Change of groundwater system from 1888 to present in highly-urbanized coastal areas in Hong Kong

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Abstract

Hong Kong has been extensively urbanized since the 1950s and now has become one of the most populated areas in the world. The direct and indirect historical groundwater since 1888 in the coastal region centered by the Mid-Levels area in Hong Kong were reviewed and compared with data collected recently to reveal the temporal changes of groundwater regimes over the last century. It was found that the groundwater flow systems had been significantly modified. The coastal springs and seeps had disappeared and the lower boundary of the seepage zone had been moved uphill. Groundwater was found to be flowing upward along the boundary of natural slopes and urbanized spaces. Artesian flows were commonly noted in the deep piezometers in the lower urbanized spaces. Moreover, an overall increase in groundwater tables in a 10-year period was observed in the urbanized spaces except the areas with good drainage. The paper then examined the major urbanization activities and their roles in modifying groundwater systems. These activities included large-scale land reclamation, deep foundations of high-rise buildings, underground transport system, leakage from water mains and horizontal drains in slopes. Although these individual activities might increase or decrease water level, the resultant effect of these human activities seems to have led to a slow but gradual increase in the water level of the hillslope groundwater system. It was suggested that further urbanization activities such as western extension of the underground transport system and major drainage system in the slopes should be assessed for possible further change in the groundwater system. The results presented here may serve as reference for other highly-urbanized coastal areas in the world.

Keywords: Foundation, land reclamation; groundwater, urbanization; Hong Kong

1. Introduction

Because of the rugged topography, most populations in Hong Kong live in the narrow strips less than one kilometer from the coasts. In order to provide more spaces for the increasing populations, large-scale land reclamations from sea has been taken place. Coastal areas are usually the ultimate groundwater discharge zones. Some studies suggested that reclamation may lead to the increase in the inland groundwater tables (Mahmood and Twigg, 1995; Jiao et al., 2001; Guo and Jiao, 2007) although the process may be slow and unobvious. Jiao (2000) proposed that reclamation increases the groundwater flow path to the sea and reduces the groundwater discharge towards the coast by blockage of submarine discharge zones. On the other hand, numerous high-rise buildings with deep foundations have been built extensively along the coastal areas in Hong Kong. Some studies suggested that the foundations were some types of barrier to groundwater movement (GCO, 1982; Pope and Ho, 1982; Nash and Dale, 1984; Johnson et al., 1985; Foster et al., 1999; Pokrovsky et al., 1999, Jiao et al., 2006a).

This study examined the historical seepage and piezometric records collected in a highly-urbanized coastal area centered by the Mid-Levels area. Most of the historical data were collected by Hong Kong government and could be found in different government reports. The historical data were compared with recent groundwater records to reveal the possible changes of groundwater regime in the rapidly urbanized coastal area over the last century. By comparing the historical and recent groundwater information, some interesting observations relating to the changes in the groundwater regime in the study area were noticed. An attempt was made to explain the possible causes for the modification in groundwater regimes by examining various anthropogenic activities in the study area.

2. Site geology and previous studies

The region centered by the Mid-Levels area, situated on the northern slope of the Victoria Peak (550 mPD) on Hong Kong Island, was chosen for this study. Simplified geological plan and cross section maps are shown in Figures 1 and 2. The study area can be divided into two parts with significantly different modes of development. The upper part of the area (>170 mPD) is essentially a natural slope with minimum development. In contrast, the lower part of the area has been extensively urbanized and is regarded as one of the most heavily-urbanized coastal areas in the world (Figure 3).

The most comprehensive study related to geology and hydrogeology in the Mid-Levels areas so far was called Mid-Levels Study conducted around 1980, which was organized by Geotechnical Controlling Office (GCO, 1982) (Now Geotechnical Engineering Office). This study was prompted by a major landslide at Po Shan Road in 1972 which killed 67 people. The geology is dominated by two rock types, acidic volcanic rocks and a granitic intrusion. The irregular contact between the granite and volcanic rocks crosses the area and was disrupted by normal faults in several locations (Figure 1). In general terms, colluvium overlies several meters of decomposed rock above the bedrock. The granite underlies most of the developed spaces. Volcanic rock underlies the upper undeveloped slopes.

The first comment regarding groundwater conditions in Hong Kong was made by Uglow (1926). On the basis of his field work of the winter 1925-1926, Uglow suggested that Hong Kong Island was completely lacking of all the conditions for the occurrence of artesian flow. In the Mid-Level Study report by GCO (1982), it was mentioned that "It is possible that confined, or partially confined, conditions exist in the main water table with the potential for high pore water pressure. No such areas, however, have been positively identified". This report, however, did state that "strong upward hydraulic gradients from bedrock to the decomposed rock aquifer have been observed in some areas".

After examining the hydraulic conductivity data from boreholes and tunnel construction and water level data from boreholes drilled for various construction sites, Jiao et al (2006b) presented a conceptual model of multiple zones for groundwater flow in the study area. The shallow zone consists of colluviums, upper part of the saprolite and fill materials. This zone is permeable and can become a perched aquifer during rainfall seasons, but may become dry during other seasons. This unconfined aquifer receives rainfall recharge and also possibly some leakage from deep fracture zones in the igneous rocks. The highly decomposed rock or lower saprolite below the colluvium can be regarded as aquitard due to its clay-rich content. The rockhead zone below the saprolite can be relatively more permeable due to well-developed fractures than the overlying completely decomposed rock. This zone outcrops at the upper part of the slope and receives rainfall infiltration in wet seasons. The infiltrated water moves downhill roughly along the high permeability zone and recharges to the sea. Part of the groundwater leaks upwards into the saprolite. The rockhead zone is a permanent confined aquifer. Based on the two-dimensional modeling, Jiao et al (2006a) speculated that both land reclamation along the coastline and deep foundations might have contributed to the modification of the flow system, but the deep foundations might have more profound impact on the flow.

A number of studies was conducted to investigate the impacts of urbanization on the groundwater chemical systems in the area (Leung and Jiao, 2005; Leung et al., 2005; Leung and Jiao, 2006). There is a spring near the Po Hing Fong Street. Leung and Jiao (2007) monitored the PHF spring for one year and studied its temporal variations of physical and hydrochemical properties. This PHF spring is quite persistent and did not run dry even in 1963, the driest year in the history of Hong Kong. It is believed that this spring is largely from the groundwater through relatively deep circulation with recharge originated from the uphill (Leung and Jiao, 2007).

3. Changes of groundwater regimes in the last century

3.1 Historical records of seepages

Seeps and springs in 1888 and shallow groundwater in 1896

There was no direct information on groundwater regimes in the 18th century. However, some indirect information could be still found from some government records. In the 1880s, malarial fever prevailed in the then Western Districted in Hong Kong. A commission was appointed by the Hong Kong Government to enquire into the causes of the fever and to recommend remedial measures. According to sessional paper on the fever prevailing in the Western District, the shallow water table was believed to be one of the causes for the fever (Hong Kong Government, 1888), "…the situation of the houses in the Western District is such that malarial fever might be expected to develop around them. The houses stand at the base of a high hill receiving a tropical rainfall. Around the houses numerous springs exist, and at no great distance from the surface, subsoil water is found standing; in addition, in many places the water finds its way to the surface causing pools in some instances…”

Although the exact locations of springs and pools of water were not mentioned, it clearly stated that springs and pools of water were common everywhere in the Western District. The boundary of this district 1888 is shown approximately in Figure 4. This area was less than 30 m above the sea level.

