Urban Land Subsidence: A Case Study in Richmond, British Columbia

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Abstract

Groundwater extraction can cause soil to consolidate and land to subside. Land subsidence increases relative sea-level rise and exacerbates inundation hazard for coastal cities. The City of Richmond is a low lying floodplain, on average 1 m above mean sea level, with increasing development due to urbanization. This makes it imperative that Richmond maintain its high water table to prevent subsidence. Furthermore, Richmond's high water table necessitates dewatering at excavation sites in order to proceed with construction processes. Subsidence occurs on the construction site itself, as well as off-site through differential settlement. This is determined by the depth of groundwater drawdown during dewatering. One particular dewatering case in Richmond had substantial off-site settlement. Examining the impacts of dewatering based subsidence in Richmond, on a neighbourhood scale, highlights why groundwater levels should be maintained on a city-wide scale. Richmond manages on and off-site settlement appropriately through correspondence with private consultants by implementing engineering practices such as deep-soil mixing walls, settlement ponds and sheet piling. Globally, exploitation of potable groundwater is the major driver of subsidence. In Richmond's unique case, groundwater is not suitable for irrigation/consumption due to its high iron content and instead is a hindrance for construction. Therefore, large scale dewatering to the extent seen in global cases is an unlikely scenario for Richmond. However, Richmond can evaluate management practices practised globally that contribute to of the maintenance of the groundwater table to further mitigate subsidence and to combat potential effects of climate change. Recommendations include balancing water inputs and outputs by decreasing impervious surfaces, incentivizing developers to install green infrastructure, monitoring elevation and groundwater levels, and implementing a combination of water drainage and storage systems to regulate established groundwater levels.

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Groundwater extraction can cause soil to consolidate and land to subside. Land subsidence increases relative sea-level rise and exacerbates inundation hazard for coastal cities. The City of Richmond, on average 1 m above mean sea level, has increasing development sites due to urbanization. Furthermore, Richmond's high water table requires these construction sites to be dewatered in order to proceed with construction processes. Dewatering not only causes subsidence at the site itself but can potentially cause off-site settlement based on the water drawdown, causing infrastructural damage. One particular case in Richmond experienced substantial subsidence in the past due to heavy dewatering during excavation. In order to mitigate subsidence, Richmond works closely with private consultants and focuses on engineering practices such as deep-soil mixing walls, settlement ponds and sheet piling. Richmond's case is unique as groundwater is not consumable and is more of a hindrance, whereas globally, exploitation of groundwater is the major driver of subsidence. However, Richmond can implement the management practices seen globally to maintain a high groundwater table to further mitigate subsidence. The City can store dewatering data taken at construction sites and enforce fines, balance water inputs and outputs by decreasing impervious surfaces, incentivize developers to install green infrastructure, monitor elevation and groundwater levels, and use a combination of water drainage and storage systems for its agricultural land.

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1.   Introduction

Land subsidence due to excessive groundwater withdrawal is a well-documented concern for structural infrastructure throughout the world (Chai et al, 2004; Poland et al 1984; 2013; Ren et al, 2014; Teatini et al; Xiaoqing et al, 2012). In the United States, 80% of identified subsidence was due to anthropogenic impact on subsurface water (USGS, 2000). San Jaoquin Valley in the US experienced over $50 million in losses during 1945 to 1970 due to subsidence.

Furthermore, subsidence degrades environmental productivity by eroding tidal marshes and disrupting drainage systems (Abidin et al, 2015). Land subsidence has the most significant economic and environmental impacts in coastal regions by amplifying the effects of rising sea levels and increasing susceptibility to floods (Pope, 2002). The development of land and water resources exacerbates land subsidence problems (USGS, 2000). Global cases of subsidence management will be reviewed to derive recommendations for the City of Richmond.

The City of Richmond encompasses 12,927 ha of land and is a rapidly urbanizing coastal city located in British Columbia, at the mouth of the Fraser River. Within the context of Richmond, urban land subsidence will be discussed at three scales:

  i. Subsidence within the development/construction site;

  ii. Off-site settlement in the area surrounding the construction site; and;

  iii. Potential subsidence on a city-wide scale.

It is important for Richmond to maintain its high groundwater levels. The groundwater acts as a subsurface support system, preventing the soil from consolidating. During excavation at construction sites, the high groundwater table necessitates dewatering to provide a dry workable environment. Subsidence within the construction site due to dewatering can be effectively mitigated using several engineering practices. Lowering of the watertable at the construction sites causes a water drawdown curve which can cause off-site settlement; however, this as well is attenuated by engineering protocols. A case in Richmond displaying off-site settlement within a neighbourhood will be used to demonstrate the impacts of lowering the water table and why city-wide drainage should be prevented. Furthermore, construction sites in Richmond where subsidence is well managed will be highlighted.

Richmond's agricultural land, consisting of 5,560 ha, faces a different issue regarding land subsidence (Figure 1) (City of Richmond, 2017). The high water table and annual precipitation of 1,126 mm requires adequate drainage allowing for; increased range of crops suitable for different soils, trafficability, rooting depth, aeration and warming of the soil (Agricultural Profile Report, 2012). However, excessive drainage can lower the water table resulting in subsidence. Furthermore, drainage of peat lands leads to shrinkage and oxidization due to increased microbial activity, causing a reduction of volume of the land. An optimal drainage system is required to regulate groundwater levels to decrease subsidence.
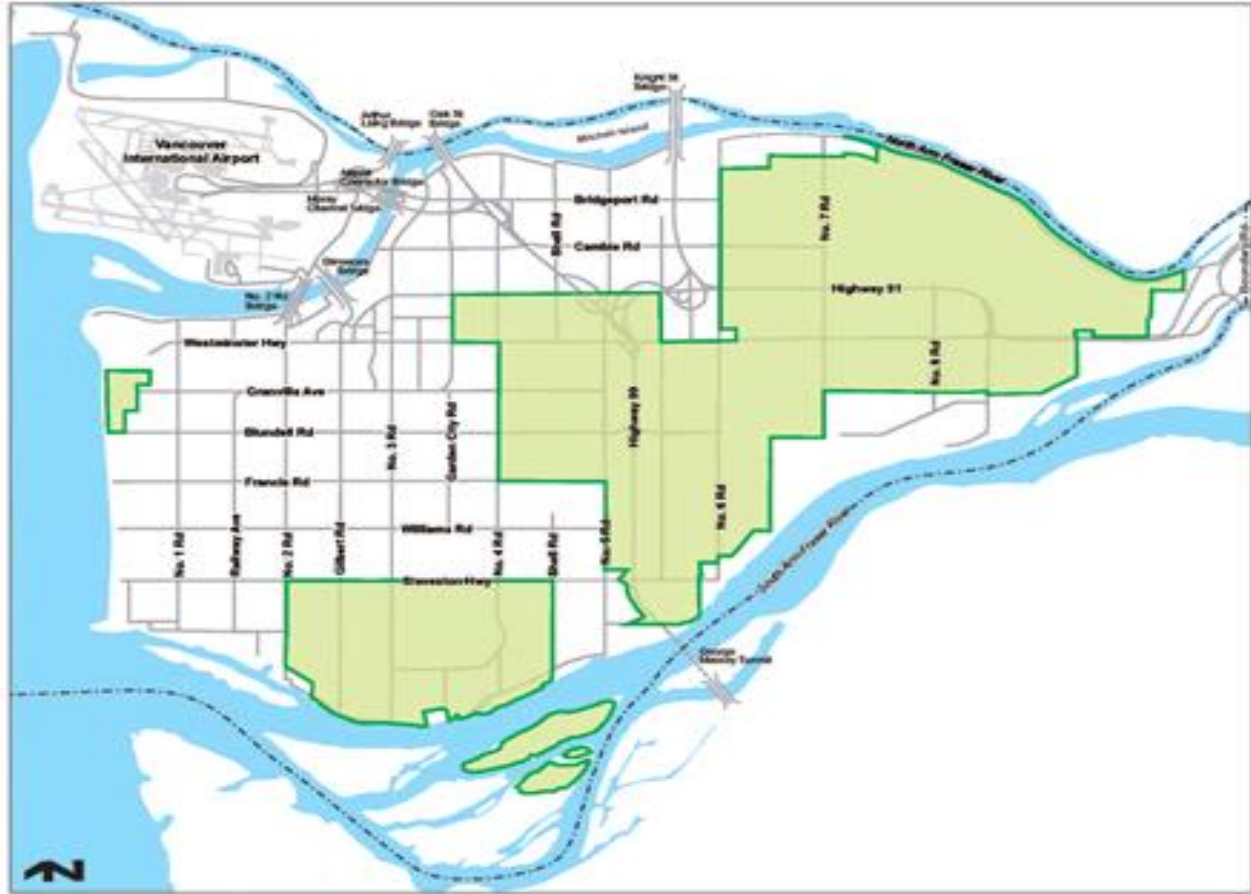
Figure 1. Richmond's Agricultural Land Reserve (approximately 43% of total land). Agricultural land use is predominantly in the East (green). *Source (City of Richmond, 2018)*.

2.   Global Issue of Subsidence and its Management

The BC Ministry of Environment (2011) anticipates a global mean absolute sea-level rise of approximately 1m by 2100 (Figure 2). Furthermore, subsidence rates in coastal cities have been observed at 2-100 mm/year with similar rates projected until 2025, which will lead to increased flood vulnerability (Erkens et al, 2015) (Appendix B-1).

While subsidence exacerbates sea-level rise, it also causes economic strain by damaging infrastructure, as seen in San Joaquin Valley U.S. (Poland et al, 1984):

i.   Deformation in the land surface due to differential changes in elevation, making it difficult to construct and maintain water-transport structures including canals, irrigation and drainage systems, and stream channels;

ii.   Compressive rupture of casings caused by compaction of aquifer systems leading to failure of deep irrigation wells (200-900 m);

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iii.   Pre-consolidation of deposits susceptible to hydro-compaction increasing construction costs by approximately $25 million; and;

iv.   Additional costs associated with surveys made by government and private agencies to determine elevations of benchmarks, revision of topographic maps, construction of subsidence maps and compensation of subsidence through land leveling.
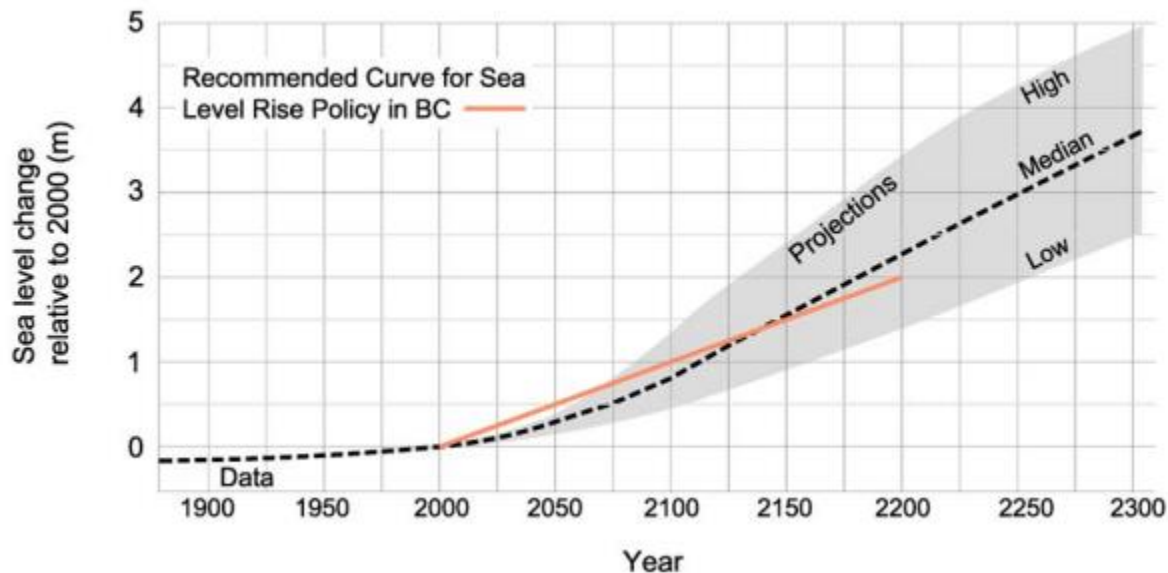
Figure 2 Projection of Global Sea Level Rise. *Source (BC Ministry of Environment, 2011).*

2.1.   Drivers of Subsidence

In a majority of cases, over extraction of groundwater and its associated subsidence occurs for the use of bulk potable water. In Asia (Table 1), excessive groundwater extraction is a result of an increased demand for freshwater for industrial and domestic uses, caused by population growth and economic expansion. Also, groundwater extraction in the Netherlands is also used as a form of drainage to increase agricultural suitability/production, and buildable areas for houses (Appendix A-3.0).

2.1.1. Groundwater in Richmond

Groundwater extraction as a potable water source or for irrigation is not the case in Richmond, as the City receives its bulk potable water from Metro Vancouver, sourced from the Capilano and Seymour reservoirs (Metro Vancouver, 2018). Richmond's groundwater is not suitable for drinking/irrigation water as it is rich in iron. Groundwater extraction primarily occurs to facilitate construction activities for development. Therefore, Richmond manages groundwater levels to buffer against subsidence. Three management concerns derived from this are:

i.   Potential structural damage to surrounding properties.

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ii. Purification standards to remove unwanted metals such as iron to suitable levels for discharge;

iii. Discharge rates into the City's storm/sanitary system; and;

2.2. Subsidence in Coastal Regions and its Management

Subsidence rates differ among cities with varying underlying causes (Appendix B-2). Moreover, there is a lack of understanding of the extent to which these drivers affect subsidence. Thus, governmental policy formulation and management systems differ among cities (Erkens et al, 2014). The cities listed below have a long history of land subsidence with experience in research and policy development to mitigate subsidence impacts (Table 1) (Appendix A for details).

Table 1. Summary of management practices seen in coastal regions globally.

Location	Management
Shanghai (Appendix A–1.1)	• Re-pressuring by recharging aquifers through wells, expensive but effective in stopping subsidence • Guideline based on geology of the area to determine specific discharge capacity
Suzhou (Appendix A–1.2)	• Government restrictions and banning on deep dewatering • Monitoring network
Bangkok (Phien-wej et al, 2006)	• Pricing policy for groundwater extraction • Total ban on groundwater extraction in certain areas • Monitoring of surface and subsurface subsidence, groundwater levels in aquifer layers and rate of pumping
Malaysia (Appendix A–2.0)	• Maintain higher water table and wetter conditions to prevent peat oxidation which mainly takes place in the upper layers of the soil
Netherlands (Appendix A–3.0)	• Monitor groundwater levels twice a month and use mean lowest groundwater levels to predict peat oxidation/subsidence • Use a combination of drains and water management. "Regular and flexible" strategies are used in dry and wet month respectively, allowing for storage of excess water in wet months and use of this water during drier periods to prevent oxidation
Tokyo (Appendix A–4.0)	• Restrictions on cross-sectional area of the outlet of pumps and strainer depths • Mandate pumpage volume reports on pumps with output of over 300 watts • Improve rainwater infiltration by creating guidelines for pumpers to counterbalance their extraction by installing infiltration facilities • Water permeable pavement projects • Incentivize public facilities to increase rain infiltration

3. Study Area

Richmond's topography has urban land in the west juxtaposed by agricultural land in the east. It is the fourth most populated municipality in Greater Vancouver, consisting of 8.1% of the total population of the region (City of Richmond, 2018). The City's estimated population as of 2017 was 219,270 with a population percent change of 18.0% from 2007-2017, compared to the provincial average of 12.3% (City of Richmond, 2018) (Statistic Canada, 2018).

The City is a lowland coastal community susceptible to rising sea levels and natural subsidence, resulting in flood risk (Malik, 2016). In the context of potential climate change, the management and maintenance of ground water in Richmond is imperative for land subsidence mitigation and to protect its growing assets.

3.1. Flooding

Given Richmond is located on a floodplain, land subsidence plays a role in the City's habitability, as seen in other similar deltaic regions (Erban et al, 2014). The City's landscape is generally flat with an average land elevation of 1 m above mean sea level, and a natural subsidence rate of 2 mm annually.

Richmond's flat land and low elevation, combined with its high water table and surrounding water bodies, necessitates the maintenance of the City's robust flood protection system, which consists of 49 km of dikes, 622 km of drainage pipes, 178 km of ditches and 39 drainage pumping stations (Flood Protection Report, 2013). In addition, the City monitors water levels electronically on a 24/7 basis and maintains its dikes at or above the 1:200 year provincial standard (City of Richmond, 2018).

With $63 billion dollars in private and public land value, the City emphasizes flood protection to mitigate the impacts of climate change by advancing policies, practices and infrastructure (Flood Protection Update, 2014). Furthermore, the City has allocated resources to mitigate climate change projected sea level increases of 1 m by 2100 (BC Ministry of Environment, 2014). The City has a target dike crest elevation of 4.7 m with considerations of raising it to 5.5 m in response to sea level rise predictions (1 m) and land subsidence (0.2 m) by year 2100 (Parsons, 2016).

