Gardens' Bulletin Singapore 70 (Suppl. 1): 191–217. 2018
doi: 10.26492/gbs70(suppl.1).2018-10

Conservation outputs and recommendations for Nee Soon freshwater swamp forest, Singapore

Y. Cai[1], G.W.H. Davison[1], L. Chan[1,2] & S.Y. Liong[3]

[1]National Biodiversity Centre, National Parks Board,
1 Cluny Road, 259569 Singapore
cai_yixiong@nparks.gov.sg
[2]International Biodiversity Conservation Division, National Parks Board,
1 Cluny Road, 259569 Singapore
[3]Tropical Marine Science Institute, National University of Singapore,
18 Kent Ridge Road, 119227 Singapore

ABSTRACT. The current paper acts as a summary to the "Nee Soon Swamp Forest biodiversity and hydrology baseline studies project", including results published previously and the results from papers of the current volume. Overall, flora and fauna surveys indicate healthy and diverse plant, fish and aquatic macroinvertebrate communities in Nee Soon freshwater swamp forest. There are some concerns over terrestrial and aquatic alien invasive species, loss of big emergent trees, small population sizes and viability of various native species, and the uncertain outcomes of changes in water quality and quantity. The findings inform management that Nee Soon freshwater swamp forest is especially vulnerable to changes in hydrology and there is much dependency on precipitation for its water budget. Projected climate change effects on precipitation and statistical analyses of biotic responses to hydrology clearly define drought as a major, perhaps the foremost, source of vulnerability to the ecosystem functioning of Nee Soon freshwater swamp forest. Potential management solutions are suggested to address five issues of concern for the forest: hydrological integrity, erosion and sedimentation, ecological integrity, the impact of the spillway, and impacts of construction and development.

Keywords. Biodiversity management, hydrological management, monitoring, wetlands

Introduction

Nee Soon constitutes Singapore's last remaining patch of primary freshwater swamp forest. From the viewpoint of ecosystem diversity alone, this makes the conservation of the Nee Soon freshwater swamp forest a priority (Clews et al., 2018). The number of plant and animal taxa currently found nowhere else in Singapore but Nee Soon only emphasises its conservation value. Given that Nee Soon freshwater swamp forest houses a large proportion of Singapore's overall flora and fauna, conservation of this habitat undoubtedly has larger-scale, positive effects for biodiversity conservation in Singapore as a whole (Ng & Lim, 1992; Turner et al., 1996), addressing the conservation of biodiversity from species to landscape scales.

Owing to the nature of its ecosystem and drainage, the Nee Soon freshwater swamp forest is extremely sensitive to external disturbances (Ng & Lim, 1992). Furthermore, many of the species found here are highly specialised and, thus, destruction of the Nee Soon freshwater swamp forest and its surrounding areas would pose a great threat to these unique groups of species. Therefore, it is important to maintain Nee Soon freshwater swamp forest in approximately its current state, as well as ensuring that it is not affected adversely by development and other environmental pressures.

The Nee Soon hydrology and biodiversity project was a response to the need for better understanding of the forest ecosystem and its dynamic processes, as a basis for management and monitoring (Davison et al., 2018). A detailed but still in many respects preliminary review of the results has been given in the accompanying papers in this same volume (Cai et al., 2018; Chong et al., 2018; Clews et al., 2018; Ho et al., 2018; Kutty et al., 2018; Lim et al., 2018; Nguyen et al., 2018; Sun et al., 2018).

Project Aims

The project aimed to undertake field and modelling investigations that were required in order to create maps and collate information for the development of eco-hydrological models of Nee Soon freshwater swamp forest. The project was carried out in two phases, from January 2011 to March 2012, and from February 2013 to August 2016. The detailed aims of each phase are listed by Davison et al. (2018).

Table 1 summarises the achievements of the project and these fully covered the listed aims.

Results

Mapping and geodatabase

Phase 1 of the "Nee Soon Swamp Forest hydrology and biodiversity project" generated important baseline datasets on the hydrology, geology, topography and flora of the area and clearly set out the research path for Phase 2. Key focus areas of relevance to mapping and imagery included: (i) the development of more refined hydrological models for systems understanding and for utilisation in scenario modelling; and (ii) establishment of current ecological status/condition across a number of biotic and abiotic components. The geospatial team had a major underpinning role in Phase 2 of the project, achieved through two broad tasks, the collection and analysis of spatial information, and the collation of all such information into a geodatabase.

The environment of Nee Soon freshwater swamp forest represented a challenge to conventional topography due to limitations in access. Moreover, line-of-sight was greatly reduced in areas of higher tree density, constraining the efficacy of direct topographic surveys. Through application of remote sensing techniques, direct topography effort was optimised, focusing on acquiring high-resolution stream data and ground control points for validation of remote-sensing models. Photogrammetry of remote sensing imagery involves the use of digital image data in conjunction with automatic image matching techniques to produce Digital Elevation Models (DEMs)

Table 1. Achievements in Phase 2 of the Nee Soon hydrology and biodiversity project.

#	Aims	Achievements
1	Establish the status of Nee Soon freshwater swamp forest in terms of vegetation hydrology and aquatic biodiversity	1. Literature Review of freshwater swamp forest literature and research on the Nee Soon freshwater swamp forest updated (Tan et al., 2013; Clews et al., 2018); new results derived from this project presented on vegetation (Chong et al., 2018), fauna (Cai et al., 2016, 2018; Li et al., 2016; Ho et al., 2018; Lim et al., 2018) and cryogenics (Kutty et al., 2018). 2. Assessment of geomorphology in relation to catchment hydrological function (Nguyen et al., 2018). 3. Consolidation and documentation of all spatial data into a geo-database (Davison et al., 2018; Sun et al., 2018).
2	Identify periodic flux in hydrology and key components of the aquatic biodiversity	1. Assessment of variation on intra- and inter-annual hydrographs (project reports). 2. Stream hydrological regimes examined as well as faunal responses to hydrology (project reports and Ho et al., 2018).
3	Develop more refined models that can confirm current conditions (water balance, nutrient balance, acid flux, faunal distribution) and then test-trial various management scenarios	1. Developed an integrated eco-hydrological model using Mike-SHE (Sun et al., 2018); 2. Simulated and assessed twelve future scenarios (Sun et al., 2018). 3. Developed conceptual models of erosion and elemental redistribution in the catchment as related to hydrological and geomorphological processes (project reports; Sun et al., 2018) 4. Elucidated faunal response models (project reports and Ho et al., 2018).
4	Identify and assess root causes of impacts, potential issues that may threaten the hydrological and ecological integrity of the swamp, and management elements to be addressed	1. Investigated, using numerical model, effects of rainfall and reservoir operating levels on the spatial distribution of surface and ground-water. 2. Impacts of climate change. 3. Investigated the responses of seedlings of six tree species common in Nee Soon freshwater swamp forest to changes in soil and hydrology and tree coring for measurements (Neo et al., 2017). 4. Investigated spatio-temporal variation in faunal communities in association with physicochemical and hydrological data to identify key issues likely to affect in-stream fauna, Management recommendations to monitor and maintain the ecological integrity of the forest stream faunal communities. 5. A synthesis of long-term (historic) and more recent/current environmental impacts on the Nee Soon freshwater swamp forest catchment.

Table 1. Continuation.

#	Aims	Achievements
5	Agree on the necessary recommendations for possible mitigation of long-term negative impacts	1. The Management Recommendations Chapter of the final report synthesises and consolidates recommendations for management of the swamp forest drawing on detail provided in preceeding chapters. 2. Proposed mitigation management for extreme flooding and drought 3. Proposed to carry out propagation of rare plant species in Nee Soon and use the propagules for restoration of potential freshwater swamp forest sites elsewhere to mitigate the risks of extinction of these native species over the longer term 4. Recommendations relevant to aquatic fauna are with respect to i) extreme flooding and drought; and ii) other potential management issues such as the introduction of non-native taxa and erosion.
6	Establish a viable, long-term monitoring programme and sampling protocols to ensure continued protection and good management	1. Recommendations for ecological monitoring of streams. 2. Set up and handed over 40 vegetation plots for long-term monitoring of tree growth, recruitment, and mortality in the wet and dry areas of Nee Soon. The GPS coordinates and tracks to the 40 plots have also been prepared.
7	Train agency staff in modelling, sampling methods and tools for monitoring	1. A training course for application of Eco-hydrological Modelling developed from this study was held on 22nd July 2016. 2. On the 11th June 2015, a workshop on the identification of fish, decapod crustaceans and macroinvertebrates from the Nee Soon freshwater swamp forest was held. Several theory and practical sessions for aquatic faunal identification purposes were facilitated by both NUS (TMSI, DBS, and LKCNHM) and NParks staff. 3. Sampling methodology for faunal collection was also introduced in the introductory field resource, "A Guide to the Freshwater Fauna of Nee Soon swamp forest" (Ho et al., 2016) which was reviewed during the workshop and revised in response to participants' feedback. 4. The e-book version of the guidebook is available at http://emid.nus.edu.sg/ebooks/web/viewer.jsp 5. In phase 1 of the Nee Soon freshwater swamp forest project, a workshop was held to train NParks staff on identification of the common plants of Nee Soon freshwater swamp forest. One book was also published to facilitate the identification of these plants.
8	Deliver workshops on development and interpretation of the models' outputs	1. Conducted workshop for non-governmental organisations and individuals at Hort Park, Singapore, December 2016 2. Seminar provided to University of Warwick, UK, March 2017 3. Other workshops to be provided as required

Table 1. Continuation.

