



Title	Changes to the groundwater system, from 1888 to present, in a highly-urbanized coastal area in Hong Kong, China
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1 **Change of groundwater system from 1888 to present in highly-urbanized coastal**
2 **areas in Hong Kong**

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30

31 **Abstract**

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

53

54

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

56

57 **1. Introduction**

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

71 This study examined the historical seepage and piezometric records collected in a
72 highly-urbanized coastal area centered by the Mid-Levels area. Most of the historical data
73 were collected by Hong Kong government and could be found in different government
74 reports. The historical data were compared with recent groundwater records to reveal the
75 possible changes of groundwater regime in the rapidly urbanized coastal area over the last
76 century. By comparing the historical and recent groundwater information, some

77 interesting observations relating to the changes in the groundwater regime in the study
78 area were noticed. An attempt was made to explain the possible causes for the
79 modification in groundwater regimes by examining various anthropogenic activities in
80 the study area.

81

82 **2. Site geology and previous studies**

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

90 The most comprehensive study related to geology and hydrogeology in the Mid-
91 Levels areas so far was called Mid-Levels Study conducted around 1980, which was
92 organized by Geotechnical Controlling Office (GCO, 1982) (Now Geotechnical
93 Engineering Office). This study was prompted by a major landslide at Po Shan Road in
94 1972 which killed 67 people. The geology is dominated by two rock types, acidic
95 volcanic rocks and a granitic intrusion. The irregular contact between the granite and
96 volcanic rocks crosses the area and was disrupted by normal faults in several locations
97 (Figure 1). In general terms, colluvium overlies several meters of decomposed rock above
98 the bedrock. The granite underlies most of the developed spaces. Volcanic rock underlies
99 the upper undeveloped slopes.

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

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

123 along the coastline and deep foundations might have contributed to the modification of
124 the flow system, but the deep foundations might have more profound impact on the flow.

125 A number of studies was conducted to investigate the impacts of urbanization on
126 the groundwater chemical systems in the area (Leung and Jiao, 2005; Leung et al., 2005;
127 Leung and Jiao, 2006). There is a spring near the Po Hing Fong Street. Leung and Jiao
128 (2007) monitored the PHF spring for one year and studied its temporal variations of
129 physical and hydrochemical properties. This PHF spring is quite persistent and did not
130 run dry even in 1963, the driest year in the history of Hong Kong. It is believed that this
131 spring is largely from the groundwater through relatively deep circulation with recharge
132 originated from the uphill (Leung and Jiao, 2007).

133

134 **3. Changes of groundwater regimes in the last century**

135

136 **3.1 Historical records of seepages**

137

138 *Seeps and springs in 1888 and shallow groundwater in 1896*

139 There was no direct information on groundwater regimes in the 18th century.
140 However, some indirect information could be still found from some government records.
141 In the 1880s, malarial fever prevailed in the then Western Districted in Hong Kong. A
142 commission was appointed by the Hong Kong Government to enquire into the causes of
143 the fever and to recommend remedial measures. According to sessional paper on the
144 fever prevailing in the Western District, the shallow water table was believed to be one of
145 the causes for the fever (Hong Kong Government, 1888), "...the situation of the houses

146 in the Western District is such that malarial fever might be expected to develop around
147 them. The houses stand at the base of a high hill receiving a tropical rainfall. Around the
148 houses numerous springs exist, and at no great distance from the surface, subsoil water is
149 found standing; in addition, in many places the water finds its way to the surface causing
150 pools in some instances...”

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

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

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

166

167 ***Seepage locations in 1981***

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

174

175 ***Seepage locations in 2002/2003***

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

183

184 ***Comparison of groundwater regimes since 1888***

185 The above historical records can be regarded as snapshots of groundwater regimes in
186 different years. A comparison of these snapshots led to several interesting findings. (1)
187 except at the eastern end of the Western District, the springs and pools of water in 1888
188 seems to have virtually disappeared; (2) the number of seepage was much smaller in
189 2002/2003 than in 1981, indicating an obvious change in the period of about 20 years; (3)

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

197

198 **3.2 Historical records of water level**

199

200 *Change in groundwater levels between 1979 and 1990*

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

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

210 110 piezometers which had data observed in periods longer enough to show
211 certain trend were selected in this study. Figure 6 shows some of the typical piezometric
212 curves (The locations of these piezometers are shown in Figure 7). For example, the data

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

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

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

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

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

236 2002/2003 such as the areas above the Po Shan Road and near the PHF spring. This led to
237 a finding that water level in the study area shows an overall increasing trend except in the
238 areas with effective horizontal drains or seepages.

239

240 *Overflow and upward flow*

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

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

256 Jiao et al (2006b) investigated two overflow standpipes BH1 and BH3 (see Figure
257 8 for location) at a construction site at No.52 Hollywood Road. After pipes were added to
258 the top of the standpipes, the water level in the two standpipes raised up to 0.64 and
259 3.73m above the ground surface, respectively, indicating that the deep groundwater was

260 significantly confined. The original boreholes were 58 m deep but the standpipes were
261 installed only down to 15 and 20 m, respectively. It was speculated that the water may be
262 originated from the deep fracture zones around the rock head near the bottom of the
263 original borehole (Jiao et al, 2006b).

