Gardens' Bulletin Singapore 70 (Suppl. 1): 175–190. 2018
doi: 10.26492/gbs70(suppl.1).2018-09

Projected impacts of climate change on stream flow and groundwater of Nee Soon freshwater swamp forest, Singapore

Y. Sun[1,2], D.E. Kim[1], D. Wendi[1], D.C.Doan, S.V.Raghavan[1],
Z. Jiang[1] & S.Y. Liong[1,2,3]

[1]Tropical Marine Science Institute, National University of Singapore,
18 Kent Ridge Road, 119227 Singapore
[2]Willis Towers Watson, 51 Lime Street,
London, United Kingdom
[3]Center for Environmental Sensing and Modeling, SMART,
1 Create Way, 138602 Singapore
tmslsy@nus.edu.sg

ABSTRACT. As Singapore's only remaining patch of primary freshwater swamp forest, the good management of the Nee Soon catchment is of utmost importance if a large proportion of the flora and fauna in Singapore is to be conserved. An integrated eco-hydrological model is developed for the area, with the objectives to numerically model the hydrological variations, to assess the possible impacts of future climate change, and to facilitate future eco-hydrological management. The numerical model considers the hydrological processes in a holistic manner, including rainfall-runoff, evapotranspiration, the interaction between surface water and groundwater, etc. The numerical model makes use of a combination of field survey data and alternative remote sensing data. With climate projection inputs from the Regional Climate Model (RCM), the numerical model is applied to run future scenarios to assess the climate change impact. A few management strategies are considered if favourable hydrological conditions are to be maintained for conserving the local ecosystem.

Keywords. Eco-hydrological model, eco-hydrology management, remote sensing, reservoirs

Introduction

Various studies have emphasised the significance of Nee Soon freshwater swamp forest to habitat and species conservation in Singapore (Ng & Lim, 1992; Clews et al., 2018). Nee Soon is the only remaining locality for hundreds of plant and animal species that have been extirpated elsewhere in the country (Tan et al., 2008), supports habitat specialists relying on acidic swamp conditions (Turner et al., 1996), contains several global endemics (Ng & Lim, 1992), and continues to be a locality for discoveries of new species and of species new to Singapore (e.g. Evenhuis & Grootaert, 2002). The environment within the Nee Soon catchment depends critically on the local hydrology (Clews et al., 2018). Changes in surface water and groundwater is likely to affect both the flora and the fauna wherever they occur, while some species will likely prove to be more vulnerable than others (Ho et al., 2018). Urbanisation and climate change is also likely to affect the surface and groundwater of Nee Soon freshwater swamp forest, both locally and in its surroundings.

A numerical model, which can anticipate the likely changes in surface and groundwater, and their impacts on fauna and flora, is highly important to any area, and to the Nee Soon catchment in particular, considering the national conservation significance of this, the last pristine freshwater swamp forest in Singapore (Sun et al., 2015). The Mike-SHE eco-hydrological modelling system, as a multi-physics modelling package, is well suited to simulate integrated catchment hydrology (DHI, 2014). Mike-SHE simulates water flow over the entire land surface based on different phases of the hydrological cycle from rainfall to river flow, via various flow processes, such as overland flow, infiltration into soil, evapotranspiration, and groundwater flow. It is thus an ideal tool for simulating the hydrology of wetlands. Such a modelling system, however, requires model inputs. Essential input data include: topography, geological coverage, soil properties, land use maps, hydro-meteorological data, evapotranspiration information, vegetation distribution, etc. For the Nee Soon freshwater swamp forest, the complex hydro-geological characteristics and the strict requirements for conservation hinder the installation of monitoring stations to acquire the necessary information. This study, therefore, adopted a combined approach to develop the numerical model, which makes use of field survey data and the alternative remote sensing data.

The numerical model is calibrated based on groundwater table and water level measurements; it is then combined with the future projected rainfall from the Regional Climate Model (RCM) to assess the hydrological impacts that might result from future climate change. A few possible management strategies are suggested corresponding to the severe drought and flood scenarios in order to maintain favourable hydrological conditions for conserving the local ecosystem.