#	Aims	Achievements
9	Publish work on swamp forest ecology and the development of eco-hydrological models in international, peer-reviewed scientific journals	So far, one guide book (Ho et al., 2016), one book chapter (Cai et al., 2016), nine journal papers (Neo et al., 2016, 2017; Sun et al., 2015, 2016; Chong et al., 2016; Li et al., 2016; Lim et al., 2016; Tan et al., 2016; Wendi et al., 2016) and 18 conference papers have been published. Another eight papers have been accepted for publication (Cai et al., 2018; Chong et al., 2018; Clews et al., 2018; Ho et al., 2018; Kutty et al., 2018; Lim et al., 2018; Nguyen et al., 2018; Sun et al., 2018).

and ortho-images to act either as direct input to a GIS system or as the basis for the production of hardcopy image maps or line maps.

Ecohydraulic models require approximation of evapotranspiration (ET), which is difficult to measure in the field. For the purposes of the Nee Soon freshwater swamp forest study, ET data from MODIS satellite were used. These satellite data compared reasonably well with Leaf Area Index (LAI), which is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation occurs. Beyond simple applications for theoretical purposes, hydrological and hydrodynamic models operate on spatial grids, requiring the different types of information to be spatially compatible. Under the broad theme of remote sensing and mapping, the Geospatial team managed and quality-assured the efforts of the direct topographic survey, conducted remote sensing for additional data acquisition, and converted all data into spatial formats suitable for utilisation by the hydrological modelling team.

Surveyors were engaged to conduct direct topographic surveys in Nee Soon freshwater swamp forest. Following quality assurance checks, the field data were converted into shape files and compiled for upload to the geodatabase. The data were then processed to generate i) a 3D drainage network for Nee Soon freshwater swamp forest; and ii) 1,647 cross-sectional profiles at 5 m spacing along the network. These outputs were provided to the hydrological modelling team.

A file geodatabase was established using ESRI's ArcGIS Platform. The Geodatabase created forms the Nee Soon Freshwater Swamp - Geographical Information System (GIS) which helps to organise, manage and analyse data spatially (geo-referenced) and non-spatially pertaining to the study.

In order to establish the geodatabase, the version of ArcGIS utilised was ArcGIS 10.1 for desktops. ArcGIS is a proprietary GIS suite of systems developed by ESRI (Environmental Systems Research Institute). The ArcGIS suite's components include ArcMap, ArcCatalog and ArcToolbox, which allow users to author, analyse, map, manage, share, and publish geographic information. ArcGIS works with geographic information managed in geodatabases as well as in numerous GIS file formats. The geodatabase is the native data structure for ArcGIS and is the primary data format used for editing and data management. Geodatabases work across a range of database management system (DBMS) architectures and file systems, come in many sizes, and have varying numbers of users. They can scale from small, single-user databases built on files up to larger workgroup, department, and enterprise geodatabases accessed by many users.

The Nee Soon file geodatabase is a single centralised location with metadata that gives information on the ownership and authorisation of data. Currently, the file geodatabase contains 68 layers of both raster and feature layers. ArcMap related layers are categorised as groups shown in Table 2. All the digital information is retained by the National Biodiversity Centre, National Parks Board, Singapore, and (with appropriate access restrictions and provisos) on the web-based information platform named BIOME.

Field hydrology and geomorphology

Effective conservation of the Nee Soon Catchment will require strategies informed by the dynamic baseline of the system, as well as the sources of current anthropogenic disturbance. While conservation efforts may be primarily concerned with preserving the unique ecosystems and highly diverse floral and faunal communities, these systems are intrinsically linked to the geomorphic and hydrological stability of the catchment. Thus, the underlying hydrology and sedimentary processes must be considered when implementing management efforts. This consideration was fundamental to the rationale, aims, design, conduct and deliverables of the project, linking all the work by the various teams.

Soil erosion reduces the water holding capacity and results in more rapid water runoff, causing soil organic matter and nutrients to be transported downslope. This process can greatly affect species diversity of plants, animals, and microbes by rapidly exporting water, nutrients, and other biological resources out of the biological system (Zuzao & Pleguezuelo, 2008). Erosional processes are aggravated by a reduction in forest land cover (Rahman et al., 1991); the canopy of vegetation stabilises the hillslopes through the adsorption of rainfall and binding root systems drawing moisture from the groundwater. This protects the ground surface by shielding it from rain impact as well as removing water from the soils and reducing the frequency of soil saturation and subsequent surface runoff. Landscape modifications to facilitate farming, irrigation, and drainage has altered stream flow and subsequently contributed to sedimentation in low lying areas (Schumm, 1973).

Stream channel bunding in the lower catchment has significantly deepened the valley floor, preventing water from spreading towards the expressway. This enhances erosion along the stream channel and limits the development of the swamp forest area as well as likely increasing the sediment load to the Lower Seletar Reservoir. One potential strategy for mitigating these enhanced erosional processes is to fill in the channel to restore the hydrological functioning of the swamp. However, this intervention may affect fish communities that have since developed in the channel.

Table 2. Group Layers in Nee Soon freshwater swamp forest file geodatabase.

Group Name	Layers
Gauges	Piezometer Sondes Water sample points HydroVegetation station
Stream network	Streamline Stream centrepoints Stream photo Profile 2014 Drain network 3D 2014 Cross section line 2014 Cross section point 2014
Restricted area	Firing range Restricted Area
Vegetation	Swampforest extent (GEO Team) Swampforest extent (Modelling Team) Tree photo Tree 2014 Tree DBH Tree plot Vegetation Plots Leaf Area Index (Hi Resolution) Leaf Area Index
Fauna	Fauna Plots FE_SamplingPts
Topographical features	Road 2014 Bollard 2014 Concrete Lining 2014 Corner of Column 2014 Drain Features 2014 Fence 2014 Filter 2014 Guardrail 2014 Inspection Chamber 2014 Line Work 2014 Sump 2014 Wooden Pole 2014 Wall 2014 Water Valve 2014 Water Pipeline 2014 Near Bamboo Veg 2014
Nee Soon boundary	Nee Soon Catchment boundary Catchment Phase2 (old)
DEM	NS_DTM_1m_Ver2 (new) Topo drainage DEM ns2_DEM (older)

Other causes for enhanced erosion rates are the presence of trails and traffic of trekkers, bikers, and hunters who damage tracks and bridges. The clearing of vegetation and increased activity along this area increases the soil mobility and transport of sediments. Further restricting visitors to the catchment and repairing damage to the tracks and bridges would help serve to stabilise these processes. Forest recovery and replanting of endemic floral families would aid in not only the ecological resurgence of the reserve, but also the retention of water, sediments, and nutrients in the system.

The excavation of a soil pit in the upper catchment uncovered ancient charcoal remains, indicating clear evidence of past fires (Nguyen et al., 2018). Fires along the hillslopes and dryland forests are not only capable of removing large swathes of primary and old secondary forest, but may expose the slopes to significant erosion during subsequent precipitation and inundation. The apparently increasing severity of El Niño effects (Sun et al., 2018), the spread of development and human activities close to the edges of Nee Soon freshwater swamp forest, and other human pressures within the nature reserve may all increase the likelihood of fires. Therefore, the catchment must be readily accessible for fire fighters appropriately trained for operation in a nature reserve. The specialised techniques required would differ significantly from fire fighting in non-forested areas. It is unlikely but conceivable that some plant species require fire for germination and the relative importance of hillslope stability and ecological succession must be considered.

The construction of the firing range, golf course, and expressway within or close to the Nee Soon freshwater swamp forest may be affecting the water and soil quality of the stream channels (Nguyen et al., 2018; Sun et al., 2018). Analysis of soils for heavy metals throughout the reserve found that soils in the lower catchment are significantly more enriched than those in the upper catchment. Due to the compositional homogeneity of soils in the enriched and normal zones, it has been concluded that some components of the heavy metal enrichments may be a result of such nearby developments (Nguyen et al., 2018).

