

Chapter 10

Groundwater Flooding Risk Assessment Using Microseismic Arrays and VES Techniques in the Northern Part of Bishkek



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Abstract Increased groundwater elevation and subsequent flooding of infrastructures are a threat to Bishkek city. Novel geophysical approaches to determine and map groundwater depths, such as microseismic arrays and VES technologies, were used in the northern part of Bishkek. These new geophysical measurements showed groundwater at a depth of 5–10 m at all points. This is considerably deeper than the 1–3 m currently shown on flood risk maps. Such discrepancy (2–7 m) is due to seasonal water level changes observed at approximately 5 meters which were not captured in past monitoring. The lower water levels measured in this study also indicate the impressive performance of the collector-drainage systems, filter channels, and tunnels, since the geophysical measurements were carried out in the wet spring and summer seasons. The study showed how geophysical measurements can be used in groundwater mapping and flood risk assessment.

Keywords Geophysical measurements · Groundwater · Floods · Central asia

10.1 Introduction

Groundwater flooding is a phenomenon that occurs when the groundwater level rises to fill infrastructure and housing foundations. Mapping of groundwater floods is not done much yet on a global scale. In Kyrgyzstan, groundwater flooding can also lead to slope geotechnical failure which is hazardous. The Chui Oblast territory is the most affected by flooding. It is there where these processes are developed with an area of about 1,700 km² along the natural nip line.

As a consequence, weakened soils form under the influence of groundwater. The main displacements and deformations of earth which occur on these zones are accompanied by the destruction of housing stock and urban infrastructure. A high level of groundwater has a significant impact on buildings and structures due

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to the deep penetration of foundations and underground facilities. Thus, appropriate mitigation measures should be taken during construction in accordance with the hydro-geographical area of development. Unfortunately, the construction of housing without appropriate measures being taken to prevent these gross violations of construction norms and rules remains the de facto practice in the area [13]. Most developers have been shown to ignore the requirements of the resolutions enacted by the district administrations. These resolutions prohibit any construction on the allocated land plots without obtaining the relevant project documentation and approval. For example, in the United States, the Recommended Seismic Provisions for New Buildings and Other Structures by the National Earthquake Hazards Reduction Program (NEHRP) serves to ensure safe construction of infrastructure and household structures in zones at risk of seismic activity [5].

This study used two relatively new technologies, vertical electric sounding (VES) and microseismic array sounding, which were previously not available in Central Asia to update current knowledge on flood risk in an expanding and flood-prone region of the city of Bishkek. The use of VES and seismic profiling as a geophysical prospecting technique is relatively inexpensive and it generates accurate hydrogeological measurements. The purpose of VES is to obtain a general idea of the structure of the geoelectric sections at sites.

10.2 Fieldwork Data

10.2.1 Study Area

The study was carried out in a residential area of Bishkek, the capital of the Kyrgyz Republic. In the study region, previous surveys indicate that there is a high risk of flooding by groundwater posing risks to urban construction and foundations (Fig. 10.1). There are 92 settlements, including Bishkek, Kant, Tokmok, and Kara-Balta in the flood zone [3].

Flooding occurs in the northern part of the city of Bishkek, north of the Big Chui Canal (BCC). This area is characterized by the sinking of the earth with a high water table. The depth of the groundwater does not exceed 3 m in 80% of the area of this zone. Groundwater levels on the surface largely depend on the conditions of the collector-drainage systems (CDS). The condition of the CDS is important, as its purpose is to divert water into run-off channels [3].

