Article

# Supporting Information Document: Groundwater-sewer interaction in urban coastal areas

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**Abstract:** In this paper, a study of the potential causes of the occurrence of high concentration of Fecal Indicator Bacteria (FIB) in dry-weather conditions (DWCs) is presented. Two hypotheses were formulated: 1) undersized sewer system and 2) groundwater infiltration into damaged sewer pipes. In both cases, more frequent combined sewer overflows (CSOs) may occur discharging untreated sewage into surface water. To evaluate the first hypothesis, a hydraulic model of a sewer was developed assuming a water-tight system. The simulation results show that CSOs never occur in DWCs but a rain event of intensity equal to 1/3 of 1-year return period may trigger them. To evaluate the second hypothesis, a model combining sewer failure with groundwater level was developed to identify the sections of damaged sewer below the water table and, therefore, potentially affected by infiltration. The risk of infiltration exceeds 50 % in almost a half of the entire network even at the lowest calculated water table. Considering 50 % of infiltration distributed throughout that part of the network, CSOs can occur also in DWCs.

**Keywords:** Coastal cities, Groundwater, Infiltration, Infrastructure, Sewer, Urban hydrology

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## 1. SI-Dataset

Data of pathogen concentration, precipitation, and tide are shown in Figure 1. The precipitation dataset was identified using the precipitation data mining tool HydroDesktop [1].