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

267

268 **4. Possible mechanisms responsible for the modifications**

269

270 4.1 Rainfall

271 One should not talk about the change of a groundwater system over the years without
272 discussing the change of rainfall in the same period because rainfall alone can cause
273 significant change in water level. Figure 9 shows that the amount of rainfall from 1979 to
274 1990, together with a trend line. Generally, there was a trend of decreasing in rainfall in
275 these years. An overall increase in groundwater levels over a particular area may also be
276 caused by the increase in rainfall. However, as shown in Figure 9, there was a general
277 decreasing trend in the amount of rainfall from 1981 to 1991.

278

279 Infiltration to underground was expected to reduce as the overall rainfall decreased. Even
280 if rainfall were not reduced, the rainwater which could actually infiltrate underground
281 was still reduced with time because the urban surface becomes progressively less
282 impermeable due to buildings, concrete road surfaces and covered slopes. It is therefore

283 unlikely that the observed overall increase in groundwater level was induced by rainfall.
284 In fact, should the rainfall remain almost constant, there would be much more
285 piezometers showing increasing trend as those shown in Figure 7.

286

287 4.2 Urbanization activities

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

294

295 *Land reclamation*

296

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

301

302 Modification of land reclamation on groundwater flow system depends on the scale of
303 reclamation relative to the length of the flow path or the size of the original groundwater
304 catchment (Jiao et al, 2001). The distance from the Victoria Peak to the original coastline
305 is about 1200 m. The coastline has been extended towards the sea by about 400 m. The

306 fill materials range from public rubbish dumps in the early days to decomposed granite
307 and marine excavated from hills or marine sand collected from the deep sea.

308

309 The permeability of fill materials in Hong Kong was discussed by Jiao et al. (2006a). The
310 permeability in a reclamation site is extremely unpredictable and varies with the nature of
311 the fill materials and the method of placement. For fill composed of completely
312 decomposed rock and marine sand, permeabilities can be on the order of 10^{-4} or 10^{-5} m/s,
313 but permeabilities of compacted fill composed of completely decomposed rock can be 10^{-6}
314 $- 10^{-7}$ and $10^{-6} - 10^{-8}$ m/s, respectively. Although the quality and nature of fill at the site
315 can be extremely variable, there is usually a layer of soft marine mud at the seabed
316 beneath reclamation sites. The permeability of this marine mud is usually extremely low
317 after it is buried by fill and becomes consolidated.

318

319 *Deep foundations of structures*

320

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

327

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

338

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

343

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

351

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

358

359 ***Leakage from water mains***

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

364

365 On the basis of groundwater chemical study, Leung (2004) concluded that from 1980 to
366 2003, due to the replacement and reparation of service pipes, there is an overall reduction
367 in the locations with major or substantial leakage from service pipes in the area. However,
368 the amount of leakage from water mains is difficult to quantify and consequently the
369 impact of the leakage on groundwater system is hard to estimate.

370

371 ***Horizontal drains in retaining walls or slopes***

372 All slopes and retaining walls in the study area were installed with weepholes or
373 horizontal drains. As can be seen from the seepage locations identified in Figure 6, most

374 of these drains in this area did not issue water except some clusters above the PHF
375 springs and above the Po Shan Road.

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

382 Over 60 drains of length ranging from 30 to 90 m were installed at the different
383 levels the slopes on the left side of the Po Shan landslide scarp in 1985. Maximum water
384 flows from the whole system of over 780 m³/day were recorded, with a maximum
385 individual drain flow of 35 m³/day. Water level monitoring data in 1983 (prior to
386 construction of the drains) and 1986 indicated that, in general, piezometric levels in both
387 wet and dry seasons were lowered by more than 5 m across most of the site during this
388 period.

389

390 **5. A conceptual model**

391

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

397

398 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

399

400 Figure 12 presented a conceptual model about the impact of urbanization on flow system.

401 In a natural state, the hillslope aquifer system received rainfall infiltration. Groundwater
402 existed in the shallow as well as deep soils. Groundwater discharged to the sea along the
403 coastal line or through the relatively deep and confined fracture zone. Near the coast,
404 some groundwater discharged to the surface in the form of springs or seeps, as observed
405 in the 18th century.

406

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

414

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

419

420 6. Conclusion

421

422 This paper compared the historical piezometric and seepage records with recent
423 groundwater records of a highly urbanized coastal area in Hong Kong over the last
424 century. The results suggested that the groundwater flow system had been modified
425 progressively with urban development. Several aspects of modifications were observed.
426 First of all, most of the springs and seeps widely existed along the coast in the 18th
427 century disappeared and the lower boundary of the seepage zone had been moved uphill
428 for about 150 meters in the last 20 years. Secondly, a number of overflows which
429 represents significantly confined groundwater condition were observed in the developed
430 spaces. And, upward flows were recorded along the boundary between the natural slope
431 and developed area. Thirdly, an overall increase in groundwater levels from 1981 to
432 1991 was noticed. The extinction of most of the springs and seeps from the shallow soils
433 near the coast indicated that the shallow aquifer dried up. The deep aquifer was well
434 confined as seen from the overflow piezometers and upward flow piezometers. Some part
435 of the deep aquifer system could be progressively more confined as indicated by the
436 temporal increase of water level in piezometers.

437

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

452

453 It was suggested that further urbanization activities such as western extension of the
454 underground transport system and new drainage system in the slopes should be assessed
455 for possible further change in the groundwater system. **Future studies are needed to**
456 **understand more quantitatively the different roles of the various human activities in**
457 **modifying groundwater flow system.** It is also suggested that the environmental and
458 engineering consequence of the changes of groundwater system should be studied in
459 extensively urbanized areas. **For example, groundwater input to the coastal sea may be**

460 reduced because of the deep foundations and land reclamation, which may have effect on
461 the coastal water quality. The regional increase in water level may cause flooding of deep
462 basements and have certain effect on slope stability.