3.2. General Soil Characteristics

The soil profile is a major component that determines the magnitude of subsidence. The urban soil in Richmond consists primarily of interbedded silt and sand layers. Groundwater extraction induces an increase in effective stress, resulting in the silt layers becoming susceptible to unrecoverable compaction (Pope, 2002). A study by Welch and Smith (2001) discussed the Holocene sediments of the Fraser River Delta, and categorizes the soil into four main layers:

i.   Surficial floodplain and peat bog deposits composed of sandy to clayey silts,

ii.   Interbedded silts and sands,

iii.   An 8 to 20 m thick layer of fine to coarse grained homogeneous sand that is continuous across the delta and lastly

iv.   Fine grained delta slope deposits (Welch and Smith, 2001). However, soil conditions vary with site specific properties.

The soil map shows geological variation in the Quaternary deposits in Richmond (Figure 3). Most of the agricultural land in Richmond (Figure 1) is characterized by surface peats and moderately thick organic silts (O*). Within this major class there are slight variations, such as sand overlaying peat (sO*) or thin interbedded sands and silts overlaying peat (szO*).

Urban land in Richmond, including some ALR land falls in the sF and szF categories which represent shallow topsets of sands (<7m) and thick interbedded sands and silts, respectively. In general, the topset grades up from a lower sandy layer, to interbedded silt and sand layer and finally an upper organic silt layer.

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Legend

sF: Shallow topset sands (<7 m).
This map unit is widespread in western Richmond and forms the "typical" topset sequence, in which the sand facies is 8 to 25 m thick and occurs within 7 m of the surface. The sand facies is generally not shell-bearing in this map unit. Many small areas where the combined interbedded sand and silt facies and organic silt facies exceeds 7 m (Unit szF) have been mapped within this map unit, and more should be anticipated. Foreset deposits underlie the sand facies in this map unit. The following subunits have the same characteristics as map unit sF except where noted otherwise:

sF^1: Sand facies over Pleistocene deposits.
This map unit is assigned to areas where the topset sand facies directly overlies overconsolidated Pleistocene deposits rather than deposits of the foreset. The thickness of the deltaic deposits is less than 20 m. This map unit occurs along the North Arm of the Fraser River, on the northern margin of the delta, and locally over the southeast trending Pleistocene ridge that crosses central Richmond.

sF^2: Sand facies over thin delta foresets.
This map unit is assigned to areas where the total thickness of the deltaic deposits is less than 25 m, and a thin foreset sequence occurs between the topset and Pleistocene. This map unit occurs between map units sF and sF^1 in northern and central Richmond.

sF^3: Shell-bearing subfacies.
This map unit is assigned to areas where the sand facies of the topset is dominantly shell-bearing and the overlying interbedded sand and silt facies is bioturbated and shell-bearing. The sand facies is generally 10 to 15 metres thick. In Richmond, this map unit is restricted to the western part of the city. As in unit sF, several small areas where the combined interbedded sand and silt facies and organic silt facies exceeds 7 m (Unit szF) have been mapped within this map unit, and more should be anticipated.

sF^y: Young sand facies.
This map unit is assigned to areas where the topset sands are inferred to be relatively young, due to their association with historic sloughs This map unit occurs on the river side of sloughs bordering the North Arm and the Main Channel, in an abandoned distributary complex that cuts through the peat bogs of central Richmond, and on the concave side of a series of sloughs in the southwestern part of the city. In the latter area, the sloughs display cross-cutting relationships that permit further subdivision of the map unit into areas underlain by relatively younger and older sands, which are mapped as sFyy and sFyo, respectively. The exact ages of these deposits are uncertain but, by comparison with dated deposits throughout the delta, they are probably less than 4000 years old. The youngest deposits along the Main Channel are associated with a channel that appears to have been still active during the 1827 Admiralty Survey, and are therefore probably only a few hundred years old (Monahan et al., 1995). Thick foreset deposits generally underlie the topset channel sands. However, young sands directly overlie Pleistocene deposits (unit sF^{y1}) or thin forest deposits (unit sF^{y2}) locally over the southeast trending Pleistocene ridge that crosses central Richmond.

> sF^{yy}: Younger of the young sands along the Main Channel.
> sF^{yo}: Older of the young sands along the Main Channel.
> sF^{y1}: Young sands directly overlying Pleistocene deposits.
> sF^{y2}: Young sands, and thickness of deltaic deposits less than 25 m.

szF: Thick interbedded sands and silts.
In this map unit the interbedded sand and silt facies thickens downwards at the expense of the underlying sand facies, so that the top of the sand facies occurs at depths greater than 7 m. The interbedded sand and silt facies in this map unit is up to 20 metres thick. Mapped areas range in scale from those that are a few tens of metres across and can be traced 100 to 200 m, to one along the Main Channel that is 700 m wide and can be traced approximately 4 km. The smaller occurrences of this map unit are dominantly sand with some silt interbeds, but in the larger and thicker ones, silt is more prominent. The western part of the large occurrence of this map unit along the Main Channel is dominantly silt and has been designated szF^1. Foreset deposits underlie the sand facies in this map unit.
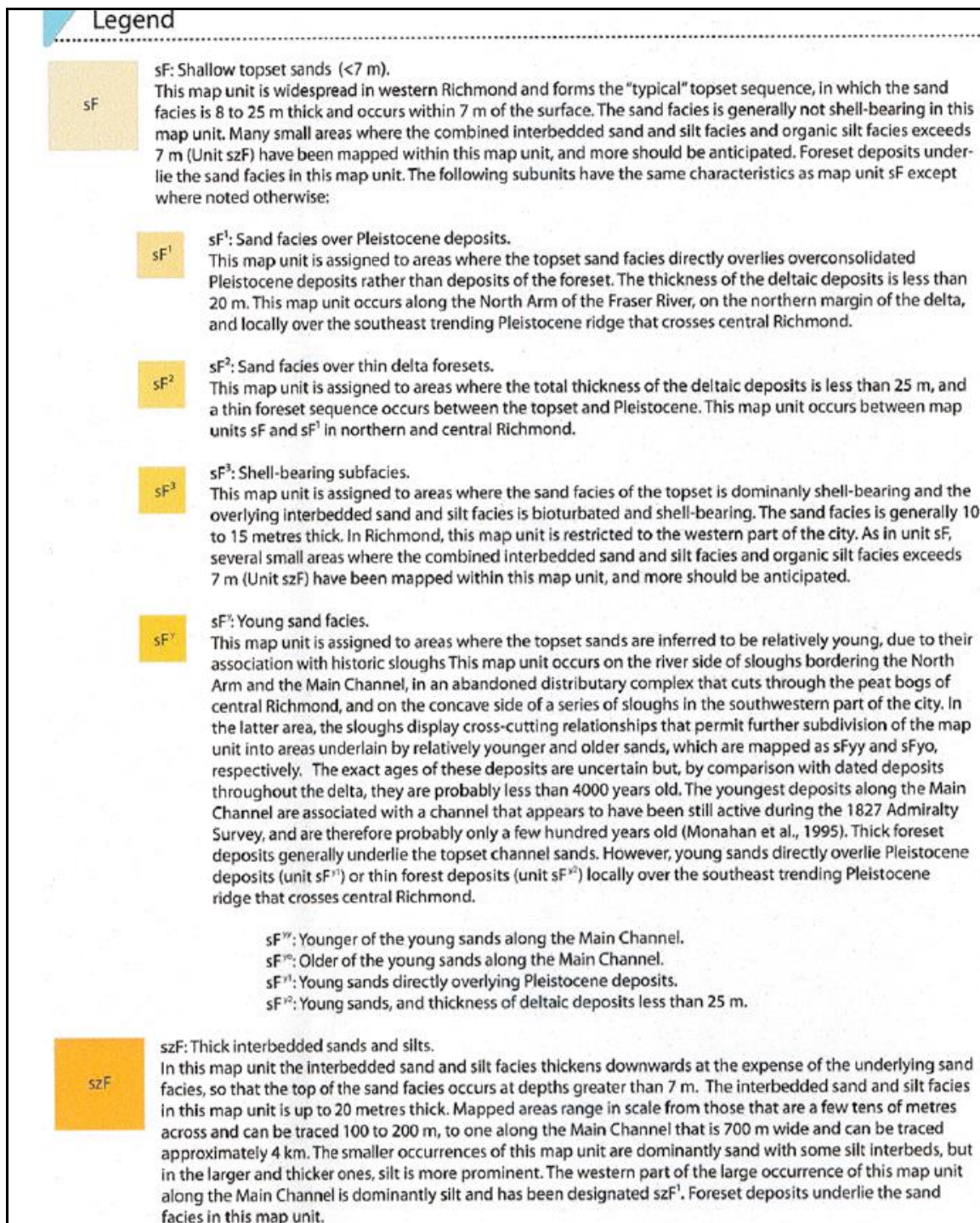
Figure 3. Soil Map of Richmond showing different textures, primarily composed of sand and silt (Monahan et al, 2010).

4.   Objective

The objective of this study was to assess construction case studies in Richmond to understand the importance of water table management in order to mitigate construction and peat based subsidence within the City. The first case study exhibits the impacts of subsidence at a local scale and highlights the importance of maintaining a high water table on a city-wide scale. The remaining four case studies present proper management used to mitigate subsidence within the construction site, as well as off-site differential subsidence. Lastly, drainage and irrigation practices in East Richmond are discussed. Recommendations derived from global case studies are suggested for consideration by the City of Richmond for subsidence management.

5.   Richmond – Subsidence through Groundwater Extraction (Urban)

In consultation with the City of Richmond Engineering Planning Department, the following five case studies were examined:

Developer	Building name	Location (Richmond)
i. ASAPC Ltd. Parcel 2	(River Green)	6031 River Road
ii. ASPAC Ltd. Parcel 8	(River Green)	6968 Pearson Way
iii. ASAPC Ltd Parcel 9	(River Green)	6633 Pearson Way
iv. Phileo Development Corp	(Quintet Phase 2)	5900 Minoru Blvd.
v. Cressey Development Group	(Cadence)	5640 HollyBridge Way

5.1.   ASPAC Parcels 1 and 2 (River Green) – No.2 Road Bridge Settlement

The first case examined is ASPAC Ltd. parcels 1 and 2 (private developers for the River Green Complex) which is located near River Rd and No. 2 Rd Bridge (Figure 4). Groundwater extraction at this site caused substantial subsidence for nearby infrastructure (3vGeomatics, 2013).

Figure 4. Map illustrating ASPAC parcels 1 and 2 along with the No.2 Road Bridge adjacent to it (Google Maps, 2018).

On May of 2013, the City of Richmond identified approximately 60 mm of vertical settlement via radar satellite monitoring (InSAR) on the south end of the No. 2 Road Bridge (Figure 5). The time frame for this settlement coincided with the dewatering operation on the ASPAC 2 site.

In the De-water License Extension Agreement, Pottinger Gaherty Environmental Consultants Ltd. (2011) stated that "the excavation work is anticipated to start in June 2010 and the dewatering will commence when the groundwater table is encountered". Dewatering of parcel 2 began on approximately Sep 1, 2010 corresponding with a large decline in vertical motion (Figure 5). Dewatering rates decreased after July 2011, from a maximum of 250,000 gallons/day to 1,000 to 30,000 gallons/day, reflected on the graph by a decrease in vertical motion (Figure 5).

The River Green project has two levels of underground parking with the bottom of the second level slab at -3.47 m geodetic elevation. ASPAC utilized a well-point dewatering system to lower the water table below excavation depth, at above average dewatering rates, to enable a workable platform for the waterproofing and formwork.
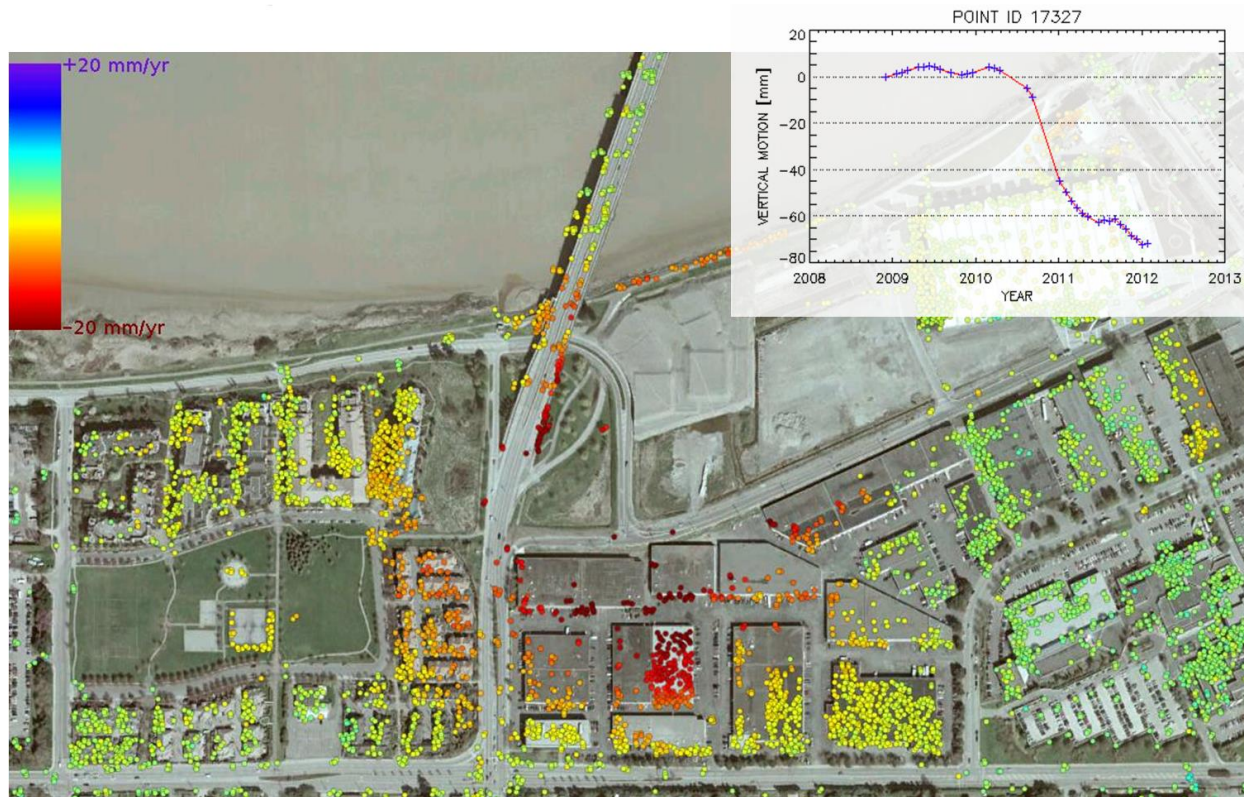
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Figure 5. Graph displaying vertical motion (mm) in a large radius around the ASPAC parcel 1 and 2 sites. Large settlement occurs around the time of parcel 2 dewatering, between 2010 and 2011 (3vGeomatics, 2013). The exact location of Point ID 17327 is not given but it is the point with the greatest settlment near the south end of the bridge (3vGeomatics, 2013).

5.1.1. Factors Inducing Subsidence

The area and extent of off-site settlement is influenced by the depth of the water table drawn down and the length of time it is maintained. Water drawdown forms a groundwater cone of depression around the pumping well (Figure 6). The area affected by subsidence, or horizontal radius of influence, is determined by the cone of depression and its associated angles of draw (Ren et al, 2015) (Figure 6). As drawdown depth increases, so does the cone of depression and horizontal radius of influence. Hydraulic conductivity of the soil also affects the cone of depression; more porous sands will have flatter drawdown curves.

Effective stress is greatest closest to the well, where the water levels are lowest (greatest change in pore-water pressure), and diminishes outward (Ren et al, 2015). In addition, increased drawdown depth leads to a greater volume of air replacing the soil's water. Water in soil is not compressible however air is, making the soil more prone to consolidation under effective stress (Ren et al, 2015).
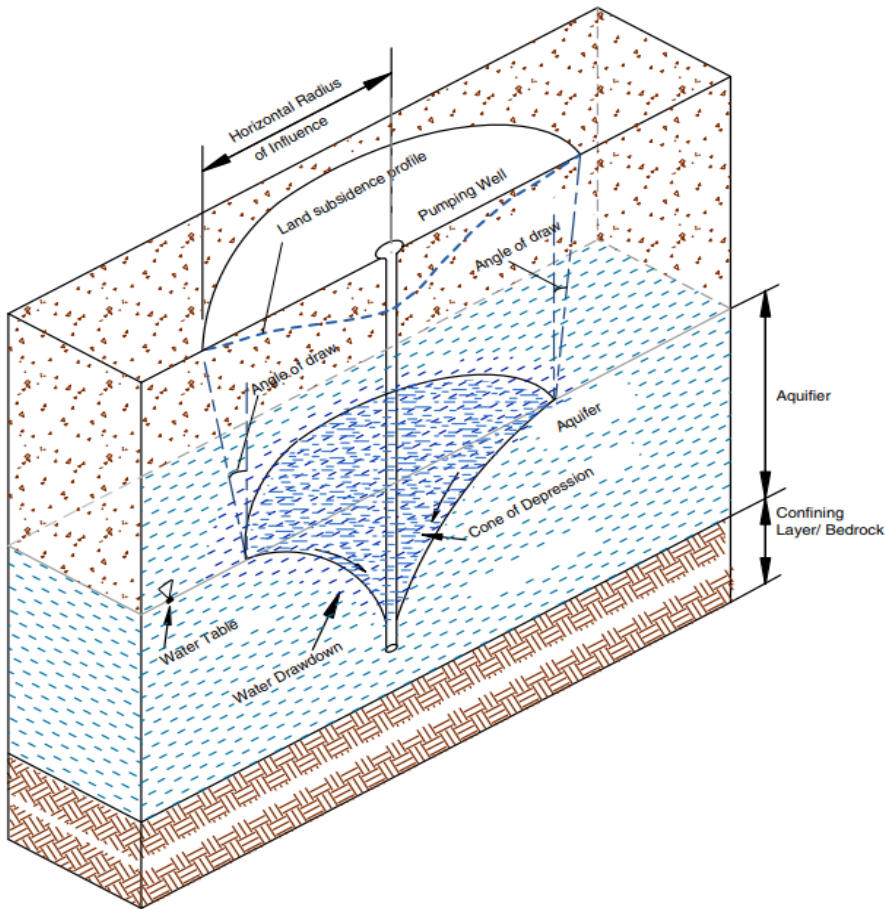
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Figure 6.Land subsidence in relation to groundwater pumping (Ren et al, 2015).