Another piece of evidence on the shallow water table could be inferred from the well distribution in 1896. The Mid-Levels and the surrounding areas were the first-developed region in Hong Kong and combined with other later developed regions on the northern Hong Kong Island as a whole named as the City of Victoria, after the British Colonization in 1841.Numerous wells were present in the City of Victoria in early days to provide potable water for the local communities. Data of wells in 1896 was obtained from a government report (Hong Kong Government, 1897) and approximately marked in Figure 4.

In the early days, wells were dug by hands. It is believed that most of the wells were therefore only about a few meters deep. The distribution in the figure then implied that the shallow soil in this region was groundwater rich and water table was very shallow.

Seepage locations in 1981

As part of the Mid-Levels Study in 1980s to investigate the cause of the landslide, seepage locations were surveyed. Seepage here represents both natural spring and water drained from weepholes or horizontal drains in retaining walls or slopes. Figure 5 presents the seepage locations identified in the dry and wet seasons in 1981 (GCO, 1982). As expected, the seepages in the wet season were much more widely distributed than in the dry season.

Seepage locations in 2002/2003

The seepage locations in September 2002 and January 2003, which denotes wet and dry seasons respectively, were surveyed by the authors and are showed in Figure 5 as well. All the natural seeps have disappeared and all the seepages were from weepholes or horizontal drains in retaining walls or slopes. There were quite a few seepages near the southwest boundary of the Mid-Level areas which were from major horizontal drains installed deep into the slope in 1985, aiming to lower the water level in the slopes and increase the slope stability.

Comparison of groundwater regimes since 1888

The above historical records can be regarded as snapshots of groundwater regimes in different years. A comparison of these snapshots led to several interesting findings. (1) except at the eastern end of the Western District, the springs and pools of water in 1888 seems to have virtually disappeared; (2) the number of seepage was much smaller in 2002/2003 than in 1981, indicating an obvious change in the period of about 20 years; (3)

In the western part of the study area, the lower boundary of seepage zone moved uphill for about 150 meters from 1888 to 2002/2003. In the eastern part, the lower boundary of seepage zone virtually did not have any significant movement; and (4) the shallow groundwater table may be much deeper or the shallow aquifer may be even dried up as indicated by the disappearance of the seepages. If one digs a few meters near the well locations in 1896, it is highly possible that there would be no water, as often seen from various pipe trenching sites along the roads.

3.2 Historical records of water level

Change in groundwater levels between 1979 and 1990

Over 300 piezometers were monitored by GCO in the study area at various times from 1979 to 1990, either manually or by the use of automatic monitoring systems. An analysis of these data provided some insights into the changes in groundwater levels in the area over the decade.

Hard copies of these piezometric curves were collected from the library of the Civil Engineering Department, the Hong Kong Special Administrative Region (SAR) and the monitoring data of these curves were read into computer for further processing. Data gathered from these piezometers were not always continuous and often contained occasional spurious or dubious readings.

110 piezometers which had data observed in periods longer enough to show certain trend were selected in this study. Figure 6 shows some of the typical piezometric curves (The locations of these piezometers are shown in Figure 7). For example, the data

in ML55A(L) in Figure 6a and ML57C in Figure 6b were rather continuous over many years and showed a decreasing and increasing trend, respectively. The data in ML8B(U) in Figure 6c and ML9A in Figure 6d, however, were only available in some years but the data spread over the periods in such a way that an increasing or decreasing tread can be clearly identified.

To find out the overall trend of groundwater level change, a simple linear regression method was adopted so that the seasonal rise or storm rise information can be removed. Once the regression line was obtained as seen in Figure 6, the regression equation and thus the slope were available. It was then easy to tell whether the trend of the ground water level was decreasing or increasing within this ten-year period.

Figure 7 shows the distributions of piezometers with increasing and decreasing trends in the study area. The average depth of the piezometer tips was over 26 m. The temporal change of water level in these piezometers then represented that of the relatively deep part of the aquifer system.

Majority of the piezometers above the Poshan Road show a decreasing trend. In the urban areas, the distribution of the piezometers with increasing and decreasing trends is complicated. In the western part of the urban area, most of the piezometers show an increasing trend, as can be seem from the piezometers around The University of Hong Kong. In the Eastern part of the area, there is also a region which is dominated by piezometers with an increasing trend (see the piezometers around Peel street). The piezometers in the area above the PHF springs, however, are mixed.

If Figures 5 and 7 were compared, it could be seen that the regions with piezometers of a decreasing trend were related to the regions with seepages observed in

2002/2003 such as the areas above the Po Shan Road and near the PHF spring. This led to a finding that water level in the study area shows an overall increasing trend except in the areas with effective horizontal drains or seepages.

Overflow and upward flow

Overflow is a phenomenon referred to by local geotechnical engineers as groundwater flowing out of a borehole, while upward flow as groundwater flowing upward but not necessarily to the ground surface. Both indicate a confined or artesian condition.

Jiao et al (2006a) identified upward sites by examining the water level in clustered piezometers with tips in different depths. A typical site with upward flow is the piezometer clusters of ML113 (Figure 8). This site has piezometers at three different depth, indicating that the water level is progressively high as the depth increases. Most of these sites with upward flow are located at the transition zone between the natural slope and the urban area, as shown in Figure 8. There are also residential buildings such as the Pearl Garden (see Figure 8 for location) suffered from a flooded basement which requires constant pumping. Pearl Garden was constructed in 1974 and it is believed that the basement was probably fine at the time of construction. All the evidence indicates that the downhill movement of groundwater flow is somehow retarded and groundwater is forced to flow upward at the transition zone.

Jiao et al (2006b) investigated two overflow standpipes BH1 and BH3 (see Figure 8 for location) at a construction site at No.52 Hollywood Road. After pipes were added to the top of the standpipes, the water level in the two standpipes raised up to 0.64 and 3.73m above the ground surface, respectively, indicating that the deep groundwater was significantly confined. The original boreholes were 58 m deep but the standpipes were installed only down to 15 and 20 m, respectively. It was speculated that the water may be originated from the deep fracture zones around the rock head near the bottom of the original borehole (Jiao et al, 2006b).

After searching for the archived site investigation reports from the government and private companies, total 24 sites with overflow boreholes were identified (Figure 8). This suggests that overflow phenomenon is quite common in the study area.

4. Possible mechanisms responsible for the modifications

4.1 Rainfall

One should not talk about the change of a groundwater system over the years without discussing the change of rainfall in the same period because rainfall alone can cause significant change in water level. Figure 9 shows that the amount of rainfall from 1979 to 1990, together with a trend line. Generally, there was a trend of decreasing in rainfall in these years. An overall increase in groundwater levels over a particular area may also be caused by the increase in rainfall. However, as shown in Figure 9, there was a general decreasing trend in the amount of rainfall from 1981 to 1991.

Infiltration to underground was expected to reduce as the overall rainfall decreased. Even if rainfall were not reduced, the rainwater which could actually infiltrate underground was still reduced with time because the urban surface becomes progressively less impermeable due to buildings, concrete road surfaces and covered slopes. It is therefore unlikely that the observed overall increase in groundwater level was induced by rainfall. In fact, should the rainfall remain almost constant, there would be much more piezometers showing increasing trend as those shown in Figure 7.

4.2 Urbanization activities

As discussed, the changes in the groundwater regime in the study area could not be explained by natural factors including the increase in rainfall and variations in hydraulic conductivity among different in-situ materials because there was not appreciable difference in permeability between granitic and volcanic rocks (GCO, 1982). Instead, the changes in the groundwater flow systems were likely to be induced by various human activities.

Land reclamation

The study area has a long history of land reclamation since 1841. Before the 19th century, reclamation works was done along the northern coast of Hong Kong Island. Later, several large-scale reclamations were completed and some are still on-going. Figure 1 shows the changes in the coastline near the Mid-Levels area.