463

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470

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548 **List of captions**

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550 Figure 1 Simplified geological map of the study area

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

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

553 Figure 4 The damp area plagued by malarial fever in 1888 (bounded by solid blue line)

554 and the well locations in 1896 (block dot)

555 Figure 5 Figure 5 Seepage locations in the study area in dry season in 1981 and January

556 in 2003 (a) and in wet season in 1981 and September in 2002 (b). The damp area

557 plagued by malarial fever in 1888 was also shown for comparison

558 Figure 6 Typical hydrographs and regression analysis of piezometers of ML55A(L),

559 ML57C, ML8B(U), ML9A (Note: rainfall is only shown in Figure 6a) .

560 Figure 7 Piezometers indicating increasing (blue dots) or decreasing (green dots) trend in

561 water level from 1979 to 1990

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

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

564 Fig 10 The mean number of storeys of high-rise buildings (>12 storeys) constructed from

565 1963 to present in the Mid-Level and surrounding areas

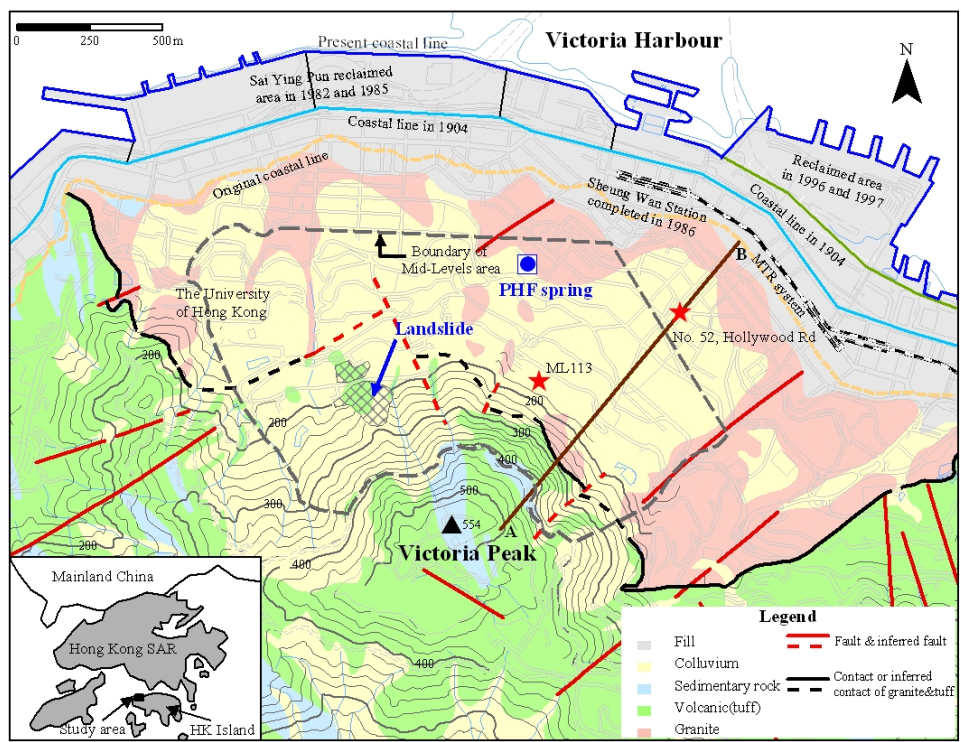
566 Figure 11 The foundation of a building in coastal area of Hong Kong Island: Hand-dug

567 caissons up to 7.4m in diameter (a) and large diameter hand-dug caissons and

568 perimeter diaphragm walls (b) (Note: CDG means completely decomposed

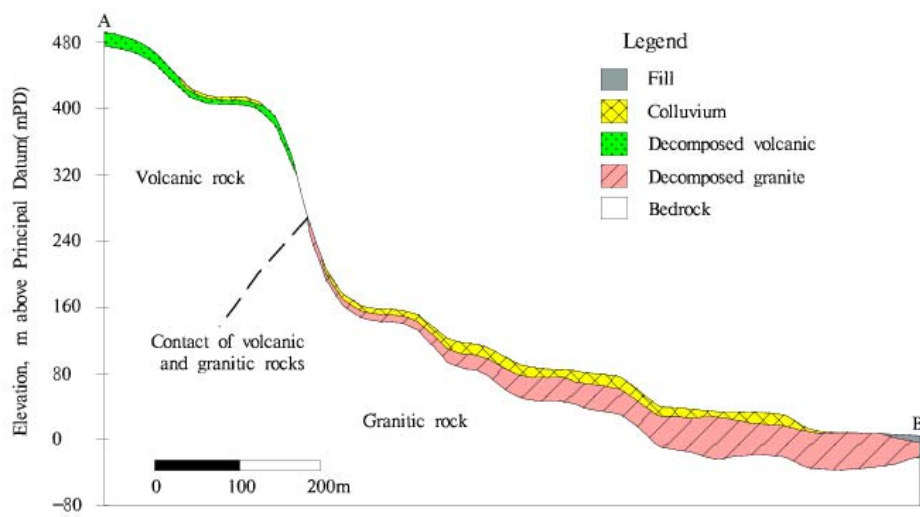
569 granite; mPD means meter above the principal datum) (based on Lam, 1991)

570 Figure 12 Conceptual model for the impact of foundations and reclamation on the
571 groundwater flow. Before urbanization, groundwater exists in shallow and deep
572 aquifers. Springs and seeps occur near the coast (a). After urbanization, shallow
573 soil becomes much drier and there is not a unified water level in the shallow
574 aquifer. Deep foundations and land reclamation reduce the discharge to the sea.
575 Deep aquifer becomes more confined and springs occur in the middle of the hill
576 (b).
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Figure 1. Simplified geological map of the study area. The area with elevation contours is also the area of natural slopes with minimum development.