It has been reported that the water supply pipeline cutting across the catchment from the Upper Seletar Reservoir to the Lower Pierce Reservoir did experience early problems with line breakages due to defective operation of the pump pipeline and contributed to significant erosion in the lower catchment (Murphy, 1997). It is important to ensure that the pipeline does not leak significantly and that the bund along its side does not erode into the swamp.

Finally, the dam at the mouth of the Upper Seletar outlet when opened has been observed causing regular back-flooding into the swamp flushing the system with reservoir water, and facilitating the influx of alien aquatic vertebrates and invertebrates. Strategies to prevent back-flooding need to be investigated.

Friess et al. (2015) estimated the entire island of Singapore had an average of 60 Mg C , which is more than the mean stocks held by 100 other cities around the world (Dobbs et al., 2014). Considering the urbanised state of the island, the natural areas disproportionately hold the majority of the carbon stocks. Sites like the Nee Soon freshwater swamp forest should thus continue to be protected and managed carefully in order to maximise its carbon sequestration potential.

Vegetation ecology

Although the field study found that soil conditions appeared to be more important than the presence of open water in structuring tree communities, experiments with seedlings showed that for three of the five species, flooding had a significant effect on growth responses but not the soil type. Taken together, these results suggest that flooding leads to the formation of the tree community structure and the accompanying soil properties in the freshwater swamp forest over time. Seedlings growing in the swamp forest substrate are likely to be more resilient against short-term droughts.

Many nationally uncommon and rare plant species are restricted to the swampy parts of the Nee Soon catchment. The catchment is also a hotspot of new plant records and rediscoveries of species that have previously been presumed to be extinct in Singapore. The Nee Soon freshwater swamp forest is therefore of high floristic conservation value locally (Chong et al., 2018; Clews et al., 2018).

The vegetation ecology team predicts that non-swamp plant species are more vulnerable than swamp species to anticipated changes in the hydrology of the Nee Soon catchment in the future. In some sense, this may be good news, as the swamp flora is generally more unusual and tends to be locally rarer. It is expected that about 2–4 weeks may elapse from the onset of a severely receded water table in originally swampy areas following extreme drought, before mass die-offs of seedlings will occur so this provides some buffer time for action to be taken, for example, for manual irrigation to be set up. However, the time lag periods for saplings and mature trees were not investigated during the study. It could be anticipated that the deeper roots of larger trees would provide them with a longer buffer period, but water stress might also be amplified.

An ordination analysis was conducted to investigate the relationship between the tree community and soil and hydrology. It was only a cross-sectional study and should be viewed as correlative rather than causal. To investigate the impacts of drought or extreme flooding on mature trees would require either of two approaches:

1) field manipulations of precipitation (e.g. using rain screens) and hydrology (e.g. digging soil trenches or creating artificial flooding) followed by monitoring of trees. "Drought-Net" is a global network of study sites that are using standardised methods such as these to artificially create drought-like conditions for plants. However, they lack partner sites in forest biomes due to the logistic and operational difficulties of creating rain screens over a forest canopy. Additionally, given that the Nee Soon freshwater swamp forest is the last substantial tract of this forest type in Singapore, there would be concerns whether such large-scale manipulations within the forest could cause more harm than the resulting science could be beneficial. Tree coring to provide direct measurements of sap flow could not be carried out during this study for the same reason. A possible solution is to find alternative patchy freshwater swamp areas outside nature reserves, which are of lower conservation value, for hydrological manipulation and sap flow experiments.

2) Long-term monitoring of soil hydrology coupled with tree health is the other approach, but will require a long time to accrue useable data, and will depend on whether different hydrological conditions will occur in the sampled areas over the

monitoring period. The trees mapped in the 40 vegetation plots that have now been handed over to NParks, will provide baseline data for future monitoring; establishing more plots would increase the probability of sampling future fluctuating hydrological conditions.

Furthermore, the plant species that were found to be rare or restricted to the Nee Soon freshwater swamp forest should be targeted for propagation. These propagules can then be transplanted elsewhere. For example, they can be used for restoring other potential freshwater swamp sites, and hence the dilution of conservation threats. The community assembly patterns within the Nee Soon freshwater swamp forest may provide further insight on restoration strategies. For example, species such as *Gynotroches axillaris* Blume and *Pellacalyx axillaris* Korth. are commonly found in other swampy areas in the Central Catchment Nature Reserve, but these sites seldom have other swamp indicator species such as *Baccaurea bracteata* Müll.Arg., *Lophopetalum multinervium* Ridl., *Mussaendopsis beccariana* Baill., *Palaquium xanthochymum* (de Vriese) Pierre ex Burck, *Pometia pinnata* J.R.Forst. & G.Forst., etc. and almost never have the rarer swamp *Syzygium* R.Br. ex Gaertn. spp. or nutmegs (Myristicaceae family). Two main reasons can be suggested: (1) these species are dispersal-limited from establishing populations in other swampy sites beyond the Nee Soon catchment; (2) specific soil or biotic conditions are limiting the establishment of these species. The first reason can be overcome by transplanting propagules obtained from the Nee Soon freshwater swamp forest. The second reason would require more detailed studies and experimentation that involve swampy sites outside of the Nee Soon catchment.

Regarding concerns about increasing tree falls and diebacks, the vegetation ecology team considered that these are more likely to occur (1) for large trees (2) of species with weaker wood, and more often observed (3) along forest edges, such as around the firing ranges and along the pipeline. Only systematic monitoring and dedicated data collection can test these hypotheses, and determine the extent of the issue, together with possible solutions. This could begin with large trees, e.g. >10-cm DBH, within visual range of the forest edge. These should be measured, mapped, identified, tagged, and checked for liana infestation of the crown that may cause it to be at risk of being pulled down by other falling trees. Whenever researchers, ground staff, or members of the public report that a tree fall has occurred, the manager in charge of the area could visit the affected site and (1) determine if any of the mapped trees have been affected, (2) salvage any crown epiphytes and rare climbers that may have been brought down by the tree fall, (3) log the exact locality, spatial extent of the affected area, and the estimated time of occurrence of the event for future analyses. The 40 vegetation plots established during this study, and the tree plots set up within the Central Catchment Nature Reserve previously, can be used as baselines for monitoring tree fall, dieback, growth and regeneration. These can be supplemented by regular (e.g. bimonthly to half-yearly) surveys along the forest edges to check the status of these trees. The field guides being published as a result of this study, in addition to the voucher specimens that were collected and that will be deposited in the two Singapore herbaria, should help future researchers and staff to identify most of the large trees.

Floristic exploration of the Nee Soon catchment should continue, with more emphasis on epiphytes and lianas as these were under-represented in our surveys. In addition, a catchment-wide survey focused on identifying very large trees, e.g. >30-cm DBH, may yield more rediscoveries, new records, or rare species that can be targeted for conservation action.

Faunal ecology

Aquatic communities vary spatially across the Nee Soon freshwater swamp forest. The variations are responses to the hydrological conditions, principally stream depth characteristics. Depth is correlated with stream order (the order of branching), from source to confluence. A higher diversity of benthic macroinvertebrate, pelagic decapods and fish were observed in larger streams. However, this diversity was not necessarily representative of the least disturbed fauna for the swamp forest streams, because non-native invasive species were commoner (and added to the species total) in the larger streams.

Spatial and temporal studies of the fish and decapods in the Nee Soon freshwater swamp forest indicate that there exists a healthy community of native fish and decapods within the Nee Soon freshwater swamp forest. However, the situation is different towards the lower catchment and the edge of the forest, where the community contains a large percentage of introduced species. Additionally, the main drivers of diversity and richness among the fish and decapod community appear to be substrate type, stream depth and stream order.

With this in mind, an important recommendation is to maintain constant monitoring of the faunal communities in the Nee Soon freshwater swamp forest, especially in the more upstream sites, so as to ensure that introduced species do not successfully establish within such sites. If any individuals from an introduced species are found they should be immediately removed, as they may have adverse effects on native species once established, as has occured in many other places (Ogutu-Ohwayo, 1990; Beisner et al., 2003).

Additionally, the temporal results suggest that the Northeast monsoon period (December to February) is an important breeding period for several species of fish. Therefore, it is important that any form of disturbance in the streams during this period be minimised. Otherwise, there may be serious effects on the long-term survival and viability of these fish populations, something which cannot be afforded as many of the fish in the Nee Soon freshwater swamp forest are endangered in Singapore.

Again, the lack of introduced species in the middle and upper catchment is heartening, and it is imperative that monitoring continues to be carried out to maintain this state of affairs and prevent establishment of introduced species deeper in the Nee Soon freshwater swamp forest.

Invertebrate communities found at the downstream “edge habitat” sites closer to the Upper Seletar Reservoir spillway were more diverse (higher richness and abundance) than in the rest of the Nee Soon freshwater swamp forest. Nevertheless the aquatic community at the “edge habitat” sites was not indicative of a “healthy” forest stream system (Blakely et al., 2014). Macroinvertebrates such as chironomids and snails that tend to be dominant in less “healthy” systems, and indicative of more enriched and alkaline conditions, were in abundance at these sites. An abundance of introduced fish species was also recorded at these sites, in comparison to the predominantly native fauna in the remainder of Nee Soon.