Modification of land reclamation on groundwater flow system depends on the scale of reclamation relative to the length of the flow path or the size of the original groundwater catchment (Jiao et al, 2001). The distance from the Victoria Peak to the original coastline is about 1200 m. The coastline has been extended towards the sea by about 400 m. The fill materials range from public rubbish dumps in the early days to decomposed granite and marine excavated from hills or marine sand collected from the deep sea.

The permeability of fill materials in Hong Kong was discussed by Jiao et al. (2006a). The permeability in a reclamation site is extremely unpredictable and varies with the nature of the fill materials and the method of placement. For fill composed of completely decomposed rock and marine sand, permeabilities can be on the order of 10^{-4} or 10^{-5} m/s, but permeabilities of compacted fill composed of completely decomposed rock can be 10^{-6} - 10^{-7} and 10^{-6} - 10^{-8} m/s, respectively. Although the quality and nature of fill at the site can be extremely variable, there is usually a layer of soft marine mud at the seabed beneath reclamation sites. The permeability of this marine mud is usually extremely low after it is buried by fill and becomes consolidated.

Deep foundations of structures

Urban development or redevelopment in Hong Kong began on a large scale in 1955 (Lumb, 1980). Since the 1960’s when the price of land became high, tall buildings become economical. High-rise buildings are now characteristic of Hong Kong. Typical buildings changed form 20 - 25 storeys in the 1960- 1970s to 30 storeys in 1980s, and now the average number of storeys is over 40 (Figure 10). High–rise buildings require more substantial and deeper foundations.

Now large diameter pier foundations ranging from 1.2 to 3.2 m are common. The diameters of the pier foundations for some buildings are over 7 m. The length of the piers ranges from 20 to 50 m, depending on the depth to bedrock. Figure 11 shows the foundation of a typical building in Hong Kong Island. In the case where a diaphragm wall is constructed around the building site, which is very common, the details of the pile or cassion foundations are not really important as far as the hydrogeological effect of the foundation is concerned. The diaphragm wall is designed to be impermeable to cut off the groundwater inflow to the construction site. To ensure there is no window of leakage, silicate grouting at the bottom of the walls is commonly used along the perimeter of a construction site (Figure 11).

Consequently, after a building is constructed, a “concrete box” of low hydraulic conductivity or an “underground dam” is left in the soil. The natural soil in the upper few tens of meters, which is usually a zone with the most active groundwater movement, is then largely replaced by foundations and other construction materials (Jiao et al. 2006a).

There are many buildings in the study area (Figure 3). Ding (2006) digitized the building distribution maps and calculated the percentage of building area. This percentage is defined as the ratio between the building areas, which include only the building blocks, over the entire urban areas, which include the building blocks and all the open area between buildings such as streets and parks. The ratio for the year of 2000 is 30%. If each building has an impermeable concrete box which is slightly larger than the building itself (Figure 11), over 30% of the urban area is impermeable to groundwater.

Besides, the underground mass transportation system, or mass transit railway (MTR), is well constructed in Hong Kong. Figure 1 shows part of the MTR ended in Sheung Wan. It was stated by McIntosh et al. (1980) that the deep cut-off to slurry and piled permanent walls, coupled with the extension to the surface of the ground, exacerbated a possible damming effect of these large underground structures on the moving groundwater in parts of Hong Kong.

Leakage from water mains

In the developed area, leakage from water service systems seems to play an important role in the developed area (Lerner, 1986). Gray (1986) stated that in some parts of the developed area the contribution to the main aquifer from leakage is very large, possibly more than the average rainfall.

On the basis of groundwater chemical study, Leung (2004) concluded that from 1980 to 2003, due to the replacement and reparation of service pipes, there is an overall reduction in the locations with major or substantial leakage from service pipes in the area. However, the amount of leakage from water mains is difficult to quantify and consequently the impact of the leakage on groundwater system is hard to estimate.

Horizontal drains in retaining walls or slopes

All slopes and retaining walls in the study area were installed with weepholes or horizontal drains. As can be seen from the seepage locations identified in Figure 6, most of these drains in this area did not issue water except some clusters above the PHF springs and above the Po Shan Road.

The drainage system above the Po Shan Road was well studied and documented (Martin et al, 1995). After the fatal landslide in Po Shan Road, the slope stability of the neighboring slopes was of great public concern. In the 1980s, it was found that the groundwater table there was generally high and the slopes had an inadequate margin of stability. Installation of horizontal drains was recommended as preferred solution to improve slope stability.

Over 60 drains of length ranging from 30 to 90 m were installed at the different levels the slopes on the left side of the Po Shan landslide scarp in 1985. Maximum water flows from the whole system of over 780 m^3/day were recorded, with a maximum individual drain flow of 35 m^3/day. Water level monitoring data in 1983 (prior to construction of the drains) and 1986 indicated that, in general, piezometric levels in both wet and dry seasons were lowered by more than 5 m across most of the site during this period.

5. A conceptual model

As summarized in Table 1, some factors increase water level while others decrease water level. Overall the water level in the study area except those above the Po Shan Road and PHF spring is increasing, indicating that the factors which increase water level overwhelm those that decrease water level. Or the factors such as land reclamation and deep foundations dominate the temporal change of the water level.

Table 1 Urbanization activities and rainfall and their impact on groundwater system

	Effect on aquifer system	Effect on water level
Reduction of rainfall	Reduce rainfall recharge	Decrease
Surface impermeabilization	Reduce infiltration	Decrease
Water main leakage	Increase groundwater recharge	Increase
Foundation (including MTR)	Reduce overall permeability and retard downhill flow	Increase
Land reclamation	Reduce seaward discharge	Increase
Horizontal drains	Increase recharge	Decrease

Figure 12 presented a conceptual model about the impact of urbanization on flow system. In a natural state, the hillslope aquifer system received rainfall infiltration. Groundwater existed in the shallow as well as deep soils. Groundwater discharged to the sea along the coastal line or through the relatively deep and confined fracture zone. Near the coast, some groundwater discharged to the surface in the form of springs or seeps, as observed in the 18th century.

When numerous building foundations inserted into the shallow soil, the shallow soil is divided into many zones. The groundwater among some zones may have weak hydraulic connection with other zones and may be even isolated hydraulically. Downhill flow through the shallow soil may be significantly reduced by the foundations and some water is forced to flow upward at the boundary between the natural slope and the urban areas. The shallow soil at the lower part of the hill becomes relatively dry and springs and seeps become extinct.

The deep fracture zone becomes more confined because the discharge to the shallow soil is reduced due to foundation materials and because the flow to the sea is retarded due to the reclamation along the coast. This causes the gradual increase of water level in the deep fracture zones.

6. Conclusion

This paper compared the historical piezometric and seepage records with recent groundwater records of a highly urbanized coastal area in Hong Kong over the last century. The results suggested that the groundwater flow system had been modified progressively with urban development. Several aspects of modifications were observed. First of all, most of the springs and seeps widely existed along the coast in the 18^{th} century disappeared and the lower boundary of the seepage zone had been moved uphill for about 150 meters in the last 20 years. Secondly, a number of overflows which represents significantly confined groundwater condition were observed in the developed spaces. And, upward flows were recorded along the boundary between the natural slope and developed area. Thirdly, an overall increase in groundwater levels from 1981 to 1991 was noticed. The extinction of most of the springs and seeps from the shallow soils near the coast indicated that the shallow aquifer dried up. The deep aquifer was well confined as seen from the overflow piezometers and upward flow piezometers. Some part of the deep aquifer system could be progressively more confined as indicated by the temporal increase of water level in piezometers.