Modelling Scheme

Study area

Fig. 1 shows the geographical location of the Nee Soon freshwater swamp forest in Singapore. Details are given by Chong et al. (2018), Clews et al. (2018), Davison et al. (2018) and Nguyen et al. (2018).

With an estimated area of about 485 ha, the catchment of the freshwater swamp forest covers the lower parts of shallow valleys with slow-flowing streams and a little higher ground supporting dryland forest. The elevation of the Nee Soon catchment ranges between 1 m to 80 m above mean sea level (MSL). The aquifer depth in the Nee Soon catchment is from 20 m to 40 m, and the major soil type features silty sand with a hydraulic conductivity of 4.05×10^{-5} m/s. The boundary of the study area on the east is defined by catchment delineation based on the catchment topography, the administrative boundary of the Central Catchment Nature Reserve, and the physical barrier formed by a major highway. The boundary on the west and south is defined by reservoirs, the inclusion of which, being an important water source for the catchment, is crucial for the numerical surface water and groundwater simulations.

Model setup

Table 1 summarises the two scenario runs performed in this study. Scenario 1 serves to search for the steady state condition of the water balance in the system, which was modelled beginning with fully saturated conditions and run for many years with assumed zero rainfall and evapotranspiration (ET). The steady state water distribution resulting from Scenario 1 is then used as the initial condition for the real simulation in Scenario 2, which considers the real operational reservoir water levels and observed rainfall as the driving forces. For tropical swamp forests, evapotranspiration plays an important role in the entire water balance and hydrological cycle. Scenario 2 utilises a 2-layer water balance model to simulate the water loss from ET and the unsaturated zone storage. The 2-layer water balance model is a simplified water balance method which divides the unsaturated zone into a root zone and a zone below the root zone; ET can be extracted from the root zone, while it does not occur in the zone below (Yan & Smith, 1994).

Setting up the 2-layer water balance model essentially requires three inputs, i.e., the root depth (RD), the leaf area index (LAI) and the reference ET. The root depth is calculated based on a linear equation

$$RD = 0.07624 \times DBH + 0.11185$$

where DBH is the diameter at breast height measured in 40 vegetation plots distributed across the Nee Soon catchment (Chong et al., 2018). The average value is used as the representative root depth in each plot; Thiessen polygon is then applied to interpolate the point values into the entire study area.

The reference ET is the rate of ET with an unlimited amount of water from a reference surface – a hypothetical grass reference crop with specific characteristics (Allen et al., 1998). The reference ET data is obtained in this study from MOD16 Global Terrestrial Evapotranspiration Data Set (Mu et al., 2013). The MOD16 project is part of the National Aeronautics and Space Administration (NASA)/Earth Observing System (EOS) project to estimate global terrestrial evapotranspiration from earth land surface by using satellite remote data. The MOD16 dataset is derived from an improved ET estimation algorithm with inputs including the GMAO and MODIS land cover, LAI, FPAR and albedo data (Mu et al, 2011). Fig. 2 (a) shows samples of the MOD16 reference ET over the Nee Soon freshwater swamp forest. The missing data accounts for about 1.2 km^2 within the Nee Soon catchment (less than one third of the catchment area), which are supplemented with the interpolated values from neighbouring cells. The 2012 reference ET ranges from 65 to 140 mm/month with an average of 100 mm/month.

The Leaf Area Index is a dimensionless quantity that characterises plant canopies. It is defined as the one-sided green leaf area per unit ground surface area in