Dewatering rates are set to establish the depth of groundwater drawdown; the greater the depth of drawdown required the higher the dewatering rate. ASPAC parcel 2 likely drew the water table down substantially resulting in a large cone of depression. This explains the vast 0.5 km radius of influence (Figure 5). In conjunction, it was an open dewatering system with no cut-wall installed to confine the area of drawdown closer to the site (Matt Kokan, 2018).

The cumulated impacts of drawing the water table down to great depths and not using a cut-off wall to manage the drawdown curve resulted in widespread off-site settlement. As expected, the greatest extent of subsidence was observed closest to parcel 2 with the well-point systems. However, this graph does not show horizontal displacement. It would be useful to see the strain distribution because while compressive strain is predominant closest to the groundwater extraction site, tensile strain becomes dominant moving outward from the site (Ren et al, 2015). Thus, examining both types of strains would better describe the impacts on surrounding properties.

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5.1.2. No.2 Road Bridge

The City recognized the subsidence that took place between 2011 and 2013 on the southern abutments of the No.2 Road Bridge (3vGeomatics, 2013). In particular, monitoring points (MPs) 19 and 20 subsided by 177 mm and 205 mm respectively (Figure 8 and 9). Additionally, a large difference in the magnitude of subsidence between western and eastern MPs was detected (Figure 8 and 9). However, this is due to the location of the MPs themselves. Eastern MPs were located at grade beside the bridge on Parcel 1, whereas western MPs on the bridge itself. The difference in magnitude was due to the subsurface soil profile, explained in the next section.

Survey settlement data was collected for the different MPs of the Bridge (Figure 8.). As aforementioned, MP-19 and MP-20 experienced the most settlement. This is because the Bridge approach is located on fill containing surficial silt and deep silt, both of which were compacted due to effective stress changes from groundwater extraction. The other MPs, located on structural components supported by friction piles, are shown to be far less affected as only deep silt is compressed. This is further confirmed by the No.2 Road Bridge Foundation Paper (1994) which shows the sandy soil profile upon which the bridge is built (Figure 7).
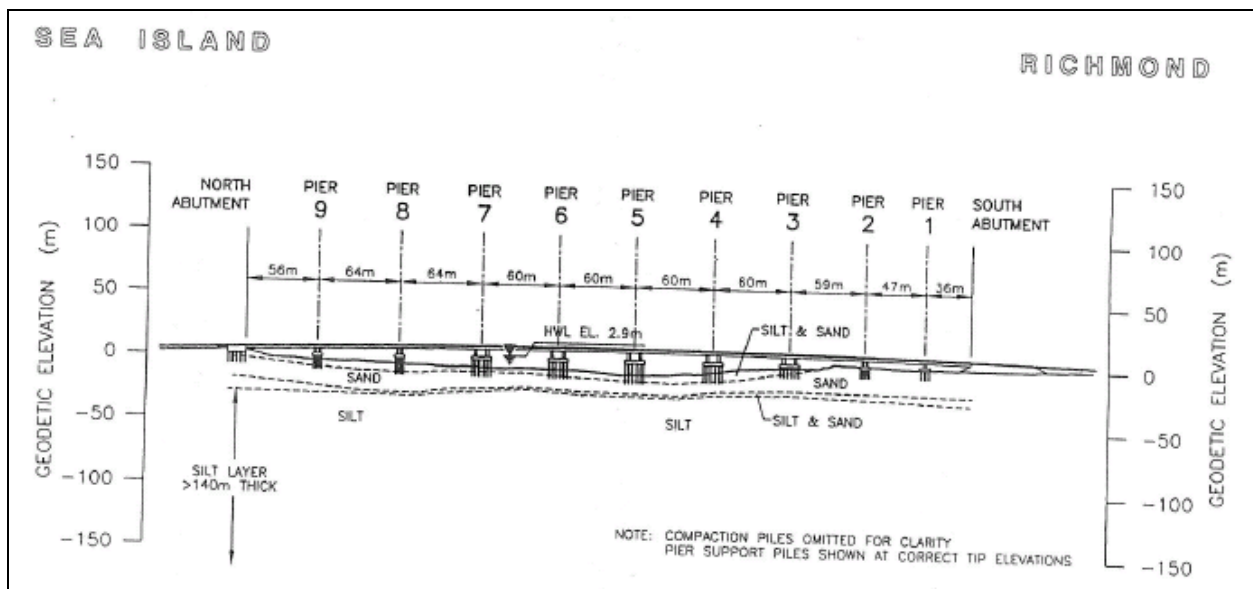

Figure 7 Geological profile of Bridge design (Smith, 1994)

Importantly, two periods of settlement between 2010 and 2013 are observed (Figure 9). The first increase in settlement corresponds with dewatering from Parcel 2, after which dewatering stops and settlement plateaus. The second period of settlement could correlate to a subsequent instance of dewatering on Parcel 2 as an extension, for the dewatering licence agreement, was requested to July 31, 2013. In addition, the duration of settlement for the second period is similar to the first, both occurring for ≈ 9 months further advocating for a second occurrence of dewatering.

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Based on observations, the second dip has a steeper slope relative to the first dip as more settlement (≈ 100 mm of settlement compared to ≈ 70 mm) is identified over the same period of time (≈ 9 months). This is likely due to the cumulative impacts of dewatering and Parcel 1's preload occurring immediately prior to the settlement (Figure 9). As Parcel 1 is closer to the Bridge and MPs than Parcel 2 (Figure 8), it is reasonable for Parcel 1 preload to cause a greater impact on the settlement data (Figure 9).

In conjunction, observations made during the second settlement period (Figure 9) indicated that sheet piles that were initially present around the site were now absent (Google Maps, August 2011 – July 2012). The potential removal and absence of these sheet piles, prior to the second dewatering, could further exacerbate groundwater drawdown and settlement resulting in the steeper observed dip (McGough, 2008) (Figure 9).

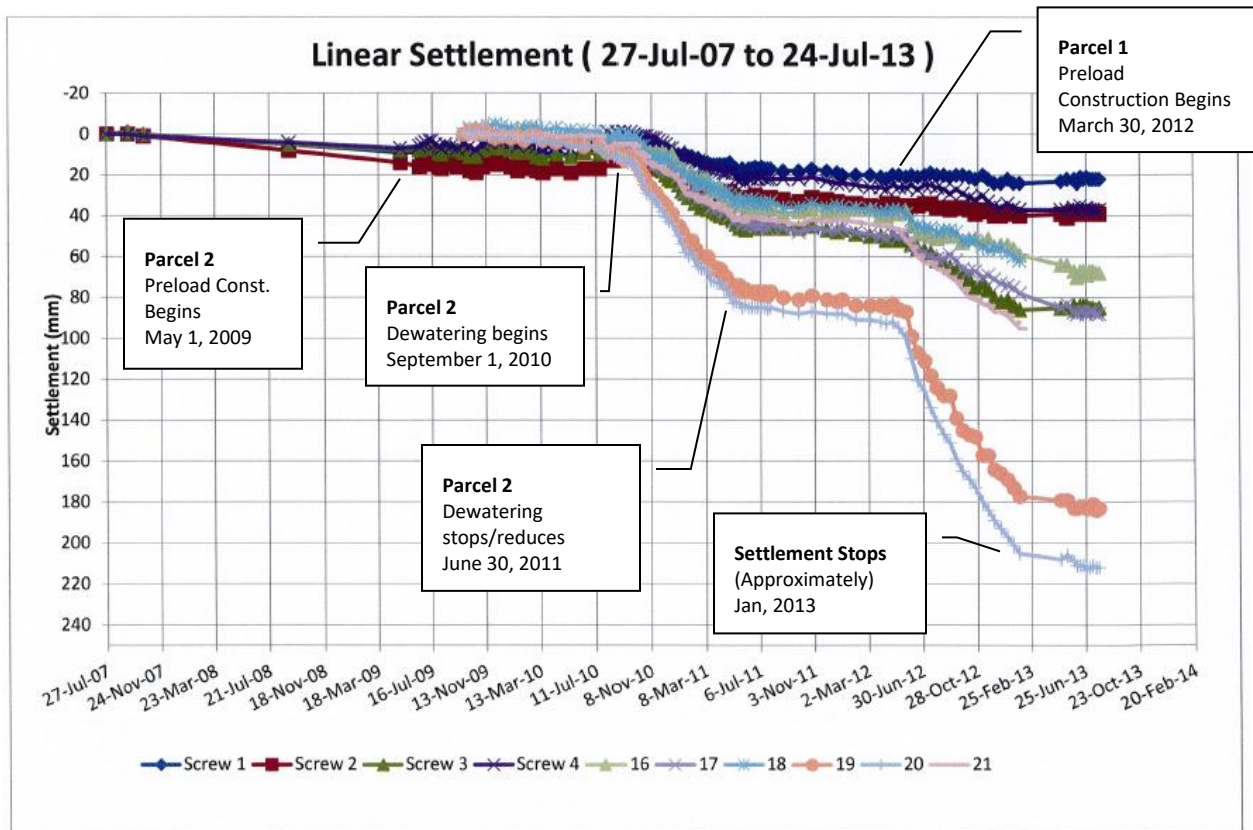Figure 8. Location of monitoring points (MPs) taken on the bridge and the adjacent grade.

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Figure 9. Graph showing settlement (mm) of No.2 Road Bridge based on MPs seen in Fig 6 with dewatering and preload dates of ASPAC parcels 1 and 2 (GeoPacific, 2013).

The observed subsidence motivated a structural inspection of the No.2 Road Bridge. MMM Group Ltd. (2013) found no deleterious effects of subsidence at the bridge's approaches, abutments or piers. In addition, the bridge was designed to compensate for some movement if such a scenario were to occur. However, MMM suggested the City implement a satellite monitoring program given the potential for future subsidence due to ongoing development in the adjacent area. Additionally, Span 1 was noted to move 50 mm south. The report attributes this to gravitational pull in the downhill direction. Span 1 was fixed onto Pier 1 and thus for Span 1 to move south Pier 1 would require southern movement as well, however Pier 1 was found to be stationary. This horizontal movement could possibly be associated with tensile strain from the vertical settlement that was found near the abutment of the bridge (Figure 4 and 7). This movement was still within the movement range of the bearings, but minor deficiencies needed to be rectified for the bridge (MMM Group Ltd., 2013).

5.2. ASPAC Parcel 8 (River Green) – Mitigation during Construction

5.2.1. Building Development

One way to mitigate subsidence directly underneath the development is to excavate and replace the clay crusts with sand fill prior to or post densification, this reduces differential

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subsidence as well. ASPAC Parcel 8 is located south of River Road and East of Hollybridge Way. GeoPacific (2010) found a near surface low-plastic silt and deep clayey silt that was considered compressible under increased ground stress from the development. These layers are not just prone to liquefaction, but also long term consolidation settlement. It was recommended the soil to be stripped first (of organic matter, topsoil, variable fill material etc.) and then filled with an "Engineered Fill" which is composed of compacted clean sand to sand and gravel. The site was also pre-loaded to compress the silt layer causing negligible subsidence of 10 mm per 5 m to nearby structures. This prevents long term settlement.

Two weeks prior to preloading, monitoring took place to gather baseline information. Monitoring of the preload along with adjacent structures, sidewalks and roads were done to recommend improvements, confirm the expected settlement and help modify the site preparation methodology, if needed. Initially, bi-weekly monitoring was required until settlement rates were established, following this, monitoring could be reduced to once per week.

Another means to mitigate settlement would be to reduce total net stress. The optimal approach to reduce the net stress is to construct the development further below grade. This allows for partial or total compensation of the new stress by way of soil removal.

Densification and soil strengthening can be done via vibro-replacement using stone columns, impact piers, or untreated timber piles. This was recommended to be carried out to a depth of 12 m in order to successfully prevent liquefaction and seismic induced ground motion (GeoPacific, 2010).

5.2.2. Off-Site Sanitary and Road Upgrades

The sanitary sewer is located east of Gilbert Road on River Road, and then south between 7771 and 7811 Alderbridge Way finally end at the intersection of Cedarbridge Way. Dewatering was required for sanitary sewer and road upgrades. Heavy seepage was expected due to high permeability of channel sands on portions of the site. To reduce seepage, large sump pumps were used instead of well-point systems (Geopacific, 2011). Water is allowed to seep into and collect at the bottom of the excavation in a sump before being pumped out. Sump pumps create a modest drawdown relative to deep well-point dewatering.

If left pumping for a long time, well-points have the potential to cause considerable water drawdown at significant distances away from the site and create off-site settlements. Seepage volumes can also be reduced by decreasing the length of the open excavation as large excavations tend to result in large seepage volumes. Well-points were only used initially to assist in establishing sump pumps after which they were decommissioned. To help reduce water drawdown and effective stress, sheet pile or jet grout shoring was recommended (GeoPacific, 2011).

5.3.   ASPAC Parcel 9 (River Green) – Seepage analysis (Impacts on Oval)

Golder Associates Ltd (2013) carried out an analysis on seepage control for Parcels 9 and Parcel 12 located east of the Oval, along Hollybridge Way and River Road. The report focused on deep soil-mix wall (DSM) to mitigate drawdown effects of Parcel 9 dewatering on the nearby Oval structure (Appendix B-3). DMS walls are often used as hydraulic barriers to minimize off-site water table drawdown. The walls are formed by mixing self-hardening slurry in-situ with the native soil.

5.3.1. Oval's Susceptibility to Subsidence

The Oval has narrow target settlement limits for both differential and total settlement (Thurber, 2006). The near-surface silt layer is weak and compressible making it prone to settlement, with deep inter-layered silt subject to long term secondary consolidation. In addition, groundwater levels are variable from elevation -0.8 to 0.4 m. Fluctuation of groundwater levels in the sand layer closely tracks tidal variation of the Fraser River. This response is more subdued in the silt due to its lower permeability (Thurber, 2006). Groundwater levels are marginally lower at the east end of the site due to localized drawdown experienced from a nearby ditch. Attention was directed to the Oval due to potential differential subsidence caused by the drawdown effects of dewatering ASPAC site 9. However, uniform preloading, densification and fill removal that took place on the Oval site prior to construction, mitigates subsidence.

5.3.2. Updated Seepage Analysis Assessment

An additional report in November assessed the impacts of temporary dewatering of Parcels 9 and 12 on the Oval area (Golder, 2013). A compressible surficial layer of silt underlain by a clean sand layer extended to moderate depths. While the north side faces minor impacts from the water drawdown; the west side could have varying drawdown up to 3 m at the nearest proximity of the Oval to the site (Appendix B-4 & 5) for tip resistance and soil behaviour type). However, this did not consider recharge effects from the nearby river or drainage canal.

Water drawdown could potentially increase effective stress up to 25 kPa, equivalent to 1.5 m of fill loading. Therefore, an effective preload of 1.5 m or more is needed to negate impacts of predicted sustained groundwater drawdown.

Another approach examined recharge of groundwater from the canal west of Hollybridge Way to potentially reduce impacts of groundwater drawdown. However, Golder (2013) stated that surficial fine grained deposits (poor permeability) likely extended below invert elevation of the canal, hindering flow rates into the underlying sand and thus preventing a reduction in the drawdown magnitude at the Oval.

Nonetheless, the piezometers along the north arm of the Fraser River found the same sand unit to be hydraulically connected to the river. Based on the hydraulic conductivity of the sand unit and distance from the river, it was determined that the river recharge was effective in

mitigating effects of drawdown from the ASPAC excavation sites. Thus, drawdown on Oval due to pumping at the adjacent ASPAC sites should be nominal.

