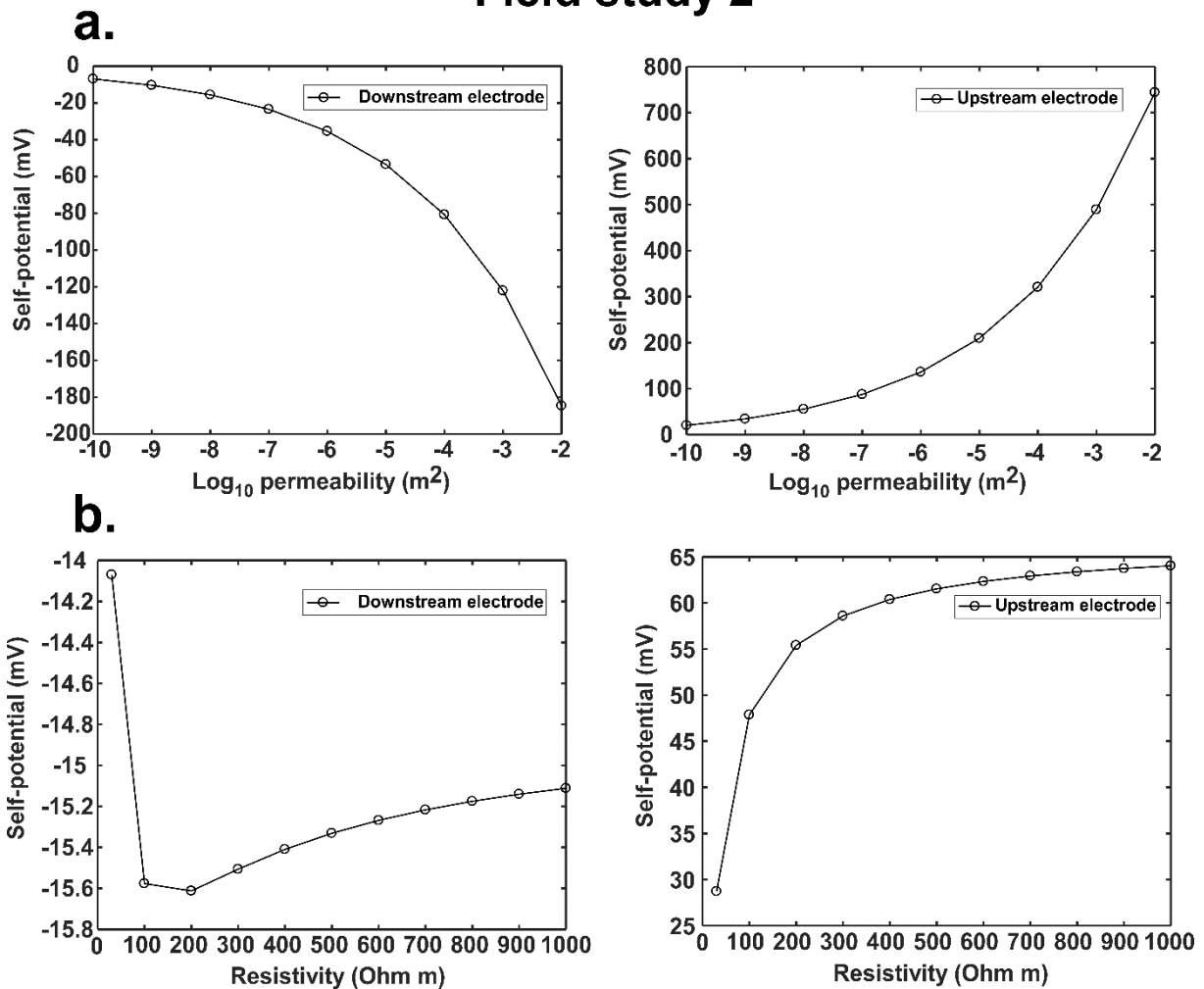
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## Field study 2



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838 **Figure 10.** Field study 2: Sensitivity analysis on the seepage flow path properties. **a.**  
839 Permeability of the seepage flow path. **b.** Resistivity of the seepage flow path. The permeability  
840 and the resistivity of the seepage flow path are varied to find the orders-of-magnitude of these  
841 properties that approximate the amplitude of observed self-potential anomalies. The sensitivity  
842 analysis shows that the permeability (expressed in m<sup>2</sup>) is in the range [10<sup>-9</sup>, 10<sup>-8</sup>]. This range  
843 will be used as a constraint will be used as constraints in the inversion process of estimating the  
844 seepage flow path permeability. The resistivity of the seepage flow path that recovers the  
845 observed self-potential observations (i.e., -15 mV upstream and + 50 mV downstream) is  
846 around 100-150 Ohm m.