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

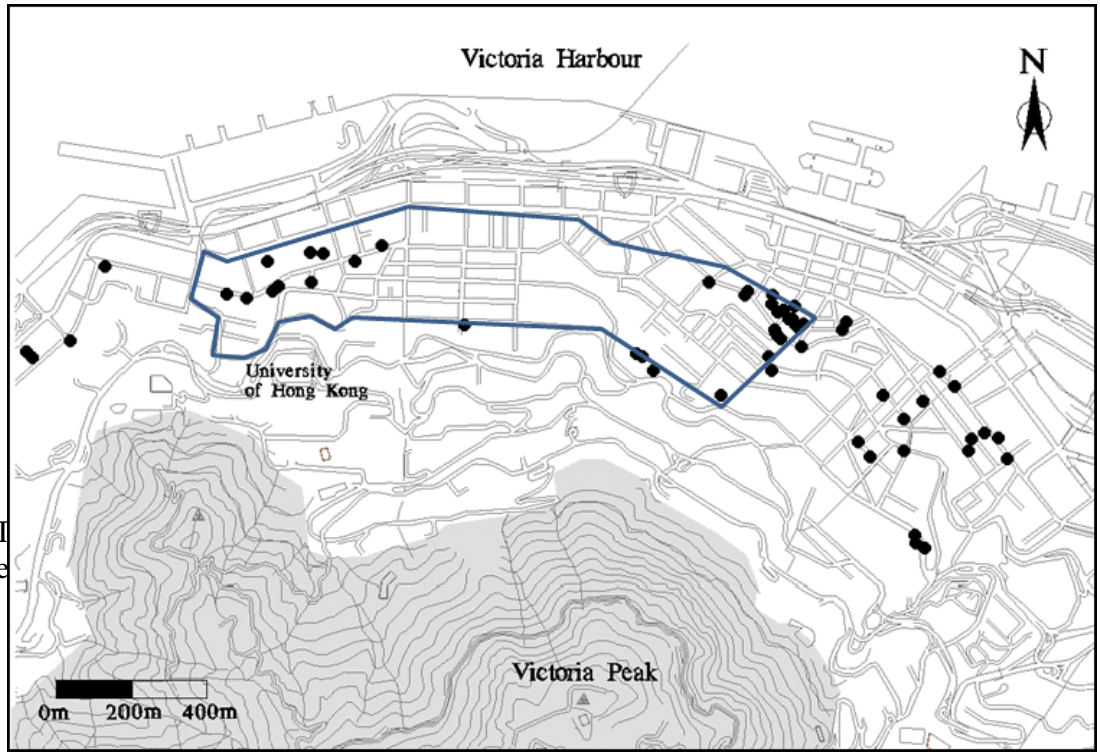
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Figure 3 Air photo of the site showing extensive urbanization at the lower part of the hill