The downstream “edge habitat” sites were likely influenced by disturbance from the spillway discharging water from the reservoir periodically, discharging mixing Nee Soon catchment and reservoir water and backing up into the stream system. The lack of riparian habitat complexity (sparse tree cover) and dominance of fast-growing vegetation, symptomatic of frequent disturbances at these sites, as well as more alkaline water chemistry, provided less suitable niches for the more sensitive native fish or rare invertebrates (e.g. Megalopterans and Plecopterans).

The hydrological conditions in Nee Soon freshwater swamp forest reflected the wet and dry seasons in Singapore (Chia & Foong, 1991), with high water levels recorded during the wet phases of early Northeast monsoon (November to December) and Southwest monsoon (June to September); and low levels during the dry phase of the late Northeast monsoon season (January to early March). The macroinvertebrate composition was reflective of short-term changes in abiotic conditions (Barbour et al., 1999), where the diversity of community corresponded to dry versus wet seasons (i.e. high abundance in wet season, low abundance in dry season).

Faunal responses to hydrology were examined for the invertebrate fauna since i) temporal patterns were evident in invertebrate communities when considered against high frequency water-level observations, whereas fish communities were generally not correlated with corresponding intra-annual changes in water level; and ii) the invertebrates tend to be relatively less mobile than fish and more sensitive to short-term changes in the aquatic environment (Barbour et al., 1999). Spatio-temporal patterns in fish communities were most strongly evident in the spatial variation of communities which points to the importance of factors such as water quality and associated tolerance and resilience of the more “typical” (native) swamp forest fish community within the heart of the catchment in contrast to the edges of the catchment and in proximity to the spillway that discharges water from the reservoir.

Faunal response models reflected the potential effects of drought and disturbance caused by elevated discharge. They revealed that when water levels were at their lowest, the richness and abundance of invertebrates were reduced. Conversely, the richness and abundance of invertebrate fauna was also reduced when maximum stream water levels were greater.

Model results suggest that effects of minimum water level are more pronounced than those of high water levels and that smaller streams are likely to be more susceptible to very low faunal counts and even absence of invertebrate fauna altogether at high maximum water levels or low minimum water levels. The most pertinent implications of these results for the long-term management of the swamp forest streams is the potential loss of individuals but perhaps more crucially, loss of taxa is anticipated from the smaller streams in particular during periods of extreme, extensive low and high flows. This is of particular relevance in the context of predictions of more intense and prolonged dry and wet periods in the face of climate change.

Faunal diversity and conservation

Diversity and abundance changes of the freshwater fish and decapod fauna of the freshwater swamp forest were investigated with the aim of facilitating future conservation actions. Surveys were carried out by hand sampling and trap sampling from February 2013 to May 2014 in 12 sites that represent different microhabitats from the outskirts to the lower, middle, and upper reaches of the streams draining the catchment. Stream water parameters (temperature, pH, DO, TDS, etc.) and stream profile characters (substrates, cross section, canopy cover, and riparian vegetation) were recorded (Cai et al., 2016; Li et al., 2016). Together with the aquatic survey, visual-encounter surveys were conducted for terrestrial snails on each side of the stream banks. The air humidity and temperature were also recorded at each site. Biodiversity baselines were also established for dragonflies of Nee Soon freshwater swamp forest based on quantitative sampling across the eight sub-catchments. Hydrological, physiochemical parameters and habitats were analysed to identify the main drivers structuring the dragonfly community (Cai et al., 2018).

Species diversity and abundance

Thirty-three species of native freshwater fish and 9 species of decapod crustaceans (5 shrimps and 4 crabs) have been documented in detail. Analysis of the species diversity at individual sites showed that one of the sites in the middle of Nee Soon freshwater swamp forest supported the highest diversity and richness of native freshwater fish and decapods. This site has a deep open pond with slow water flow and is directly connected to the forest boundaries at both ends by shallow streams. The sandy substrate, uneven stream bed flanked with large patches of aquatic vegetation and leaf litter contained a variety of microhabitats stratified for different species of fish and crustaceans, which could account for the high species diversity. Sites at the outskirts of Nee Soon freshwater swamp forest supported the highest species diversity of introduced fish and shrimp. The periodic release of water from the Upper Seletar Reservoir might have contributed to the high species diversity of introduced fish and shrimp. The four most abundant native species of fish found in Nee Soon freshwater swamp forest were *Trigonostigma heteromorpha, Hemirhamphodon pogonognathus, Rasbora elegans* and *Betta pugnax*, and the most abundant species of shrimp and crab are *Macrobrachium malayanum* and *Parathelphusa maculata* respectively (Cai et al., 2016; Li et al. 2016). A total of 10 families, 18 genera and 19 species of land snails were recorded from the Nee Soon freshwater swamp forest. The outskirts had the highest species diversity, while the Upper Swamp had the lowest species diversity. The three most abundant species found in Nee Soon freshwater swamp forest are *Liardetia convexoconica*, *Helicarion perfragilis* and *Hemiplecta humphreysiana* (Lim et al., 2018). Fourty-nine species of odonates, belonging to 34 genera in 11 families were recorded in the current study. An updated species list of Nee Soon dragonflies is provided for future reference, with 67 species belonging to 47 genera in 11 families, representing about half of all odonates ever recorded in Singapore. Among the eight sub-catchments, the three mid sub-catchments all show low abundance and species richness. This is followed by the two upper sub-catchments. The three low sub-catchments all had high abundance and species richness. Hierarchical clustering and Detrended Correspondence Analysis (DCA) indicated that three main groupings of sites existed, each with a distinct community of associated species. Further analysis by Canonical Correspondence Analysis (CCA) with 12 significant environmental variables showed that these groups were significantly associated with respective environmental variables (Cai et al., 2018).

New records of native species

The current survey recorded a native fish species new to Nee Soon freshwater swamp forest: *Barbodes lateristriga*. It was observed mostly in the middle swamps with moderate canopy coverage and deep, open stretches of water converging to large ponds. One semi-slug, *Damayantia* cf. *simrothi* is believed to be a new record for Singapore and was found at six sites in Nee Soon. Eighteen native species of odonates were new to Nee Soon freshwater swamp forest though most of them are widespread common species in Singapore and only found at the outskirts or in open parts of the study area, viz. *Podolestes orientalis*, *Libellago lineata*, *Argriocnemis rubescens, Pseudagrion australiasiae*, *Pseudagrion microcephalum*, *Copera marginipes*, *Onychargia atrocyana*, *Acisoma panorpoides*, *Crocothemis servilia*, *Lathrecista asiatica*, *Neurothemis fluctuans*, *Orthetrum sabina*, *Orthetrum luzonicum*, *Psedothemis jorina*, *Rhyothemis triangularis*, *Trithemis aurora*, *Trithemis festiva* and *Tyriobapta torrida*. In addition, two specimens of the Blackwater mud snake *Phytolopsis punctata* were found at Mid 1 sub-catchment. This species presents a new record for Singapore and is currently only found in Nee Soon freshwater swamp forest (Tan et al., 2014; Thomas et al., 2014).

Presence of introduced species

Introduced species can have severe impacts on the native species, causing decline of population and possibly extinction. Through the course of this study, six species of introduced fish and one species of shrimp were recorded and all are common and widespread throughout Singapore. These species include *Osteochilus vittatus, Parambassis siamensis, Poecilia sphenops, Puntigrus tetrazona, Rasbora borapetensis, Rhinogobius giurinus* and *Macrobrachium nipponense*. Larson & Lim (2005) documented that *Rhinogobius giurinus* has been outcompeting the local species of freshwater goby, *Pseudogobiopsis oligactis* at locations where the two populations overlap, a result corroborated by this survey. The less acidic water in the outskirts could have encouraged propagation of introduced over native species. As the lower reach of Nee Soon stream is connected to the spillway of the Upper Seletar Reservoir it is subject to occasional flooding when excess water is released from the Reservoir. Such events might inadvertently introduce foreign aquatic species that reside in the water bodies of the reservoir and thus account for the introduced species found. With the discovery of introduced species, it is of great importance to implement preventive measures to reduce the possibility of alien species from being introduced. Possible mitigation procedures might include monitoring and physical removal of the introduced species on a regular basis, as well as the stepping up of existing enforcement in the nature reserves. Enhancing riparian vegetation along the banks of streams and retaining woody debris in the streams helps to preserve the natural habitat of the native species, providing an advantage over invasive alien species which generally prefer disturbed habitats. Construction of artificial barriers can also prevent the infiltration of alien species into the core area of Nee Soon freshwater swamp forest. *Prodasineura humeralis* is believed to have been introduced into Singapore within the last decade. Observations from the present study show that the species is abundant in the outskirts and stream stretches that are associated with an open canopy. The species is commonly associated with fast flowing water, but hardly found in shaded forest streams with high canopy cover. *Achatina fulica* is an invasive species originating from Africa and is commonly known as the Giant African Snail. In Nee Soon freshwater swamp forest shell heights of 7.5 cm or more have been observed. It is commonly found in parks and degraded forest but rarely in undisturbed forest. Unfortunately, several specimens were recorded deep in the forest indicating that this species may have already established a population within Nee Soon. *Lamellaxis gracilis* is an introduced species found in the outskirts of Nee Soon freshwater swamp forest. It is likely to have spread from nearby plant nurseries and gardens. *Bradybaena similaris* is commonly found throughout the moist tropics in urban areas such as gardens and plant nurseries. It is an agricultural pest and is most likely to have been introduced due to the horticultural and agricultural trade. It was observed in high numbers near the outskirts of Nee Soon but none was recorded within the freshwater swamp forest (Lim et al., 2018). The potential impact upon other native damselfly and snail species needs to be closely monitored.