Furthermore, the report concludes that DSM walls would result in significantly less drawdown in comparison to using well-point dewatering without a cut-off wall (Figure 10). A successful cut-off wall depends on; proper mixing to ensure homogeneity in the cement-soil mix, a contiguous barrier and uniform thickness of the wall.
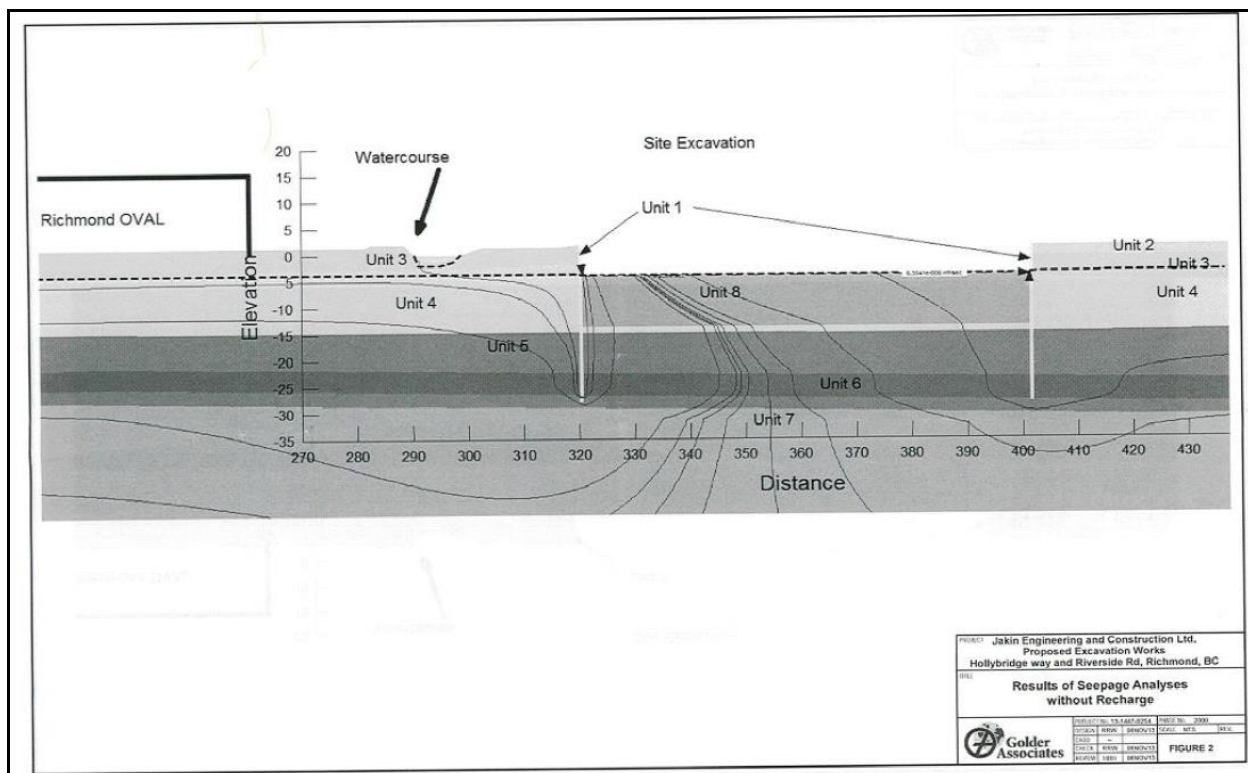

Figure 10 Unit 1 indicates the DSM walls on Parcel 9. The graph shows how the use of DSM walls would mitigate the drawdown effects on the surroudning area, minizing impacts on the Oval (Golder, 2013)

5.4. Phileo Development Corp. (Quintet Phase 2) – Accounting for Subsidence

The site is located at 5900 Minoru Bvld in the heart of the City Centre with potential to cause considerable offsite structural damage through improper dewatering. For Quintet, appropriate measures were taken to account for on and offsite subsidence. The soil report indicated primarily silty and clayey material to be present at various depths (Exp, 2012). Profiling the soil helps in the site preparation, prior to construction. Exp (2012) suggested fill procedures similar to ASPAC lot 8 (likely due to similarities in their soil profiles), to reduce post construction settlement. Densification was recommended to prevent post construction compaction of loose silt and sands, mitigating liquefaction and increase bearing capacity. To achieve soil densification, Vibro-replacement was suggested by constructing stone columns

deep in the soil using a down-hole vibrator to reinforce all soils and densify granular soils (Exp, 2012).

Table 2. Soil conditions described for varying depths in the Quintet area (Exp, 2012).

Unit	Thickness	Depth of Top of Layer	Description
A	0.5 to 1.0m	@ surface	**Asphalt overlying variable Fill & Buried Topsoil** Brown SILT some organics, trace gravel & sand *to* SAND trace silt *to* silty SAND & GRAVEL
B	1.6 to 2.5m	@ 0.5 to 1.0m	**Clay Crust** grey-brown clayey SILT coarsening to SILT trace clay, firm to soft, frequent sand lenses, wood debris, organics; 38% < MC < 65%
C	1.0 to 3.0m	@ 2.4 to 3.0m	**Silts** grey sandy SILT to silty SAND, occasional organics
D.	15m ±	@ 3.7 to 6.5m	**Sand** grey SAND trace to no silt, occasional silty sand layer in upper 5m of deposit, clay-silt interbeds present between 18-19m depth;
E	to bottom	@ 20m ±	**Clay Silt** Primarily consisting of clayey SILT inter-bedded with SILT trace clay, occasional to frequent inter-bedding of silty SAND to sandy SILT; interlayer thickness typically in order of 10 to 50mm 30% < MC < 35%

Dewatering was required to allow construction at depths. Well-points system was advised for deep construction along with sump pumps, similar to ASPAC 9 (Exp, 2012). A dewatering contractor was commissioned to design, build and review dewatering activities in order to manage subsidence on adjacent structures. The contractor developed a settlement pond and groundwater recharge system to reduce discharge flow rates. In addition, registered land surveyors would note settlement surveys of adjacent structures and properties. Settlement analysis indicated a long term settlement (30 years) of 150 to 200 mm. The anticipated long term differential settlement between high and low rise structures (75 to 100 mm) would not be significant enough to cause structural damage. Dewatering was well mediated in this case.

5.5.   Cressey Development Group (Cadence) – Raft Foundations

Cadence, located at 5640 HollyBridge Way, was another project where the depth of the development and dewatering could cause off-site water table reduction in the absence of a cut-off wall. GeoPacific (2014) recommended many of the aforementioned practices such as usage of sump pumps, preloading and densification. These practices would limit but not preclude the impacts of water table drawdown. Total anticipated settlement would be based on whether the excavation is phased and the presence of a cut-off wall.

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While the deeper silt sand to sand layers were managed with densification, the upper 3 to 5 m of weak and compressible silt/clay were deemed not suitable for support of the proposed tower. Thus, GeoPacific recommended construction of a raft foundation slightly below the weak upper silt/clay layer. GeoPacific's review (2014) indicated that only a moderate amount of reduction in the water table would be required in construction of the raft, leading to a relatively gradual off-site reduction in water table as well. Given the use of a sump pumps and no cut-off wall, the anticipated settlement 10 to 20 years after construction at the property line was predicted at approximately 50 mm, and 15 to 20 mm of settlement 4 to 5 m away from that point. This would not significantly impact surrounding structures.

5.5.1. Oval Parking Lot Subsidence

Cadence's dewatering began approximately April of 2015. Subsequently, piezometer recordings near the Oval found a 0.7 m decrease in the water table. Before dewatering started, the City of Richmond began monitoring the elevation at 4 points within the Oval parking lot (Appendix B-Fig 6). The overall average elevation of the 4 points decreased over the period of dewatering (Fig 11). This is possibly due to the groundwater drawdown compacting silt layers beneath the oval. Variation in elevation could represent periods of tidally controlled groundwater recharge from the Fraser River in conjunction with other construction activities in the vicinity (Appendix B-7). During 2015, preloading and dewatering activities were taking place at various sites within close proximity to the Oval, both of which could impact elevation.
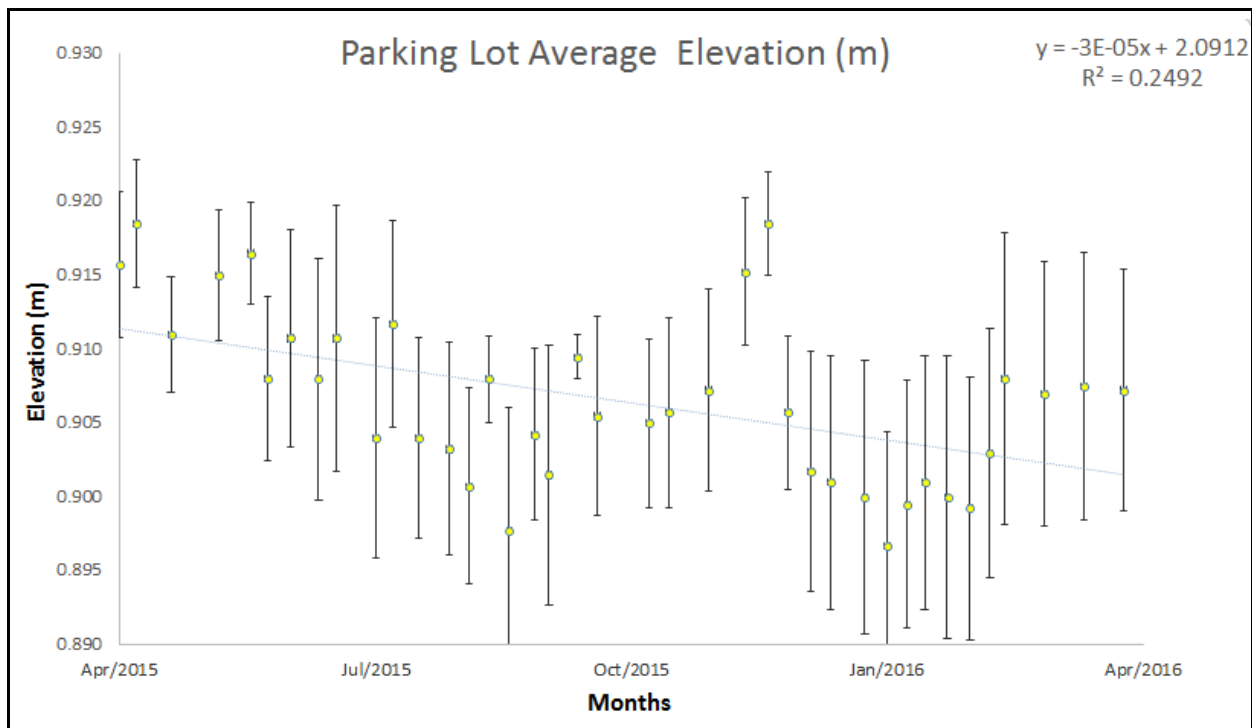

Figure 11. Average elevation (m) for the 4 MPs located in the Oval parking (Appendix B-6 for map) over the duration of dewatering activities in the area; *Data Sourced:* (City of Richmond, 2015).

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Comparing individual monitoring points in the parking lot revealed clear differences in the rates of elevation. MPs 2 and 4 have a much higher rate of settlement than MPs 1 and 3 (Figure 12). This is likely because points MPs 2 and 4 lie on a different horizontal plane than MPs 1 and 3 (Appendix B-6), with different soil conditions underneath. The 2006 Oval report (Thurber) explains this by stating that the transition zone in the soil varies laterally in terms of displaying properties of cohesive soil (silt) and granular soil (sand).

The high permeability of sandy soils causes rapid drainage of pore water, causing immediate settlement and consolidation. Thus, MPs 2 and 4 could be located on a sandy layer, whereas MPs 1 and 3 settle more gradually, likely being located on silt layered transition zone.
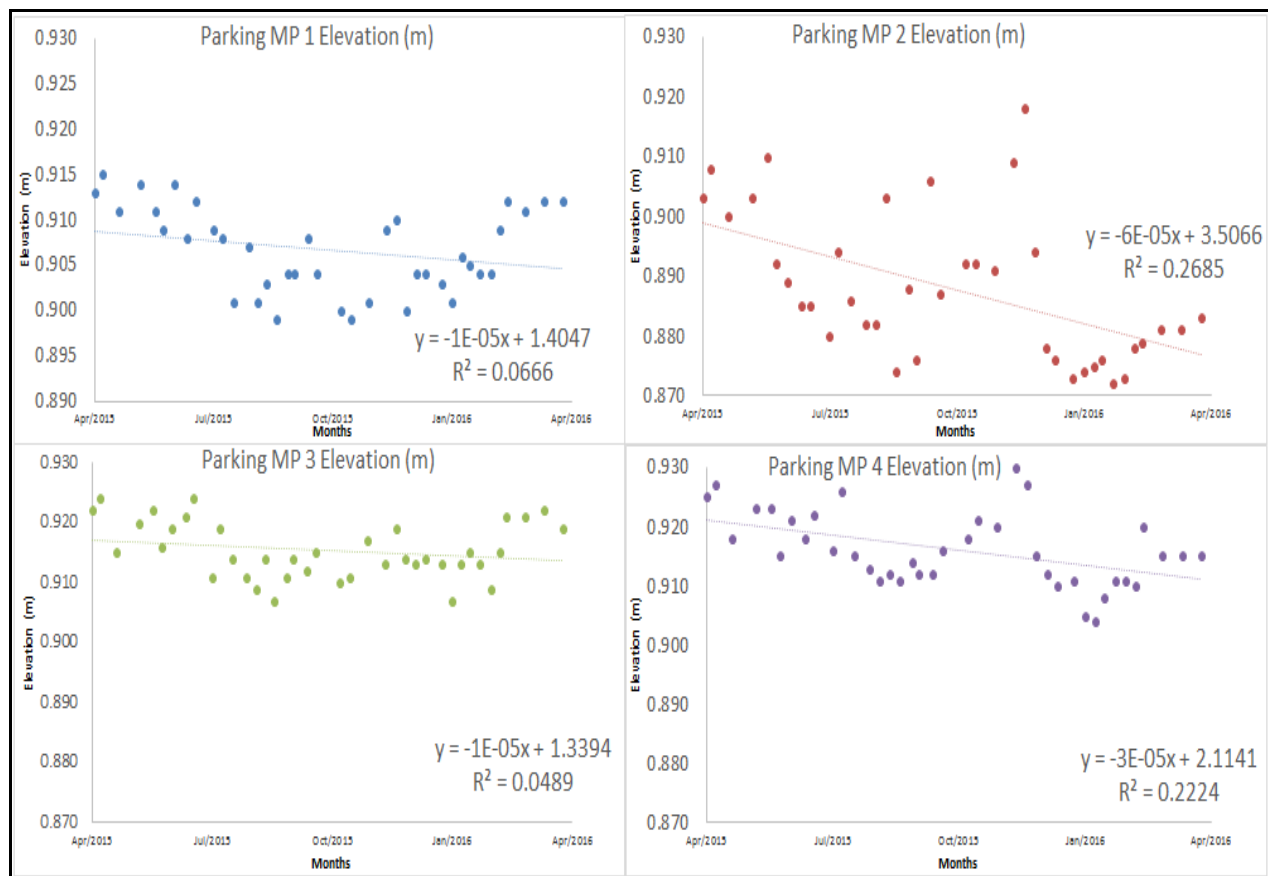

Figure 12. Graphs comparing rates of elevation decline amongst the 4 monitoring points located in the Oval parking lot. MPs 2 and 4 have higher rates of elevation decline due to the compressible soil underneath their horizontal positioning; *Data Sourced:* (City of Richmond, 2015).

5.6.   Richmond Agricultural Drainage and Irrigation

Water management on Richmond's agricultural land is noteworthy as it encompasses approximately 43% of the total land (City of Richmond, 2017). The East Richmond Agricultural Water Supply Study (2013) reviewed irrigation and drainage practices in relation to agriculture. Cranberry cultivation is the primary land use north of Highway 91 and requires intensive

ditches, reservoirs, control structures and pumping irrigation equipment for harvest and frost prevention purposes. Whereas, the south is mostly used to grow blueberries and vegetables. Irrigation is more complicated in the south due to high salinity levels, particularly in the late summer and early fall, when river flow levels are the lowest. Conductivity meters at the pump stations close water intake when salinity levels reach 700 micro/Siemens. High salinity causes reverse osmosis preventing plant root water uptake, stressing the plant. This leads some farmers to use alternate sources of City supplied potable water, or river water channeled into canals and supplied as per request from the City's Drainage Department (AECOM, 2013).

5.6.1. Factors Affecting Agricultural Land Subsidence

Shrinkage, compression and oxidation are processes that affect subsidence; as these processes are derived from lowering of the water table:

i.   Shrinkage is the reduction in volume caused by withdrawal of water from the upper soil layer;

ii.   Compression takes place in the deeper layers due to a loss of buoyant force of water; and;

iii. Microbial oxidation of soil organic matter under oxic conditions causes major peat loss post drainage. Oxidation is the major process and accounts for up to 85% of subsidence (Brouns et al, 2014).

5.6.2. Drainage

While the dikes maintain a barrier against flooding by the sea, drainage infrastructure is needed in Richmond to divert excess water through rainfall. Agricultural land in Richmond is drained via a network of sloughs, canals, ditches, flood boxes and pump stations (Appendix B-8 & 9). During low tide, water drains by gravity through canals, ditches and other water conveyance systems. However, during peak flows at high tide, pumping mechanisms are required to get water into the Fraser River. Richmond's farmers also have private drainage ditches as well as tile drains in their fields to regulate water and mitigate flooding. This water is also drained into the City's infrastructure (Agricultural Profile Report, 2012).

5.6.3. Irrigation

Irrigation is supplied through the same infrastructure used for drainage, consisting of seven pump stations along the North and South Arms of the Fraser River which have irrigation valves (Appendix B-8). Furthermore, three irrigation intake structures are located along the North Arm that intake water from the Fraser at high tide. Lastly, the No. 8 Road pump is modified to allow for intake at low tides. Distribution of all irrigation water to fields is done through drainage canals and ditches.