10.2.2 Fieldwork Data

Data collection was carried out at all four sites over two periods of fieldwork, one in spring (May 2018) and one in summer (June 2018). Groundwater level (GWL)

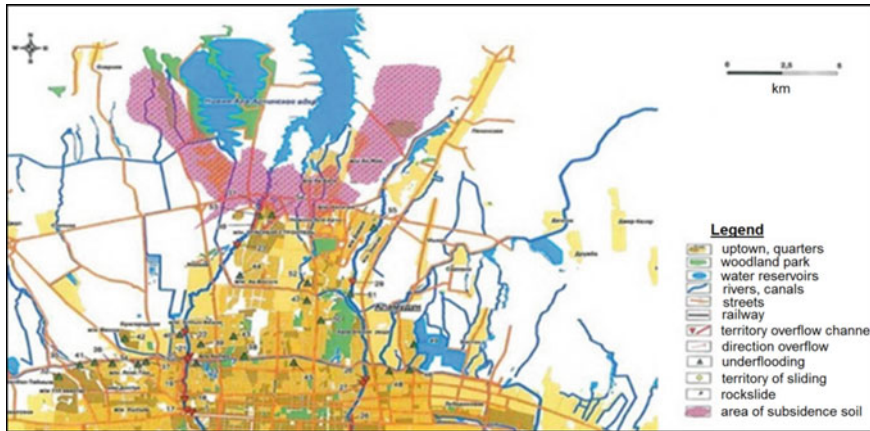


Fig. 10.1 Map displaying areas of urban development and hazardous natural processes in the north part of Bishkek (MES report, 2014)

observations were performed from May 01 to June 15 of 2018. Four sites were identified for exploration (Fig. 10.2). These points are characterized by a complex geological structure and were determined to have hydrogeological zonality inherent in all alluvial cones. The head and middle parts of the alluvial cone are the loci for the main area of groundwater accumulation. Here, the source of power are filtration losses from both the BCC and the nearby Komsomolskoye Lake. As a result, an aquifer complex with a free surface of 100–190 m has been formed (the highest values are indicative for the middle part of the cone).

The depth of occurrence of the aquifer system decreases in the northern direction from 55 m to the first meters on the southern boundary of the wedge zone where the water return is 15–23%. The amplitude of level fluctuation reaches 0.5–2 m south of the BCC according to data from the periodic observations conducted by the MES KR [3].

GW1, GW2, GW3 and GW4 investigated sites shown in Fig. 10.2. The first well was established at the Komsomolskoe Lake (GW1), where the GWL is close to the surface. The other three soundings were arranged in a northwestern direction near the Big Chui Canal (BCC). GW2 was positioned in the 110-ward, then moving northwards GW3 was positioned, near Nijnaia Maevka. Lastly, GW4 was established near the central part of the north side of the city, Karagachevaya Rosha. A total of four VES profiles were obtained for two seasons: spring and summer.