Various factors were discussed to understand the reasons behind the change of the groundwater system. These factors included the factors which might lead to an increase in water level, such as land reclamation, deep foundations, and leakage from mains, and those which might lead to an decrease in water level, such as reduction in rainfall, reduction in infiltration due to surface impermeabilization, and PHF spring in the urban area and horizontal drains above the Po Shan Road. After all the factors were considered, it seems the factors which lead to an increase in water level dominates the change of the groundwater system because there is an overall increase in the water level in the study area except for the areas above the Po Shan Road and near the PHF spring. It was well known that water main leakage would increase the water level. This paper demonstrated that deep foundation might increase the water level by reducing the overall permeability of the soil and retarding the downhill flow and that land reclamation might play the similar role by reducing the seaward groundwater discharge. A conceptual model was presented to explain the change of the groundwater regimes in the study areas.

It was suggested that further urbanization activities such as western extension of the underground transport system and new drainage system in the slopes should be assessed for possible further change in the groundwater system. Future studies are needed to understand more quantitatively the different roles of the various human activities in modifying groundwater flow system. It is also suggested that the environmental and engineering consequence of the changes of groundwater system should be studied in extensively urbanized areas. For example, groundwater input to the coastal sea may be reduced because of the deep foundations and land reclamation, which may have effect on the coastal water quality. The regional increase in water level may cause flooding of deep basements and have certain effect on slope stability.

Acknowledgements: This study is supported by the Hong Kong Research Grants Council (RGC) (HKU 7013/03) of the Hong Kong Special Administration Region, China. Hard copies of piezometric curves were collected from the library of the Civil Engineering Department, the Hong Kong Special Administrative Region (SAR). The authors acknowledge the help of Dr Hu Li-tang in producing Figure 12.Comments from two anonymous reviewers are also appreciated.

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Figure 1 Simplified geological map of the study area

Figure 2 Simplified geological section through A-B (see Fig. 1 for location).

Figure 3 Air photo of the site showing extensive urbanization at the lower part of the hill

Figure 4 The damp area plagued by malarial fever in 1888 (bounded by solid blue line) and the well locations in 1896 (block dot)

Figure 5 Figure 5 Seepage locations in the study area in dry season in 1981 and January in 2003 (a) and in wet season in 1981 and September in 2002 (b). The damp area plagued by malarial fever in 1888 was also shown for comparison

Figure 6 Typical hydrographs and regression analysis of piezometers of ML55A(L), ML57C, ML8B(U), ML9A (Note: rainfall is only shown in Figure 6a) .

Figure 7 Piezometers indicating increasing (blue dots) or decreasing (green dots) trend in water level from 1979 to 1990

Figure 8. Location of overflow and upward flow in the study area.

Figure 9 Annual rainfalls in Hong Kong Observatory from 1979 to 1990

Fig 10 The mean number of storeys of high-rise buildings (>12 storeys) constructed from 1963 to present in the Mid-Level and surrounding areas

Figure 11 The foundation of a building in coastal area of Hong Kong Island: Hand-dug caissons up to 7.4m in diameter (a) and large diameter hand-dug caissons and perimeter diaphragm walls (b) (Note: CDG means completely decomposed granite; mPD means meter above the principal datum) (based on Lam, 1991)

Figure 12 Conceptual model for the impact of foundations and reclamation on the groundwater flow. Before urbanization, groundwater exists in shallow and deep aquifers. Springs and seeps occur near the coast (a). After urbanization, shallow soil becomes much drier and there is not a unified water level in the shallow aquifer. Deep foundations and land reclamation reduce the discharge to the sea. Deep aquifer becomes more confined and springs occur in the middle of the hill (b).

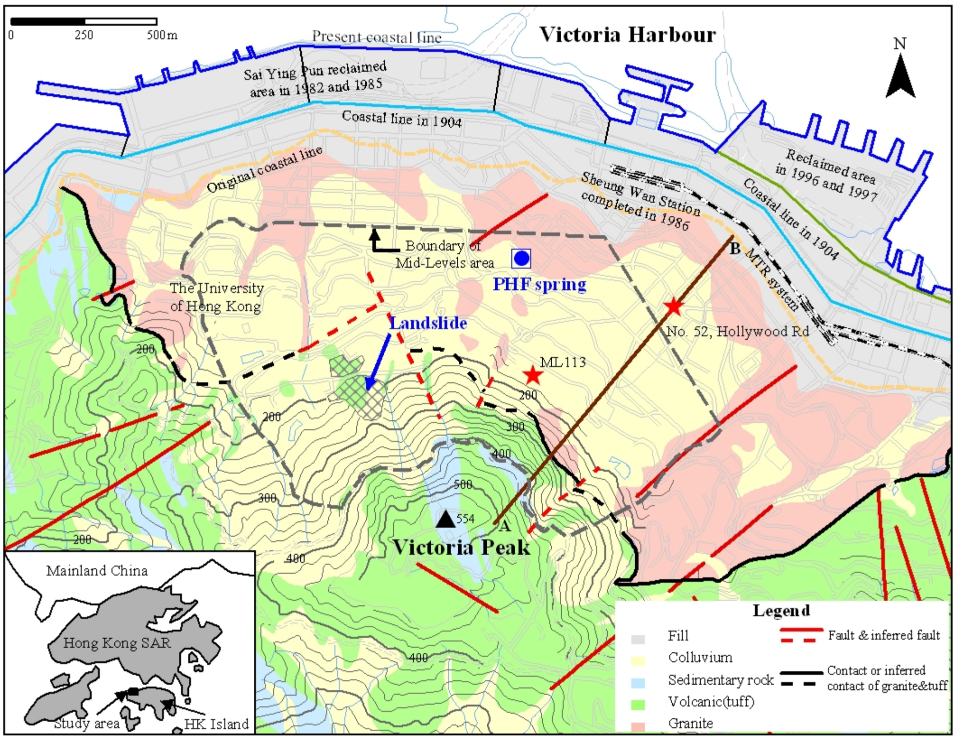

Figure 1. Simplified geological map of the study area. The area with elevation contours is also the area of natural slopes with minimum development.

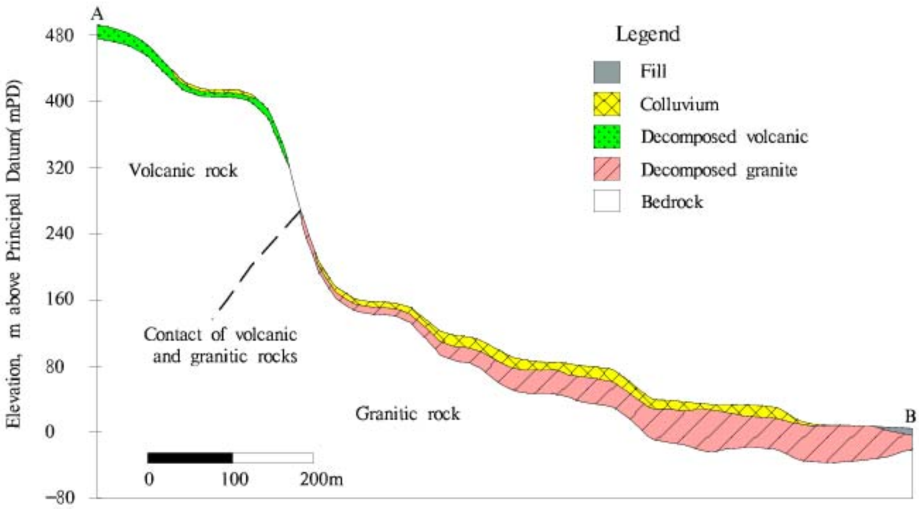

Figure 2 Simplified geological section through A-B (see Figure 1 for location).

