doi: 10.26492/gbs70(suppl.1).2018-03

The hydro-geomorphic status of Nee Soon freshwater swamp forest catchment of Singapore

C.T.T. Nguyen[1], R.J. Wasson[2] & A.D. Ziegler[3]

[1]Tropical Marine Science Institute, National University of Singapore,
18 Kent Ridge Road, 119227 Singapore
[2]Lee Kuan Yew School of Public Policy, National University of Singapore,
469C Bukit Timah Road, 259772 Singapore
[3]Department of Geography, National University of Singapore,
1 Arts Link, 117570 Singapore
geoadz@nus.edu.sg

ABSTRACT. This paper presents initial findings from research on the hydro-geomorphic status of Nee Soon freshwater swamp forest catchment in Singapore. The hydrological system of Nee Soon contains a swamp that is best described as an organic-rich wetland, with organic matter content as high as 40% near the surface (too low to be classified as peat). Total long-term denudation rate in the catchment is an estimated 23.4 ± 2.08 Mg km^{-2} yr^{-1}, with physical erosion (5.6 ± 0.5 Mg km^{-2} yr^{-1}) and chemical weathering (17.8 ± 1.58 Mg km^{-2} yr^{-1}) accounting for 24% and 76% of the totals, respectively. Age dating of a 1.95-m sediment core from the lower swamp indicates several distinct periods of variable sediment deposition (0.04 to 0.009 cm y^{-1}) since 15,000 BCE, across a variety of climate regimes. A missing layer, representing more than a 7000 year period, verifies substantial channel erosion in the swamp occurring since 1950. Accelerated erosion associated with forest conversion to agriculture in the upper catchment could not be verified through examination of sediment cores. High concentrations of several heavy metals (e.g. As, Cr, Mn, Ni, Sr, V) in the lower catchment, compared with the upper catchment, appear to be natural (e.g. related to differences in the underlying bedrock), rather than contamination. The very high concentrations of lead, copper, and zinc associated with firing activities in the military range in the lower catchment are spatially isolated (e.g. shooting berms), and currently not posing a threat to the swamp environment. Other hydro-geomorphic degradation processes/activities now include disruption to hillslope soils and streams by trampling and mountain biking, back-flow of reservoir release water into the lower swamp area, and atmospheric deposition of contaminants.

Keywords. Conservation, erosion, heavy metals, hydrology, Pleistocene, vegetation history

Introduction

The transformation of Singapore from a forested island to a modern first-world city over the last two centuries has been rapid and has been termed environmentally "catastrophic" (Sodhi et al., 2004), leaving the island nation with less than 1% of its original forest cover. Historically, the 582 km^2 island was covered by three types of forest ecosystems (Corlett, 1991; O'Dempsey, 2014): lowland dipterocarp forest (80–82%), mangroves (13%), and freshwater swamp forests (5%). Between the arrival of Stamford Raffles in 1819 and the turn of the 21st century, nearly all forests had been converted to other land covers. Today, only about 0.2% of the total area (719 km^2) of Singapore is considered to be primary forest (Brook et al., 2003).

The 7.55 km^2 Nee Soon area, in the heart of Singapore's Central Catchment Nature Reserve (Fig. 1), contains virtually the last freshwater swamp forest in Singapore. Nee Soon freshwater swamp forest catchment occupies 4.8 km^2 (boundary in Fig. 1). The catchment, which is bounded by the Upper Seletar Reservoir to the northeast and the Upper and Lower Pierce Reservoirs to the south, is recognised for its conservation value (e.g. Ng & Lim, 1992; Wee & Ng, 1994; Briffett & Ho, 1999; O'Dempsey & Chew, 2013; Li et al., 2016; Clews et al., 2018), yet very little has been written about its physical nature—which is the goal of this paper.

Herein we draw from the results of a recently conducted project entitled "Nee Soon Swamp Forest Biodiversity and Hydrology Baseline Studies" Phase II (Tropical Marine Science Institute, 2016). The background and objectives of the project, to guide future management of the catchment in anticipation of increasing urbanisation, are described by Davison et al. (2018). We present initial findings related to the hydro-geomorphological status of the catchment. The interpretations of the findings may change as new data are collected.

Geology

Nearly all of the Nee Soon catchment is underlain by the Triassic Bukit Timah Granite Formation, which varies from granite through adamellite, granodirite and several hybrid granitoids (Ives, 1977). Few core stones or outcrops are present in Nee Soon catchment, except on the hilltops in the southwest, and therefore variations in the bedrock can only be inferred from scattered outcrops outside the Nee Soon catchment. A ground penetrating radar survey, conducted along a publicly restricted walking trail, the Woodcutter's Trail, indicated the maximum depth to bedrock is about 9 m (Tropical Marine Science Institute, 2016). However, because of the difficulty in distinguishing the interface between the residual soil and the moderately weathered granite, solid unweathered bedrock may be as deep as 20 m to 70 m in some locations.

A granite rock sample we tested from the upper catchment has medium-to-coarse grains and contains about 76% SiO_2, 13% Al_2O_3, and 1.5% Fe_2O. It also contains substantial Ba (797 ppm), Mn (197 ppm), and Sr (83 ppm), relative to other minor elements. Aluminum (6.3%), Na (2.9%) and K (3.5%) are the most abundant major elements.

Soils

Ives (1977) identified two dominant soil types within the catchment (Fig. 2a): (1) Rengam Series, developed on igneous rock; and (2) Tengah Series developed on alluvium. The Rengam Series is generally a clayey, kaolinitic, isohyperthermic, Typic