6. Measures and Recommendations - Richmond

As groundwater is often unseen, it is looked to as an inexhaustible resource. However, it is a vital reserve that is susceptible to pollution and over-extraction (Hori, 2016). In addition, settlement reduces hydraulic conductivity in soft layers of soil, decreasing groundwater recharge of deep aquifers (Chen et al, 2002). Thus, there is need for governance to ensure sustainable groundwater policies are put in place. The general consensus of experts, who study groundwater around the world, is that too little is known about the institution and policies that govern groundwater use. Regardless, new approaches to groundwater management have been developing over the past decade worldwide (Varady et al, 2013).

6.1. Discussion of Case Studies

Matt Kokan (2018) from GeoPacific stated that ASPAC Parcel 2 was the only case reviewed where an open dewatering system was used; subsequent ASPAC excavations used a full depth soil cut-off wall. Substantial off-site settlement on ASPAC 2 was caused due to the lack of a DSM wall and depth of dewatering. The groundwater drawdown depth led to a large horizontal area of influence causing consolidation due to increased effective stress. The other four cases demonstrated onsite settlement prevention through practices such as preloading, densification and use of engineering fill. These are generally standard practices used to ensure a stable foundation for the building. On a local scale, off-site settlement is best mitigated through use of sump pumps, DSM cut-off walls, sheet piles. Local off-site settlement better depicts the potential settlement that could occur if excessive drainage occurred on a city-wide scale Ultimately, both on and off-site settlement need to be monitored and accounted for.

Table 3 Table Summary of Richmond's case studies and how dewatering/construction processes were managed.

Case Study	Summary
ASPAC 2	• No use of DSM wall/sheet piles (hydraulic barrier) while dewatering at great depths for prolonged durations.

ASPAC 8	• Building development:
	  o Excavate and replace clay/silt with "Engineering Fill", removing compressible soil and filling it with material that meets specifications by an engineer for its given use
	  o Densification/soil strengthening via vibro-replacement using stone columns, impact piers or untreated timber piles
	  o Preload
	  o Monitoring prior to and post preload
	  o Reduce total net stress by building below grade (soil removal)
	• Sanitary and road:
	  o Sump pumps
	  o Sheet piles or jet grouting to reduce drawdown

	o Decrease length of open excavation
ASPAC 9 and Oval	• DSM (deep soil-mix) wall to reduce drawdown • Groundwater recharge via permeable sand layers
Phileo 2	• Dewatering contractor who developed settlement ponds and groundwater recharge systems
Cressey	• Construction of raft foundation right underneath upper layer as soil was not suitable for support

There are unique differences between the Richmond and the global case studies (Section 2.2). Richmond focuses primarily on various engineering practices to mitigate on/off-site settlement. The City corresponds with private consultants and reviews engineering procedures before proceeding with construction. On a city-wide scale, Richmond is in the early stages of dewatering based subsidence relative to countries in 2.2. Comparatively, the issues of groundwater extraction seen in section 2.2 are more severe, at a larger scale and over a longer period of time, requiring heavy government regulation.

6.2.   Existing Practices

Richmond liaises with consultants and registered professionals to establish case specific dewatering criteria. The City requires developers to hire a qualified environmental professional to assess dewatering and purification processes, along with engineering consultants to analyze discharge capacity and seepage issues. The City allows the developer's consultant to decide their mode of discharge, either through storm or sanitary infrastructure. However, discharge to the storm drainage system is widely chosen based on its capacity relative to the sanitary drainage system. In addition, discharge to the storm system only requires approval from the City of Richmond, whereas using the sanitary system requires approval from Metro Vancouver as well.

Upon choosing to drain discharge through the storm system, the consultant is responsible for suggesting a discharge location and designing a dewatering plan. The plan is then reviewed by the Engineering Planning and Sustainability Departments within the City. The Sustainability Department specifically focuses on groundwater quality via Bylaw #8475 (Pollution Prevention bylaw) preventing contamination of groundwater metals such as Fe and Mg into receiving water bodies.

During the construction, the City mandates proper monitoring by registered professionals to ensure enforcement of guidelines. In addition, if maximum instantaneous peak flow and daily discharge rates are exceeded and the storm system is surcharged, construction operations are halted. Given discharge of groundwater is planned for the sanitary system; Richmond requires developers to receive approval from the GVRD (Greater Vancouver Regional District) as they operate the sanitary pump stations within Richmond. Lastly, Bylaw #8475

states that all monitoring data pertaining to water quality and discharge flow rates must be handed over to the City if requested for.

6.3. Recommendations

Richmond is unique as dewatering occurs mainly to keep excavation sites dry whereas in most other cases (Section 2.2) groundwater extraction occurs on a much larger scale for its consumption and utility. However, Richmond can draw from strategies commonly applied in subsiding coastal regions. On a local scale for construction sites, the City could further enforce dewatering regulations by keeping record of data gathered from the consultants pertaining to daily dewatering rate, groundwater levels and elevation. The City could implement penalties to developers for exceeding allowable dewatering rates and allocate that money towards their Flood Protection plan.

6.3.1. Maintaining Richmond's Water table

The City could also emphasize the balance between inputs and outputs of water to better maintain water table levels (Appendix A-4.2). Richmond's dewatering occurs at a smaller scale with lesser impacts relative to those seen in section 2.2. Less water extracted makes it easier to compensate for the effects by promoting groundwater input/recharge through rainfall infiltration. The Tokyo Metropolitan Government has guidelines that require pumping facilities to ensure the same volume of water pumped is permeated back through the soil (Sato et al, 2006).

Richmond could mandate guidelines on rainwater permeation that request developers to install rainwater infiltration facilities, including an infiltration pit, increasing green space and minimizing pervious area. Additionally, Richmond can implement the Water Balance Model by requiring developers to install green infrastructure that would help meet pre-set performance targets allowing the property to capture, store and slowly release rainwater into the ground (Dnv.waterbalance-express.ca, 2018).

Most importantly, continuous subsidence monitoring is essential to substantiate subsidence prediction models in later stages: Global Position Systems, Optical Leveling, Laser Imaging Detection and Ranging (LIDAR) and Interferometric synthetic aperture radar (InSAR) satellite imagery are some examples. This should be used in conjunction with benchmarks and extensometers that can detect sources of subsidence based on changes in subsurface volume.

Similarly, monitoring of highest and lowest groundwater levels should take place on agricultural land to help predict peat land subsidence due to oxidation (Appendix A-3.3). Short and long term groundwater monitoring can help determine hydraulic properties of aquifers, changes in recharge and storage, effects of climatic variability etc. (Taylor et Alley 2001) (Appendix B-10).

Lastly, Richmond does not have specific criteria for maintaining groundwater levels at a given depth. The City can consider implementing a flexible and ridged range within which

groundwater levels are maintained. During dry seasons, a switch is made from the more flexible (larger) to the ridged (smaller) range, producing a surplus of water which can be stored and used later. This combination of water conservation and drainage practices, as seen in the Netherlands, most effectively minimizes dependencies on water while mitigating subsidence by maintaining a high groundwater table (Querner et al, 2012) (Appendix A-3.3).

6.4.   Additional Water Table Management Practices

Richmond could consider rainwater infiltration measures within their Flood Protection Guidelines and incentivize the public to implement various other practices that can help mitigate water table fluctuations and its impacts (Deltafact 2014):

- Building systems on private or public properties that store and recover water seasonally, buffering against groundwater fluctuations;
- Decrease paving and/pervious surface to increase water percolation;
- Avoid construction of crawl spaces;
- Enforce small scale storage and infiltration of water ex. cisterns, crates, swales, trees etc; and;
- Ribbed surface to temporarily retain excess water

7.   Conclusion

In Richmond's particular case, groundwater is instrumental in buffering against subsidence, and is not exploited as a resource. Rather, groundwater is predominantly extracted if construction processes are hindered, thus large scale extraction is unlikely. Currently, the City manages for local neighbourhood scale subsidence primarily through engineering practices, reviewed in correspondence with private consultants. In some cases, the city monitors groundwater levels as a proxy for subsidence. Environmental safety is ensured by the Pollution Protection Bylaw which encompasses dewatering rates, modes of discharge and purification standards.

Relative to regions discussed (Section 2.2); Richmond is in its early stages of dewatering based impacts and can take any necessary measures to maintain a high groundwater level. The City could seek out two different strategies for subsidence management, mitigation and adaptation. A combination of both strategies is ideal.

Mitigation can be used for human induced subsidence. Measures include: regulating groundwater extraction, artificially recharging aquifers, raising phreatic water levels in organically rich soils and building with light material to decrease load on soft soils. However, in the case these cannot be implemented, due to financial or technical difficulties, adaptation measures can be implemented (Erkens et al, 2015).

Adaptation measures, against inundation as a result of subsidence include: reinforcing dikes, constructing on mounds or piles, conducting spatial planning to build on elevated areas. In regards to structural damage, flexible pipes/cables, better foundation for structures and spatial planning based on support soil type can be used (Erkens et al, 2015).

For Richmond, subsidence based on water table drawdown due to large scale groundwater extraction/drainage is not as pertinent. Instead, city-wide subsidence should be examined based on anticipated construction projects (and urbanization rates) and peatland oxidation. Accounting for subsidence could help better predict relative sea-level rise. A robust flood protection plan and water table management will make the City more resilient towards the compounding effects of subsidence, on an already rising sea level.

8.   Appendix A.

1.0 China

The primary cause of land subsidence in China was due to groundwater withdrawal resultant of rapid economic development (Xue et al, 2005). Major Coastal deltaic regions such as Shanghai and Suzhou have taken rigorous measures to restrict exploitation of groundwater.

1.1 Shanghai – Managing groundwater levels by Re-pressuring

Aquifer re-pressuring is an expensive but effective means to decelerate or halt subsidence. Subsidence was first recorded in Shanghai in 1921; by 1965 the maximum cumulative subsidence was 2.63 m. To reverse impacts of dewatering, river water was injected through wells to recharge the principal aquifers circa 1964. By 1966 more than 200 wells had joined the recharge mission causing an instantaneous cessation of subsidence as seen from the recorded benchmarks. A slight rebound of 34 mm in the benchmarks from 1966 to 1976 also occurred.

Chai et al (2004) further elaborates with pumping volumes (Table 2). Aquifer re-pressuring began in 1966, in conjunction net groundwater pumped decreased by half. Subsequently, settlement rates drastically decreased from 60 to 2 mm/year. This allowed for continual pumping of groundwater while still keeping subsidence subdued.

Table 4. A positive relationship is shown between groundwater pumping and subsidence in Shanghai. Settlement rate decreases when recharge occurs in 1966 (Chai et al, 2004).

No.	Period	Average settlement rate: mm/yr	Area of settlement > 500 mm: km²	Average amount of groundwater pumping: 10^6 m³/yr	Average amount of recharge to groundwater: 10^6 m³/yr	Net groundwater pumped: 10^6 m³/yr
1	1921–1948	23	19·3	9	–*	9
2	1949–1956	43	92·8	140	–	140
3	1957–1961	100		200	–	200
4	1962–1965	60		156	–	156
5	1966–1989	2		89	17	72
6	1990–2001	16	Expanded to suburban area	127	14	113

* No data recorded. In practice it can be considered as zero recharge rate.

1.2 Shanghai – Managing Subsidence through Discharge Capacity & Soil Texture guidelines.

A report showing the soil profile with physical and mechanical properties was created by the Shanghai's geological office in 1976. The report is referenced to form a guideline for the aquifer's soil type, depth, thickness and specific discharge capacity (SDC) (Table 3). Following the guideline helps prevent major subsidence.

Table 5. Example of a SDC guideline which is used to manage subsidence by regulating discharge rates (Chai et al, 2014).

Aquifer	Soil type	Depth: m	Thickness: m	SDC: $m^3/h\,m$	Remarks
I	Fine sand	~35	0−20	1·5−2·0	Connected to aquifer II at some places
II	Sand, cobble and gravel	60−75	20−30	10−30	
III	Coarse sand	90−130	10−50	10−20	
IV	Fluvial sand	160−180	20−70	20−30	
V	Fluvial sand	~250	15−90	0·5−5·0	

1.3 Suzhou – Managing groundwater levels by Local Government

Another study by Shi et al (2012) examines Suzhou China, a city west of Shanghai. In Suzhou, measures were taken by the local government to lessen the impacts of the increased pumping. Rapid development of the economy led to groundwater exploitations, which caused heavy pollution of surface water circa 1990. The local government started to put restrictions on groundwater exploitation in 1997, allowing for the piezometric level to gradually rise (Fig 10), however areas of land subsidence still extended. A progressive law to prohibit deep groundwater exploitation was put in place in 2000, promoting rapid recover of groundwater levels (Fig 10) but a regional cone of depression had already formed. Monitoring networks were set up in 2003 with 8 extensometer groups and about 100 observation wells. Finally, in 2005 deep groundwater extraction was banned altogether. Groundwater level rose rapidly soon after with annual land subsidence rates controlled at 10 mm annually.
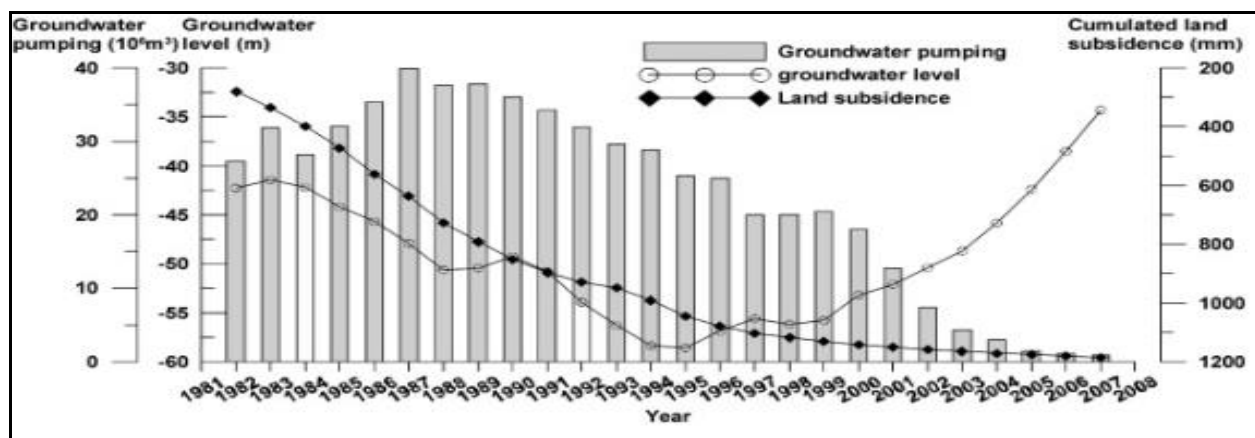

Figure 13. History of groundwater levels, pumping rates and land subsidence in Suzhou's II aquifer (main pumping aquifer). Land subsidence decreases as groundwater pumping volumes decrease and groundwater levels increase (Shi et al 2012).

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2.0 Background – Agricultural/Peat Land Subsidence

As aforementioned, most of eastern Richmond is covered in peat; this entails different factors of subsidence that can potentially be influenced by climate change. Netherlands and Malaysia will be examined as they are coastal regions covered in peat at risk of flooding, similar to Richmond.

Globally, peat soils cover more than 420 million ha (Wösten et al, 1997). Peat ecosystems are fragile with vital biological and hydrological functions. These saturated peat lands are reclaimed for agriculture through drainage practices to optimize oxygen and nutrient availability.

Shrinkage, compression and oxidation are processes that affect subsidence; however, these processes are derived from lowering of the water table. Based water levels, draining deep within the soil profile leads to rapid subsidence of ≈ 2 cm/year (Brouns et al, 2014). Subsidence is irreversible and can only be halted if the peat is re-saturated again.

The rate of subsidence heavily depends on factors such as type of peat (clay covers), rate of decomposition, density and thickness of peat layers, climate, and drainage depth. Land use history is also an important factor; use of heavy machinery can compact the land leaving less room for subsidence. Fertilizer application also changes biological activity in peat soils and contributes to subsidence. Lastly, burning for land clearing and removal of crop residues also increases subsidence.

2.0 Malaysia

Wösten et al (1997) conducted a study showing three different relationships: (i) Peat subsidence and its relation to time, (ii) Peat subsidence versus water management and (iii) Oxidation and shrinkage components of total subsidence. The approach recommended by the study is to switch from a system that exclusively drains excess water to one that combines drainage and conservation, in order to maintain a high groundwater level and reduce subsidence.

2.1 Subsidence vs. Time

Initially, subsidence rates were recorded at 4.6 cm/year but decreased with time to 2.0 cm/year (Fig 11). This decrease is expected as the prevailing groundwater level is establishing a new balance with the depth of unsaturated peat soils. The establishment of the new balance is slowed down as groundwater levels remain constant. Additionally, the reduced thickness of unsaturated peat layers led to wetter conditions thus reducing oxidation. Furthermore, easily decomposable organic matter is oxidized leaving behind more resilient material.