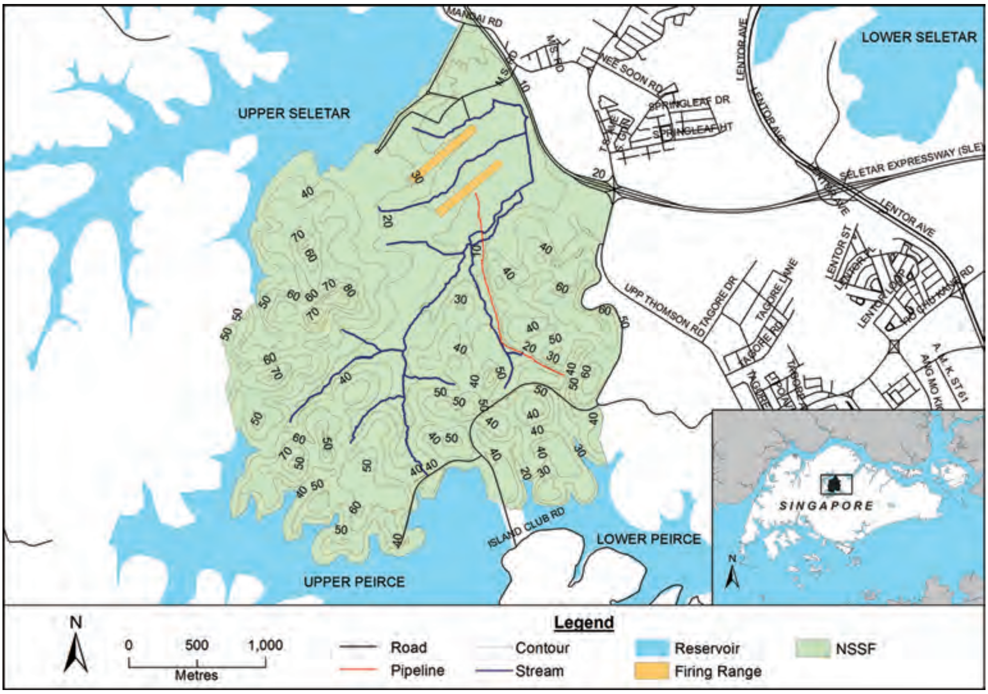


Fig. 1. Geographical location of the Nee Soon freshwater swamp forest in Singapore.

Table 1. Summary of essential information in mode setup.

Input type	**Scenario 1** **(Search for steady state condition)**	**Scenario 2** **(Real simulation)**
Simulation duration	01/01/2001 – 31/12/2012	01/01/2001 – present
Grid size	20×20 m	20×20 m
Soil type	Silty sand (hydraulic conductivity = 4.05×10^{-5} m/s)	Silty sand (hydraulic conductivity = 4.05×10^{-5} m/s)
Rainfall	No rainfall	Observed rainfall
Evapotranspiration	Not triggered	2-layer water balance model
Initial condition	Fully saturated soil (at 01/01/2001)	Extracted from Scenario 1 (condition at 31/12/2012)
Inner boundary condition (reservoir)	Mean observed reservoir levels	Observed reservoir levels
Outer boundary condition (land-land)	-5% gradient	-5% gradient
Outer boundary condition (land-water)	Zero flux	Zero flux