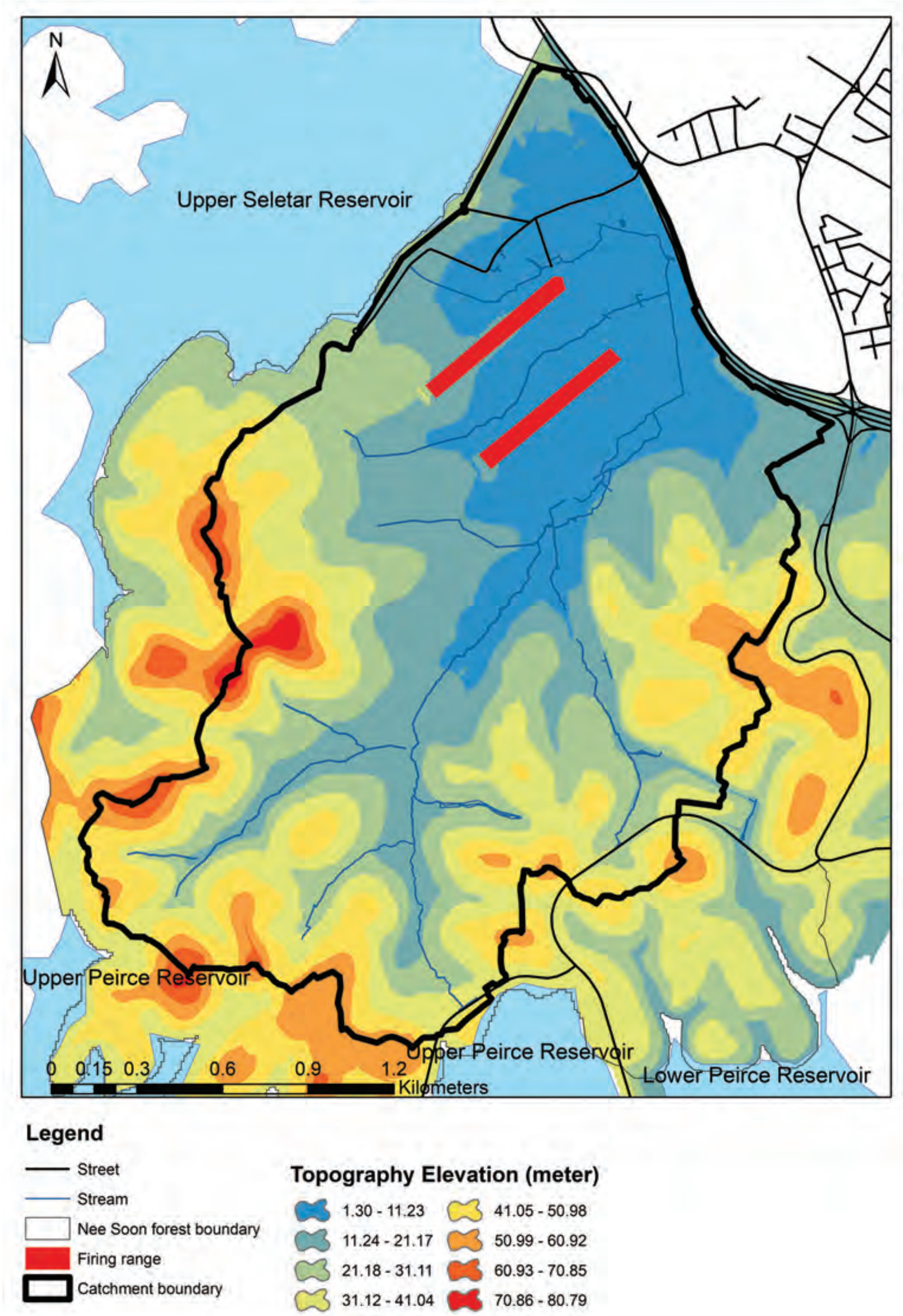

Fig. 1. Location (inset) and topography of the Nee Soon Catchment (defined by thick boundary) in the Nee Soon Forest Reserve in Singapore.

Paleudult that forms on highly weathered Bukit Timah Granite (Chia et al., 1991; Fauziah et al., 1997). We cannot find a description of the Tengah Series, which in Nee Soon is associated with the freshwater swamp in the centre of the lower catchment, where mineral sediments and organic material have accumulated over time (Fig. 2a). Based on sampling this material to 2m depth, we do not believe it is a peat soil, which was reported in the past (Taylor et al., 2001), because the organic matter content is less than the 65% threshold defined by the FAO (Andriesse, 1988). The highest percentage of organic material we measured was about 40–50%. We therefore recommend referring to the Nee Soon freshwater swamp forest as an organic-rich wetland, not a peat swamp. Further, the Tengah Series appears to be a depositional material consisting of substantial clay with small layers of sand and varying contents of organic matter.

Ives (1977) demarcated a "high ground" zone within the Rengam soils in Nee Soon (Fig. 2a). In agreement, we find the upper and lower portion of the catchment to have different soil geochemical signatures. The differences are present in the mineralogy of the soil in two pits in the upper and lower catchment (Fig. 2a). For example, the soil in the upper-catchment pit (at 250 cm depth) is composed largely of Quartz (79%), followed by Kaolin (17%) and small amounts of Gibbsite (3%) and Goethite (1%). The soil in the lower pit (at 250 cm depth) has much more Gibbsite (42%), and comparatively less Quartz (33%). The Kaolin content is similar (18%). Goethite is slightly higher (5%) and a small amount of Illite is present (1%). This mineralogy is typical of a highly weathered residual soil.

Soil in the upper pit is slightly more acidic (all horizons in the 2 m profile): pH (determined in water) ranges from 3.4 to 4.2 versus 4.3 to 4.6 in the lower pit. Soil organic carbon in the 20–30 cm A horizons ranges from 2 to 5% and 2 to 3% for the upper versus lower pits, respectively, and discussed further by Rahman (2016). The texture of the B horizon in the upper pit is a sandy clay and sandy clay loam, whereas the B horizon in the lower pit is mostly clay (upper 1 m) and sand clay loam (lower 1 m). The upper pit has SiO_2 concentrations of 55–69 ppm within the profile, whereas the ranges of concentrations in the lower pit profile varies between the upper (58–65 ppm) and lower (35–52 ppm) 1 m halves. The lower pit soil also contains more Fe_2O_3 (4–10%) and TiO_2 (0.40–0.5%) than the upper pit (2–3% and 0.1–0.2%, respectively).