At an average subsidence rate of 2 cm/year shallow peat with a depth of 1.5 m will disappear in 75 years, converting 17% of the total peat soil (95,000 ha) into mineral soils (215 ha loss). Similarly, a peat with 3 m depth will dissipate in 150, a 40% loss of total peat area. Lastly, it would take 225 years for deep peat soils of 4.5 m depth to disappear (Wösten et al, 1997).
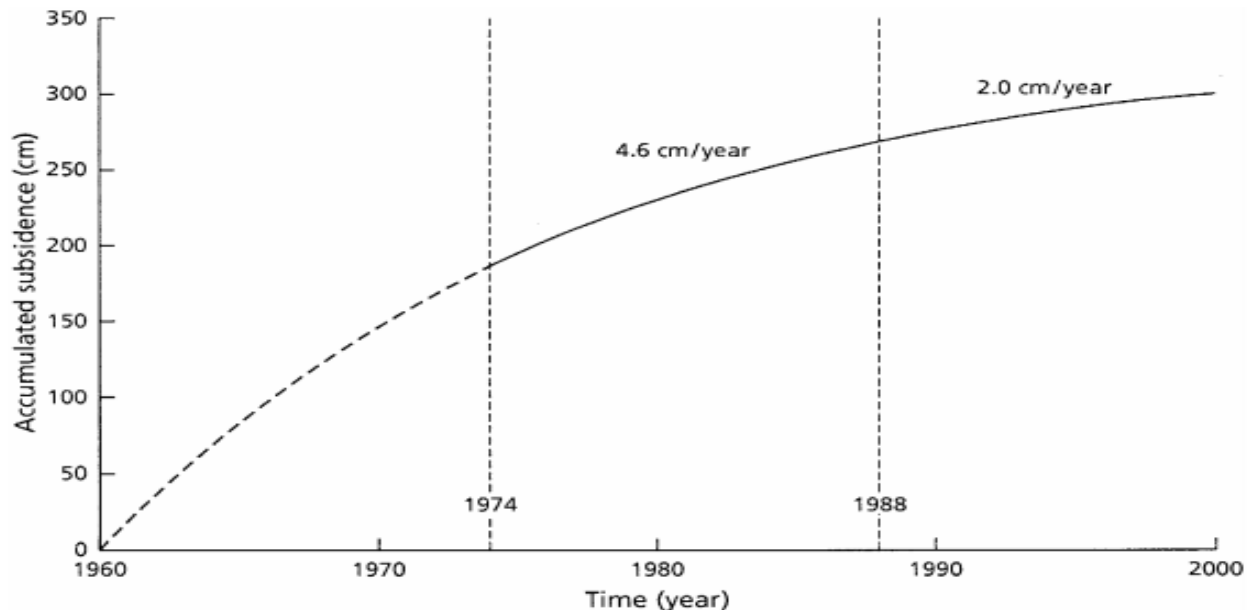

Figure 14. Dotted line is reconstructed data which was unavailable for the time period. Graph depicts a decreasing average subsidence rate over time in the Malaysia study area (Wösten et al, 1997).

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2.2 Subsidence vs. Groundwater level

Subsidence increases as groundwater level decreases. With each 10 cm decrease in groundwater level, subsidence rates increased by 0.7 cm/year. However, this relation decreases with time. Initially, the increase in subsidence rate was 0.9 cm/year per 10 cm lowering in groundwater level, overtime it decreased to 0.4 cm/year (Wösten et al, 1997).

Results from the study were compared to findings from other areas of the world showing long-term average relationships between subsidence and groundwater table management. As displayed in Figure 12, there is an increase in subsidence at all groundwater levels from temperate to tropical parts of the world, this is due to an increase in soil temperature and absence of winter-summer periodicity. Thus, an optimal groundwater level must be maintained in order to mediate land subsidence.
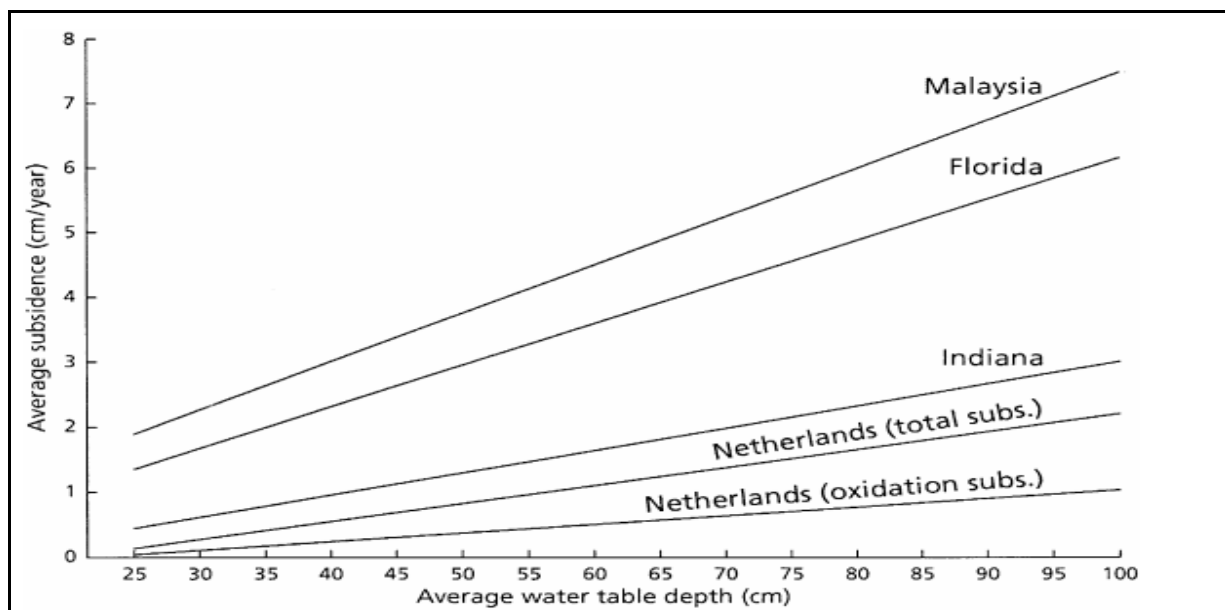
Figure 15. The different extents of the positive relationship between subsidence rates and groundwater levels, compared in different parts of the world (Wösten et al, 1997).

2.3 Portion of oxidation and shrinkage component of total subsidence

Oxidation of peat contributes to greenhouse effects. The average for multiple sites in the Malaysia case study found, 60% of the total subsidence (16.5 cm over 5 years) was a result of oxidation (decomposition of organic matter causing CO2 release), with the remainder 40% due to shrinkage (loss of water leading to increased bulk density). The oxidation effect was strongest in the peat layers between 10 cm below ground level and 10 to 20 cm above the groundwater level. Based on peat's bulk density of 0.1 g/cm3, 12 tonnes of peat is decomposed per ha/year. This amounts to 26.5 tonnes of CO2 production ha/year.

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3.0 Netherlands

Peatland ecosystems once encompassed 40% of the Dutch land surface but are now reduced to < 10 % due to drainage since the 11th century (Brouns et al, 2014). This subsidence was largely due to decreases in the water table. In Netherlands, damage from peat subsidence costs every resident of the country approximately €250 a year (Boersma, 2015). For example, sewers need to be replaced twice as often in municipalities where the soil is not soft. Building, roads, pavements and fencing also incur damages. Potential underground electricity networks and gas pipelines can also break. Hence, less money is available for recreational projects or green infrastructure.

3.1 Climate change and Impacts of Peat based subsidence

Peat areas are projected to subside by 40 to 60 cm between 1999 and 2050 due to climate change. On average, temperatures are to rise by 1 to 2 C during 1990 and 2050 (Brouns et al, 2014). The Netherlands Royal Meteorological Institute predicts drier summers due to atmospheric circulation. Drier summers, in conjunction with the predicted rise in temperature, changes in precipitation, and increased frequency of extreme events, will likely impact organic matter decomposition. Literature shows that as temperature increases, organic matter decomposition increases. A 10 C increase in temperature causes decomposition rates of peat to triple (Berglund et al. 2008; Dorrepaal et al. 2009). Furthermore, the drier summers could enhance long-term decomposition rates.

The compounding effects of increasing temperatures and decreasing groundwater levels, during the summer in peat meadows, can lead to a 70 % increase in subsidence (Brouns et al, 2014). Increased subsidence rates would lower soil levels drastically. A lack of management for these peat areas can cause damages to building foundations, desiccation of nature reserves, greenhouse gas emissions, increased costs for water management and infrastructural maintenance, deterioration of surface water quality and loss of the characteristic landscape (Brouns et al, 2014).

3.2 Groundwater level and Subsidence Monitoring

A long term study by Nieuwenhuis and Schokking (1997) shows the relationship between subsidence and drainage depth in peat meadows. The average land subsidence rate was 5 mm/year from 1920 to 1960, later increasing to 12 mm/year from 1960 to 1995. This was due to an increase in the vertical distance between the ground surface and ditch water level.

The subsidence can be further compounded by climate change due to disturbances in groundwater levels. Short term climate change was found to have a big impact; drier years had relatively faster rates of subsidence compared to wetter years. Interestingly, surface levels rose in some cases for wetter years, showing that shrinkage and compression are partially reversible. This is consistent with previous findings suggesting that subsidence rates are highest

immediately after reclamation, followed by a gradual leveling out thereafter. Factors responsible for this early reaction to water level drawdown are consolidation and degradation of easily degradable organic components.

In order to better predict subsidence levels, Netherlands monitors its groundwater levels twice a month. The three highest (HG3) and lowest (LG3) groundwater levels are measured annually and averaged. Then the mean highest and lowest groundwater levels (MHW and MLW respectively) are determined by averaging the HG3 and LG3 for at least 8 years. MLW has the best correlation with soil subsidence rates as it indicates the thickness of the peat that is being oxygenated during the summer. The lowest groundwater levels occur in August and September corresponding with the highest soil temperature enabling maximum oxidation during these months. Even though MLW has the best correlation to subsidence rates, Karlijn et al (2015) uses average GDL in workshops with local stakeholders. GDL is easier to implement and interpret, and provides reliable estimates similar to using MLW.

3.3 Optimal combination of drains and water management

Querner et al (2012) looked at controlling subsidence and minimising water supply in dry periods via subsurface drains and water level control strategies, i.e. pumping water in or out of polders based on set water levels. Multiple scenarios were evaluated; (i) forming wetter conditions through higher surface water levels (ii) absence and presence of subsurface drains (iii) an optimal scenario where the ideal water level management practice is used in combination with subsurface drains.

The optimal strategy is a combination of subsurface drains with 2 water table management strategies (Regular and Flexible) that switch between one another based on the climate. Water input and output is channelled via the drains. For dry periods, the regular strategy was used where the variation in the water level is rigid at ±0.02 m. During rainfall, flexible strategy is used where the water level variation was permitted to ±0.1 m. This optimal strategy was evaluated in a scenario where target surface water level remained at a depth of 0.5 m throughout the year.

When a dry period occurs, a switch is made from flexible to regular, thus reducing the fluctuation to 2 cm. This switch causes an excess of water in the system between 2 and 10 cm above the target level. Instead of pumping out surplus water, it is stored in the system. If the water level drops more than 2 cm below the target level, the stored water is instantly supplied to counteract the loss. This reduces dependencies on supplementary water. However, if the switch from flexible to regular is not fast enough, groundwater levels can reach a critical low causing subsidence. Comparing the different strategies, the optimal strategy leads to less subsidence and while requiring less water input (Table 4).

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4.0 Tokyo

Tokyo faces similar problems to Richmond in terms of inundation from nearby water bodies and demonstrates effective management of subsidence through policy. Prolonged subsidence began in the Koto district in the eastern part of Tokyo circa 1920. Excessive withdrawal of groundwater for industrial use caused subsidence and a gradual decline of the artesian head. The artesian head in the confined aquifer declined to as much as 60 m below sea level in 1965 (Poland et al, 1984). Consequently, 80 km² of land had sunk below mean high-tide level by 1969 in eastern Tokyo. The lowest ground was about 2.3 m below sea level with 2 million people living in this area. Many protective measures were taken such as; raising banks of through-flowing rivers, building walls around areas below high-tide level, and water gates to prevent water entering depressed areas. However, upon regulating pumping depths, drilling of new wells and industrial groundwater extraction, pumping decreased by half and subsidence seized by 1970 (Okada, 2017).
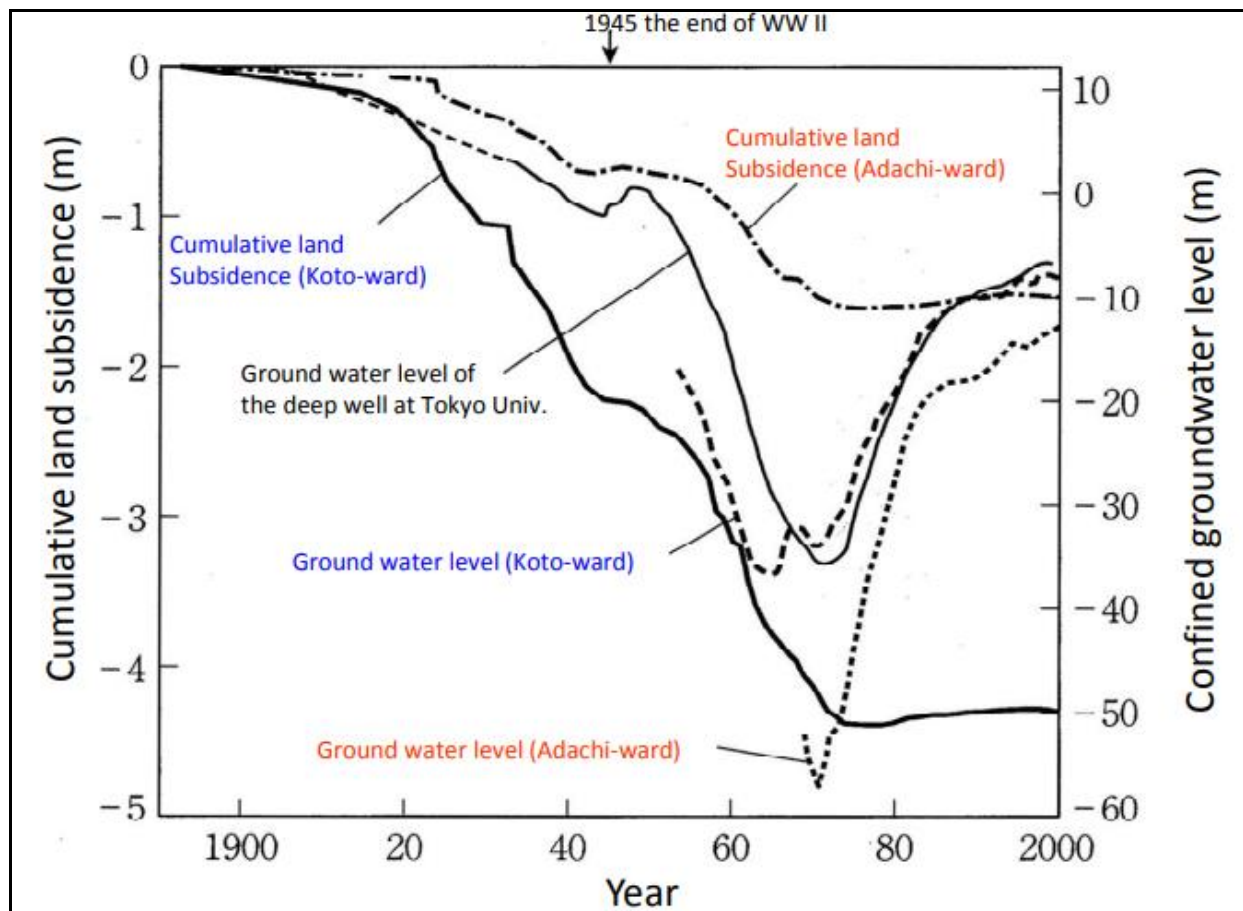
Figure 16. Groundwater level recover and land subsidence plateauing in different ward in Tokyo due to policy implementation in the 1970s (Okada, 2017).

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4.1 Governance through Local Ordinances

Unlike the City of Richmond that receives its water from Metro Vancouver, Tokyo requires pumping of 550,000 m^3 of groundwater daily, for municipal and industrial use (Sato et al, 2006). Thus, the local government is required to conserve its groundwater independently by implementing ordinances. The Tokyo Metropolitan Government (TMG) introduced pumping regulations for groundwater extraction that were specifically aimed towards the structural design of the pumping facilities. The regulations aimed at banning new and existing wells that failed to meet requirements regarding the cross-sectional area of the outlet/strainer depth in particular zones. The local ordinance prevents installation of such wells while regulating daily discharge rates of existing wells. However, pumping efficiency increased over time causing small wells to bypass this. Therefore, in 2004, the TMG became stricter by mandating that all small wells, using pumps with an output of over 300 watts, were to report pumpage volumes once a year (Sato, 2006).

4.2 Rainwater Infiltration Measures

In conjunction with dewatering restrictions, Tokyo emphasizes groundwater recharge as a means to maintain equilibrium (Table 5). Undeveloped land allows for a large portion of rainwater to infiltrate and percolate through the soil and recharge groundwater. While Tokyo's farmland is sinking, buildings cover 80% of Tokyo's surface, causing an increase in impervious surface and runoff, while decreasing groundwater recharge (Sato et al, 2006). Consequently, the TMG created guidelines on rainwater permeation. All installers of groundwater pumping facilities are requested to simultaneously install rainwater infiltration facilities (infiltration pits), to ensure balance in extraction and infiltration volumes.