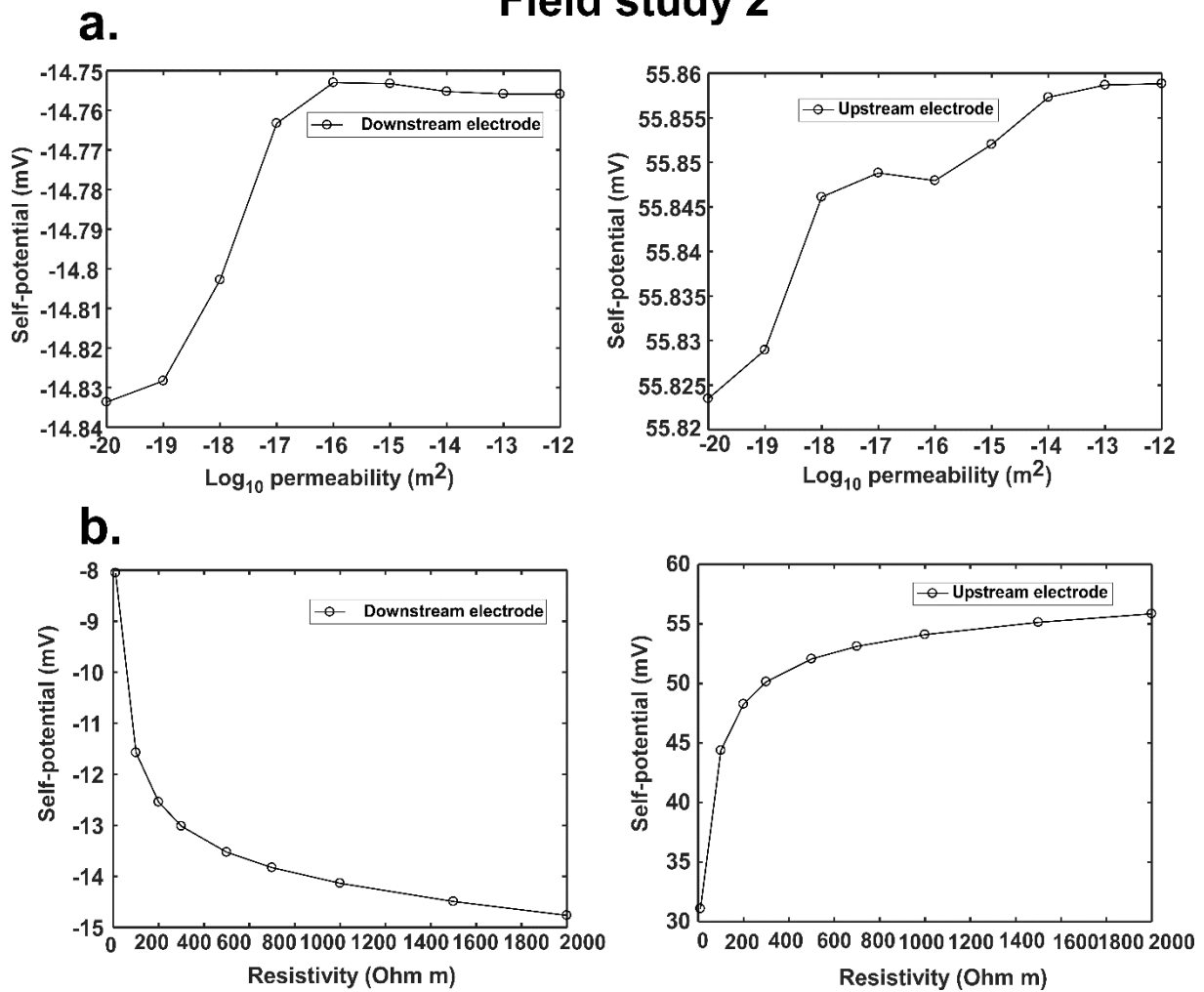
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## Field study 2



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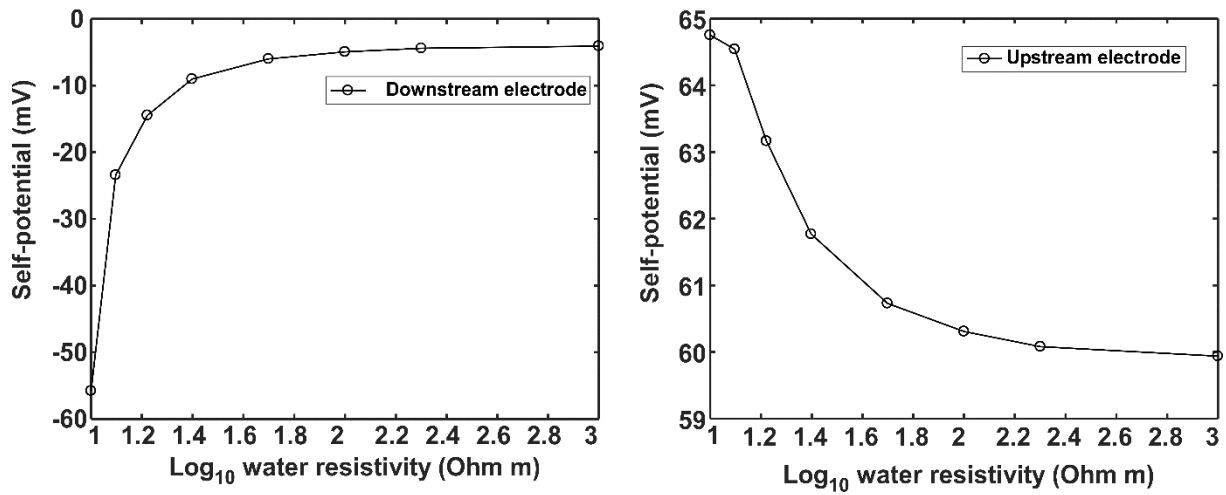
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854 **Figure 11.** Field study 2: Sensitivity analysis on the dam structure properties. **a.** Permeability  
 855 of the dam structure. Despite the wide range of permeability used in this sensitivity analysis,  
 856 we notice that self-potential signal does not vary significantly, which suggests that the  
 857 permeability of the structure is not the main parameter that influence self-potential signal  
 858 generated on a dam. However, the resistivity of the structure appears to have a larger impact on  
 859 the self-potential signal especially when are working in conductive media.