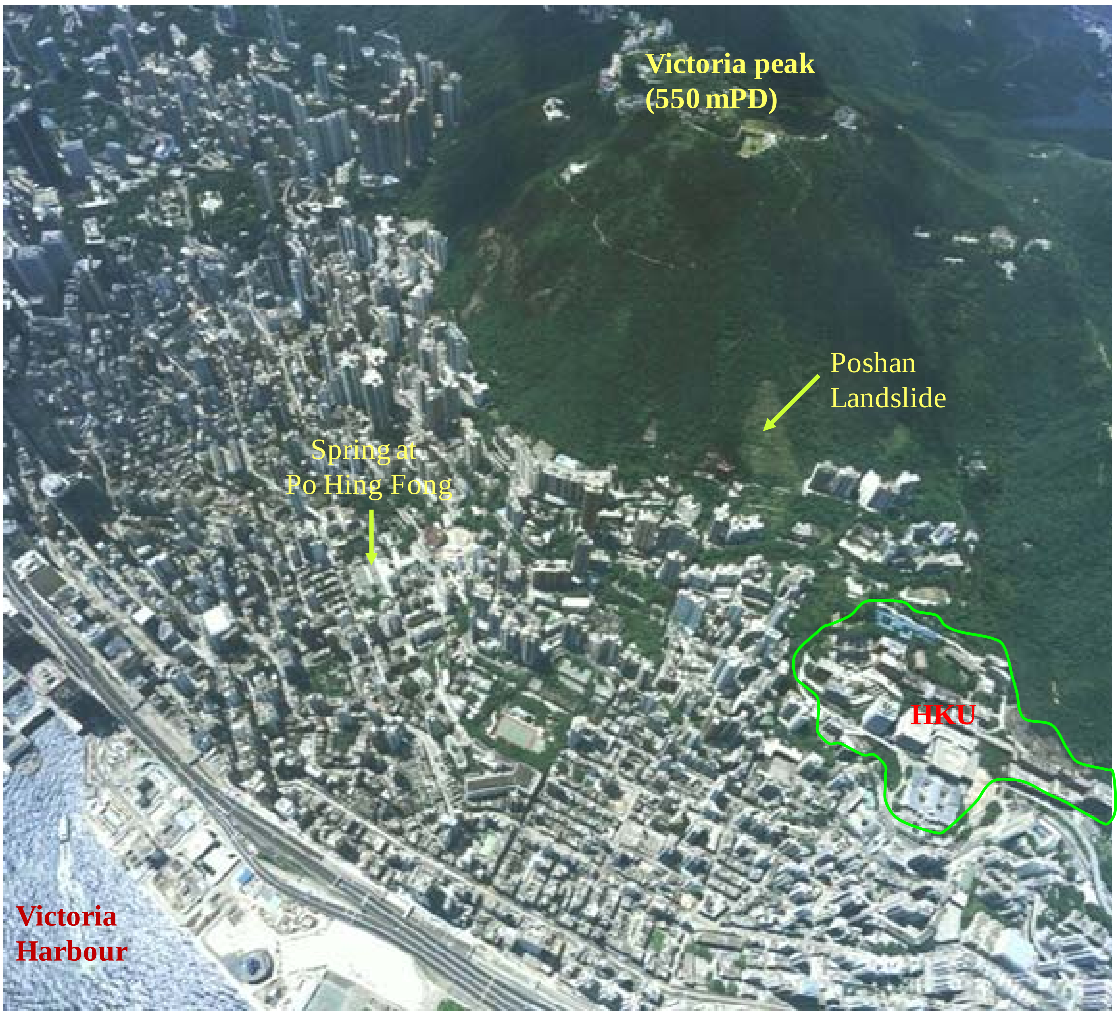

Figure 3 Air photo of the site showing extensive urbanization at the lower part of the hill

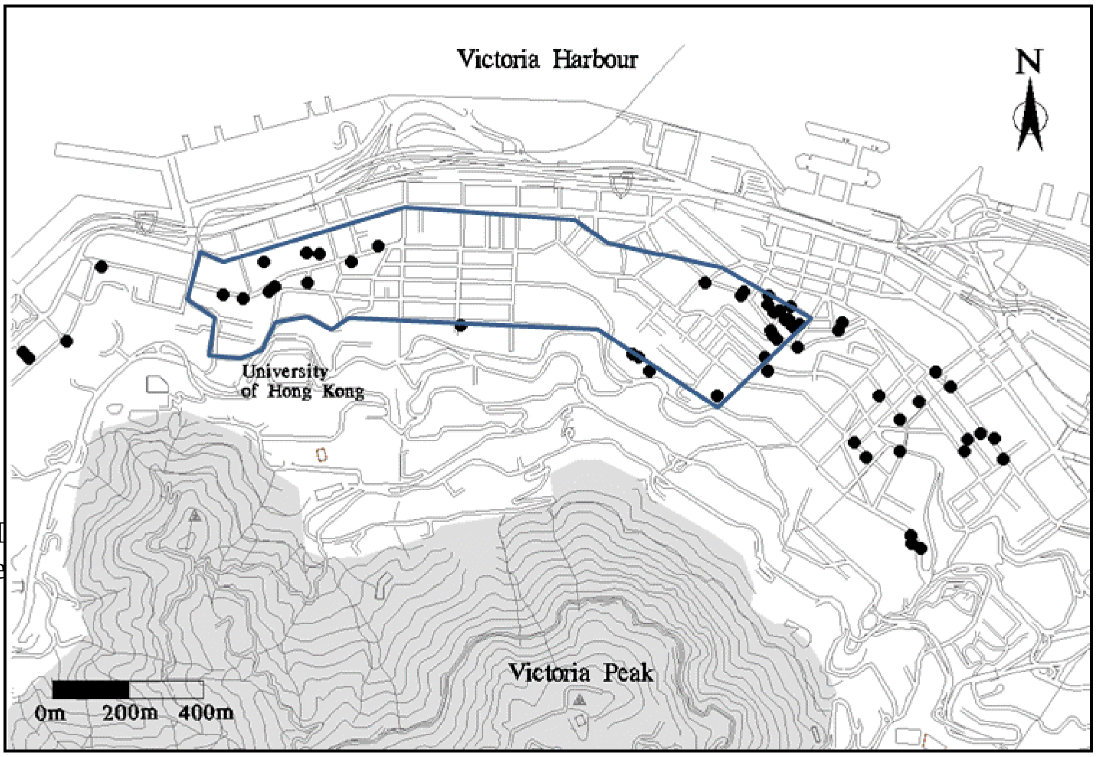
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Figure 4 T