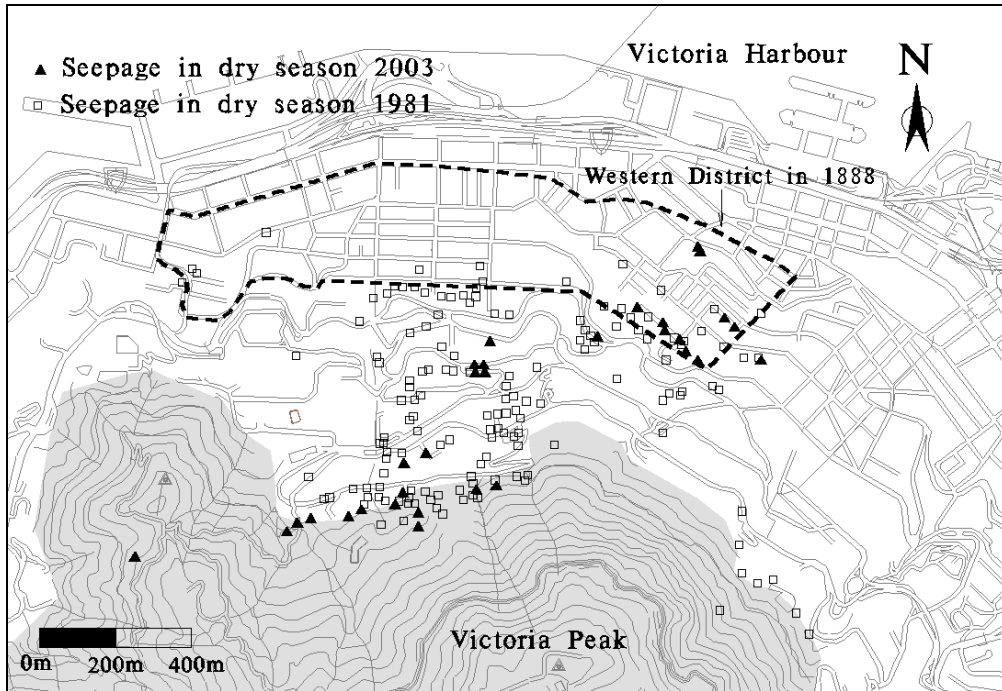
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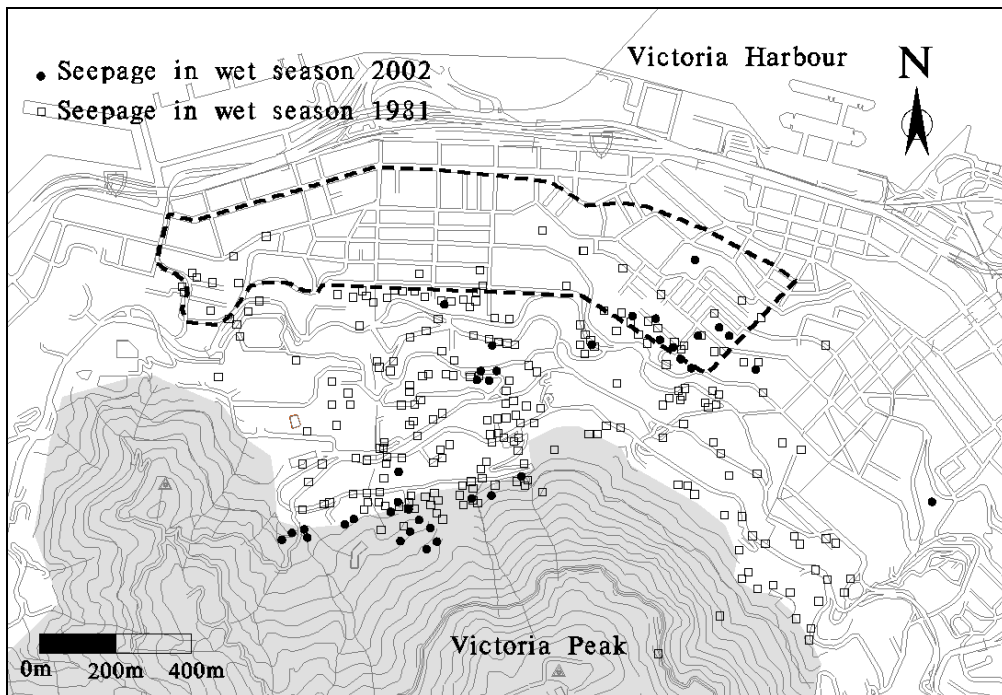
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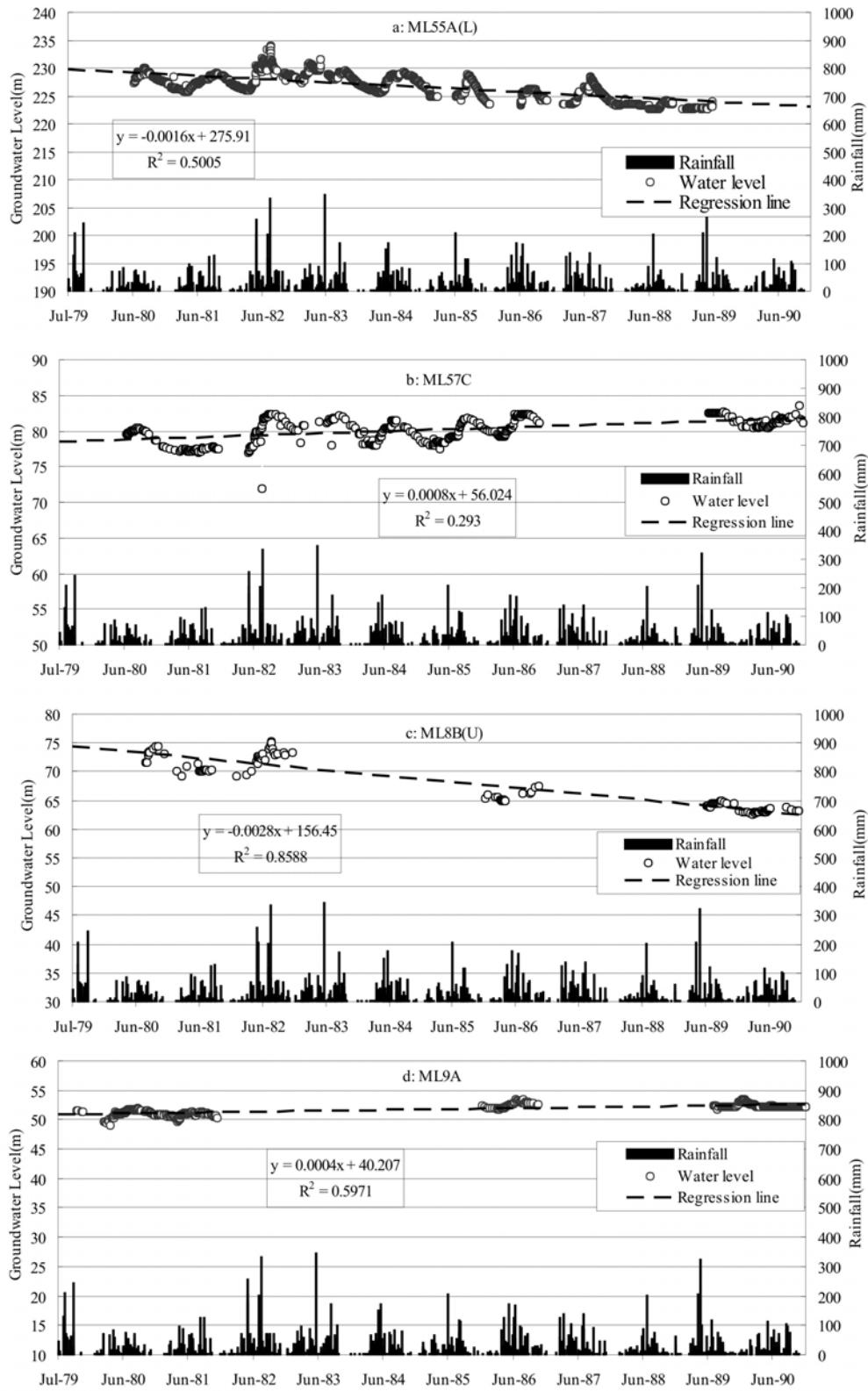