The geochemical zonation in the catchment soil is apparent in the spatial distribution of several elements in 227 surface and 30 subsurface samples. Several elements have significantly higher concentrations in the lower catchment, compared with the upper catchment (Mann-Whitney U-test; $\alpha = 0.05$): As, Ba, Cr, Cu, Fe, Mn, Pb, Sr, Ti, V, and Zn (data not shown). Subsurface samples tend to corroborate the geochemical patterns found in the surface samples, indicating that enrichment in the forested lower catchment is natural. The enrichment in some heavy metals gives the impression of contamination in the lower catchment (shown for Cr in Fig. 3a). However, we believe the enrichment is natural, reflecting a zonation in the underlying granite bedrock, or some topographically controlled hydro-geomorphological process affecting soil chemistry occurring over very long time scales (i.e., not anthropogenic). The higher concentration of Fe_2O_3 and TiO_2 in the lower soil pit provides corroborating evidence that the enrichment of some associated metals is natural (assuming that oxide

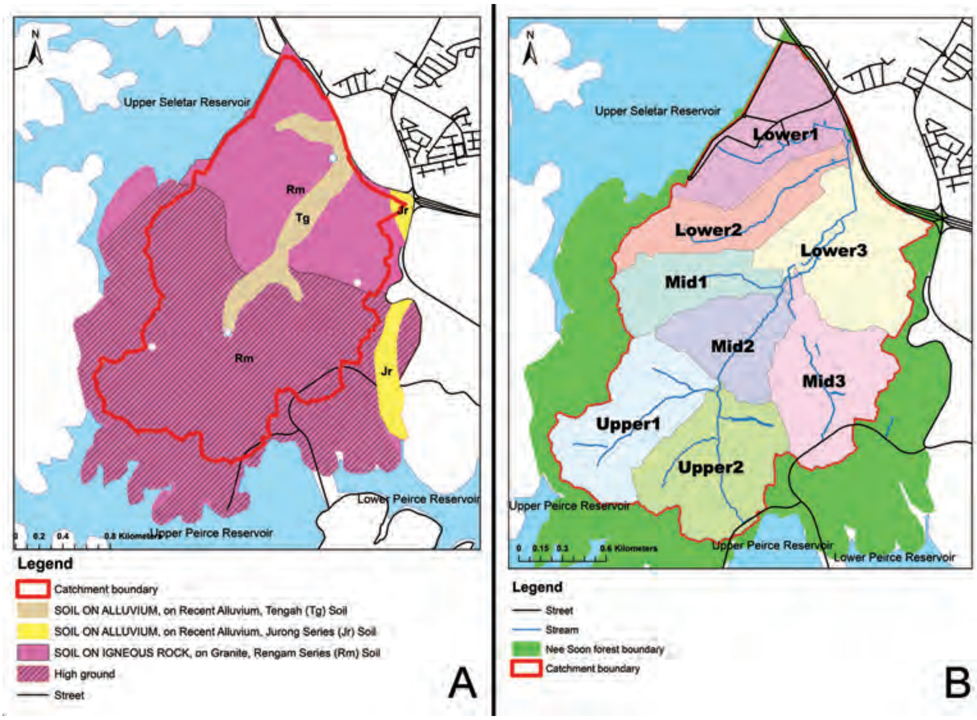

Fig. 2. (a) Major soil types in the Nee Soon Catchment (based on Ives, 1977). Locations of the soil pits in the upper and lower catchment are indicated with circles. Locations of cores collected in the mid and lower catchment are indicated with crosses. (b) Stream network and the hydrological "operational units" (based on Murphy, 1997) within the Nee Soon Catchment.

concentrations are not associated with contamination). Further, higher concentrations of many elements to depths below 6 m in the lower pit, compared with the upper pit, support this interpretation (shown for Cr in Fig. 3b).

With respect to anthropogenic disturbance, we find very high concentrations of some elements, which are associated with human disturbance, in the lower part of the catchment—i.e., military lands (ML) or variably disturbed lands (VDL) containing roads and golf courses. For example, maximum values of some elements greatly exceed those measured on lands in the forested upper catchment: As (252 versus 70 ppm); Cr (224 versus 55 ppm); Cu (632 versus 16 ppm); Fe (17.32 versus 3.35%); Mn (1362 versus 110 ppm); Na (1.32 versus 0.16%); Pb (>10,000 versus 188 ppm); Sn (21.5 versus 8 ppm); Sr (336 versus 11 ppm); Ti (3.83 versus 0.45%); V (521 versus 65 ppm); and Zn (431 versus 55 ppm).

The general similarity between the Nee Soon forested upper catchment and forested lower catchment soil chemistry and concentrations determined in the nearby MacRitchie Catchment give support to the reliability of the values we have determined in Nee Soon, despite the wide range found within such a small area (Table 1). Further, the maximum values associated with disturbed lands at Nee Soon (372, 679, and 1926

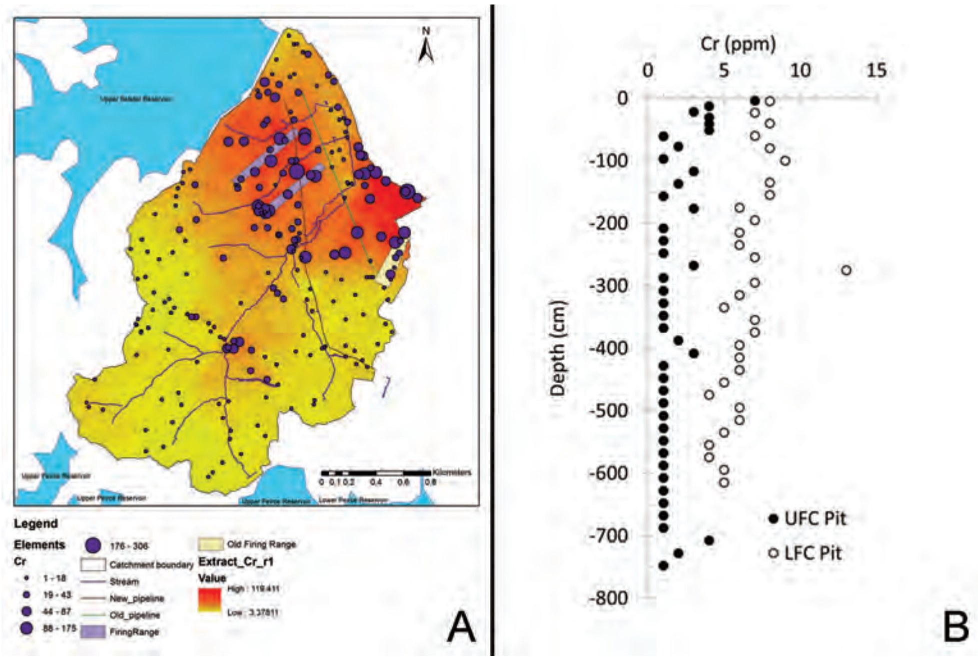

Fig. 3. (a) Near-total (mixed acid digestion; ICP-MS; see footnote in Table 1). Chromium concentrations (ppm) at 227 surface samples within the Nee Soon Catchment. Shading indicates spatial distribution determined by ordinary kriging on the samples. (b) Near-total chromium concentrations within the soil profile of pits located in the upper and lower catchment (see Fig. 2a for pit locations).

ppm for Cu, Pb, and Zn, respectively) demonstrate the likelihood that human activities have elevated concentrations in a manner similar to that reported by Chen et al. (1996) for industrial surface soils in Singapore (485, 235, and 3594 ppm, for Cu, Pb, and Zn). For Nee Soon, the high Cu and Pb concentrations associated with the military lands (Cu = 632 ppm; Pb > 10,000 ppm) indicate potent sources of anthropogenic enrichment in isolated areas (e.g. near the berms on firing ranges) that may require remediation in the future.