Update on conservation status

Out of the 15 species of nationally threatened freshwater fish listed in the *Singapore Red Data Book* (Lim et al., 2008), 13 species have been recorded from Nee Soon freshwater swamp forest in the current survey. Although *Trigonostigma heteromorpha* has been listed as “Endangered” in the *Singapore Red Data Book*, it was found at all but one of the sites surveyed in Nee Soon freshwater swamp forest and in a high abundance of an average 17 individuals per site per sampling occasion, with the highest being 168 in a single sampling event. Similarly, *Nemacheilus selangoricus*, which was previously listed as “Critically Endangered”, had relatively high mean population abundance and presence at 10 out of 12 sites. Although current results revealed numerical dominance of these species in Nee Soon freshwater swamp forest, it remains true that within Singapore they are confined to the Central Catchment Nature Reserve and (in the case of *Nemacheilus selangoricus*) have stringent habitat requirements. Using IUCN Red Data Book criteria adapted to national level (Davison, 2008), no change in their current conservation status is justified. More in-depth studies have to be conducted to understand their detailed distribution in the nature reserves. For the remaining 11 species, *Boraras maculatus*, *Desmopuntius hexazona*, *Pangio muraeniformis*, *Pseudomystus leiacanthus*, *Silurichthys hasseltii*, *Parakysis longirostris*, *Clarias nieuhofii*, *Macrognathus maculatus*, *Luciocephalus pulcher*, *Channa gachua* and *C. melasoma*, the results are consistent with their current national status (Li et al., 2016). No new records of shrimp species were found in this study but the absence of *Macrobrachium idae, M. neglectum* and *Caridina gracilirostris* implies that these species may have been extirpated from Nee Soon freshwater swamp forest. All three species need brackish waters to complete the development of their larvae. It is likely that the dam built to construct the Lower Seletar Reservoir in 1986 prevented the downstream breeding migrations of these three species and rendered them unable to complete their life cycles (Cai et al., 2016). The Green Tree Snail, *Amphidromus atricallosus temasek* was listed as "Endangered" in the Singapore Red Data Book and was found to have a widespread population in Nee Soon freshwater swamp forest being recorded at eleven sites, although its mean abundance was low. Other rare species may deserve a national conservation status of Endangered or Vulnerable such as *Cyclotus rostellatus, Japonia ciliocinctum* and *Microparmarion strubelli*. All were extremely restricted in their distribution and exist only within a few isolated patches of Nee Soon freshwater swamp forest.

Recommendations

In view of these results in the context of existing scientific knowledge, specific recommendations for i) long-term monitoring, ii) future research, and iii) management options to ensure continued protection of the aquatic fauna of the Nee Soon freshwater swamp forest are as follows:

i) Future monitoring

Long term monitoring and sampling of faunal populations are needed to build on current knowledge and capture long-term trends. This is to optimise the value of the knowledge/data of Nee Soon freshwater swamp forest faunal communities gained from this study. Ecological and water quality monitoring at the downstream "edge habitat" sites in association with similar monitoring of (and access to physicochemical data from) the spillway itself as well as in Upper Seletar Reservoir (close to the spillway outlet) and access will be particularly valuable to assess the medium- to long-term effect of the spillway transfer on the Nee Soon freshwater swamp forest faunal communities and/or the stability (e.g. resistance, resilience, adaptation) of these communities to disturbance. A spatially localised project of this nature (of at least 2 year duration to capture temporal and seasonal patterns) is highly feasible, and would help to answer important questions pertaining to the spillway and its effects on Nee Soon freshwater swamp forest.

Adoption of standardised survey techniques, such as those applied here for faunal as well as habitat and other abiotic factors will enable comparison of long-term changes as well as spatial comparisons within the forest catchments but also against locations elsewhere in the context of a national monitoring programme. Ecological monitoring programmes for inland waters including aspects of these techniques are in various stages of application across Singapore, supported by NParks and PUB (e.g. Clews et al., 2012, 2014; Blakely et al., 2014; http://emid.nus.edu.sg/Inland/ecostandards.jsp) in line with programmes developed internationally (e.g. Barbour et al., 1999; ANZECC 2000a, 2000b; CEC, 2000). Ideally, at least annual screening for surveillance monitoring should be conducted at multiple stations (preferably representing a range of stream orders) alongside higher intensity investigative monitoring to investigate potential issues (e.g. within sites proximal to the spillway) and to improve system understanding (see recommendations below for future research).

Monitoring of fish should include as many sampling methods as possible to maximise coverage spatial (microhabitat) and taxonomic coverage, enabling tracking of populations of as many species as possible. Utilisation of additional trapping methods, such as differential trapping with bait, i.e. traps with different mouth sizes and/or mesh size, to exclude predators or unwanted organisms. This will allow for more complete/comprehensive sampling.

Constant monitoring of Nee Soon freshwater swamp forest fish and decapod fauna for introduction, establishment, and impacts of alien species within the catchment (especially along the edges of Nee Soon freshwater swamp forest).

Establishment of a viable, long-term monitoring programme should also be relevant for more broad-scale surveying of Singapore's environment within other water catchments. Training has been provided for agency staff on faunal sampling and identification methods as tools for monitoring. In June 2015, a workshop was held on the identification of fish, decapod crustaceans and macroinvertebrates from the Nee Soon freshwater swamp forest. Several theory and practical sessions for aquatic faunal identification purposes were facilitated by both NUS (TMSI, DBS, and LKCNHM) and NParks staff. Sampling methodology for faunal collection was also introduced in the introductory field resource, "A Guide to the Freshwater Fauna of Nee Soon Swamp Forest" which was reviewed during the workshop and revised in response to participants' feedback (Ho et al., 2016).

ii) Future research

Aquatic food web and trophic structure studies of Nee Soon freshwater swamp forest would be beneficial, to (i) serve as a basis for understanding of and further research on community and ecosystem interactions/ecology; and (ii) inform conservation and management actions for Nee Soon freshwater swamp forest.

Investigating the effects of release of water from Upper Seletar Reservoir is required on various aspects (e.g. establishment, survival, interactions, ecology, distribution) of introduced fish species as well as native fish species found at the edges and lower reaches of Nee Soon freshwater swamp forest (to as far upstream as the released water may affect).

Sedimentation and, potentially, sediment transport into and within the forest streams should be investigated to examine the sources of sediments, effects of erosion on stream fauna as well as trialing potential mitigation techniques such as "soft engineering" of stream banks through the planting of appropriate plant species.

Minimum and maximum acceptable water levels need to be identified through refinement and application of faunal response models, and integrated with the other physical and ecological aspects of the swamp forest. Without agreed minima and maxima, it will be difficult to identify triggers that initiate conservation actions and responses.

Statistical elucidation of acute faunal responses to hydrological events was not possible for this study based on overt surveying but warrants further investigation. For example, targeted studies should be aimed specifically at capturing rainfall events along with a high temporal resolution of faunal responses including passive and active drifting invertebrates (i.e. at scales over hours to days).

iii) Future management

Communication and cooperation among stakeholders should be enhanced by forming a working group or committee comprising all relevant stakeholders (ministries, statutory boards, academia, NGOs, public). Stakeholders should include any group with potential influence, impact and interest not just in Nee Soon freshwater swamp forest alone, but its watershed upstream and downstream.

Reduction of the influence of the spillway/discharge from reservoirs would help to i) mitigate against changes in water quality; ii) reduce input of and local expansion in the distribution of less desirable (non-native) fish species within the swamp forest streams; and iii) maintain more "typical" forest stream communities of fish and invertebrates, notably the rarer taxa that are less prevalent elsewhere.