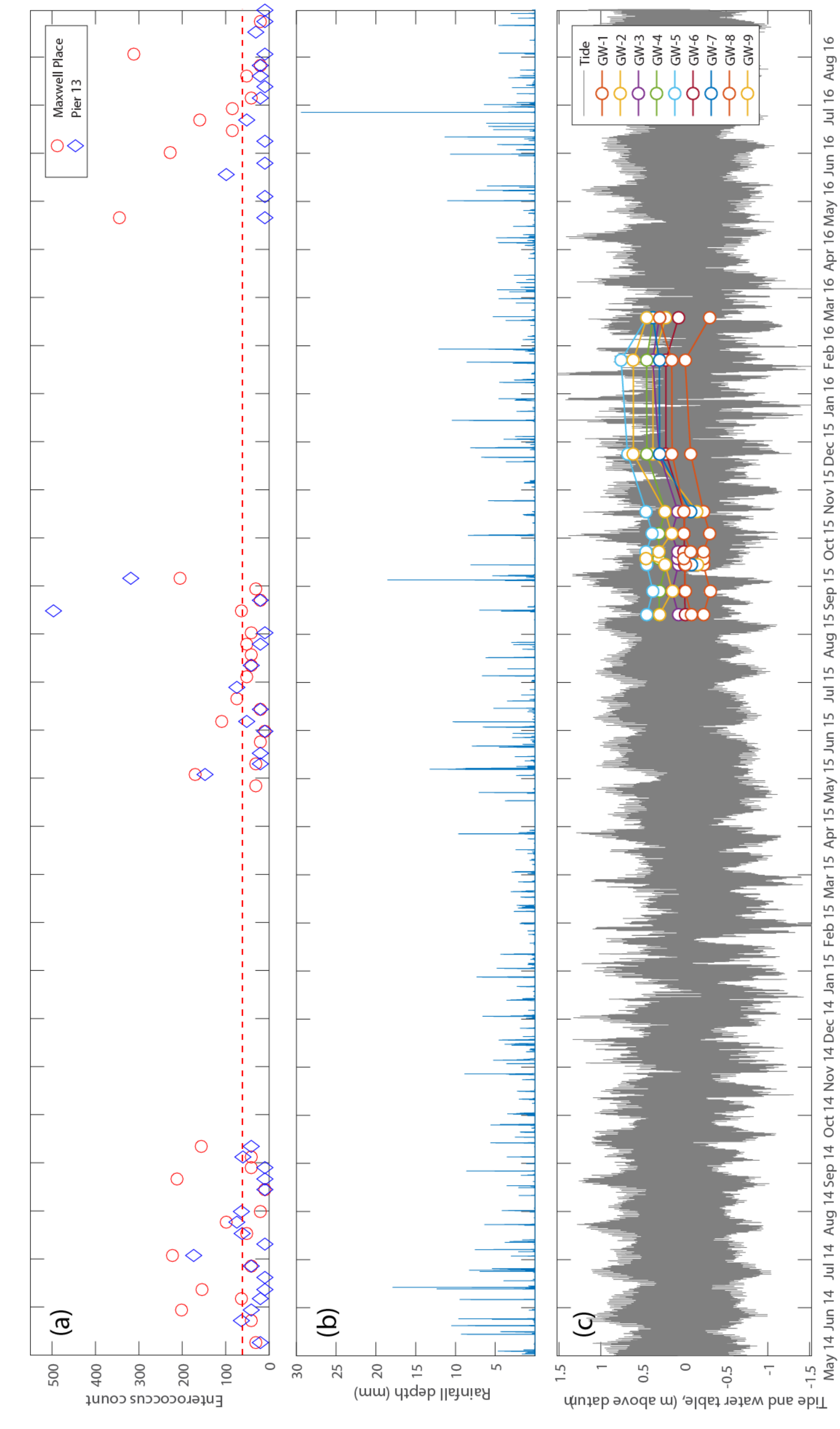



**Figure 1.** (a) Dataset of Fecal Indicator Bacteria (FIB) concentration (Enterococcus count per 100 mL) in the Hudson River at the two locations in Hoboken (NJ) as indicated in parts b and c of Figure 1 in the manuscript [2]. (b) Rainfall depth [3]. (c) Tidal river and water table elevations with respected to NAVD88 datum [4].

## 2. SI - Sewer flow model

### 2.1. Source of data and processing

The basic information of the sewer network in the city of Hoboken, including the geographical locations and the parameters of manhole, sewer pipe, and outfalls was provided by the local water authority, i.e., North Hudson Sewage Authority (NHSA). The information was provided in the format of GIS shapefiles [5] and historical design drawings [6]. In the developed model implemented in the software SWMM [7], the GIS shapefiles were regarded as the most reliable resource for the sewer network, as they were the latest updated, with the majority of the parts verified by NHSA upon survey. However, some significant errors were observed, namely, not realistic slope of sewer pipe, missing basic pipe information (i.e., invert elevation, pipe dimensions, material, etc.), all of which required correction, which were made on the basis of the historical drawings. There were few parts of the sewer system with missing necessary information in both the GIS shapefile and the design drawing (e.g., connection parts from subcatchment to interceptor, and interceptor pipe lines). This issue was resolved by inferring the sewer characteristics from the neighbouring pipes.

According to NHSA's 2011 annual report [8], the sewer in Hoboken is a combined system with the majority of it installed before the 1940s. Until 1958, the wastewater was conveyed by gravity directly to the Hudson river. In 1958, an interceptor line together with pump stations was installed to redirect the wastewater to a waste water treatment plant (WWTP). However, since the WWTP was designed to treat dry weather wastewater and small precipitation events, wastewater exceeding this limit was discharged into the river as overflow, namely, combined sewer overflow (CSO). After the installation of the first interceptor, pumps along the network have been replaced several times. In this work, the implemented network reflects the sewer in year of 2011, where there were two pumping stations with five dry-weather pumps and one wet-weather pump. Currently, there are three pumping stations, four wet-weather pumps, and three dry-weather pumps.

### 2.2. Network structure

The sewer system in Hoboken is divided into nine drainage areas. We implemented in detail six of them (namely, H1, H2, H3, H4, HWF, and HSI) and a layout of the network as visualized by SWMM software is shown in Figure 2a. The remaining drainage areas were accounted for with a single representative pipe. The junctions, conduits, and sub-catchments in SWMM model were processed and imported from GIS shapefiles by inp.PINS [9], with uniform coordinate system of NAD83, New Jersey FIPS 2900 (US ft). The other elements in SWMM model, including rain gauges, outfalls, dividers, outlets, tidal curves, precipitation data, and time patterns are imported directly to SWMM GUI.

### 2.3. Sub-catchments and hydrology

In SWMM, the hydrology calculation is performed on each sub-catchment and accounts for evapotranspiration, surface runoff, and infiltration into the ground. The ratio between pervious and impervious surface in a sub-catchment was determined by assigning the land-use data to sub-catchments as provided by the New Jersey Department of Environmental Protection (NJDEP) [10]. The data are shown in Figure 3.