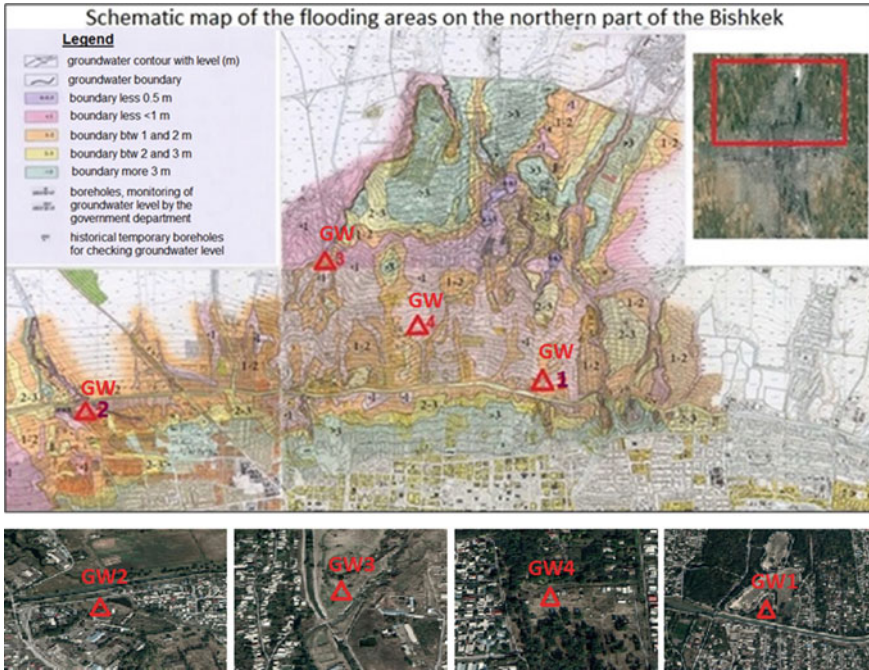


Fig. 10.2 Map of groundwater flooding in Bishkek and location of experimental fieldwork (red triangles indicate areas for conduction of seismological and vertical electrical soundings)

10.3 Methodology

10.3.1 Methods

The effectiveness of the application of geophysical methods is important. We used two different physical methods: seismic and electrical. The VES and seismic array (SA) methods were used in the study. The reliability of the obtained results depends, to a large extent, on the correct choice of methodology for the geophysical field conditions, especially in the search for and the exploration of groundwater.

10.3.2 Vertical Electrical Sounding

We used the LandMapper ERM-02, the newest device among the licensed Landviser, LLC (Penza, Russia) devices [10, 11]. This portable device measures three important electrical properties in solid, semi-solid, and liquid environments: electrical resistance (ER), electrical conductivity (EC), and electrical potential (EP).

Electrical exploration using the VES method was used to search for pore-porous waters in the loose sediments of the lower part of the BCC and in the river valleys. During both the first and second stages of data collection, the sites were selected according to the results of reconnaissance geophysical studies carried out by the authors via their literature review of the extant hydrogeological survey data.

The Land Mapper ERM-02 was utilized to acquire the VES data from the profiles. The spacing of the electrode probes was set at 2.00, 4.00, 6.00, ..., 20.00, 22.00, 24.00, ..., 40.00, 44.00, 46.00 m, where the depth of each electrode was set at approximately 0.15 m with the electrode spacing measured at each point. The VES data for each month was measured within two days. This VES data was processed and interpreted by a method of curve matching using the RES1D software [12]. All data was inverted with an average root mean square (RMS) error of less than 5% in each VES profile.

The VES fieldwork began with the implementation of a small amount of reconnaissance VES. The results allowed for the study of the main elements of the relief (river beds, floodplains, terraces, slopes, and watersheds) and areas within the reconnaissance limits. The areas of study differ sharply in terms of geological and tectonic conditions, the nature of water manifestations, and so on. The number of reconnaissance soundings at the research site was 23 points in each of the four sites. Past literature and stock material available for the area of research such as survey and drilling work data were used to select the specific points for VES affixation.




In field studies, significant distortions of VES curves can indicate inhomogeneities associated with technogenic processes that develop due to the disturbance of vegetation and soil cover and/or changes in temperature and humidity conditions near mining excavations. It is effective to perform parametric VES at small distances from mining projects, outside of sites with disturbed surface conditions for this reason (usually 5–10 m from the mouths of wells and pits). It is necessary to set up crosses and either circular, symmetrical, or bilateral three-pole VES to crosscheck results with two components in order to detect possible lateral influences.

The largest volume of the VES work was conducted after preliminary processing of reconnaissance and parametric sounding data, and following the on-site survey of the microseismic array data. Detailed work on the VES method was confined to sites that were promising concerning groundwater levels according to the seismic survey methods. The remaining probing profiles were performed on a smaller network. The minimum distance between VES in the most difficult and variegated conditions was 10 m. The maximum distances under relatively homogeneous geological conditions were approximately 200 + m. In our case, the distance was 92 m.

10.3.3 Microseismic Surveys

Measurements were made in four different areas of the city using 16 stations over the course of two hours in order to obtain information on local velocity structures. Records were digitized at a rate of 100 samples per second and the time series was divided into 60 rows. A configuration of the seismic network is shown in Table 10.1.