To impede the spread of alien species into Nee Soon freshwater swamp forest, it may be possible to create a weir or low head dam downstream of Nee Soon freshwater swamp forest / upstream of reservoir input. However, this will probably bring about hydrological issues stemming from flooding or ponding upstream of such a weir or dam. An electric fish barrier (e.g. see http://www.smith-root.com/barriers/) could be created across the channel downstream of Nee Soon freshwater swamp forest / upstream of reservoir input, However, this would require funding, and would raise development, infrastructure, maintenance, long-term commitment; and safety issues.

Environmental impact assessments (EIAs) would first have to be carried out to ensure that the faunal communities of Nee Soon freshwater swamp forest are not inadvertently impacted by the development and operation of any of these approaches. In addition, consultations with management of multiple agencies and other stakeholders will also be required prior to deployment of any engineering solutions (i.e. weirs, low head dam and electric fish barrier) to ensure minimal impact to ongoing operations (i.e. water transfer operations along spillways).

Reduction of maximum water levels could be considered to avoid unnecessary disturbance of communities, by reduced input from the spillway, and by riparian and forest planting to reduce peak flows. Improvement of the current spillway and dam design, such as having a flap gate to prevent backflow of the reservoirs into the swamp, could also prevent peak flow disturbances to the Nee Soon freshwater swamp forest faunal communities.

Maintenance of greater than minimum water levels in small streams could be considered, in particular to support the diversity of aquatic fauna found within the freshwater swamp forest, especially the rare taxa such as stoneflies that are generally not well supported in other catchments in Singapore.

Although not explicitly investigated as part of this study, field observations of the main (3^{rd} order) stream channel suggest that the banks of the channel are eroding, and suspended sediment may be relatively high as well as the settling of sediments downstream, potentially reducing water depths in larger streams and/or changing benthic habitats towards more, finer, "softer" sediments further downstream. In concert with research to investigate this, trails of "soft-engineering" approaches conducted initially off-site could be used to identify i) suitable plants; and ii) suitable techniques to mitigate against stream bank erosion.

Cryogenic collection, imaging and barcoding

Being able to identify specimens to species level is important for most in-depth study of biological systems. However, getting these identifications is particularly challenging in tropical environments. Fortunately, a number of new tools promise to make this task less daunting (Kutty et al., 2018). New imaging techniques help with illustrating relevant characters and new and cheaper DNA barcoding techniques will allow for the generation of databases that can be used by many researchers.

Making the fauna and flora of Nee Soon freshwater swamp forest and of Singapore identifiable is achievable. The samples that have been collected and stored have the potential to reveal the presence of several hundred or even thousands of species. By focusing on particular taxa belonging to different ecological guilds, it is feasible to begin understanding species turnover rates across habitats in Singapore and to use this information for conserving Singapore's native fauna and flora. A particularly high priority should be using the newly developed plant barcoding techniques for all of Singapore's vascular plant species. This will allow for in-depth studies of species interactions between plants and animals (e.g. pollination).

Eco-hydrological modelling

An integrated eco-hydrological model was developed in this study for the Nee Soon freshwater swamp forest using Mike-SHE (Sun et al., 2018). The Mike-SHE model simulates various water flow processes in the hydrological cycle, such as rainfall, reservoir water of 3 reservoirs (Upper Seletar, Upper Peirce, Lower Peirce), evapotranspiration, overland flow, infiltration, and groundwater flow.

The surveyed GIS data, including the stream network, the cross-sections and the updated DEM, were incorporated in the model setup to make the model more representative. The spatial and temporal variations of leaf area index (LAI) and reference evapotranspiration (ET) retrieved from the remote sensing data, with the aid of the root depth (RD) information from Vegetation Ecology team, were used to establish a two-layer water balance model to account for the water loss from evapotranspiration and the amount of water recharging to the saturated zone. In addition, the field measurements from piezometers and stream sondes were processed and integrated to calibrate and validate the model parameters.

A swamp forest extent map was derived from the numerical model simulation, following the definiton of groundwater table shallower than 0.2 m below the surface level. The model's simulated swamp forest extent matches rather well with the swamp forest map resulting from the study of O'Dempsey & Chew (2013), with an increased area of 140 ha from 111 ha. The Nee Soon freshwater swamp forest was divided into 8 sub-catchments based on catchment delineation according to the topographic features.

Various characteristics were derived for each sub-catchment, such as, elevation, slope, rainfall, evapotranspiration, leaf area index, root depth, groundwater table, and surface water area extent. Groundwater table map and surface water depth map were also produced from the numerical model for the present hydrological condtion. Both maps show the spatial distribution of surface and groundwater of the present climate. These serve as references in assessing the hydrological vulnerability of the catchments towards climate change. In addition, an eco-hydrology model which links the hydrological conditions with the ecological recordings also helps to assess the climate change impact on local eco-hydrology.

Twelve scenarios were introduced; they are combinations between various reservoir water operating levels and the projected future rainfall amounts resulting from a climate change study. Despite rainfall appearing to be the most influential factor affecting the overall catchment water, i.e., the spatial average over the catchment, it is interesting to observe the differing contributing factors of both rainfall and reservoir level at sub-catchment levels. The effects of the two inputs differ depending on the locations as it can be seen from hydrological maps (Sun et al., 2018). This spatial distribution information is of importance should eco-hydrological management be approached at sub-catchment level or spatially distributed.

Several management strategies were suggested to mitigate severe drought and flood resulting from projected climate change impacts. These included the possibility of adding water during droughts, and retaining water during floods.

Introducing additional water from the reservoirs to the upstream points of the catchment is a conceivable option for the severe drought scenario. Two systems were suggested for a point source management strategy. A pump and pipe system would be required to increase the water head if the point sources are located at higher elevations than the reservoir water levels. A pump system could provide broad coverage, but would incur higher cost in construction and management. A pipe system alone could be recommended if the point sources are located at lower elevations (i.e. lower than the operating reservoir water level) or near the stream. A pipe system would cover smaller areas, but would be more effective in conserving the swampy area at lower cost and with less water consumption. There would be severe issues to be considered. Amongst these are changes in water quality and the accidental introduction of alien vertebrates and invertebrates. There would also be questions over disturbance to soils and vegetation through the construction and maintenance of any such systems. Practicality could also be questioned if low water levels in the stream system were to coincide with water shortages in the reservoirs and in Singapore generally, as expected during a severe regional drought. In lieu of the water quality of the reservoirs waters, to protect the fauna in Nee Soon freshwater swamp forest the introduced reservoir water to the point sources might have to be first filtered. In addition, the importance and the highest priority of providing drinking water during drought is fully understood and acknowledged. The proposed irrigation of the swamp will only take place when reservoir water yield permits to do so.

Retention ponds are a conceivable option for severe flood scenarios. Rentention ponds not only can reduce the affected flooding areas, but also promote habitat for fauna. The study shows that rentention ponds with a fixed depth of 1 m could effectively reduce the flooding areas by about 90%.

Summary conclusions and recommendations

Management objectives for the Nee Soon freshwater swamp forest are driven by the need to conserve freshwater swamp forest habitat along with the fauna and flora supported by this (now) rare habitat in Singapore. The conservation value of the forest is relatively high since it is the last remaining freshwater swamp forest in Singapore and a high proportion of fauna found in the Nee Soon freshwater swamp forest are not found elsewhere in Singapore (e.g. Ng & Lim 1992, 1997; Yeo & Lim 2011). This study has vastly expanded our understanding of the history and current status of the Nee Soon freshwater swamp forest. Pressures on the ecology of the forest extend beyond those identified at the onset of this project, namely susceptibility to flood and drought, to encompass reservoir effects as well as potential impacts of erosion, land-use change and water quality. Biological baselines have been extensively updated, with rediscoveries of plant taxa previously thought to be locally extinct in Singapore, and discoveries of potentially new taxa. The research has also yielded new records of both flora and aquatic fauna. Extensive barcoding and imaging work has provided the tools for more rapid identification of taxa to a higher taxonomic resolution. Habitats closer to Nee Soon freshwater swamp forest edges, particularly in the vicinity of the spillway, comprised greater proportions of introduced species and macroinvertebrates associated with a different environment. Overall, faunal surveys indicate a healthy and diverse fish and aquatic macroinvertebrate communities in Nee Soon freshwater swamp forest. Hydrological influences were found to be substantial and potentially limiting community composition. Soil and water chemistry were also found to have significant effects. These results aid in identifying bottlenecks and thresholds for the maintenance of key aspects of Nee Soon freshwater swamp forest biodiversity.

This paper has therefore presented a number of potential management solutions for the conservation and management of the swamp forest, some of which can be evaluated in the context of eco-hydrological modelling and others which warrant further investigation and consideration. For hydrological-engineering management options, the potential implications of modelled scenarios for in-stream faunal communities are presented. Proposed solutions are then discussed in the context of management objectives, cost-benefit and feasibility.