The inlet of the surface runoff into the sewer system is considered located at road crosses (Figure 2b). Mass conservation of precipitation on surface writes as, [11]:

$$\frac{\partial d}{\partial t} = i - e - q - f, \tag{1}$$

where $d$ is the water depth; $t$ is the time; $i$ is the rate of precipitation, m/s; $e$ is the surface evaporation rate, m/s, provided by the NASA Earth data (NLDAS dataset) [12] and accessible


**(a)** **(b)**

**Figure 2.** a) Drainage areas built in detailed in SWMM. b) Example of the location of the boundaries of the sub-catchments and their relationship with street blocks and surface runoff inlets.

through Hydrodesktop [1]; $q$ is the surface runoff rate, m/s; and $f$ is the surface infiltration rate, m/s. For both the pervious and impervious surfaces ($\sim 75$ %), the depression storage was considered, i.e., the water accumulates on the ground due to uneven surface condition. Depression storage is not accounted for in either the infiltration or the runoff as it is considered to be depleted by evaporation. Kidd [13] provided an expression for the depression storage ($d_s$, m) of impervious surfaces [11], i.e.,

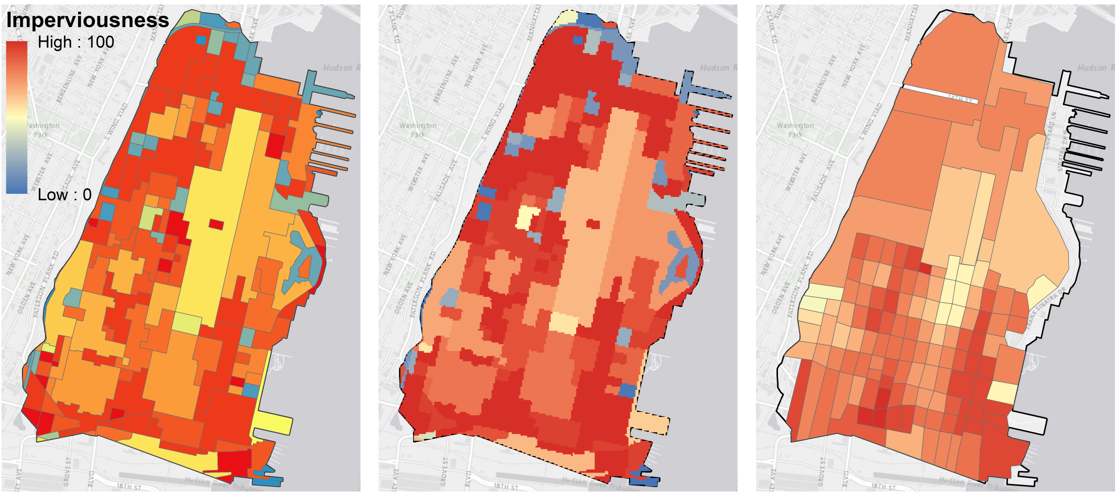
$$d_s = 0.303 S^{0.49}, \tag{2}$$

$S$ is the slope rate. For pervious surface, the depression storage is approximately equal to $2.5\times10^{-3}$ m (grassed urban surfaces) [11].

To calculate surface runoff in a sub-catchment, Manning's equation was used, i.e.,

$$q = \frac{1.49}{n} W S^{\frac{1}{2}} (d - d_s)^{\frac{5}{3}}, \tag{3}$$

where $n$ is surface roughness coefficient, which can change significantly depending on pavement condition; $W$ is the width of a rectangular sub-catchment area; $S$ is the average slope of sub-catchment; and $d$ is the water depth above the subcatchment surface. The pervious surface in the South of Hoboken is mainly covered by grass land with little portion of bare packed soil, while impervious surface is mainly paved with concrete, rough asphalt, and bricks. Following Yen [14], the median values of $n$ of grass land and concrete pavement were selected equal to 0.050 and 0.017, respectively. The width of a rectangular sub-catchment area, i.e., $W$ in eq. 3 was calculated by considering each sub-catchment of rectangular shape [11]. This was performed using the minimum




(a) (b) (c)

**Figure 3.** a) Imperviousness as provided by NJDEP 2012 land use data [10]. b) Raster imperviousness converted from panel a. c) Average imperviousness assigned to the sub-catchments from the raster imperviousness layer.

bounding geometry tool in ArcGIS [15]. Finally, the slope $S$ at eq. 3 was calculated by averaging the raster data of slope generated from the digital elevation model (DEM) [16] (see Figure 4).