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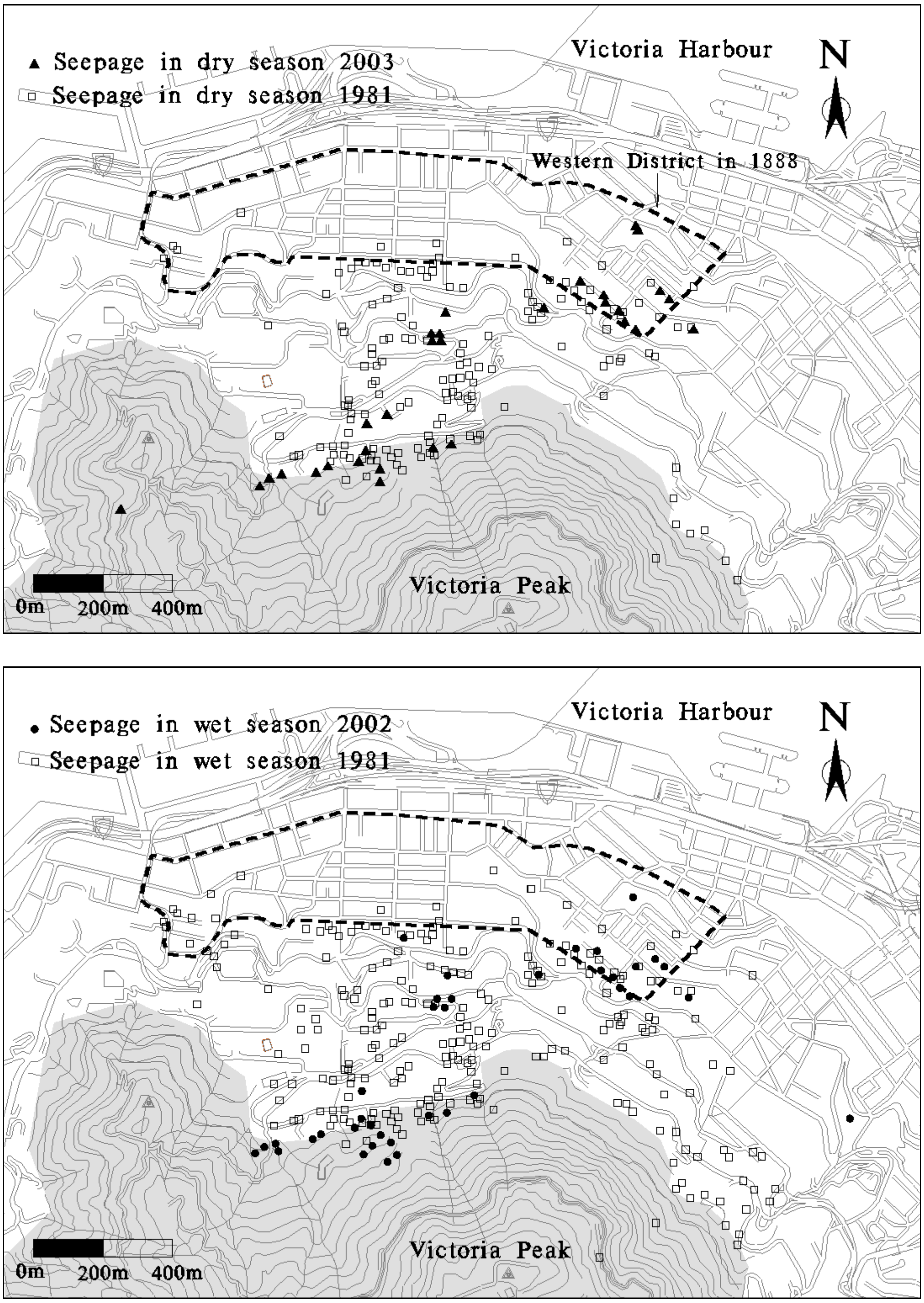

Figure 5 Seepage locations in the study area in dry season in 1981 and January in 2003 (a) and in wet season in 1981 and September in 2002 (b). The damp area plagued by malarial fever in 1888 was also shown for comparison

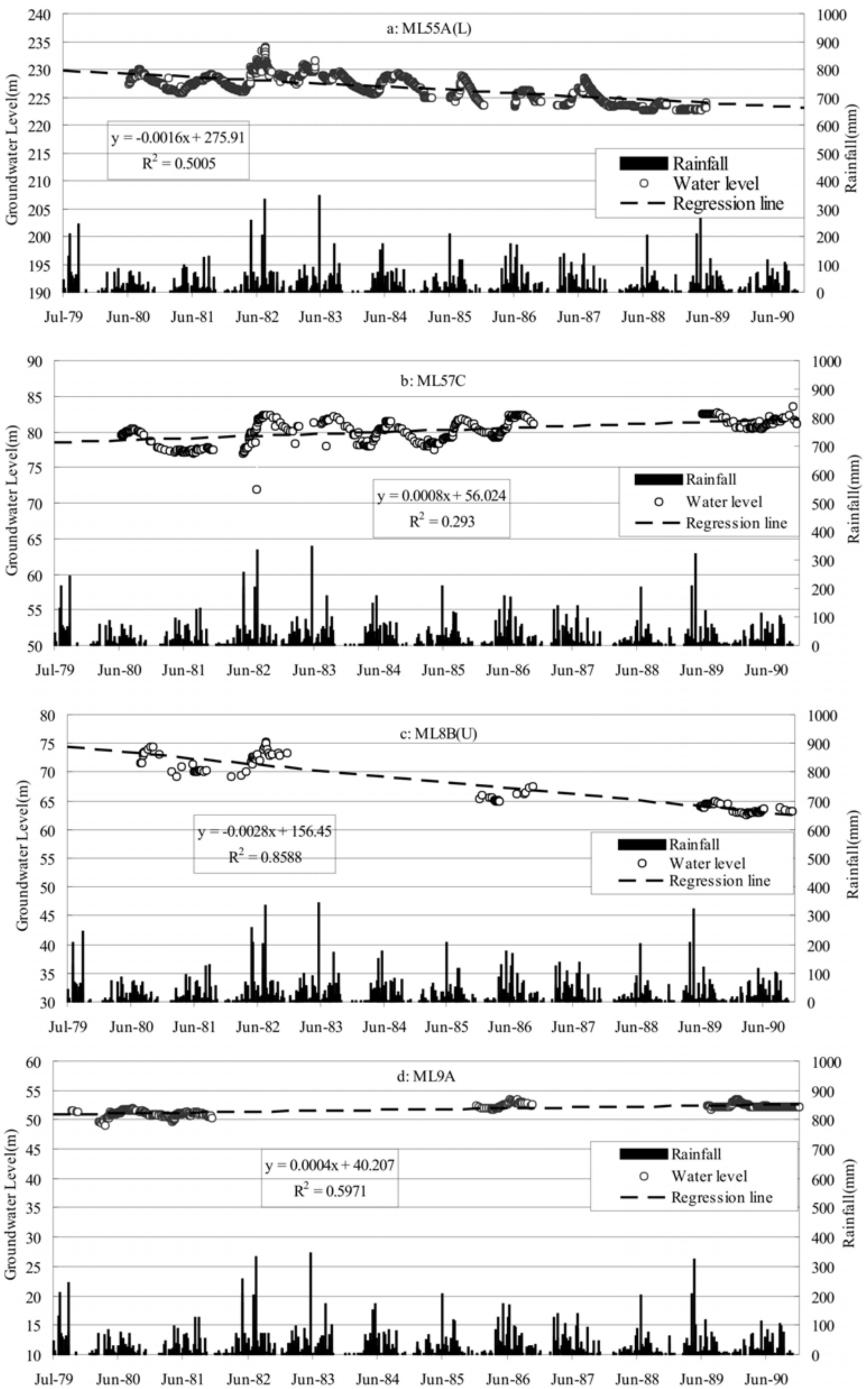

Figure 6 Typical hydrographs and regression analysis of piezometers.