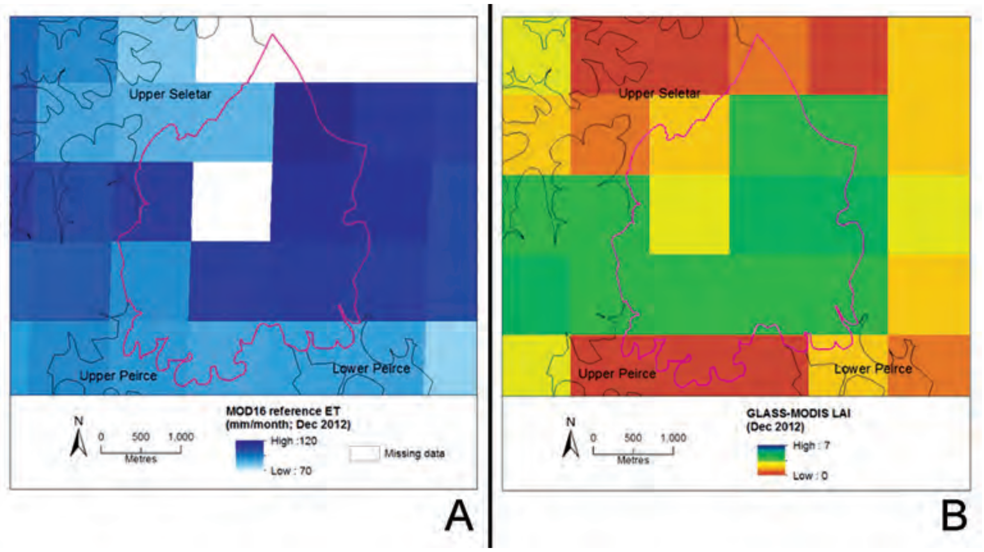


Fig. 2. (a) Reference ET over Nee Soon freshwater swamp forest catchment in Dec 2012 (Source: MOD16); (b) Leaf Area Index across Nee Soon freshwater swamp forest in Dec 2012 (Source: GLASS-MODIS).

broadleaf canopies (Watson, 1947). LAI can be determined directly through sample measuring and indirectly such as hemispherical photography. This study acquires the LAI information from the Global and Surface Satellite (GLASS)-MODIS LAI dataset, a global LAI product released by the Center for Global Change Data Processing and Analysis (CGCDPA) of Beijing Normal University (Liang & Xiao, 2012). The GLASS-MODIS LAI dataset is retrieved using the general regression neural networks (GRNNs) trained with the MODIS and CYCLOPES LAI products as well as the reprocessed MODIS reflectance products (Xiao et al., 2013). Samples of the GLASS-MODIS LAI over the Nee Soon catchment are plotted in Fig. 2 (b). Typical LAI values range from 0 to 7, implying areas from no vegetation to dense canopy coverage.

Simulation results

Fig. 3 compares the simulated with the observed water depths at Upper and Mid stream gauges, whereas Fig. 4 shows the comparison between the simulated and the observed groundwater tables at stations DP4 and DP9. The numerical model simulates the water depth reasonably well, with root mean square error (RMSE) respectively being 0.11 m and 0.17 m for these two stations. Both DP4 and DP9 are located upstream, where the water table varies within 1 m below the ground surface. The numerical simulation successfully captures the rising and falling trends within the series of observations, producing insignificant model errors (RMSE respectively being 0.08 m and 0.11 m). The model errors are mainly caused by the uncertainty in the reference level arising from the smoothing effect of the 20 m grid.