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## Field study 2



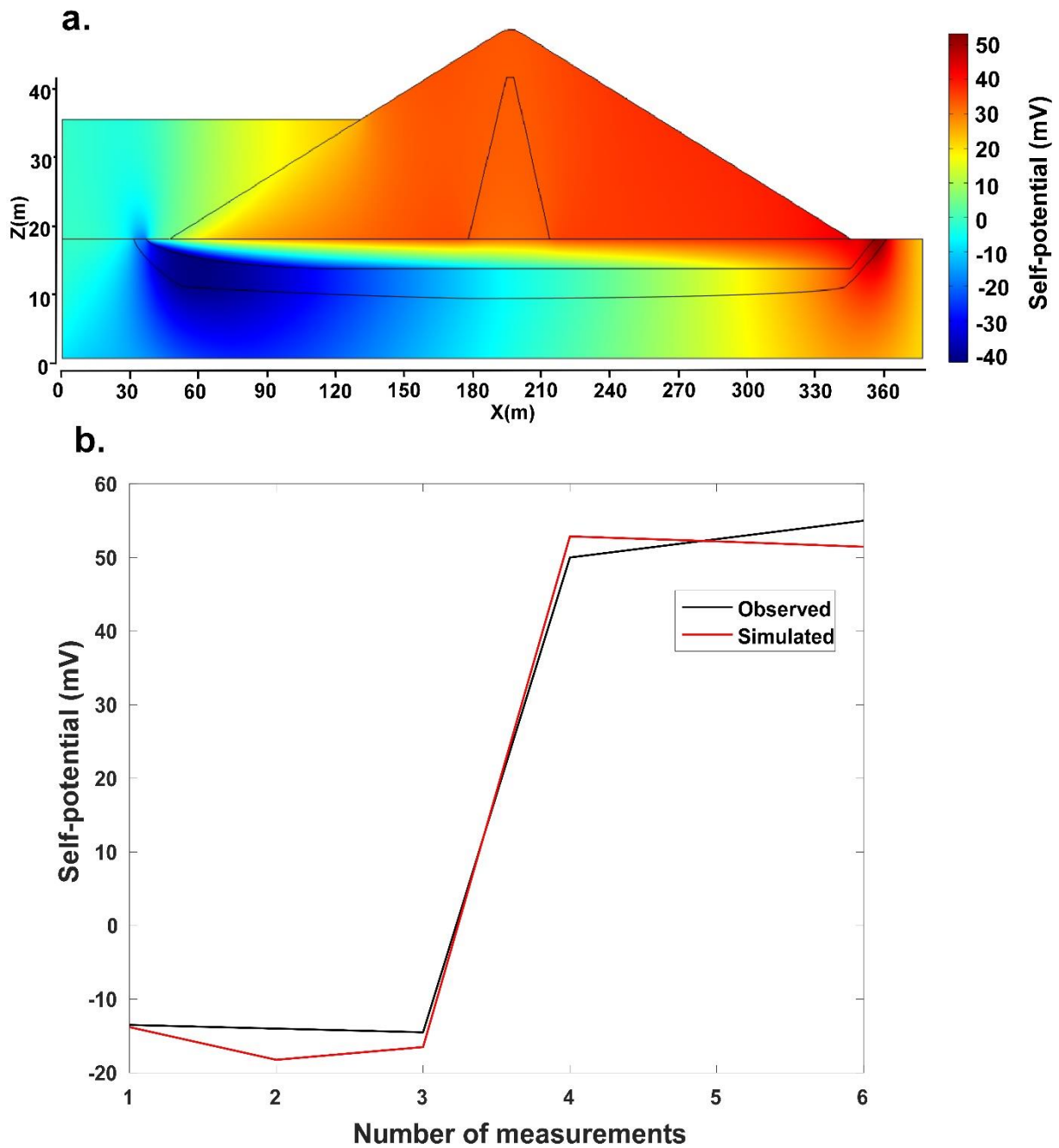
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865 **Figure 12.** Field study 2: Sensitivity analysis on the resistivity of the water of the reservoir.  
 866 This sensitivity analysis is performed to check the correctness of the water resistivity  
 867 measurement that we performed on the field, which was 100 Ohm m. Observing the figure  
 868 shows that the observed self-potential amplitudes are retrieved using resistivities ranging from  
 869 12.5 to 100 Ohm m.