Some elements that are considered to be pollutants, including As, Cu, Pb, can potentially move into the subsoil (Teo, 2016). Measurements of saturated hydraulic conductivity (and indicating property for infiltrability) in the soil profiles indicates a sharp decrease from about 485 mm h^{-1} to 23 mm h^{-1} by a depth of 50 cm (Kho, 2014, 2016). This decrease, which is typical of a natural tropical forest hillslope with a thin, organic-rich and permeable A horizon formed over a clay-rich B horizon (cf. Ziegler et al., 2006), may prevent the movement of enriched elements to great depths in the soil profile, possibly preventing them from interacting with the groundwater. In 20 water samples tested for heavy metals (ICP-MS), we found very low concentrations, suggesting limited (if any) movement of potentially harmful elements from the soil to the stream system (data not shown), or our failure to detect a synoptic signal. From

Table 1. Comparison of the concentrations of selected elements in Nee Soon with those from others studies at MacRitchie and other locations in Singapore.

Site	Description	CR (ppm)	Mn (ppm)	CU (ppm)	Pb (ppm)	Zn (ppm)	(N)
MacRitchie vs Nee Soon (undisturbed lands)							
MacRitchie[1]	Natural Area	14	58	15	28	65	4
Nee Soon[4]	FUC	7	38	5	13	23	86
Nee Soon[4]	FLC	18	160	12	18	33	56
MacRitchie vs Nee Soon (disturbed lands)							
MacRitchie[1]	Industrial Area	47 (3)	146 (3)	47 (3)	71 (2)	268 (4)	8
Nee Soon[4]	ML	35 (5,2)	248 (7,2)	44 (9,4)	56 (4,3)	77 (3,2)	40
MacRitchie[1]	Mixed Disturbance	28 (2)	83 (1)	83 (1)	32 (2)	124 (2)	20
Nee Soon[4]	VDL	23 (3,1)	188 (5,1)	16 (3,1)	24 (2,1)	43 (2,1)	44
Other locations vs Nee Soon							
Unspecified[2]	Residential soil (0-5cm)	–	–	3–93	6–70	89–93	25
Unspecified[2]	Industrial soil (0-5cm)	–	–	1–485	51–235	15–3594	13
Main Island[3]	Main island soils	–	–	5–16	14–26	11–31	6
Nee Soon[4]	FUC (Nee Soon)	2–55	1–11	1–16	3–188	7–65	87
Nee Soon[4]	FLC (Nee Soon)	1–175	30–1184	3–84	3–377	11–98	56
Nee Soon[4]	ML (Nee Soon)	5–224	38–1362	7–632	8–10,000	17–431	40

Individual values are all medians. The mixed disturbance lands in MacRitchie include land used as a golf course, residential areas, and roadside soils. Values in parentheses refer to the amount the median natural concentration is increased by disturbance; two values for Nee Soon are based on calculations using the natural values from the Forested Upper Catchment (FUC) and Forested Lower Catchment (FLC). ML refers to military lands; VDL refers to variably disturbed lands (e.g. roads, golf course). Values have been rounded to the nearest integer; N is sample number. Data for "other locations" are ranges. Data sources and methods: (1) HCL-HNO3-HF digestion and a flame atomic absorption spectrophotometer for high concentrations and a graphite furnace atomic absorption spectrophotometer for low concentrations (Zhou et al., 1997); (2) mixed acid method (1 ml HF (49%) added to 14 ml 3:1 HCL (36%): HNO_3 (68%) added by 20-min microwave digestion (Chen, 1999); (3) samples digested using another microwave oven (Milestone, Ethos D, Monroe, C.T., USA) with a mixture of 9 ml HNO_3 and 3 ml of HF in a closed vent medium pressure vessel with a ramp to 180° C at 600 W for 10 min and held at 180° C, 600 W for 10 min (Ng et al., 2006); (4) This study. Values have been rounded to the nearest integer; N is sample number.

these results we conclude that polluted areas do not currently pose a threat to the freshwater aquatic ecosystem, but this issue should be monitored and some of the polluted areas may require remediation.

Stream hydrology

The drainage system in the 4.8 km^2 Nee Soon catchment includes a third order stream that flows into the Lower Seletar River (Fig. 2b). Comparison with old maps and field observations shows that the stream has been altered drastically in the lower part of the catchment. For example, the main channel was straightened above where it joins the outflow from the spillway of the Upper Seletar Reservoir (Fig. 2b; Lower 3 section). Because the stream system has been so greatly altered, Murphy (1997) divided it into hydrological "operational units" (Fig. 2b), rather than dividing the drainage network it into meaningful hydrological sub-catchments (discussed below).

Streams draining from the upper catchment typically have slope gradients less than or equal to about 5° and coarse sandy or sandy-loam streambeds. Streams on low-gradient terrain accumulate dense mats of organic material. Where the streams reach the swamp, they are shallow and narrow, and they move across the swamp, as evidenced in cores by thin layers of channel sand separated by organic-rich clay. Streams in the upper catchment tend to maintain flow year round, indicating a significant groundwater contribution that returns to the surface via springs.

The water balance of the Nee Soon catchment is primarily driven by rainfall associated with two monsoon seasons, the Northeast monsoon (October to early January) and the Southwest monsoon (late March to May), yet rainfall is typically plentiful even in the inter-monsoon seasons—except in occasional droughts that are, for example, associated with phenomena such as El Nino (Ziegler et al., 2014). Mean annual rainfall at Nee Soon is 2330 mm; monthly means range from 159 to 288 mm (http://www.weather.gov.sg/climate-climate-of-singapore/). In the simulation of the water balance for the catchment, modelled evapotranspiration (1100 mm) and stream runoff (2200 mm) represented 33% and 66% respectively of the total rainfall input (Sun et al., 2018; Liong Shui-Yui, Tropical Marine Science Institute, personal communication).