(a) (b) (c)

**Figure 4.** a) Digital elevation model (DEM) [16]; b) Slope rate calculated from DEM; c) average slope rate assigned to sub-catchments from the raster slope layer.

The equation to calculate infiltration rate ($f$, m/s) was modified from SCS curve number method, i.e.,

$$f = \left(\Delta i - \Delta\left(\frac{i^2}{i + SC}\right)\right) / \Delta t, \tag{4}$$

where $SC$ is the moisture storage capacity. After a long dry period before the precipitation event, $SC$ reaches its maximum and it is calculated from the curve number ($CN$),

$$SC = SC_{max} = \frac{1000}{CN} - 10, \tag{5}$$

otherwise adjusted by storage recovery constant ($k_r$),

$$SC = k_r SC_{max} \Delta t, \tag{6}$$
$$k_r = \frac{1}{24T_{dry}}, \tag{7}$$

where $T_{dry}$ is the drying time. The value of $T_{dry}$ is related to groundwater recharge rate, which is described in section 4. Here, $T_{dry}$ was assumed equal to 6 days, which is a reasonable number as the top layer of Hoboken is mostly filling soil, with relatively large vertical hydraulic conductivity. The curve number is determined by Natural Resources and Conservation Service (NRCS) through the soil group and land use. The soil group identified by survey from the U.S. Department of Agriculture (USDA) [17] for Hoboken is B (i.e., soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures). Therefore, the $CN$ of a high density urban area (i.e., size of an average lot smaller than 506 $m^2$) such as Hoboken with a soil of type B is 85. This number was applied to all investigated catchment.

### *2.4. Conduit and hydraulics*

The shape, maximum depth, length and roughness of conduit is from NHSA sewer shape files [5] and Hoboken sewer design drawings [6]. The loss coefficient is set as 0 as the number is negligible in sewer pipes. For the routing method, dynamic wave method was applied, which uses the implicit backward Euler method to calculate 1 dimensional Saint-Venant equation [18]. The inertial force in the flow was determined by the Froude number. And the normal flow limitation criteria is checked by both Manning's equation and Froude number.

### *2.5. Regulator and outfalls*

Five outfalls of Hoboken sewer system are along the interceptor line with flow from south to north. Among the 5 outfalls, 4 outfalls are combined sewer outflow and one is the outfall from the WWTP. Regulators are installed in front of the CSOs. Figure 5 shows the structure of regulator. During a storm event, the water exceeding the height of the weir will be diverted into the outfall. Flap gates are installed at the end of the outfall to prevent backflow water from the river during the high-tide periods.

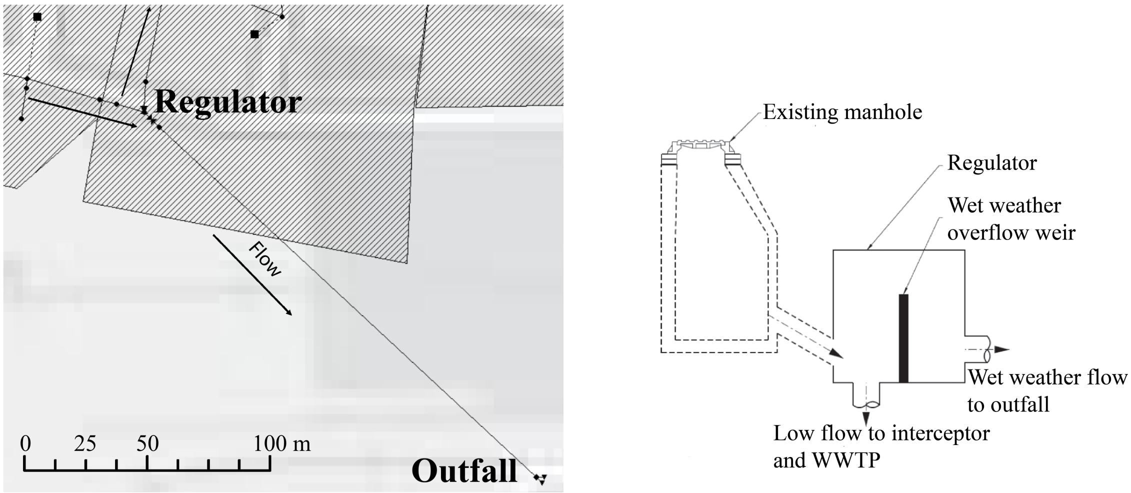
## 3. SI - Simulation results of wet weather sewer flow