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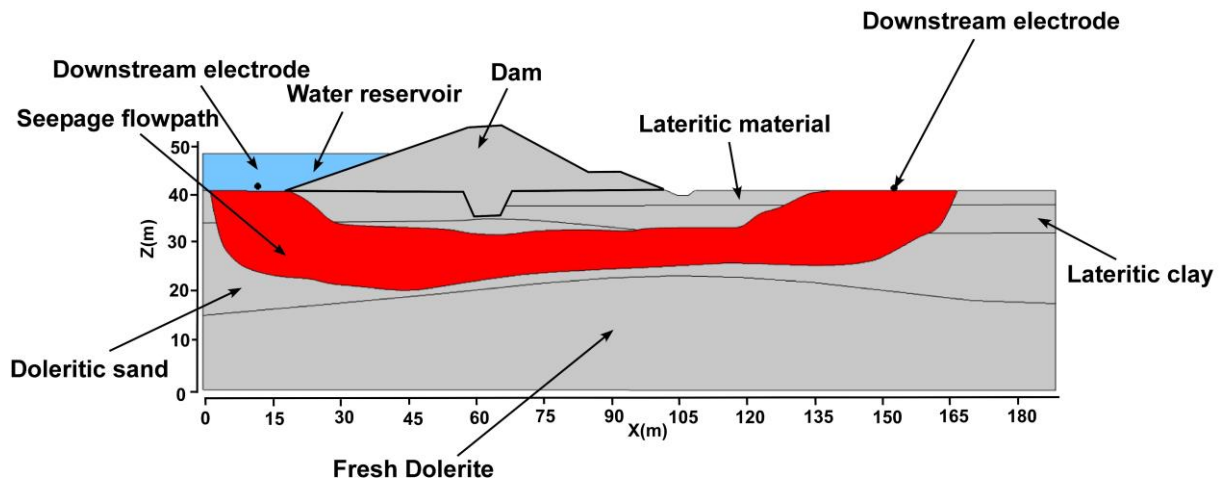
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874 **Figure 13.** Field study 2: self-potential signal: **a.** Simulated self-potential distribution. **b.**  
 875 Observed against simulated self-potential signal. There is a very good match between the  
 876 observed and self-potential signal. The self-potential distribution clearly shows regions of  
 877 negative and positive self-potential anomalies at the ends of the preferential flow path.

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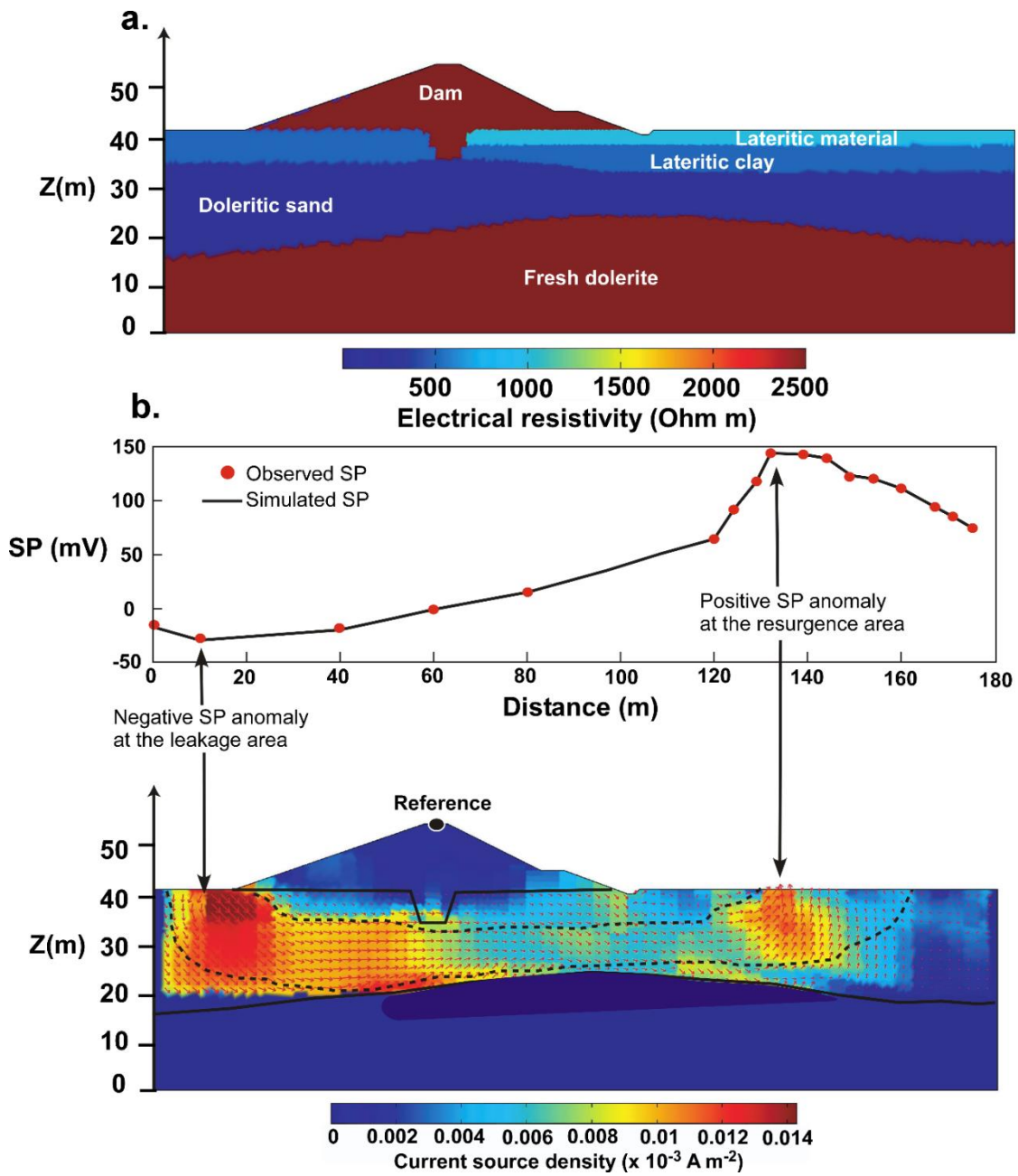
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881 **Figure 14.** Sketch of the domain geometry for the field study 3: The different components of  
882 the dam are modelled as well as the geological units of the site. The self-potential simulated  