We find that the main stream draining the upper part of the catchment has a mean pH value of 6.29 ± 0.38 (n = 27). Two tributary streams to the main channel have very similar mean values of 6.05 ± 0.27 and 6.03 ± 0.44. The springs in the upper part of the catchment are the most acidic, with values ranging from 4.49 ± 0.18 to 4.88 ± 0.33. Other surface water and ground water samples have pH values less than 6.0, including the swamp in the mid part of the catchment (5.69 ± 0.48). We believe stream pH in Singapore is low because of both natural (low buffering related to acidic granite) and anthropogenic (influenced through acid rain) phenomena. During the last two years of the study, we measured rainfall pH values ranging from 3.41 to 6.35 (collected at the National University of Singapore). Our initial analysis of rainfall pH does not reveal a strong relationship between low pH and indicators of acid rainfall, SO_4^{2-} and NO_3^-, but this is expected, as other acid-related constituents, sea-spray, dust, and aerosols from biomass burning all contribute to acid rain in Singapore (Balasubramanian et al., 2001).

The ranges of specific conductivity values determined at five sites (n=64 samples) tend to be lower in the upper catchment streams (19–30 µS cm^{-1}), springs (16–38 µS cm^{-1}), and groundwater (23–73 µS cm^{-1}), than in the lower catchment main channel (16–404 µS cm^{-1}), streams (27–207 µS cm^{-1}), and ground water (25–149 µS cm^{-1}). The lower catchment waters tend to have higher concentrations of Cl^- (6 vs 2 ppm) SO_4^{2-} (6 vs 1 ppm), Na^+ (5 vs 2 ppm), and Ca^{2+} (4 vs 2 ppm). Values vary depending on rainfall conditions (with respect to depth and acid rain associated with the urban environment). As with the case of pH, however, insufficient data have been collected to determine controls, natural versus anthropogenic, of the differences among streams in the catchment.

Hydrological resilience

The Nee Soon freshwater swamp forest appears to be somewhat resilient to weather/climatic fluctuations, including the 2014–2016 drought, which contained the second driest year recorded for Singapore (Meteorological Service Singapore, 2015). In the simulated water balance for the 3-year study period, mean annual water storage loss in the catchment was an estimated 70 mm (Sun et al., 2018), a depth that surely taxed groundwater reserves feeding the swamp. Nevertheless, while many Singapore streams dried during the drought, much of the swamp area in Nee Soon remained wet or moist (observations by the authors).

Evidence of long-term resilience can be gleaned from our preliminary pollen analyses of a 1.95 m core taken from the lower swamp at Nee Soon. For example, old growth forest pollen was only about 20% at about 600 BCE, increasing to about 60% by 1000 CE. During this period, increasing numbers of fern spores and palm pollen provide evidence of increasing rainfall, because the other key variable for vegetation, temperature, can be assumed to have varied little at the equator in this time period. An abundance of rainfall is also suggested by the low values of charcoal found in the cores (i.e., few fires). Pollen and spores within a third sediment layer suggests gradually increasing cover of old growth forest and ferns, and decreasing grass. This period may be associated with increasing rainfall following the Little Ice Age (~1300–1870 CE). In recent times (the last 70 to 100 years), little change in the vegetation can be observed. Given that we have dated the deposits to more than 15,000 years, our initial pollen analyses indicate the swamp has remained despite the vegetation being quite different (e.g. from grasslands to forest) in response to changing climates.

Another form of resilience is associated with the persistence of the swamp despite inundation of the lower stream system when excess water is released over the slipway of the Upper Seletar Reservoir and released water flows backwards up the main stream channel, flooding the lower part of the swamp by several centimetres. The reverse flow transports sediments, nutrients, and biota into the swamp and up the stream network for short periods (typically less than a day). This artificial flooding occurs in response to weather conditions when water is exchanged between reservoirs, to maximise storage, relative to use, rainfall, and evaporative loss. Model results provide estimates of the magnitude of these flows: the reservoir contribution to total modelled catchment outflow was about 55% higher than that of natural stream flow in the lower part of the catchment (Liong Shui-Yui, personal communication).

Despite this hydrological resilience, we found evidence that substantial erosion has taken place within the stream network. Our analysis of the 1.95 m sediment core and the corresponding sedimentation rates, together with the observations of Murphy (1997), suggest that stream channel erosion has been significant in the past. In the sediment core we examined, dates derived from ^{14}C analysis (on pollen) corresponded to 1950 CE and 5500 BCE at depths of 50 cm and 51 cm, respectively (also discussed below). This large, abrupt age gap is best explained by the erosion of sediment layers that had accumulated over about 7000 years.

Murphy (1997) indicated incision of the stream by as much as 1 to 2 m may have resulted from runoff and accelerated erosion related to construction and maintenance of a water pipeline that bisects the catchment. During our recent surveys, disturbance by the pipeline, roads, and trails on the stream channel are apparent, but their geomorphological impacts are now less severe than indicated by Murphy (1997). The greatest disruption to the stream system is trampling during military training activities, by unauthorised personnel during hikes, as well as unauthorised mountain biking on sloping trails and stream crossings.

Soil erosion and denudation

By measuring the radionuclides ^{10}Be, ^{137}Cs, and ^{210}Pb and major elements in rocks and soils, we are able to assess the following: (a) element accumulation/loss related to physical and chemical weathering processes; and (b) catchment short- and long-term erosion and sedimentation rates (in accordance with human influenced and natural processes). Several elements, including Ca, K, Mg, Ba, Na, Mn, Ti, Co, Sr, Ni, Zn, Cr, Fe, and V, are depleted throughout the soil catena, relative to stable Zr. Loss in concentrations of elements of low mobility (e.g. K, Ti, Cr, and V) suggests intense weathering has occurred in the catchment. However, element depletion/enrichment is variable within soil profiles in the catchment. Alternating zones of enrichment and depletion of selected elements along catenas are not associated with commonly reported micro- or macro-environmental forcing variables (gradient, organic matter, soil texture, infiltration) but may be a result of pulses of surface erosion and deposition along the slopes.