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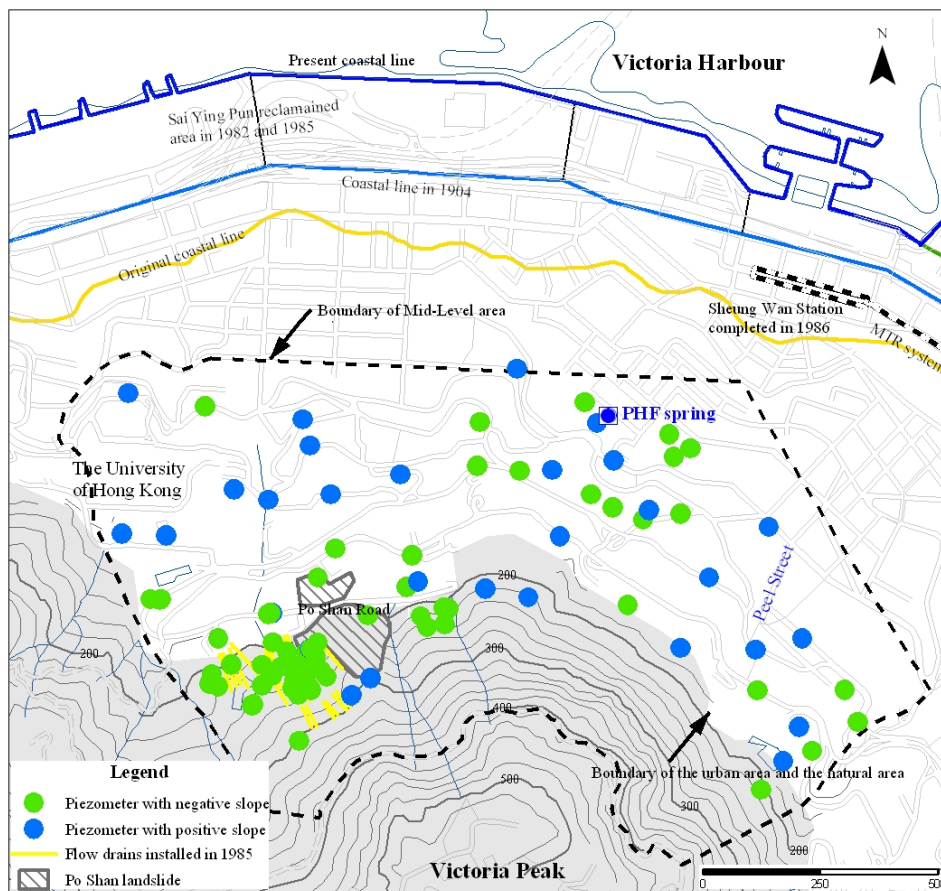
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Figure 5 Seepage locations in the study area in dry season in 1981 and January in 2003 (a) and in wet season in 1981 and September in 2002 (b). The damp area plagued by malarial fever in 1888 was also shown for comparison



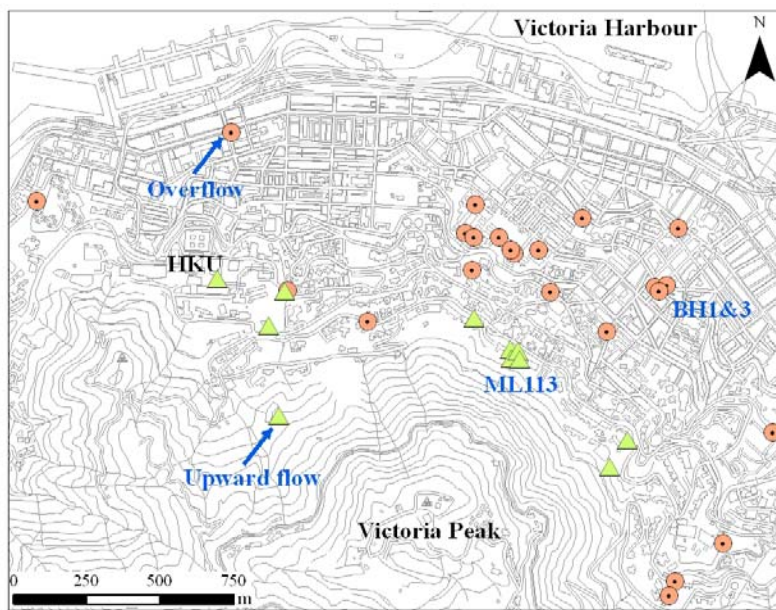
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Figure 6 Typical hydrographs and regression analysis of piezometers.