883 signal is collected at an electrode located at one 1 m from the bottom of the reservoir and another  
884 electrode located upstream at ground surface. The seepage flow path geometry (Figure 15) has  
885 been approximated using a linear inverse process, which depicts the source current density from  
886 self-potential observations.

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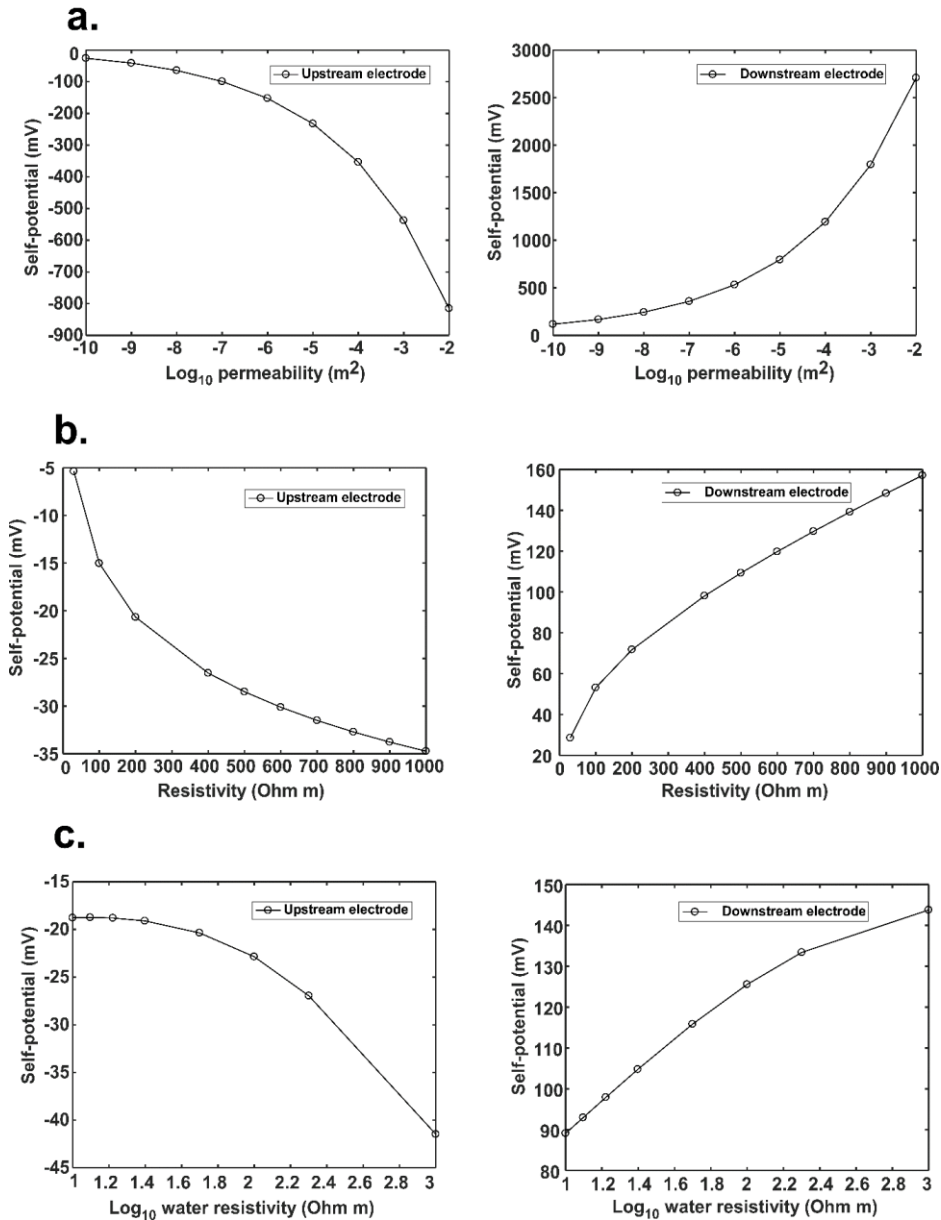


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892 **Figure 15.** Field study 3: Resistivity model and self-potential measurements. **a.** The resistivities  
 893 of each of the components are estimated from ERT. This resistivity model is used in the forward  
 894 problem to generate the simulated self-potential response. **b.** The observed self-potential signal  
 895 shows a negative anomaly upstream and a positive one downstream. The estimated current  