The adoption of potential management solutions should reflect stakeholder priorities and management objectives and the relative importance of effects on the hydro-ecology of the system carefully balanced. Implementation of management efforts must consider ecological, hydrological and sedimentary processes. For example, management to restore hydrological integrity should be evaluated alongside ecological impacts. Protection and management of the Nee Soon freshwater swamp forest should aim to maximise carbon sequestration potential and functionality on the system as far as possible.

Potential management solutions are subject to review and agreement amongst primary stakeholders; given the primacy of water management and defence as national priorities, these would include the Public Utilities Board, Ministry of Defence and National Parks Board. Management solutions can be broadly classified to address five issues of concern for the forest: hydrological integrity, erosion and sedimentation, ecological integrity, the impact of the spillway, and impacts of construction and development.

Maintaining hydrological integrity

a) Irrigation via the introduction of water sources (point sources) in the catchment upstream could be an option to mitigate future extreme drought. There would be major implications over water availability from other sources, cost, physical and ecological effects, risks of introducing alien aquatic species, and water quality, as well as costs, all of which would need to be included in an evaluation.

b) Retention ponds could be an option to mitigate flooding and simultaneously promote additional habitats for flora and fauna. The study showed that retention ponds with a depth of about 1 m could effectively reduce the flooded areas by about 90% but such steps would require evaluation of many factors similar to those for irrigation solutions to address drought.

c) Reduction of maximum water-levels by i) reducing disturbance of communities via reduced input from the spillway; ii) riparian and forest planting to reduce peak flows.

d) Maintenance of minimum water-levels in small streams in particular to support the diversity of aquatic fauna found within the freshwater swamp forest, in particular more rare taxa such as stoneflies which are generally not well supported in other catchments in Singapore.

Mitigating erosion and sedimentation

a) Manage recreation: Restricting visitors to the catchment and repairing damage to the tracks and bridges would help serve to reduce erosion.

b) Mitigation of stream-channel erosion: fill in the re-sectioned channel to restore the hydrological functioning of the swamp. However, this should be accompanied by an assessment of potential effects on fish communities that have since established in the channel.

c) Mitigation of stream-bank erosion: Investigation of sedimentation and potentially sediment transport into and within the forest streams to formally examine the sources of sediments, effects of erosion on stream fauna as well as trailing potential mitigation techniques such as “soft engineering” of stream banks through planting of appropriate plant species.

d) Mitigation of hillslope soil erosion: management of fire-associated loss of hillslope vegetation, possible revegetation of hillslopes after considering the importance of hillslope stability and ecological succession.

e) Monitor and manage tree falls and diebacks: i) investigate and potentially mitigate against increased rates of tree falls and diebacks; and ii) manage loss of forest cover caused by increased risk of fires due to drought / extended dry periods by improving accessibility for fire fighters appropriately trained for operation in a nature reserve.

Maintaining ecological integrity

a) Forest recovery and replanting of endemic plant species to aid the ecological resurgence of the reserve as well as the retention of water, sediments, and nutrients in the system.

b) Propagation of rare plant species or those restricted to Nee Soon freshwater swamp forest to facilitate replanting.

c) Continued exploration of flora and fauna alongside the further development of barcoding techniques to yield more rediscoveries, new records, or rare species that can be targeted for conservation action.

d) Long-term monitoring and standardised sampling of faunal communities as part of a comprehensive, national ecological monitoring programme for inland waters to build on current knowledge, capture long-term trends, and inform management decisions. At least annual screening for surveillance monitoring should be conducted at multiple stations (preferably representing a range of stream orders) alongside higher intensity monitoring to investigate potential issues and to improve system understanding. Establishment of minimum/maximum acceptable water-levels through refinement of faunal response models can be applied as thresholds/targets for management.

e) Manage the spread of alien species into Nee Soon freshwater swamp forest from up- and down-stream sources through the use of systems such as weirs, low head dams, flap gates or electric fish barriers downstream from Nee Soon freshwater swamp forest and/or upstream of reservoir input.

f) Mitigate against the high pH of reservoir water via chemical dosing or (preferably) filtration through vegetated, “peaty” soil high in organic matter and tannins derived from typical freshwater swamp forest plants (whereby the leaf litter provided by the typical swamp forest flora provides acidity via humic acids typical of freshwater swamp forest soils).

Mitigating effects of spillway

a) To reduce/prevent back-flooding into the swamp that flushes the system with reservoir water (from the dam at the mouth of the Upper Seletar outlet, or “spillway”) the feasibility and utility of a dam at the lower end of the lower channel to prevent upstream encroachment should be investigated. This may be a flap gate designed to allow outflow but prevent backflow of the reservoir water into the swamp.

b) Reduction of the influence of the spillway/discharge from reservoirs i) to mitigate against changes in water quality; ii) to reduce input of, and local expansion in the distribution of, less desirable (non-native) fish species within the swamp forest streams; and iii) to maintain more "typical" forest stream communities of fish and invertebrates, notably rarer taxa less prevalent elsewhere.

Mitigating impacts of construction and development

a) Identify, reduce, monitor and regulate impacts from new and existing construction and development (e.g. water quality issues associated with heavy metals).

b) Ensure continued maintenance of the pipeline linking Upper Seletar Reservoir and Lower Pierce Reservoirs to avoid leaks/input of reservoir water into the Nee Soon freshwater swamp forest system.

Considering the views of stakeholders, public perceptions and the views and interests of other agencies should also be factors in deciding conservation measures for Nee Soon freshwater swamp forest. All management options should be considered in concert, in the form of a whole-catchment plan of research, monitoring and management to address both hydrological (flood, drought) conditions as well as emerging pressures such as erosion and reservoir discharge.

ACKNOWLEDGEMENTS. This paper is based on contributions from leaders of the multidisciplinary team, listed here in alphabetical order: Cai Yixiong, Chong Kwek Yan, Esther Clews, Liong Shie-Yui, Rudolf Meier, Hugh Tan Tiang Wah, Robert Wasson, Sin Tsai Min, Darren Yeo Chong Jinn, and Alan D. Ziegler. We thank them for the opportunity to include their findings and recommendations here. We would like to thank staff of the National Parks Board, especially the Conservation Division and National Biodiversity Centre, who have provided support, helped to acquire permits, and worked tirelessly from the beginning of the project. We thank the Ministry of Defence for permitting research teams to access areas around the firing ranges. Colleagues from the Public Utilities Board have been very helpful and cooperative in providing essential hydrological data (e.g. rainfall, reservoirs' water levels) required for the numerical eco-hydrological model. PUB's participation in this project is greatly appreciated. Past and present staff and students at the Tropical Marine Sciences Institute, the Department of Biological Sciences and the Department of Geography, National University of Singapore, contributed to the body of work and knowledge-base on which this study was developed as well as providing practical, logistical and technical support for the project team. Our gratitude goes to the Ministry of Finance and the National Parks Board for their funding without which it would have been impossible to carry through this project.

References

ANZECC (Australian and New Zealand Environment Conservation Council) (2000a). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality (the Water Quality Guidelines). National Water Quality Management Strategy (NWQMS) Document 4.* The Australian and New Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand. www.mincos.gov.au/publications/australian_and_new_zealand_guidelines_for_fresh_and_marine_water_quality.

ANZECC (Australian and New Zealand Environment Conservation Council) (2000b). *Australian Guidelines for Water Quality Monitoring and Reporting 2000 (the Monitoring & Reporting Guidelines). National Water Quality Management Strategy (NWQMS) Document 7.* The Australian and New Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand. www.mincos.gov.au/publications/australian_and_new_zealand_guidelines_for_fresh_and_marine_water_quality.

Barbour, M.T., Gerritsen, J., Snyder, B.D. & Stribling, J.B. (1999). *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, 2nd ed, EPA 841-B-99-002. Washington, D.C.: U.S. Environmental Protection Agency, Office of Water.

Beisner, B.E., Ives, A.R. & Carpenter, S.R. (2003). The effects of an exotic fish invasion on the prey communities of two lakes. *J. Anim. Ecol.* 72(2): 331–342.

Blakely, T.J., Eikaas, H.S. & Harding, J.S. (2014). The Singscore: a macroinvertebrate biotic index for assessing the health of Singapore's streams and canals. *Raffles B. Zool.* 62: 540–548.

Cai, Y., Li, T., Lim, W., Tok, C., & Woo, C.M. (2016). Biodiversity assessment of freshwater shrimps and crabs in the Nee Soon swamp forest, Singapore. In: Kawai, T. & Cumberlidge, N. (eds) *A Global Overview of the Conservation of Freshwater Decapod Crustaceans*, pp. 373–418. Heidelberg: Springer Nature.

Cai, Y., Ng, C.Y. & Ngiam, R.W.J. (2018). Diversity, distribution and habitat characteristics of dragonflies in Nee Soon freshwater swamp forest, Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 123–153.