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



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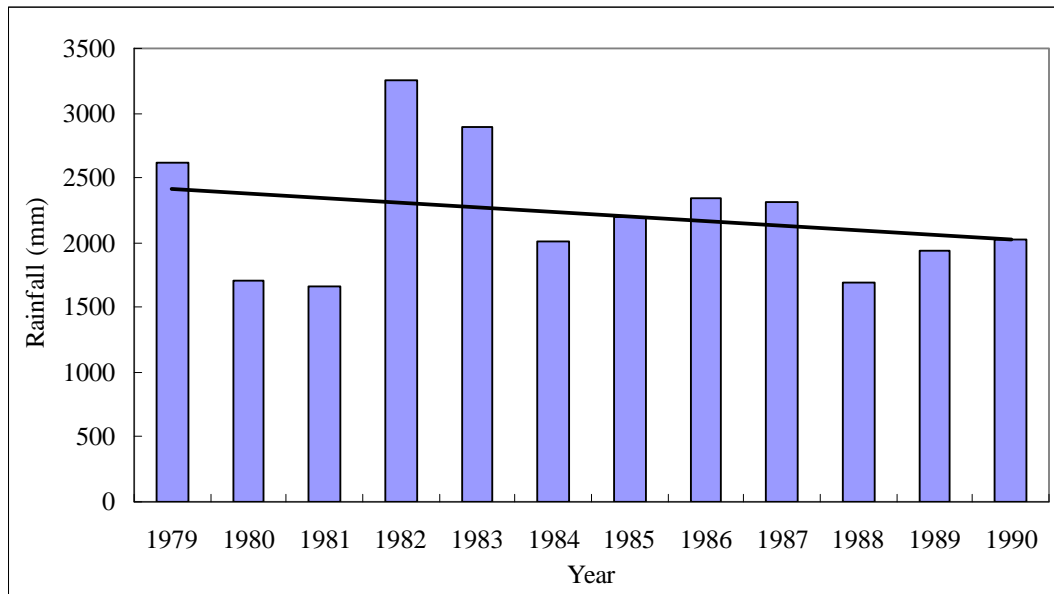
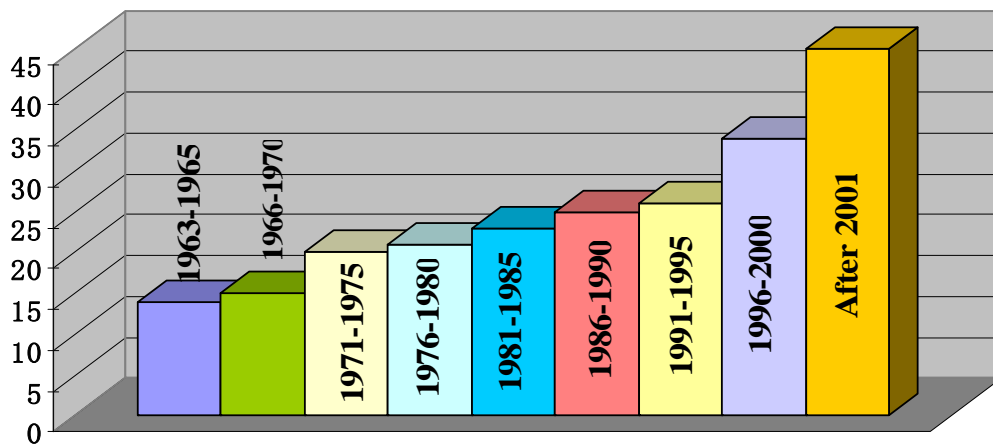