In addition, TMG promotes the importance of rainwater to its citizens. Building owners are also required to submit proposals on environmental consideration and plans, on the use of reclaimed wastewater or rainwater infiltration. Overall, the TMG plans to expand water-permeable pavement projects, incentivize public facilities to increase rain infiltration, and work on measures within the framework of their urban development project and flood control plan (Sato et al, 2006).
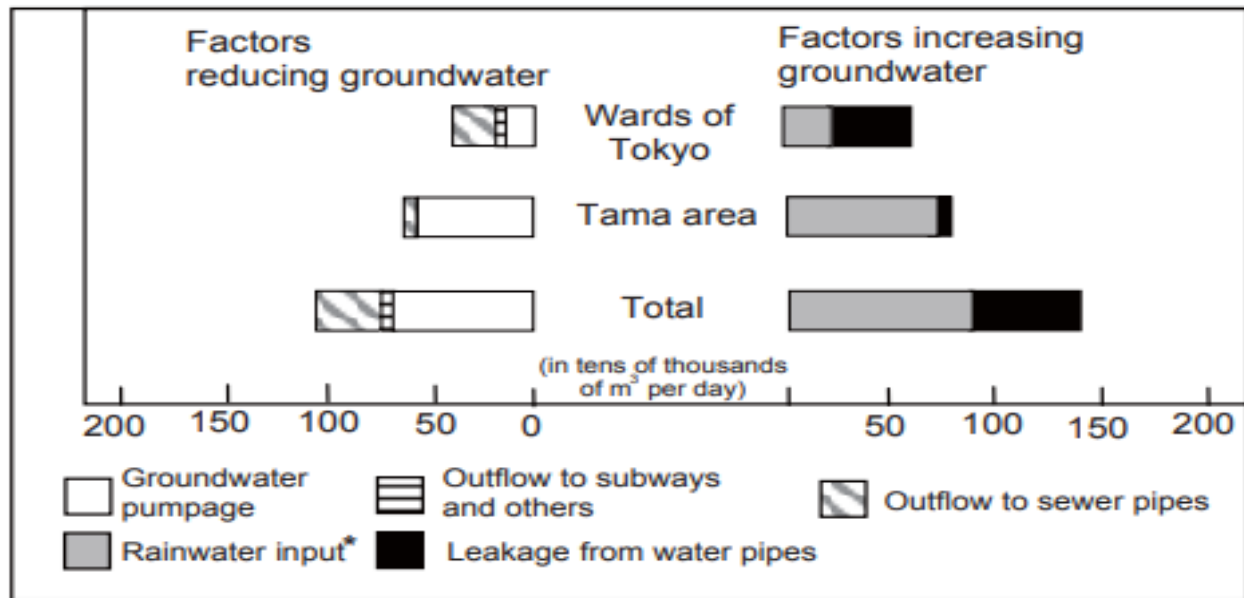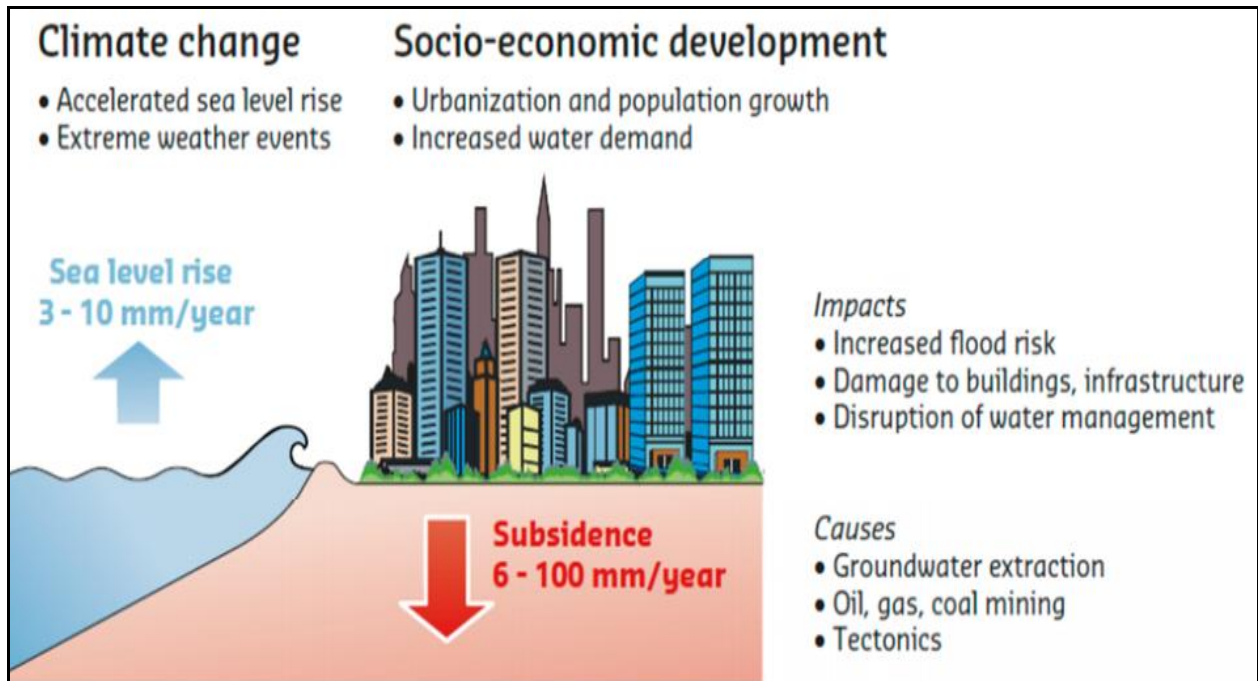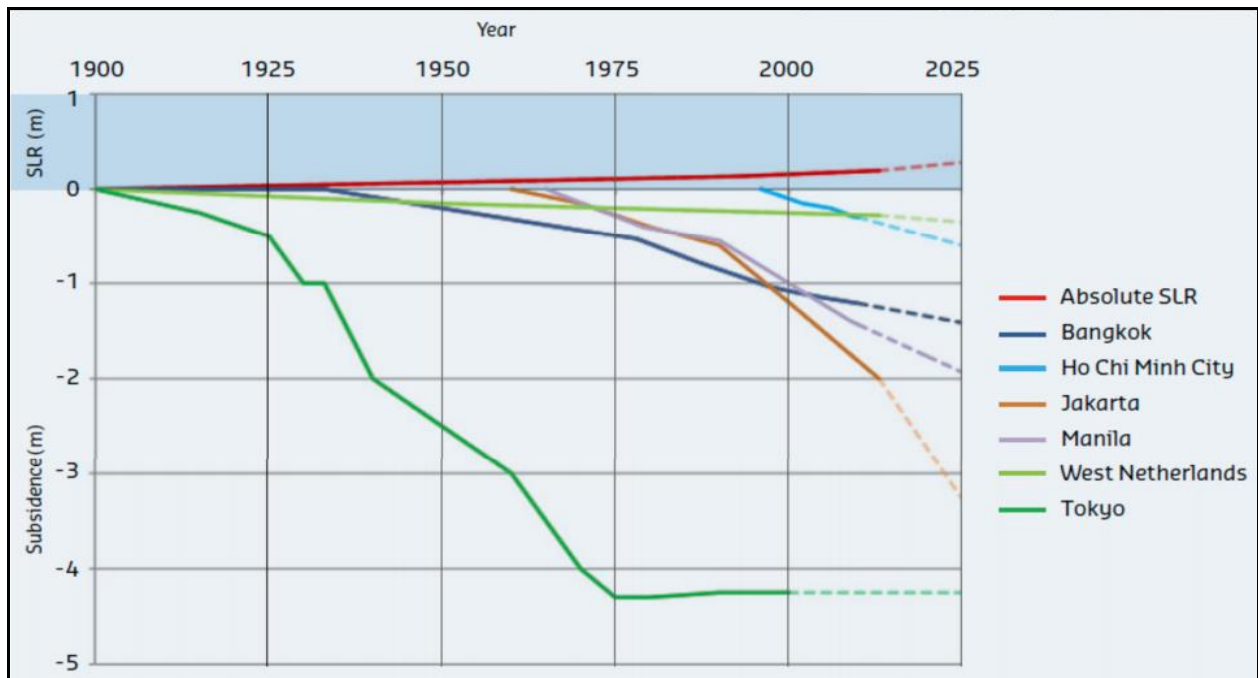
Figure 17. Balancing groundwater inputs and outputs through water infiltration (Sato et al, 2006).
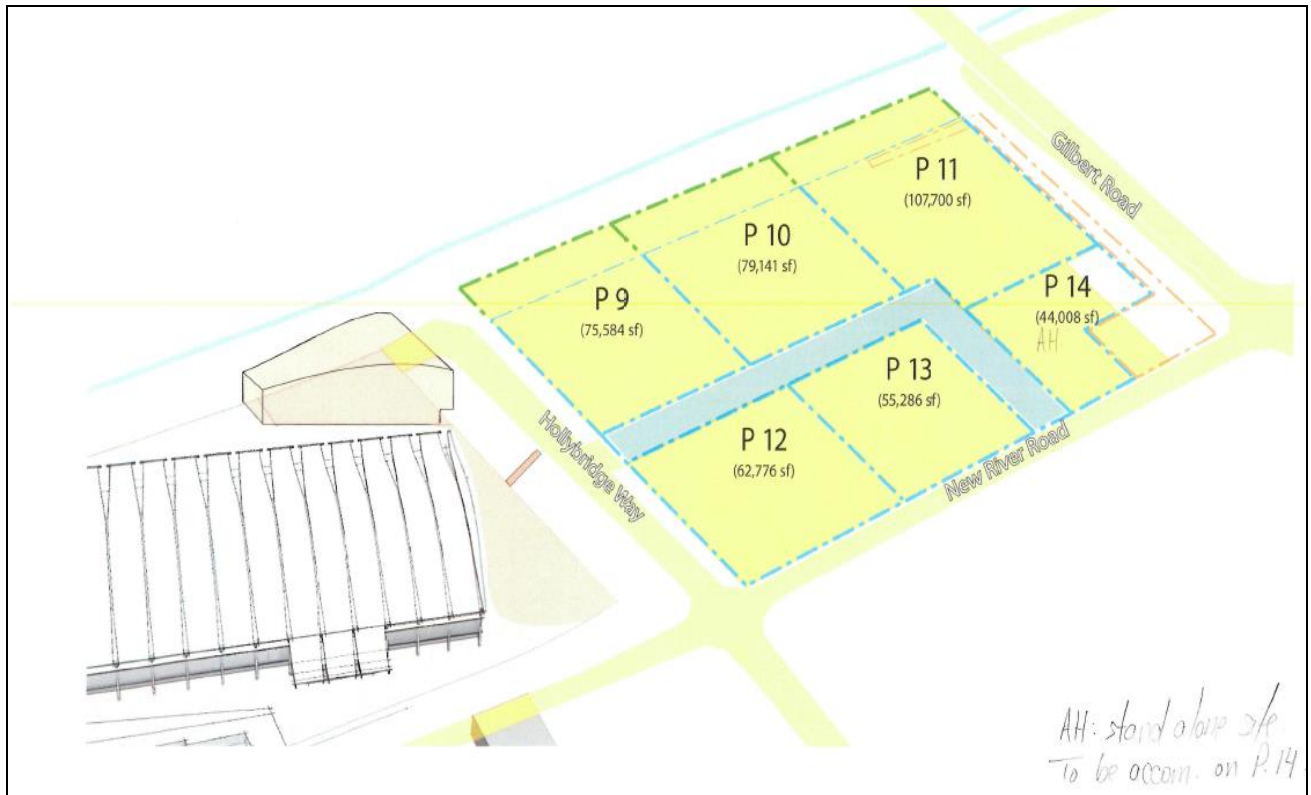
9.   Appendix B.

B- 1. Factors involved in landsubsidence in coastal regions. Subsidence can outscale global absolute sea-level rise by a factor of 10 (Erkens et al, 2015).
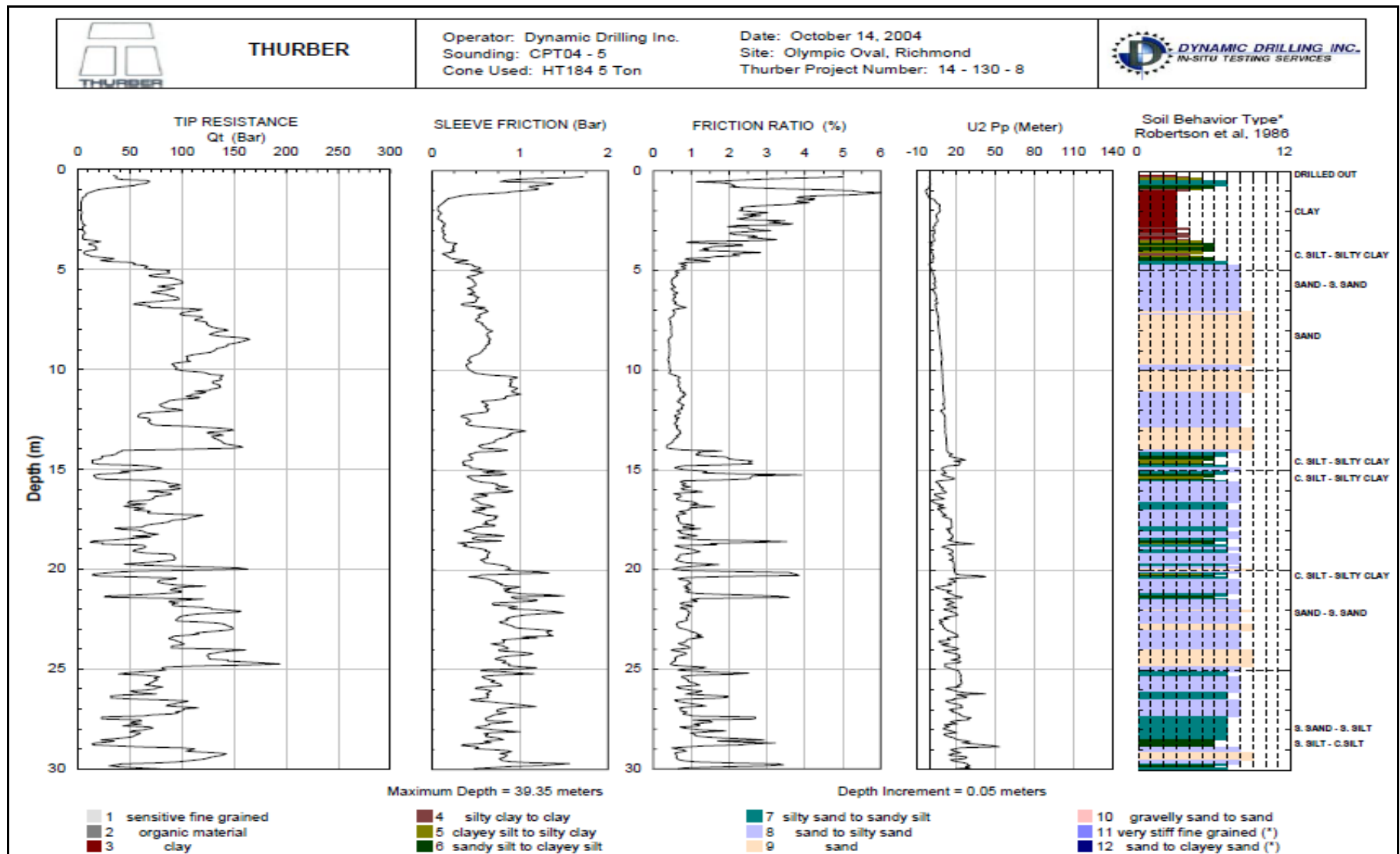

B- 2 History of subsidence in coastal cities around the world with absoulute sea level rise as a reference (Erkens et al, 2015).