Total denudation rate, determined from the cosmogenic nuclide ^{10}Be in Nee Soon stream sand (recalculated using the correction for quartz enrichment) is ~9 ± 0.8 m Ma^{-1}, or about 23.4 ± 2.08 Mg km^{-2} yr^{-1} (assuming a rock density of 2.6g cm^{-3}). The estimated physical erosion rate (5.6 ± 0.5 Mg km^{-2} yr^{-1}) and the chemical weathering rate (17.8 ± 1.58 Mg km^{-2} yr^{-1}) for soil are calculated from the total denudation rate based on a mass balance approach (Nguyen, 2017). These calculations suggest physical erosion accounts for only about 24% of total denudation, compared with 76% for chemical weathering and loss from the soils.

Low denudation rates are not unexpected in the Nee Soon catchment, given the gently sloping terrain (steepest stream slope is ~5^0) and dominance of forest vegetation. The unusually high contribution of chemical weathering (43–84%) is indicative of the warm temperatures and high rainfall of this tropical locale (N01.39017°, E103.80893°). We believe that the physical erosion rate (5.6 ± 0.5 Mg km^{-2} yr^{-1}) is slow compared with other studied granite-derived soil environments (e.g. in Riebe et al., 2001, 2004). However, because chemical weathering is high (accounting for c. 76% of the total denudation), biochemical processes likely play an important role in soil formation.

Our field observations suggest that tree uprooting, which causes redistribution downslope of the soil in the root mat, as well as bioturbation by abundant termite and ant activity extending into the B horizon, are important for soil formation/alteration. Moreover, volumetric strain calculations suggest that rock deformation and soil formation has been intense over a period of hundreds to thousands of years (Nguyen, 2017).

Dating of swamp sediments by the use of ^{137}Cs and ^{210}Pb(ex) suggests that a period of accelerated erosion may have occurred during and/or since the 1950s due to disturbance from the construction and maintenance of a water pipeline in the catchment and other peripheral activities at the lower catchment. Again, accelerated erosion related to these disturbances is not substantial today. Accelerated erosion associated with forest conversion to agriculture in the upper parts of the catchment also cannot be ascertained with these methods.

Sedimentation rates

We collected cores from the middle and lower swampy areas with a 6.36 cm gouge auger to determine sediment deposition and to support a variety of analyses (description, total organic carbon (TOC), bulk density, texture, elemental and oxides concentrations, radioisotope dating). Core depths vary from 1 to 1.95 m depending on the ability to penetrate subsurface material and recover an intact core. For the lower reach, we focus primarily on one core, but use others to provide additional material for analysis and to examine spatial patterns of deposition. Ages of various layers were determined from a variety of isotope techniques (^{14}C, ^{210}Pb and ^{137}Cs) on pollen, charcoal, and sediments. Thus, our interpretations reference a composite core, constructed from data from several cores (Fig. 4).

Within the total length of the composite core for the lower swamp, we demarcate several distinct layers having highly variable deposition rates (Table 2; see also Fig. 4). The ages of these layers extend back through the Holocene (0–11,700 BP) to before the Late Glacial Maximum (10,000–13,000 BP). However, the contemporary periods of maximum disturbance related to forest conversion to agriculture (from about 1850) are missing due to channel incision (layer 2), as mentioned above.

Only three dates can be determined for the middle swamp core. Radiocarbon

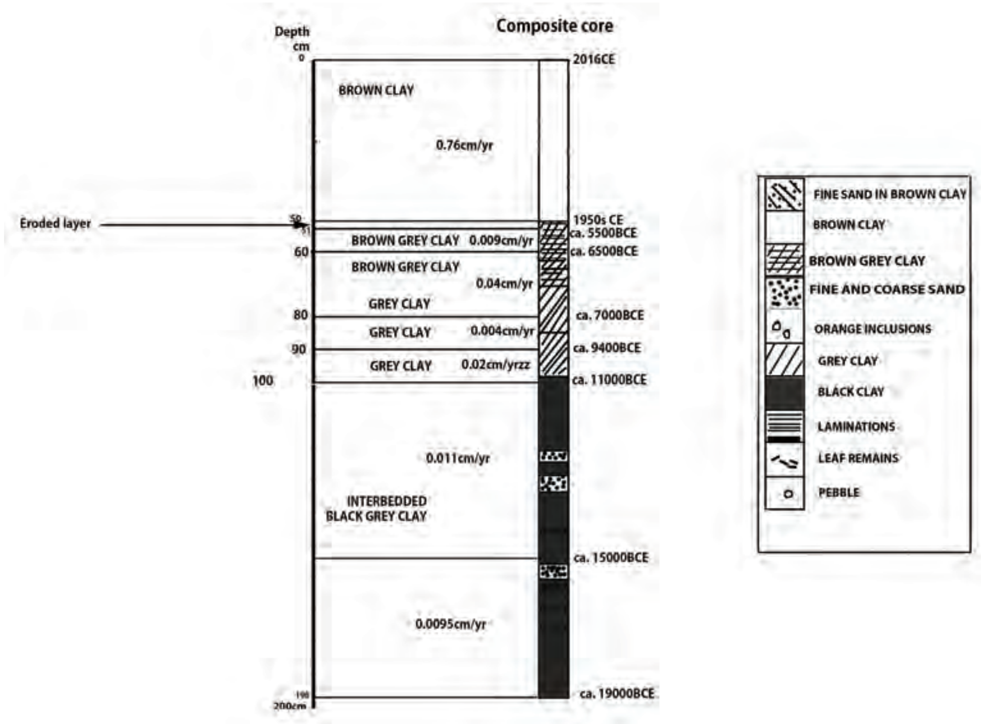

Fig. 4. Distinguishable layers and associated ages and deposition rates within the sediment core collected in the lower swamp of Nee Soon Catchment (location shown in Fig. 2a).

Table 2. Estimated deposition rates within layers revealed by composite soil core for the lower swamp area of Nee Soon freshwater swamp forest.