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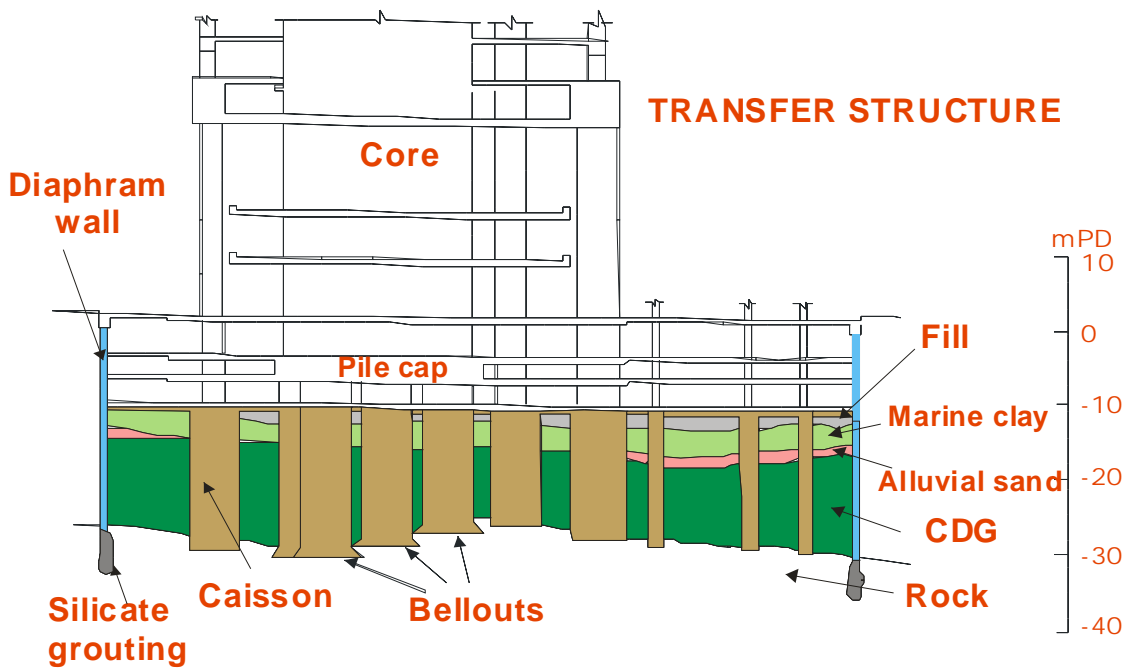
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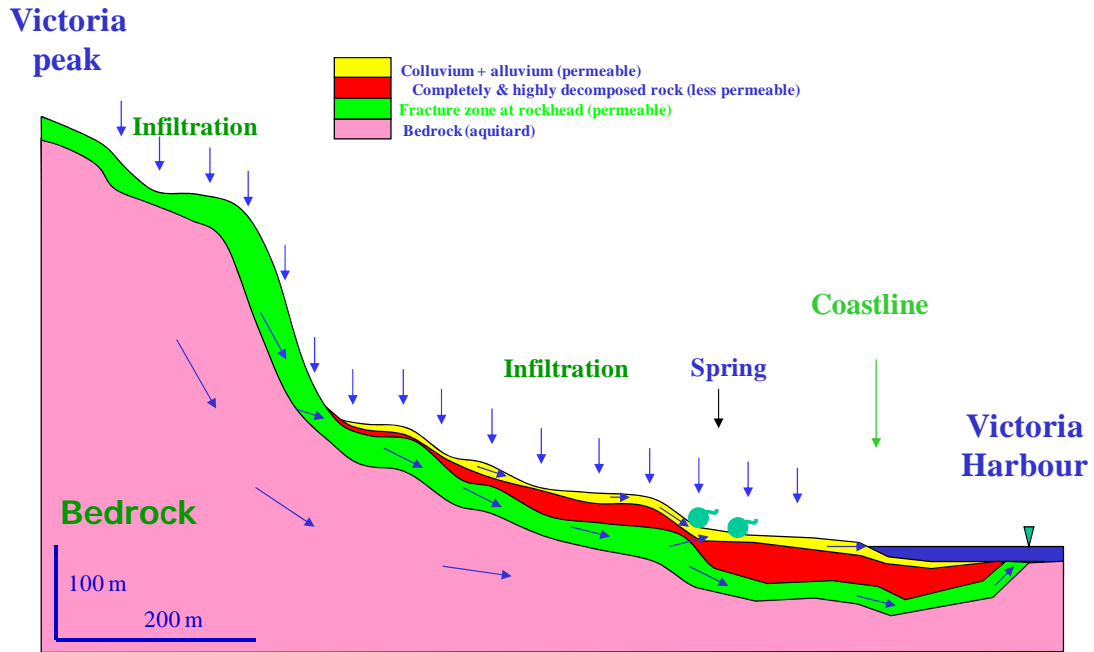


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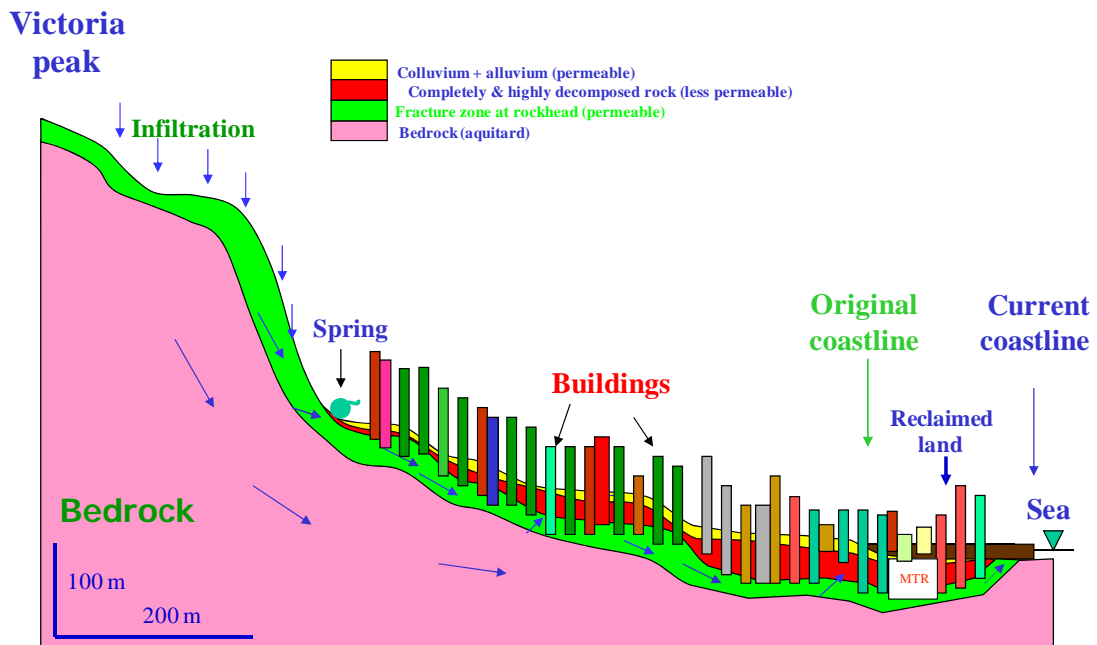
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(a) Before urbanization



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(b) After urbanization



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