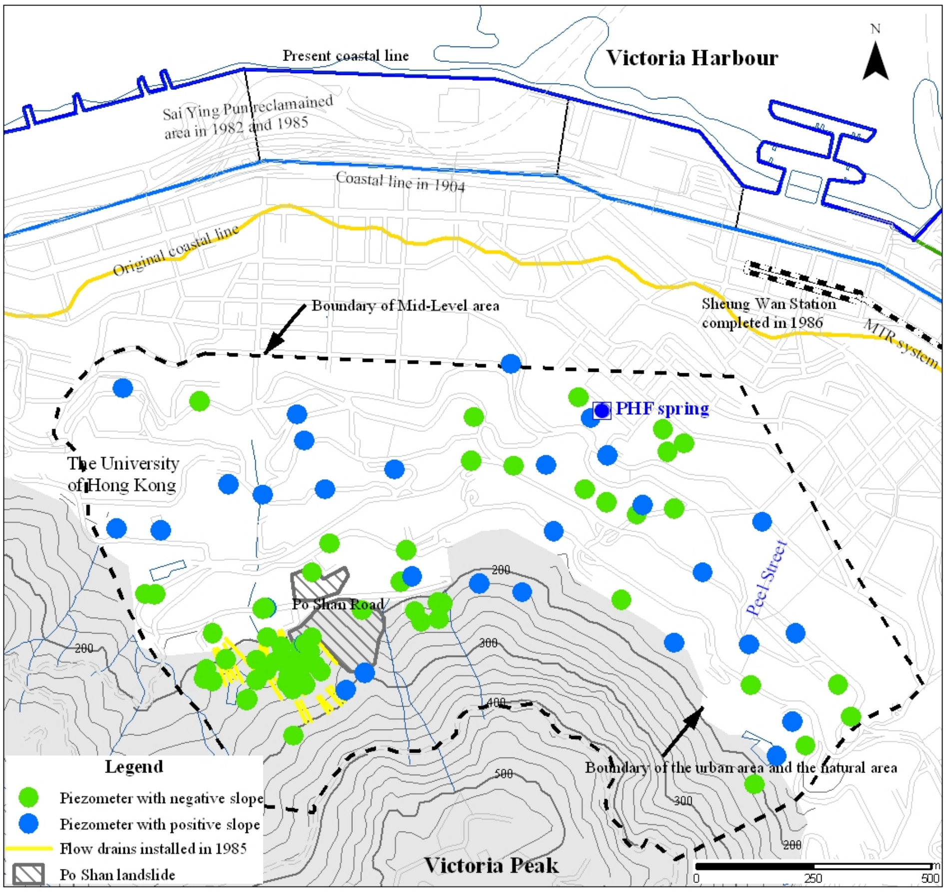

Figure 7 Piezometers indicating increasing or decreasing trend in water level from 1979 to 1990

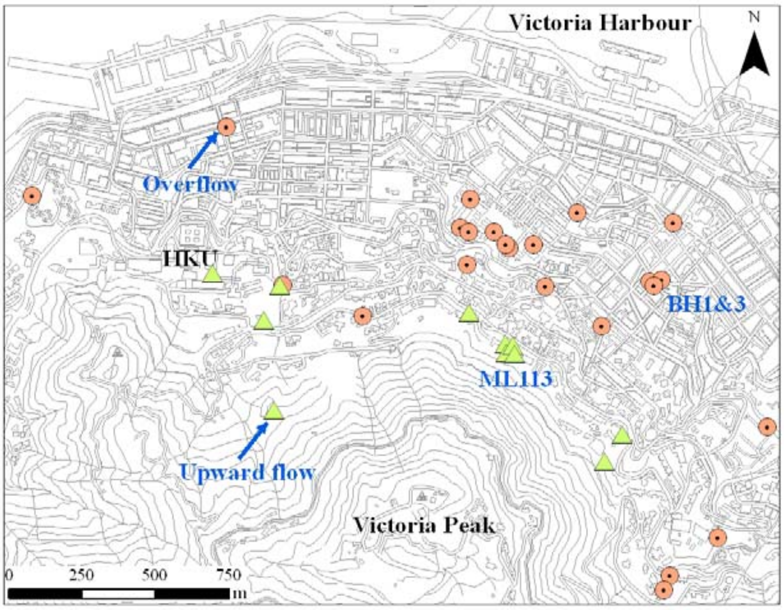

Figure 8. Location of overflow and upward flow in the study area and the Mass Transit Railway Hong Kong Island Line (solid black line).

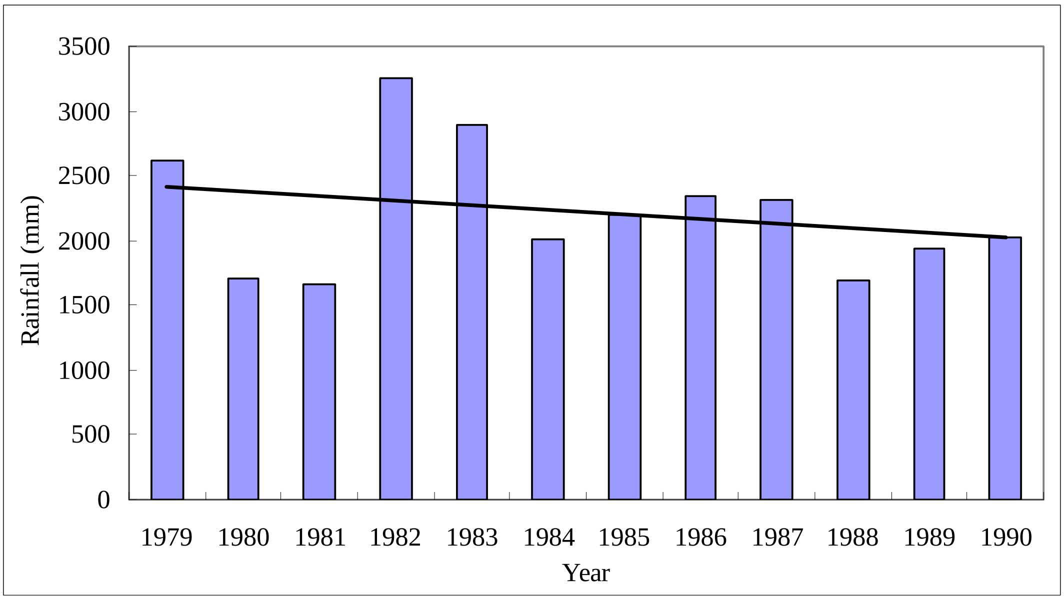

Fig 9 Annual rainfalls in Hong Kong Observatory from 1979 to 1990

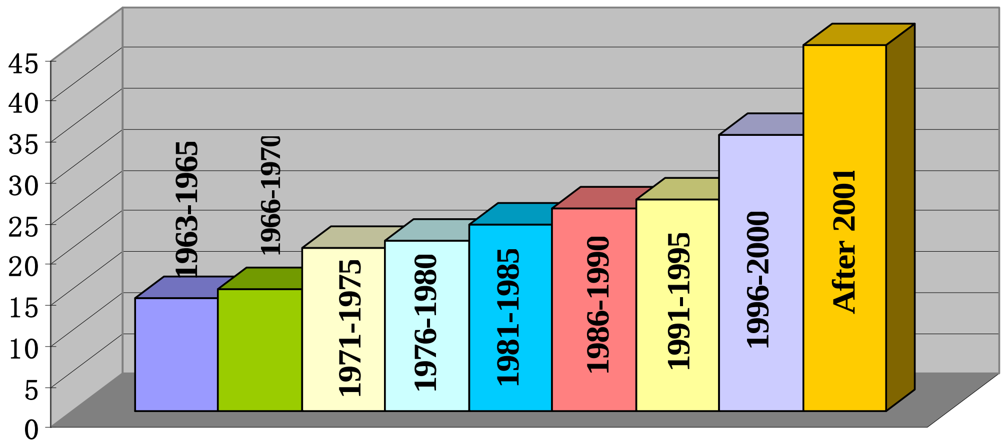

Fig 10 The number of storeys of high-rise buildings (>12 storeys) constructed from 1963 to present in the Mid-Levels and surrounding areas