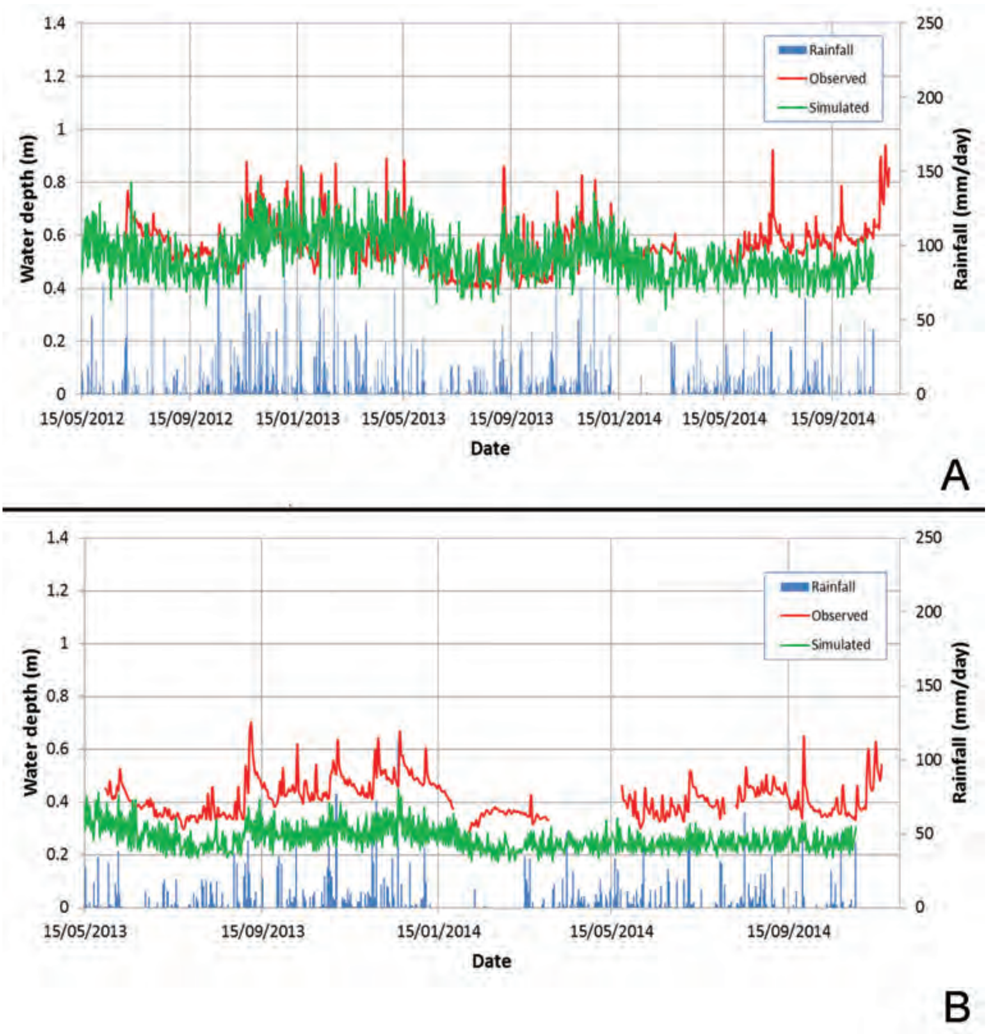


Fig. 3. Simulated vs. observed water depths (a: Upper stream gauge; b: Mid stream gauge).

Model Application

Impacts of climate change

The numerical model, as shown in the previous section, having been calibrated based on field measurements, is applied to assess the climate change impacts by simulating future scenarios. The future scenarios, as defined in Table 2, combine the effect of two factors: reservoir level and rainfall. Reservoir level is categorised as low, medium or high, respectively represented by bottom, mean and top operating levels as managed by the responsible government agency. Rainfall scenarios comprise no rainfall, low, medium and high rainfall conditions. Future rainfall is projected from the numerical climate model formulated as