CEC (Commission of the European Communities) (2000). Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for community action in the field of water policy. *Off. J. Eur. Communities* L327: 1–72.

Chia, L.S. & Foong, S.F. (1991). Climate and weather. In: Chia, L.S., Rahman, A. & Tay, D.B.H. (eds) *The Biophysical Environment of Singapore*, pp. 13–49. Singapore: Singapore University Press for the Geography Teachers' Association Singapore.

Chong, K.Y., Neo, L., Tan, S.Y., Koh, C.Y., Lim, R.C.J., Loh, J.W., Ng, W.Q., Seah, W.W., Yee, A.T.K. and Tan, H.T.W. (2016). Towards a field guide to the trees of the Nee Soon Swamp Forest (I): Lauraceae. *Nat. Singapore* 9: 1–28.

Chong, K.Y., Lim, R.C.J., Loh, J.W., Neo, L., Seah, W.W., Tan, S.Y. & Tan, H.T.W. (2018). Rediscoveries, new records, and the floristic value of the Nee Soon freshwater swamp forest, Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 49–69.

Clews, E., Lin, Y. & Eikaas, H. (2012). Biomonitoring of Singapore's Freshwater Ecosystems. *City Green* 5: 28–33.

Clews, E., Low, E., Belle, C.C., Todd, P.A., Eikaas, H.S. & Ng, P.K.L. (2014). A pilot biotic index of water quality for Singapore's reservoirs. *Ecol. Indic.* 38: 90–103.

Clews, E., Corlett, R.T., Ho, J.K.I., Koh, C.Y., Liong, S.Y., Memory, A., Ramchunder, S.J., 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.

Davison, G.W.H. (2008). Appendix 1. Criteria for determining category of threat. In: Davison, G.W.H., Ng, P.K.L. and Ho, H.C. (eds) *The Singapore Red Data Book: threatened plants and animals of Singapore*, 2nd ed., pp. 268–271. Singapore: Nature Society (Singapore).

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

Dobbs, C., Nitschke, C.R. & Kendal, D. (2014). Global drivers and tradeoffs of three urban vegetation ecosystem services. *PLoS ONE* 9(11): e113000.

Friess, D.A., Richards, D.R. & Phang, V.X. (2015). Mangrove forests store high densities of carbon across the tropical urban landscape of Singapore. *Urban Ecosyst.*: 1–16.

Ho, J.K.I., Ramchunder, S.J., Memory, A., Theng, M., Li, T., Clews, E., Cai, Y., Tan, H.H. & Yeo, D.C.J. (2016). *A Guide to the Freshwater Fauna of Nee Soon Swamp Forest.* Singapore: Lee Kong Chian Nature History Museum & Tropical Marine Science Institute, National University of Singapore, Singapore.

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.

Kutty, S.N., Wang, W., Ang, Y., Tay, Y.C., Ho, J.K.I. & Meier, R. (2018). Next-generation identification tools for Nee Soon freshwater swamp forest, Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 155–173.

Larson, H.K., & Lim, K.K.P. (2005). *A guide to gobies of Singapore*. Singapore: Singapore Science Centre.

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

Lim, K.K.P. (2008). Fishes. In: Davison, G.W.H., Ng, P.K.L. & Ho, H.C. (eds) *The Singapore Red Data Book*: *Threatened Plants & Animals of Singapore*, 2nd ed. Singapore: Nature Society (Singapore).

Lim, R.C.J., Chong, K.Y., Neo, L., Tan, S.Y., Koh, C.Y., Loh, J.W., Ng, W.Q., Seah, W.W., Yeee, A.T.K. & Tan, H.T.W. (2016). Towards a field guide to the trees of the Nee Soon Swamp Forest (III): Myristicaceae. *Nat. Singapore* 9: 29–39.

Lim, W.H., Li, T.J. & Cai, Y. (2018). Terrestrial snails and slugs diversity in Nee Soon freshwater swamp forest, Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 109–121.

Murphy, D.H. (1997). Odonata biodiversity in the Nature Reserves of Singapore. *Gard. Bull. Singapore* 49: 333–352.

Neo, L., Chong, K.Y., Tan, S.Y., Koh, C.Y., Lim, R.C.J., Loh, J.W., Ng, W.Q., Seah, W.W., Yee, A.T.K. and Tan, H.T.W. (2016). Towards a field guide to the trees of the Nee Soon Swamp Forest (II): *Cratoxylum* (Hypericaceae). *Nat. Singapore* 9: 29–39.

Neo, L., Chong, K.Y., Koh, C.Y., Tan, S.Y., Loh, J.W., Lim, R.C.J., Seah, W.W. & Tan, H.T.W. (2017). Short-term external effects of increment coring on some tropical trees. *J. Trop. For. Sci.* 29: 519–529.

Ng, P.K.L. & Lim, K.K.P. (1992). The conservation status of the Nee Soon freshwater swamp forest of Singapore. *Aquat. Conserv.* 2(3): 255–266.

Ng, P.K.L. & Lim, K.K.P. (1997). The diversity and conservation status of fishes in the nature reserves of Singapore. *Gard. Bull. Singapore* 49(2): 245–265.

Nguyen, C.T.T., Wasson, R.J. & Ziegler, A.D. (2018). The hydro-geomorphic status of the Nee Soon freshwater swamp forest catchment of Singapore. *Gard. Bull. Singapore* 70 (Suppl. 1): 33–48.

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" – 16 October 2011*, pp. 121–166. Singapore: Nature Society (Singapore).

Ogutu-Ohwayo, R. (1990). The decline of the native fishes of Lakes Victoria and Kyoga (East Africa) and the impact of introduced species, especially the Nile perch, *Lates niloticus*, and the Nile tilapia, *Oreochromis niloticus*. *Environ. Biol. Fish.* 27(2): 81–96.

Rahman A. (1991). Soils. In: Chia, L.S., Rahman, A. & Tay, D.B.H. (eds) *The Biophysical Environment of Singapore*, pp. 89–133. Singapore: Singapore University Press.

Schumm, S.A. (1973). Geomorphic thresholds and complex response of drainage systems. *Fluv. Geomorphol.* 6: 69–85.

Sun, Y., Wendi, D., Kim, D.E. & Liong, S.Y. (2015). Technical Note: Application of artificial neural networks in groundwater table forecasting – a case study in Singapore swamp forest. *Hydrol. Earth Syst. Sci. Discuss.* 12: 9317–9336.

Sun, Y., Wendi, D., Kim, D.E. & Liong, S.Y. (2016). Development and application of an integrated hydrological model for Singapore freshwater swamp forest. *Procedia Engineer.* 154: 1002–1009.

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.

Tan, H.H., Li, T.J. & Lim, W.H. (2014). A food item of the blackwater mud snake. *Singapore Biodivers. Rec.* 2014: 311–312.

Tan, S.Y., Koh, C.Y., Siow, H.J.M., Li, T., Wong, H.F., Heyzer, A., & Tan, H.T.W. (2013). *100 Common Vascular Plants of the Nee Soon freshwater swamp forest, Singapore.* Singapore: Raffles Museum of Biodiversity Research, National University of Singapore, Singapore.

Tan, S.Y., Chong, K.Y., Neo, L., Koh, C.Y., Lim, R.C.J., Loh, J.W., Ng, W.Q., Seah, W.W., Yee, A.T.K. & Tan, H.T.W. (2016). Towards a field guide to the trees of the Nee Soon Swamp Forest (IV): *Xanthophyllum* (Polygalaceae). *Nat. Singapore* 9: 29–39.

Thomas, N., Li, T.J., Lim, W.H. & Cai, Y. (2014). New record of the blackwater mud snake in Singapore. *Singapore Biodivers. Rec.* 2014: 309–310.

Turner, I.M., Boo, C.M., Wong, Y.K., Chew, P.T. & Ibrahim, A. (1996). Freshwater swamp forest in Singapore, with particular reference to that found around the Nee Soon Firing Ranges. *Gard. Bull. Singapore* 48: 129–157.

Wendi, D., Liong, S.Y. Sun, Y. & Doan, C. D. (2016). An innovative approach to improve SRTM DEM using multispectral imagery and artificial neural network. *J. Adv. Model. Earth Syst.* 8: 1–12.

Yeo, D.C.J. & Lim, K.K.P. (2011). Freshwater ecosystems. In: Ng, P.K.L., Corlett, R.T. & Tan, H.T. (eds) *Singapore Biodiversity – An Encyclopedia of the Natural Environment and Sustainable Development*, pp 52–63. Singapore: Raffles Museum of Biodiversity Research, Department of Biological Sciences, National University of Singapore, Singapore.

Zuzao, V.H.D. & Pleguezuelo, C.R.R. (2008). Soil-erosion and runoff prevention by plant covers: A review. *Agron. Sustain. Dev.* 28(1): 65–86.