Layer	Depth	Age range	Sedimentation rate ($cm\ y^{-1}$)
1	0 – 50 cm	2016 to 1950 CE	0.76
2	Missing	No data	No data
3	51 – 60 cm	1950 BCE to 5500 BCE	0.009
4	60 – 80 cm	5500 BCE to 6500 BCE	0.04
5	80 – 90 cm	6500 BCE to 9400 BCE	0.004
6	90 – 100 cm	9400 BCE to 10,000 BCE	0.02
7	100 – 155 cm	11,000 BCE to 15,000 BCE	0.011
8	155 – 193 cm	15,000 BCE to 19,000 BCE	0.0095

dates on pollen indicate three distinct periods of accumulation: (1) present to 1273 CE (0–58 cm; 0.08 cm y^{-1}); (2) 1273–1241 CE (58–62 cm; 0.125 cm y^{-1}); and (3) 1241 CE to 657 CE (62–115cm; 0.09 cm y^{-1}). However, given the uncertainty in each estimate, as well as the similarity in accumulation rates, one rate of 0.1 cm y^{-1} can be assumed for the entire core, representing about 1360 years of deposition. The sedimentation rates suggest that the upper catchment swamp was not disturbed substantially by forest conversion to agriculture in the mid-19th century, whereas disturbance/change in the lower catchment has been dynamic with respect to climate and human activity. Again, direct comparison with the lower swamp is impossible, because sediments associated with the period between 1950 CE and 5500 BCE are missing in the lower core.

Lastly, anthropogenic inputs of Pb, and perhaps Ba and Cu, are detectable in the upper few centimetres of the cores (Kho, 2014, 2016; Nguyen, 2017). According to Chen et al. (2016) there are several possible sources contributing Pb to the nearby MacRitchie Reservoir in Singapore, including power generation-based coal combustion from nearby Indonesia (Lucarelli, 2010). Our isotope data are less variable than those of Chen et al. (2016), but also appear to be enriched by external sources, although it is not possible to calculate a source budget at this time.

Conclusions

The hillslopes and stream network of the Nee Soon catchment have been degraded by many decades of human impact, but their resilience is being demonstrated by clear evidence of recovery of the vegetation, soils, swamps and streams. Resilience of the hydrologic system helps to explain the apparent resilience of the aquatic fauna (e.g. Ng & Lim, 1992; Ho et al., 2018), including the survival of hyperendemics, despite disturbance of the associated vegetation. The upper catchment forested hillslopes were disturbed by anthropogenic activities beginning about 1850 when agriculture was first established. Some of the greatest disturbances occurred about 70–100 years later when the firing ranges were established, the lower stream and swamp network were disturbed by channel straightening, and erosion was accelerated from building and maintaining a water pipeline. Further, much of the lower catchment vegetation has been converted to urban land uses, including a golf course and roads, and the existence and operation of nearby reservoirs alters the catchment hydrology.

With respect to management, the following represent some of the most obvious current challenges to address: (a) disruption of the natural stream flow by water release from adjacent reservoirs; (b) high concentrations of some heavy metals in the soils within the military firing range; (c) inputs of heavy metal contaminants to the catchment through atmospheric deposition; and (d) disturbance of the forest slopes and the stream network by hikers, mountain bikers, and military personnel during training. Given that Nee Soon is the last remaining freshwater swamp forest in Singapore and an important site of biodiversity, we recommend addressing these management issues in tandem with conducting additional baseline research and a campaign of educational awareness.

Beyond identifying negative impacts, the goal of this study was to develop a hydro-geomorphological baseline for the Nee Soon catchment from which future studies and management activities could be developed. The initial findings, summarised briefly above, reveal shortcomings with respect to establishing such a baseline. Additional research is needed to improve our understanding of basic hydrological and geomorphological phenomena in the catchment: e.g. a) water balance components; b) stream dissolved and particulate fluxes; c) soil formation and denudation rates; d) hillslope degradation and transport processes; e) hydrological pathways; and f) anthropogenic contamination; g) and recommendations for management, particularly remediation of polluted sites.

ACKNOWLEDGEMENTS. This paper was completed as part of the research project titled "Nee Soon Swamp Forest Biodiversity and Hydrology Baseline Studies" Phase I and II (Project: TMSI-NS-FR-0816), executed by the Tropical Marine Science Institute, National University of Singapore, for the client National Parks Board (NParks), Singapore. We thank several students and researchers who provided insights and input to this work: Charlene Teo, Elvagris Segovia Estrada, Karisham Pai, Rachel Y.T. Kho, Lim Meng Wee, Muhd Herzad bin Mohd Rahman, Nisha Ramzdan, Ong Mia Xiang, Sebastian Canterrero, and Win Swe Hlaing.

References

Andriesse, J.P. (1988). *Nature and management of tropical peat soils*. *FAO Soils Bull.* 59. Rome: Food & Agriculture Organisation.

Balasubramanian, R., Victor, T. & Chun, N. (2001). Chemical and statistical analysis of precipitation in Singapore. *Water Air Soil Pollut.* 130: 451–456.

Briffett, C. & Ho, H.C. (1999). *State of the natural environment in Singapore*. Singapore: Nature Society (Singapore).

Brook, B.W., Sodhi, N.S. & Ng, P.K.L. (2003). Catastrophic extinctions follow deforestation in Singapore. *Nature* 424: 420–426.

Chen, F. (1999). *A study of heavy metal distribution in Singapore*. M.Sc. thesis, Nanyang Technological University, Singapore.

Chen, W., Tan, S.K. & Tay, J.H. (1996). Distribution, fractional composition and release of sediment-bound heavy metals in tropical reservoirs. *Water Air Soil Pollut.* 92: 273–287.

Chen, M., Boyle, E.A., Switzer, A.D. & Gouramanis, C. (2016). A century long sedimentary record of anthropogenic lead (Pb), Pb isotopes and other trace metals in Singapore. *Environ. Pollut.* 213: 446–459.

Chia, L.S., Rahman, A. & Tay, D.B.H. (1991). *The Biophysical Environment of Singapore*. Singapore: Singapore University Press.

Clews, E., Corlett, R.T., Ho, J.K.I., Koh, C.Y., Liong, S.Y., Memory, A., Ramchunder, S., Siow, H.J.M.P., Sun, Y., Tan, H.H., Tan, S.Y., Tan, H.T.W., Theng, M.T.Y. & Yeo, D.C.J. (2018) The biological, ecological and conservation significance of freshwater swamp forest in Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 9–31.

Corlett, R.T. (1991). Plant succession on degraded land in Singapore. *J. Trop. Forest Sci.* 4(2): 151–161.

Davison, G.W.H., Cai, Y., Li, T.J. & Lim, W.H. (2018). Integrated research, conservation and management of Nee Soon freshwater swamp forest, Singapore: hydrology and biodiversity *Gard. Bull. Singapore* 70 (Suppl. 1): 1–7.