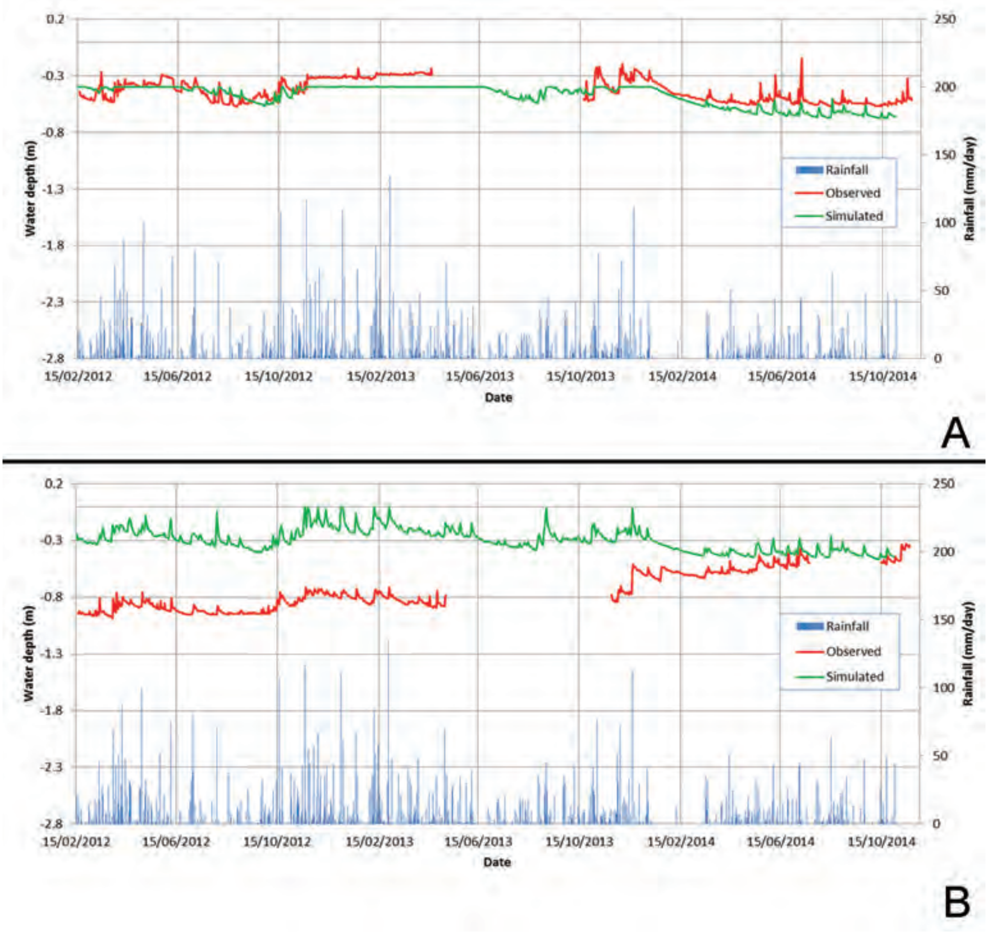


Fig. 4. Simulated vs. observed groundwater tables (a: Piezometer DP4; b: Piezometer DP9).

$$\textit{Future Rainfall} = \textit{Current Rainfall} \times \textit{Change Factor}$$

where *Change Factor* is calculated based on the climate projections simulated from the Regional Climate Model - WRF (Weather Research and Forecasting model, http://www.wrf-model.org; Liong & Raghavan, 2014). The matrix of three reservoir levels and four rainfall conditions results in a total of 12 simulated future scenarios.

Fig. 5 and Fig. 6 respectively present the simulated groundwater table maps and surface water extent maps after 5 years corresponding to the management scenarios. Scenario 11, based on projected medium rainfall and high reservoir level, unsurprisingly is the most similar to the current conditions, due to the similar forcing resulting from (1) similar rainfall amount, and (2) the reservoir levels being kept close to their maximum capacity.

Table 2. Scenarios for future eco-hydrology management.

Reservoir Level	**Rainfall**			
	No.	Low	Medium	High
Low	1	2	4	4
Medium	5	6	7	8
High	9	10	11	12

Table 3. Proposed drought mitigation management strategies for Scenario 9.

Drought Mitigation Management Strategies	**Location and Symbols**	**Discharge rate at each point source (m3/s)**	**Volume at each point source (m3/day)**	**Total Discharge Volume (m3/ day)**	**Proposed System**
9A	● in Fig. 7	0.02	1,728	26,000	Pump + Pipe
9B	● in Fig. 7	0.04	3,456	52,000	Pump + Pipe
9C	▲ in Fig. 7	0.02	1,728	26,000	Pipe
9D	▲ in Fig. 7	0.01	864	13,000	Pipe

Scenario 1 would have been the obvious severe drought case to be studied and a series of drought mitigation managements would be recommended accordingly. However, we consider Scenario 9 more appropriate in the Singapore context, as Singapore is unique in its number of desalination plants and recycled water plants. During the unusually long dry periods in early 2014 and 2015, many of the desalination and recycled water plants were operating at their full capacity. With this in mind, in this study the focus is placed on Scenario 9 as the severe drought scenario. Scenario 12 is selected as the severe flood case; it is analysed and a series of flood mitigation management strategies is proposed.