Table 10.1 The configurations of the registration network used for conducting field measurements using the MS array [6, 7, 14]

N	Description	Type of array
1	Shooting with 4 seismic sensors and 2 different interoffice distances	
2	Shooting with 7 seismic sensors and 5 different interoffice distances	
3	Shooting with 10 seismic sensors and 8 different interoffice distances	

10.4 Analysis and Interpretation

10.4.1 Methodology of Interpretation of VES Curves

The VES method is a geophysical method used to search for groundwater. Despite the difficulties of interpretation, as discussed below, it is so far the only method that allows a quantitative interpretation of the results of observations under favorable geoelectric conditions. It is possible to determine the depth of occurrence of the roof and the base of frozen rocks as well as the depth of occurrence of groundwater, and to approximately estimate their mineralization with the help of this method. Correctly selecting fieldwork methodology suited to the location and the inclusion of distorting factors in the processing and interpretation of field materials improves the effectiveness of the VES method.

The main factors that complicate the interpretation of the VES curves in the upper part of the section are: the variability of the specific electrical resistance (SER), in terms of area and depth due to changes in composition and temperature of rocks and seasonal change in the parameters of the geoelectric section, and types of VES curves. Thus, the geoelectrical complexity of the zones of tectonic faults and contacts of rocks of different petrographic composition needs to be considered.

The processing of field materials began with the grouping of the VES curves on large geomorphological elements (river valleys, root slopes, watersheds, etc.). The types of curves were divided into small elements due to their variety (beds, low or high floodplains, terraces, etc.). Further grouping of the curves was carried out if the characteristics of the curves changed significantly with each element. A qualitative analysis was performed and the types of curves and geoelectric sections were established. The observed forms and types of VES curves often conform to the lateral influence of vertical and inclined boundaries of frozen and thawed rocks, irregularities in the roof of frozen rocks, gradient changes in resistance over depth,

and do not always correspond to the real structure of the geoelectric section [4]. All this data was taken into account when analyzing the curves.

10.4.2 Methodology of Interpretation of Seismic Array Measurements

The measurement of seismic noise in local areas through changes in shear wave velocity with depth is a key factor in assessing seismic hazards and is widely used in seismology engineering. It provides information on local effects on the soil and is important for characterizing soil properties.

Seismic noises (microseisms) obtained on area measurements are composed by and generalized as Rayleigh and Love waves, these are analyzed in order to obtain information on the structural velocity of the S-wave in the investigated area. Several methods for obtaining information on the basis of seismic noise records and on the speed of propagation of seismic waves in the sedimentary layer are described in the literature [1, 2, 6, 7, 14]. There were four seismic networks installed in the four research locations in the northern part of Bishkek.

Some of the figures presented in this manuscript have been generated using this GMT software package.

10.5 Results and Discussions

10.5.1 Methodology of Interpretation of VES Curves

Four wells were analyzed to assess the reliability of the VES method in determining the groundwater level (GWL) for two seasons, spring and summer (Table 10.2). Based on the results and interpretation of the VES data collected and the soil layer points at GW1, the depths of the GWLs ranged from 4.0 to 5.6 m during the studied period. The corresponding GWLs when measured seasonally ranged between 3.7 and 6.3 m (Fig. 10.3).

Figure 10.3a depicts a classical 3-layer curve, which shows a decrease in resistance with increasing depth. The resistance decreases by 4–6 m and then slightly increases at the depth of 9–12 m, then again decreases with increasing depth. These can be natural layers or artificial disturbances of the cover of the upper layer. This layer can be very dry and sandy-stony.

At the GW2 site, the depths of the GWLs ranged from 7.3 to 8.5 m during the studied period. The corresponding GWLs when measured seasonally ranged between 6.7 and 8.3 m (Fig. 10.3b).