 896 density is higher at leakage and resurgence areas and it exhibits a continuous pattern which is  
 897 indicative of the seepage flow path.  
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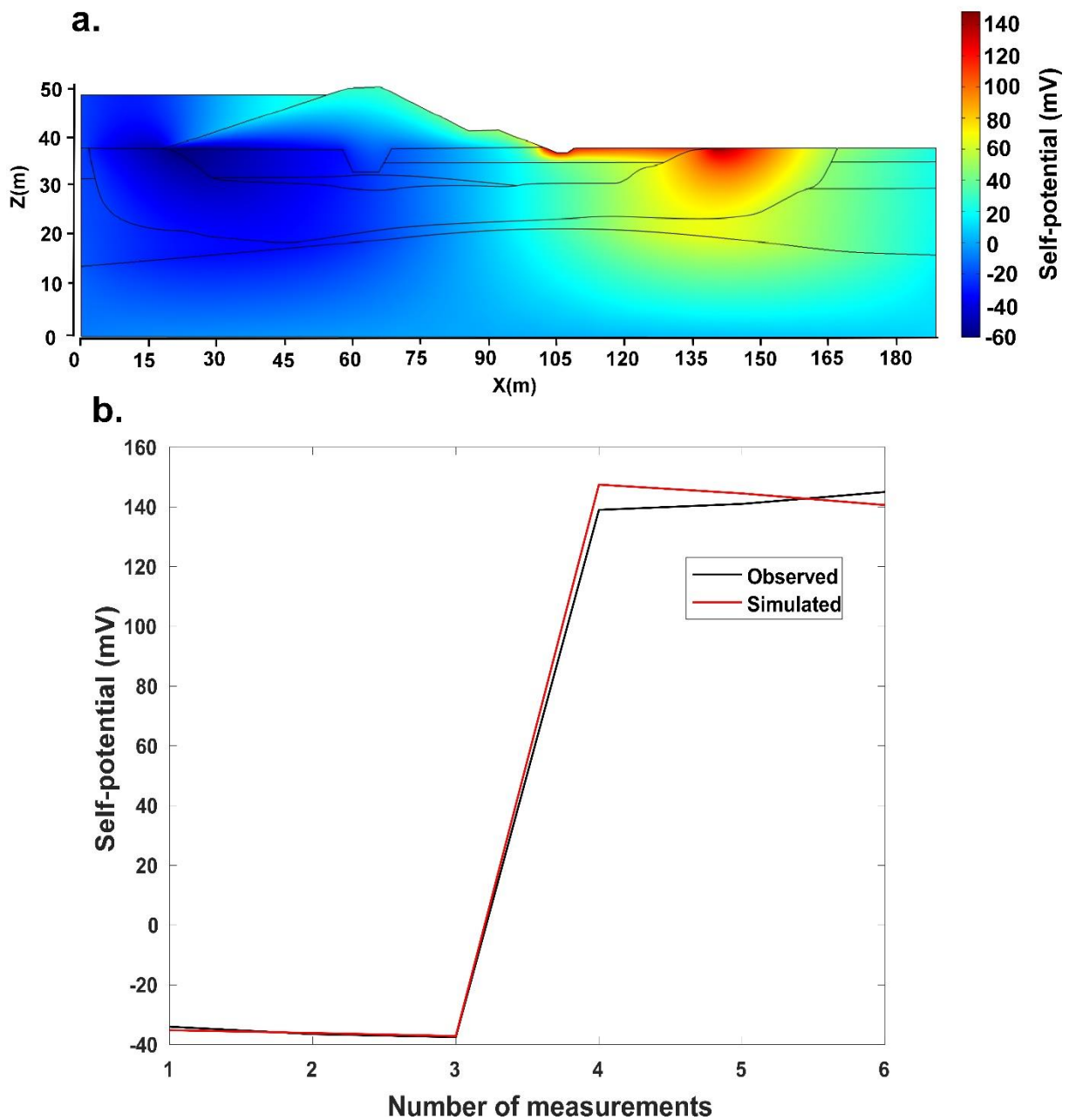


### Field study 3



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900 **Figure 16.** Field study 3: Sensitivity analysis on some of the components of the studied dam.  
 901 **a.** Sensitivity analysis on the permeability of the seepage flow path properties. The self-  
 902 potential anomalies are retrieved with a permeability of the seepage flow path that is ranging  
 903 between  $10^{-10}$  m<sup>2</sup> and  $10^{-9}$  m<sup>2</sup> **b.** Sensitivity analysis on the resistivity of the seepage flow path.  
 904 A resistivity comprised between 600 Ohm m and 900 Ohm m reproduces the observed self-  
 905 potential anomalies of -10 to -15 mV upstream and 150 mV downstream. This resistivity range  
 906 is in accordance with the order of magnitude observed on the resistivity tomograms. **c.**  
 907 Sensitivity analysis on the resistivity of the water in the dam reservoir. The resistivity of the  
 908 pore water is varied within a wide range of resistivities as shown in the figure. The downstream  
 909 and upstream self-potential anomalies are well reproduced with a resistivity whose logarithm  
 910 is ranging from 2.4 to 3.  
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**Figure 17.** Case study 2: self-potential signal: **a.** Simulated self-potential distribution. **b.** Observed against simulated self-potential signal. There is a very good match between the observed and self-potential signal. The self-potential distribution clearly shows regions of negative and positive self-potential anomalies at the ends of the preferential flow path.