Management strategies

Severe drought case

Based on the climate projections for Singapore, the unprecedented five consecutive severe drought years that occurred in California (Reid, 2015), and the severe droughts experienced in other places such as North Korea, Brazil and South Africa, Scenario 9 is selected for the severe drought case study; the drought mitigation management strategies for the Nee Soon freshwater swamp forest are then proposed. Table 3 summarises the proposed drought mitigation management strategies to tackle the dry situation in Scenario 9. Point sources at strategically selected locations, as shown in

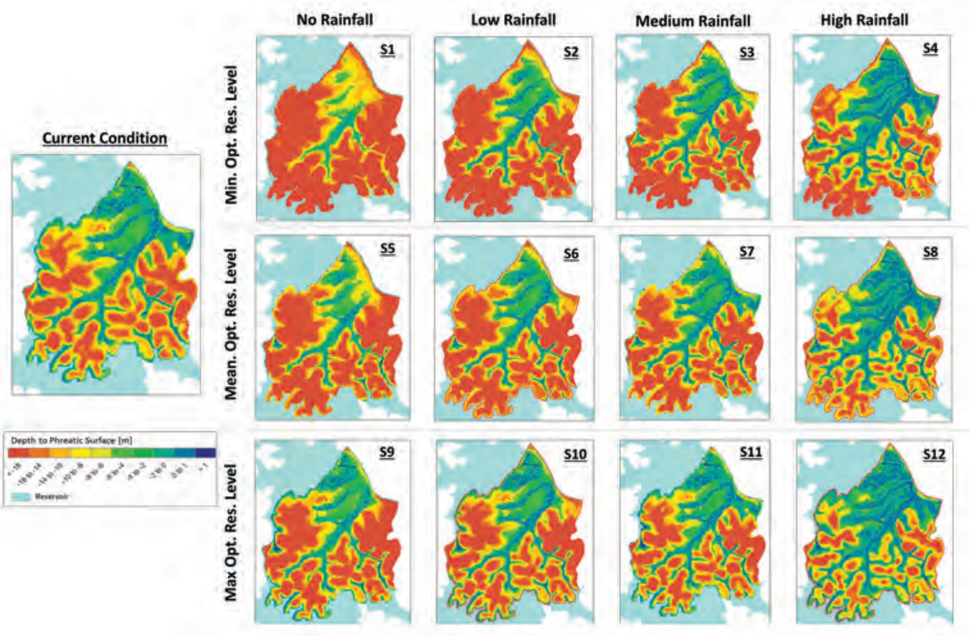


Fig. 5. Simulated groundwater table maps, after 5 years, for all 12 Scenarios.

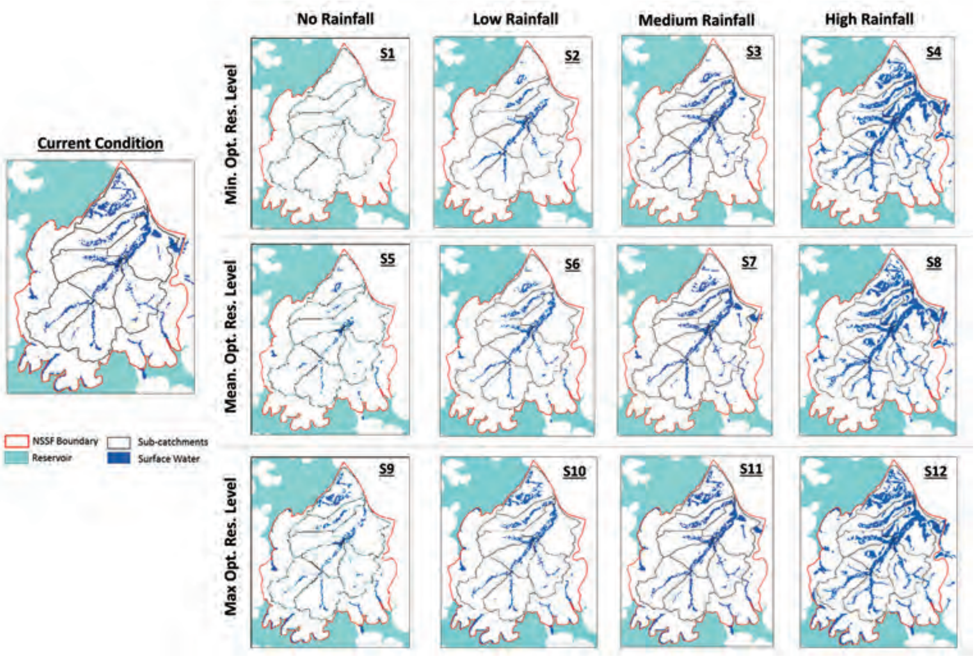


Fig. 6. Simulated surface water depth maps, after 5 years, for all 12 Scenarios.