Figure 6 shows the simulated CSO in wet weather conditions for a 72-hours rain event with a peak of hourly intensity equal to 1/3 the intensity of 1-year return period.

## 4. SI - Groundwater flow model

### *4.1. Geology*

Hoboken is underlain predominantly by the Stockton rock formation with significant portions of Serpentine and Manhattan schist in the regions bordering the Hudson River [10]. The more superficial soil consists of rahway-till, deltaic, and estuarine/salt-marsh deposits with some outcrops of fractured bedrock (i.e., fractured serpentine) [20]. In the West side of the city, the most superficial layer of the urban soil consists of filling that was laid at the end of the 1800 [21]. Boring logs of the




**(a)** **(b)**

**Figure 5.** a) Outfall; b) Front view of the regulator [19].

city of Hoboken obtained from public institutions (i.e., USGS, U.S. EPA, and NJDEP) and engineering companies (i.e., Langan, Dewberry, and ECDI drilling company) have also provided additional information on the urban subsurface of the investigated area. Figure 7.a shows the shallow geology and the location of the available boring logs. At each star symbol multiple logs were provided. Part b of the figure reports an example of the stratigraphy along the section A–A indicated in part a. In this panel, it is possible to see that the most superficial layer of the subsurface in the West side of Hoboken consists of filling and estuarine/salt-marsh deposits, which are a combination of organic silt and clay, and peat, with some sand and fine gravel. In the center of the city, filling lays above deltaic deposits, which are characterized by fine-to-coarse sand and some pebble gravel and minor cobble gravel. In the East part of the city, the upper layer is rahway-till silty sand to sandy clayey silt containing pebbles, cobbles, and a few boulders.

### *4.2. Model development*

Given the complexity of the geology of the area because of the vertical and horizontal heterogeneity as well as the presence of urban utilities and constructions, the hydraulic conductivity ($K$, m/s) of the groundwater domain was represented by an effective value calculated following the one dimensional (1D) equation of the hydraulic diffusivity ($D_{amp}$, m$^2$/s), [22,23],

$$D_{amp} = \frac{Kb}{S_y} = \frac{x^2 \pi}{\ln^2 A\o}, \tag{8}$$

where $b$ is the aquifer thickness, m; $S_y$ is the specific yield, -; $x$ is the distance between an observation well and the shore, m; $A$ is ratio of the amplitudes of the oscillation of the water table at the observation well and of the tide, -; and $\tau$ is the oscillation period of the tide, s. According to the boring logs information, $S_y$ was assumed equal to 0.24 to resemble an average specific yield for medium sand, medium gravel, and silt [23]. Applying eq. 8 to each observation well along the boundaries, the resulting calculated $K$ was equal to $0.63 \pm 0.60$ m/s. Regarding the geometry of the groundwater domain, the upper boundary was selected corresponding to the surface elevation. While the bottom aligned with the Hudson River bed, which is -13 m below datum [24].