The measured GWLs were deeper than the estimated GWLs from the map (Fig. 10.2) at the GW2 site. The differences between the measured and estimated

Table 10.2 The characteristics of a geoelectrical section on the investigated area GW1

Results of inversion by RESIDINV software				
Iteration 8				
Layer	Resistivity, (Ohm)	Thickness, (m)	Depth, (m)	Resistivity, (Ohm)
1	714.301	1.02	1.02	714.301
2	916.935	1.275	2.295	916.935
3	15.252	1.594	3.889	15.252
4	34.716	1.992	5.881	34.716
5	142.408	2.49	8.371	142.408
6	67.361	3.113	11.484	67.361
7	15.694	3.891	15.375	15.694
8	7.171	4.864	20.239	7.171
9	11.525			11.525

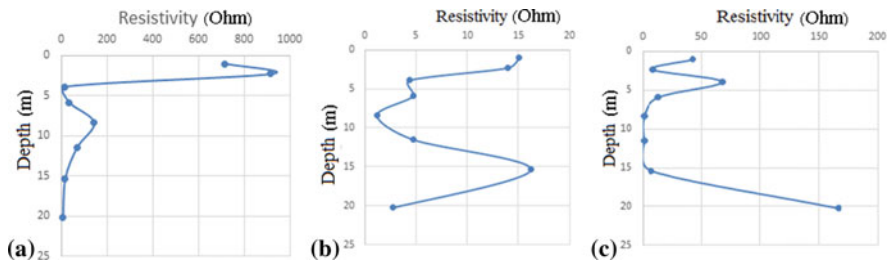


Fig. 10.3 The results of measurements on the distribution of resistivity with depth: **a** at the site GW1, May 2018, **b** in the section GW2, May 2018, **c** at the site GW3, May 2018

measurements ranged from 6 to 7 m, which were within the range of capillary rise in the studied area. The low resistance values (<1 O), at about 8 m, indicate the salinization of the surface layer, where the resistance (10–15 O) is characterized as clayey well-moistened soil according to the results shown in Fig. 10.4b.

For area GW3, the results and interpretation of the VES data point to the depth of GWs which ranged from 2.3 to 3.5 m during the studied period (Fig. 10.3c). The corresponding GWs measured seasonally ranged between 1.7 and 3.3 m.

The VES method was used to detect salinity. At the level between 2 and 3 m of the vertical profile in GW3 appears GW and surface part to be saline (Fig. 10.3c) for spring measurements. This site was taken for experimental measurements since Nijnaya Mayevka is sufficiently isolated enough from the problematic areas below the BCC. This lateral influence of thawed rocks is observed under probing in the vicinity of continuous permafrost.

The following seismic velocity profiles are determined by seismic survey data on the Komsomolskoye Lake territory (GW1, Fig. 10.4), an area of 110 m², (GW2, Fig. 10.4) and Karagachevaya Roschya (GW4, Fig. 10.4).