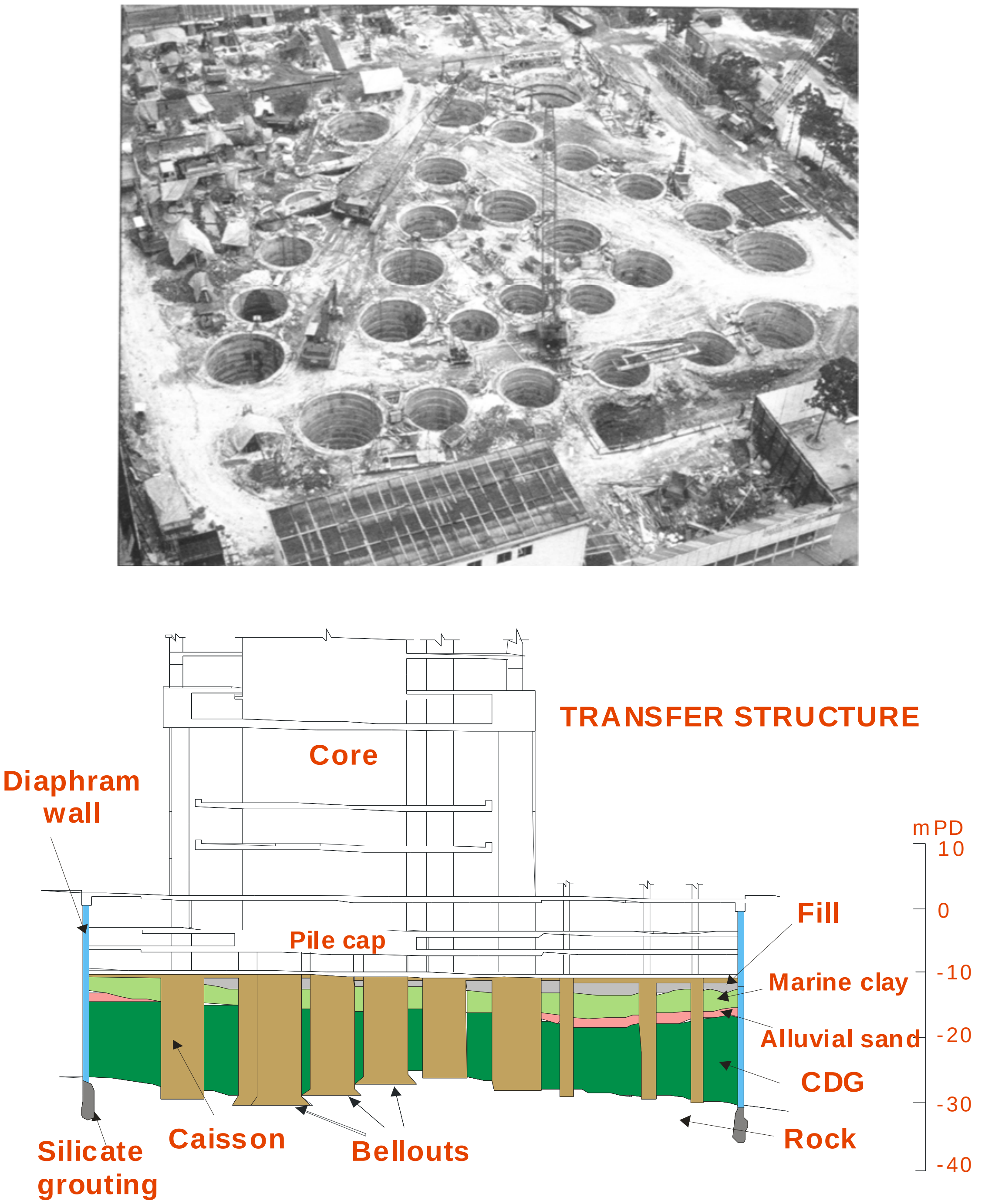

Figure 11 The foundation of a building in coastal area of Hong Kong Island: Hand-dug caissons up to 7.4m in diameter (a) and large diameter hand-dug caissons and perimeter diaphragm walls (b) (Note: CDG means completely decomposed granite)

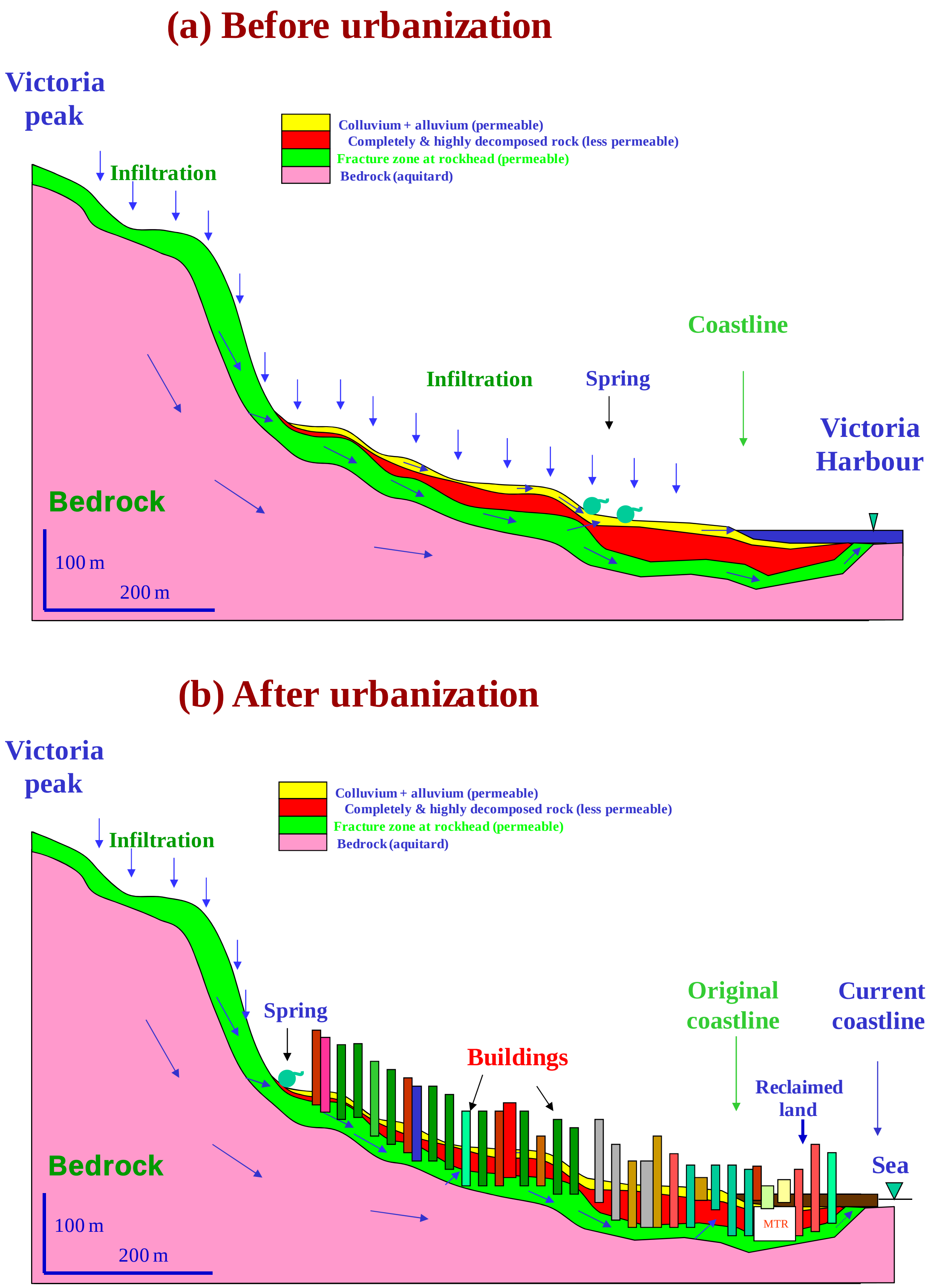

Figure 12 Conceptual model for the impact of foundations and reclamation on the groundwater flow.