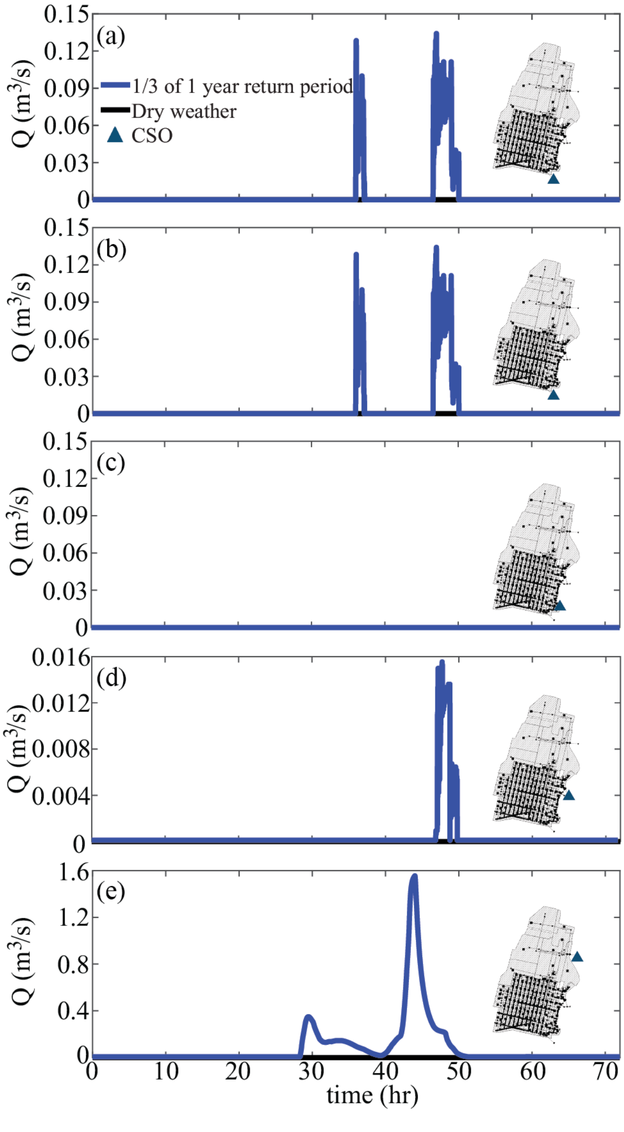



**Figure 6.** Flow rate as function of time at the five outfalls of Hoboken in both dry weather and wet weather conditions. The wet weather condition was selected as the minimum rain event at which CSOs occur, which corresponds to a 72-hours rain event with peak hourly intensity equal to 1/3 of 1-year return period.

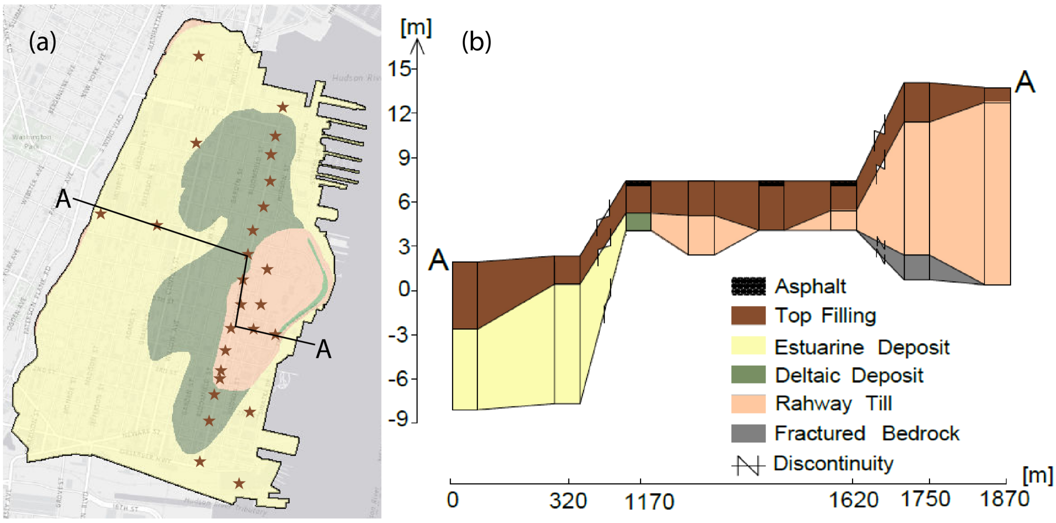



**Figure 7.** Geology of Hoboken. (a) Shallow geology within the domain with boring log locations; (b) stratigraphy along the section A–A.

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