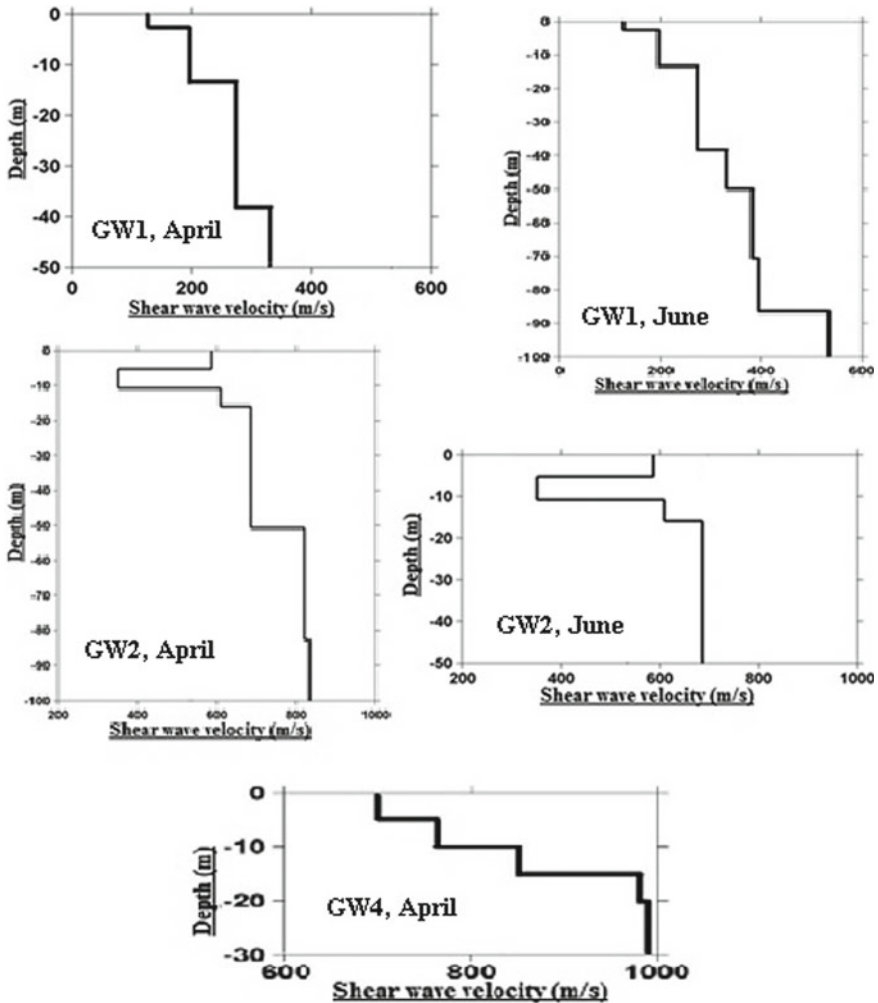


Fig. 10.4 The results of seismic survey measurements on the GW1, GW2, and GW4

10.6 Results and Discussions

In order to assess the risks and dangers associated with further development northward in Bishkek, we identified areas with the highest level of probability of flooding for subsequent geophysical assessment. We then carried out measurements, compared the results of two different methods (VES and MS) for determining groundwater levels, the interpolation of shear wave velocity for the upper 30 m for other parts of the region, and assessed the functionality of the collector-drainage systems (CDS) in place. It is desirable that the full consideration of seismic, geodynamic,

hydrogeological, and geological conditions within the territory in this study will allow for more rational planning concerning the development of the northern part of Bishkek. This research has the potential to influence the new buildings being constructed there, since many unfavorable plots are being allocated for development due to the lack of alternative plots of available land.

The complex geophysical studies in the studied areas were carried out using seismic array and VES methods. Analysis of the velocity profiles (Fig. 10.4) shows that the lithological boundaries are distinguished and that the sections are homogeneous according to different measurements. Furthermore, according to the geophysical data, the sections on the measurement points have resistance parameters with their range indicative for alluvial-pro-alluvial deposits and loessal soils.

The advantages of the array method include the fact that microseisms/microtremors can be recorded anywhere. When surface waves dominate in microseisms/microtremors, there is a dominance of the fundamental fashion and plane waves do not intersect (with correlation zero). When the method is applied to Bishkek [8, 9], it builds a map of shear wave velocity for the city, using slope as a proxy. Therefore, it is recommended to record results for more than 30 min so that there is the possibility of excluding temporary interference from nearby traffic and other factors.

The distortions of the VES curves are most significant and often cannot be accounted for if they are near the receiving electrodes. It is not recommended to perform sounding on old glades, paths, roadsides, or along tracks laid by all-terrain vehicles, for this same reason.