B- 3 Map with designated ASPAC parcels showing Parcel 9's close proximity to the Oval raising concern for subsidence (City of Richmond, 2018).
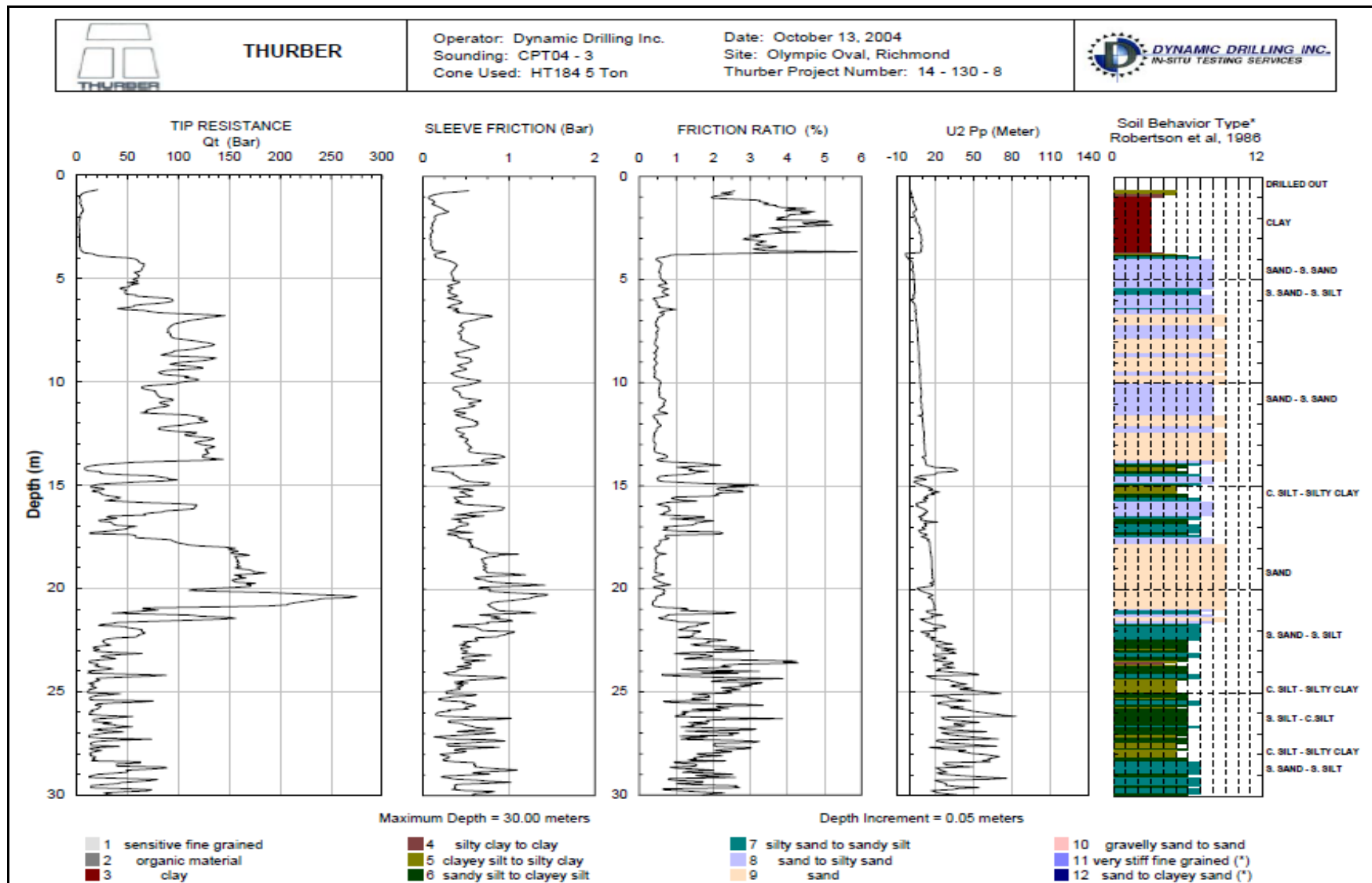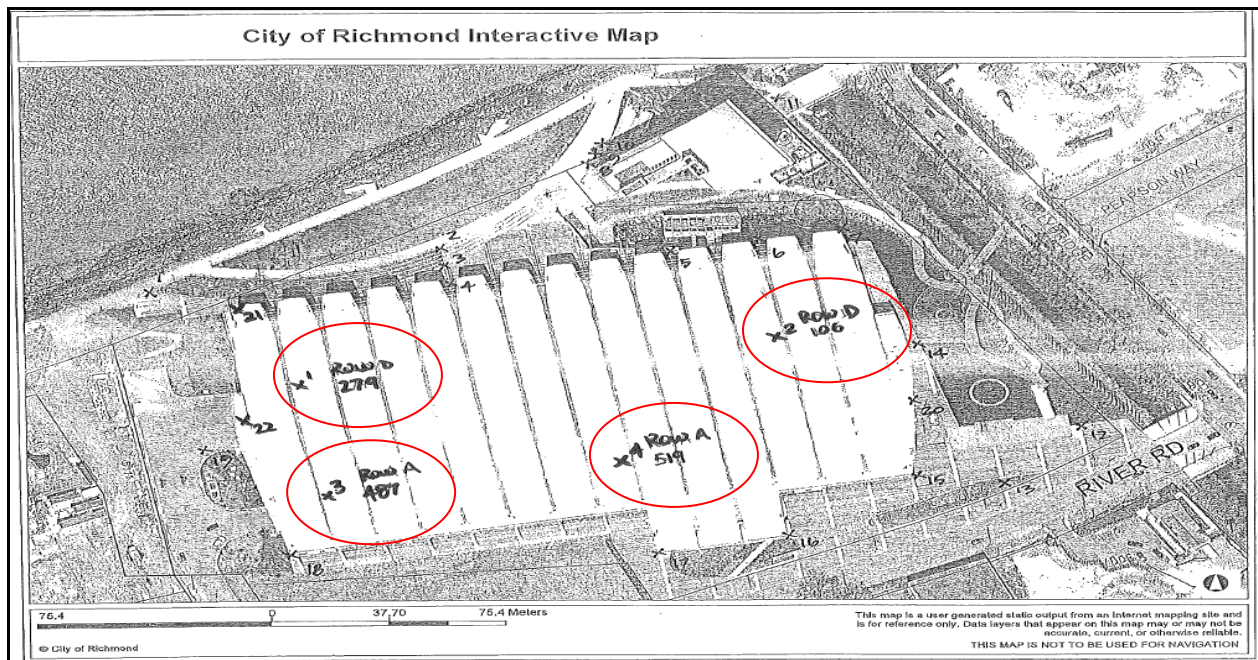
B- 4 Tip resistance and soil behaviour gathered from samples on the west side of Oval (Thurber, 2006).
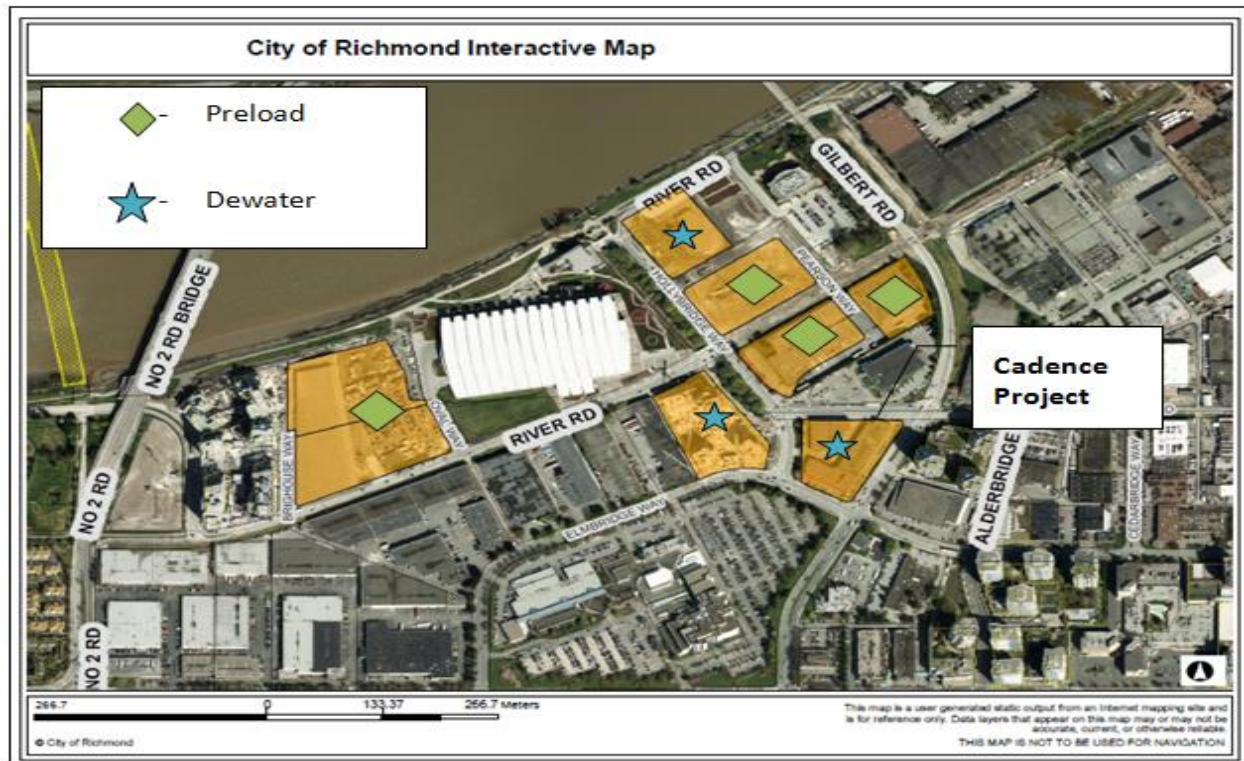
B- 5 Tip resistance and soil behaviour from north side of Oval.
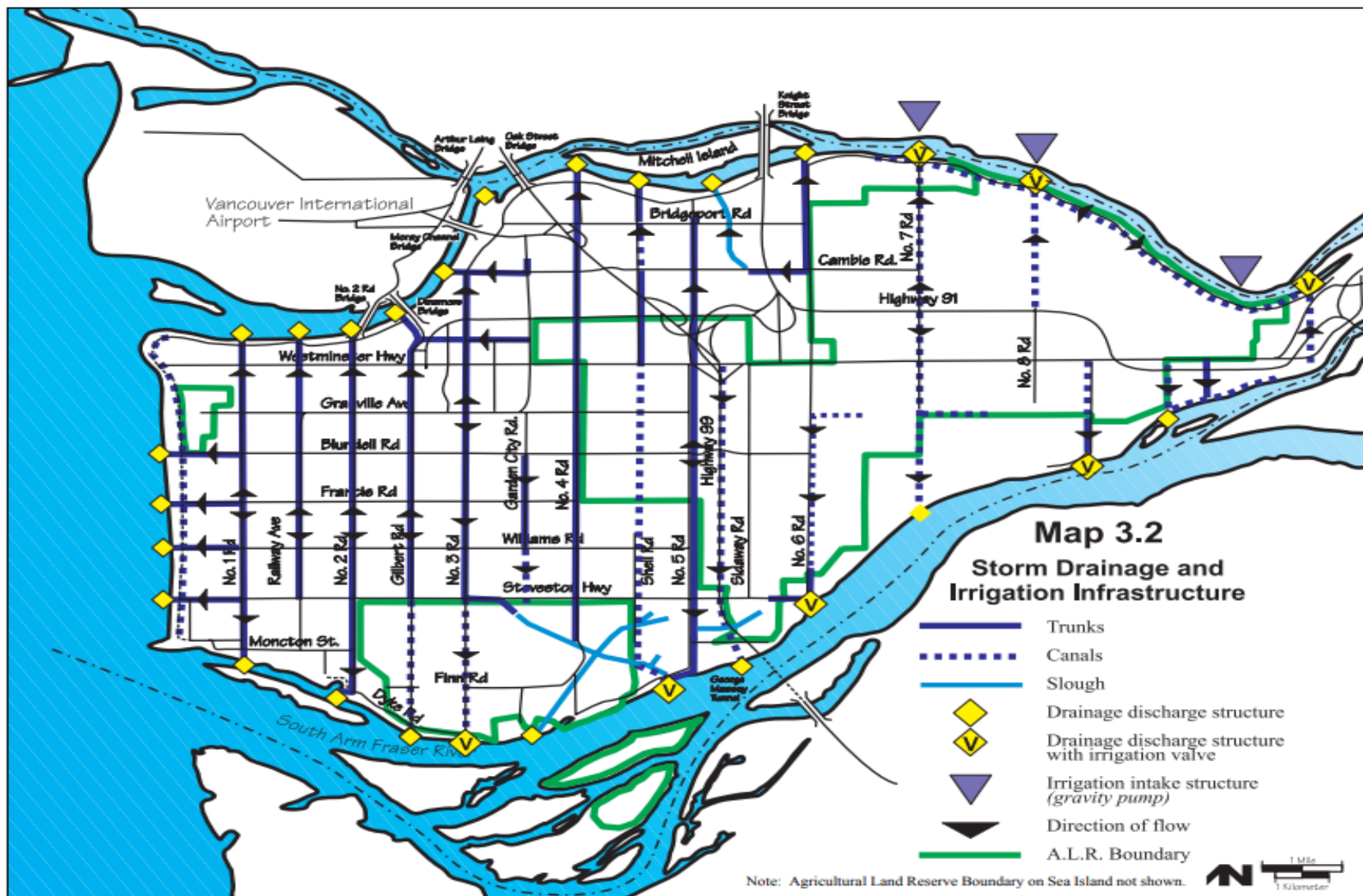
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B- 6 Map showing where the 4 monitoring points on Oval were taken and their horizontal alignment (City of Richmond, 2014)
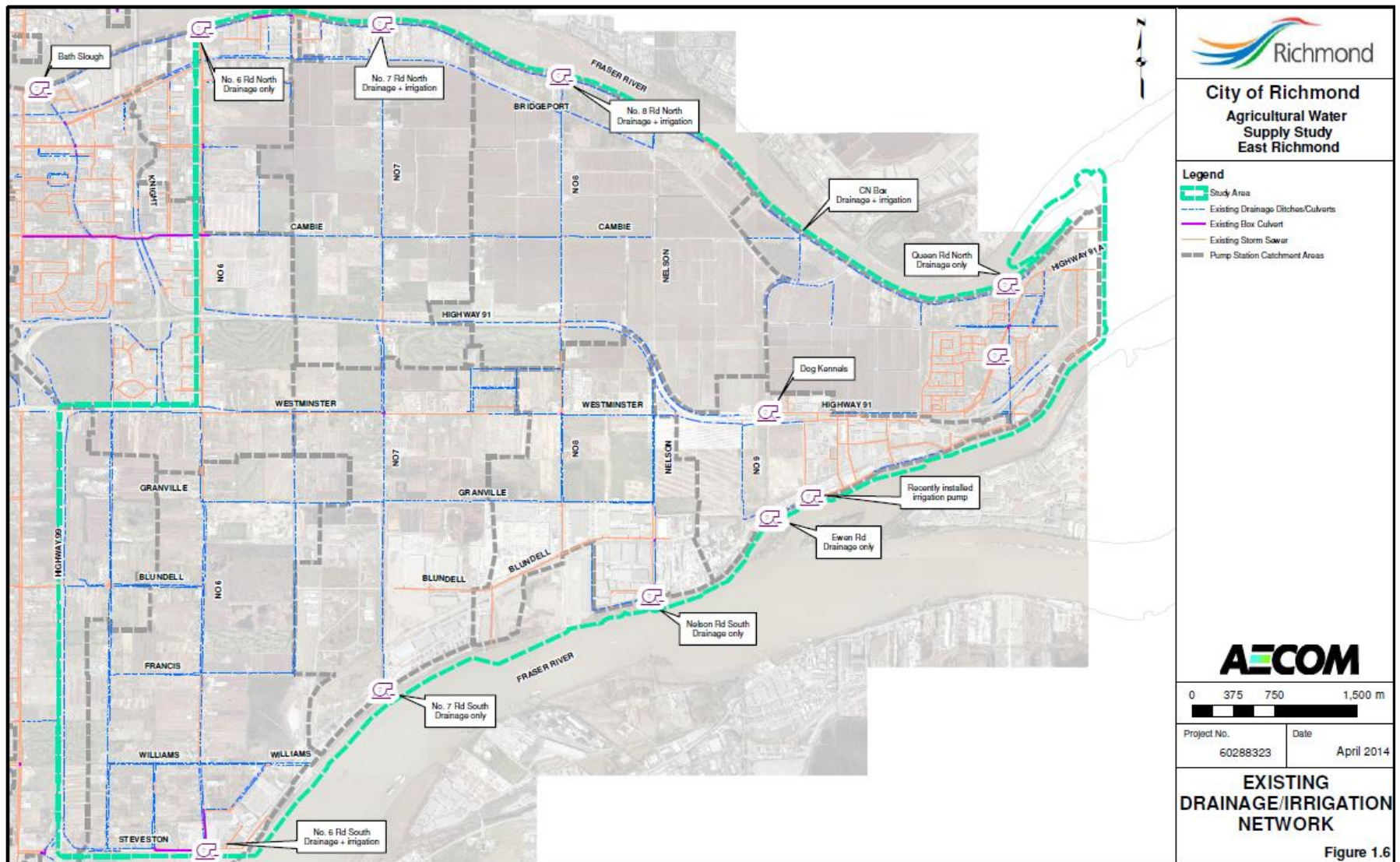

B- 7 Map showing various dewatering and preloading activities that could have impacted Oval subsidence in conjuction with the Cadence project circa 2015.

B- 8 Map showing drainage and Irrigation infrastructure laid out in Richmond (City of Richmond & Richmond Farmers Institute Agricultural profile report, 2002).

B- 9 Map showing drainage and irrigation along with several pump stations located along the North and South Arms of the Fraser River (AECOM, 2014).

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Intended use of water-level data	Typical length of data-collection effort or hydrologic record required			
	Days/weeks	Months	Years	Decades
To determine the hydraulic properties of aquifers (aquifer tests)	✓ (most)	✓ (sometimes)		
Mapping the altitude of the water table or potentiometric surface	✓ (most)	✓ (sometimes)		
Monitoring short-term changes in ground-water recharge and storage	✓ (most)	✓ (most)	✓ (sometimes)	
Monitoring long-term changes in ground-water recharge and storage			✓ (most)	✓ (most)
Monitoring the effects of climatic variability			✓ (most)	✓ (most)
Monitoring regional effects of ground-water development			✓ (most)	✓ (most)
Statistical analysis of water-level trends			✓ (most)	✓ (most)
Monitoring changes in ground-water flow directions	✓ (sometimes)	✓ (most)	✓ (most)	✓ (most)
Monitoring ground-water and surface-water interaction	✓ (most)	✓ (most)	✓ (most)	✓ (most)
Numerical (computer) modeling of ground-water flow or contaminant transport	✓ (sometimes)	✓ (most)	✓ (most)	✓ (most)

EXPLANATION

✓ Most applicable for intended use   ✓ Sometimes applicable for intended use

B- 10 Table showing uses of short and long term groundwater level monitoring in the hydrological context (Taylor et Alley, 2001).

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