Fauziah, C.I., Jamilah, I. & Syed Omar, S.R. (1997). An evaluation of cation exchange capacity methods for acid tropical soils. *Pertanika J. Trop. Agric. Sci*. 20: 113–119.

Ho, J.K.I., Quek, R.F., Ramchunder, S.J., Memory, A., Theng, M.T.Y., Yeo, D.C.J. & Clews, E. (2018). Aquatic macroinvertebrate richness, abundance and distribution in the Nee Soon freshwater swamp forest, Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 71–108.

Ives, D.W. (1977). *Soils of the Republic of Singapore*. *New Zealand Soil Survey Report* 36. Lower Hutt: New Zealand Soil Bureau, Department of Scientific and Industrial Research.

Kho, R.Y.T. (2014). *A sedimentary record of land use change and heavy metal deposition in Nee Soon Swamp Forest, Singapore*. B.Sc. (Hons) thesis, Geography Department, National University of Singapore, Singapore.

Kho, R.Y.T. (2016). *Impacts of different types of vegetation cover on soil hydraulic characteristics in Nee Soon Swamp Forest, Singapore*. B.Sc. (Hons) thesis, Geography Department, National University of Singapore, Singapore.

Li, T., Chay, C.K., Lim, W.H. & Cai, Y. (2016). The fish fauna of Nee Soon Swamp Forest, Singapore. *Raffles Bull. Zool.,* Suppl. 32: 56–84.

Lucarelli, B. (2010). *The history and future of Indonesia's coal industry: impact of politics and regulatory framework on industry structure and performance*. Program for Sustainable Energy Development, Freeman Spogli Institute of International Studies, Stanford University, Stanford, California, USA. https://pesd.fsi.stanford.edu/sites/default/files/WP_93_Lucarelli_revised_Oct_2010.pdf. Accessed 12 Dec. 2017.

Meteorological Service Singapore (2015). *Annual Climate Assessment 2015*. http://www.weather.gov.sg/wp-content/uploads/2016/03/Annual-Climate-Assessment-Report-2015.pdf. Accessed 2 Sep. 2016.

Murphy D. H. (1997). *Final report on map work and arthropod survey in 1994–96*. Singapore: National Parks Board.

Ng, O.-H., Tan, B.C. & Obbard, J.P. (2006). Lichens as bioindicators of atmospheric heavy metal pollution in Singapore. *Environ. Monit. Assess.* 123: 63–74.

Ng, P.K.L. & Lim, K.K. (1992). The conservation status of the Nee Soon freshwater swamp forest of Singapore. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 2: 255–266.

Nguyen, C.T.T. (2017). *Is Nee Soon catchment disturbed? A holistic approach to the catchment's elemental distribution, movement and deposition in soils and sediments.* Doctoral thesis, Department of Geography, National University of Singapore, Singapore.

O'Dempsey, T. (2014). Singapore's changing landscape since c. 1800. In: Barnard, T.P. (ed.) *Nature Contained: Environmental Histories of Singapore*, pp. 17–48. Singapore: NUS Press.

O'Dempsey, T. & Chew, P.T. (2013). The Freshwater Swamp Forests of Sungei Seletar Catchment: A Status Report. In: Leong, T.M. & Ho, H.C. (eds) *Proceedings of Nature Society, Singapore's Conference on "Nature Conservation for a Sustainable Singapore" – 16th October 2011*, pp. 121–166. Singapore: Nature Society (Singapore).

Rahman, M.H.B.M. (2016). *Soil Organic Carbon Stocks in the Nee Soon Swamp Forest*. B.Sc. (Hons) thesis, Geography Department, National University of Singapore, Singapore.

Riebe, C.S., Kirchner, J.W., Granger, D.E. & Finkel, R.C. (2001). Strong tectonic and weak climatic control of long-term chemical weathering rates. *Geology* 29: 511–514.

Riebe, C.S., Kirchner, J.W. & Finkel, R.C. (2004). Erosional and climatic effects on long-term chemical weathering rates in granitic landscapes spanning diverse climate regimes. *Earth Planet. Sci. Lett.* 224: 547–562.

Sin, Y.M., Wong, M.K., Chou, L.M. & Alias, N.B. (1991). A study of the heavy metal concentrations of the Singapore River. *Environ. Monit. Assess.* 19: 481–494.

Sodhi, N.S., Koh, L.P., Brook, B.W. & Ng, P.K.L. (2004). Southeast Asian biodiversity: an impending disaster. *Trends Ecol. Evol.* 19: 654–660.

Sun, Y., Kim, D.Y., Wendi, D., Doan, D.C., Raghavan, S.V., Jiang, Z. & Liong, S.Y. (2018). Projected impacts of climate change on stream flow and groundwater of Nee Soon freshwater swamp forest, Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 175–190.

Taylor, D., Yen, O.H., Sanderson, P.G. & Dodson, J. (2001). Late Quaternary peat formation and vegetation dynamics in a lowland tropical swamp; Nee Soon, Singapore. *Palaeogeogr. Palaeocl.* 171: 269–287.

Teo, W.T.C. (2016). *Assessment of Soil Heavy Metal Concentrations within the Nee Soon Swamp Forest.* B.Sc. (Hons) thesis, Geography Department, National University of Singapore, Singapore.

Tropical Marine Science Institute (2016). *Nee Soon Swamp Forest Biodiversity and Hydrology Baseline Studies Phase 2.* Final project report. Singapore: Tropical Marine Science Institute, National University of Singapore.

Wee, Y.C. & Ng, P.K.L. (1994). *A first look at Biodiversity in Singapore*. Singapore: National Council on the Environment.

Zhou, C.Y., Wong, M.K., Koh, L.L. & Wee, Y.C. (1997). Soil lead and other metal levels in industrial, residential and nature reserve areas in Singapore. *Environ. Monit. Assess.* 44: 605–615.

Ziegler, A.D., Negishi, J.N., Sidle, R.C., Noguchi, S. & Nik, A.R. (2006). Impacts of logging disturbance on saturated hydraulic conductivity in a tropical forest in Peninsular Malaysia. *Catena* 67: 89–102.

Ziegler, A.D., Terry, J.P., Oliver, G.J.H., Friess, D.A., Chow, T.W.L., Chuah, C.J., Wasson, R.J. (2014). Increasing Singapore's Resilience to Drought. *Hydrol. Process.* 28: 4543–4548.