The initial material results of the VES method was the VES graphs and the digital material on which they were based. The resulting VES field charts were processed by a standard procedure, including 2 processing steps: qualitative processing and quantitative processing (interpretation). Qualitative processing consisted of comparing the obtained types, as well as of studying spatial patterns of distribution along the profile of regions with different values of apparent electrical resistances on geoelectrical sections.

A qualitative interpretation of the VES results was carried out with the aim of determining the parameters of the geoelectric section, the thicknesses and specific electrical resistances of the horizons composing the section, as well as the depths of their occurrence. The interpretation of each VES observation point was carried out by RES1DINV software. The computer automatically selects a theoretically calculated VES schedule for the greatest coincidence with the VES field chart, according to the program. In this case, the values of the electrical resistance of the selected horizons and their power, according to the chosen schedule (theoretically), are taken as true.

It was very difficult to interpret the VES curves obtained from the GW4 section (Fig. 10.5). The soil is strongly saline throughout the profile rendering interpretation over the layers is meaningless (see Fig. 10.3c).

The geoelectric sections were constructed for each point of the VES (resistance and power) with the correspond horizons and values of their electrical resistances

Fig. 10.5 The results of the measurement of the resistivity distribution with depth at section GW4, May 2018

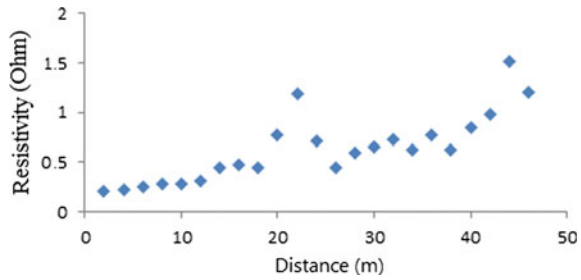


Table 10.3 Overall characteristics of the results of executed work

Nº Section	Length of the profile/area, m	Resistance of the soil (KC), ohm*m	Level of ground water (VES), m	Velocity profile, Vs30, m/s	Level of ground water (array), m
GW1	96	5–150	4–6	175	1–4
GW2	96	1–20	7–9	420	5–10
GW3	96	0–70	5–15	–	–
GW4	96	–	–	180	4–8

based on the results of the interpretation. Interpretation of the results of electro-sounding is presented in the form of graphs of VES and geoelectric profiles on the profiles constructed based on these graphs.

The sites selected for the conduction of geophysical measurements were those with the highest probability of flooding based on a groundwater level between 1 and 3 m. The results, however, indicate that the groundwater table is observed on average at a level between 5 and 10 m based on the VES and array data (Tab 10.3).

The differences between the observed and expected values of between 2 and 7 m at the sites can be explained by

- (a) fluctuations in groundwater, which can be up to 5 m, and/or;
- (b) an excellent level of work by collector-drainage systems (CDS).

As the geophysical measurements were carried out in the spring and summer when the water table is typically higher, the finding that the groundwater was at a depth of 5–10 m likely indicates positive performance by the CDS and filter channels/tunnels. The only exception was at the GW1 site, where the groundwater level was at 1–2 m, possibly indicating the need for a better filtration tunnel.

High groundwater levels not only increase flood risk, but the influence seismic resistance within the soil and buildings increases the likelihood for liquefaction during a large earthquake.

10.7 Conclusions

The results of complex geophysical measurements (seismic array and VES) show groundwater at a depth of 5–10 m at all points where previous flood maps record levels of 1–3 m. High variation in groundwater levels (2–7 m) was observed.

The results of this study indicate the excellent conditions of the collector-drainage systems in place. Groundwater levels at the locations estimated to pose the highest flood risk were calculated to be 5–10 m. This is in contrast to the current literature which indicates a level of 1–3 m. With a gap of 2–7 m it is possible the amplitude variation of groundwater is about 5 m over the long term. However, measurements were carried out in the spring and summer seasons, when groundwater level is the highest following the rainy period, suggesting that the effectiveness of the CDS played a role in regulating the level.

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