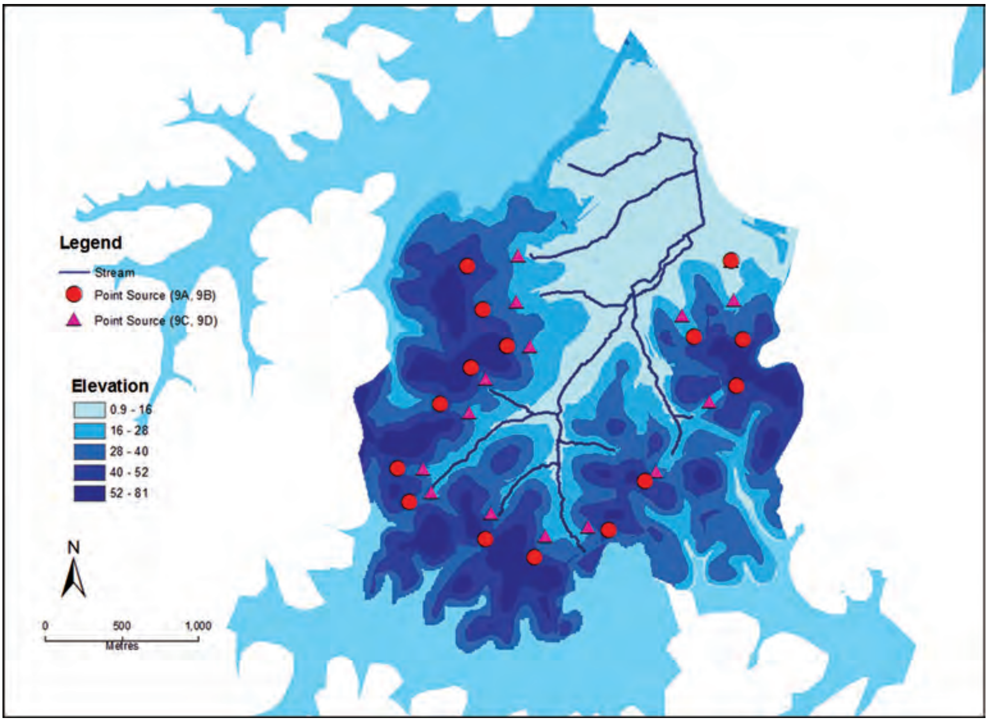


Fig. 7. Locations of the proposed point sources for drought mitigation management strategies of Scenario 9.

Fig. 7, and discharge rates (volume) are inserted and simulated in the numerical model.

Fig. 8 and Fig. 9 respectively present the simulated groundwater table maps and surface water maps in their current condition, after 5 years of Scenario 9, and after 5 years of Drought Mitigation Management Strategies 9A, 9B, 9C and 9D. The point sources of Strategies 9C and 9D are located in the catchment downstream (nearer to the stream) as compared to Strategies 9A and 9B. Therefore, the piped-in water in Strategies 9C and 9D has more direct effect in nourishing the swampy area near the stream than in Strategies 9A and 9B.

Fig. 10 illustrates a suggested drought mitigation system for management of the point source strategies. A pump and pipe system would be required for Strategies 9A and 9B, whereas Strategies 9C and 9D would only need a pipe system due to the lower elevation of the point sources than the maximum operating reservoir water levels (thus, a gravity flow system). Despite providing lower coverage, a pipe system would not only incur lower cost in construction and management, but would also require less water consumption compared to a pump and pipe system.

Severe flood case

Flooding often results in poor soil aeration, polarisation of soil pH, accumulation of organic matters, unfavourable sedimentation and/or erosion, etc. It, therefore, hampers

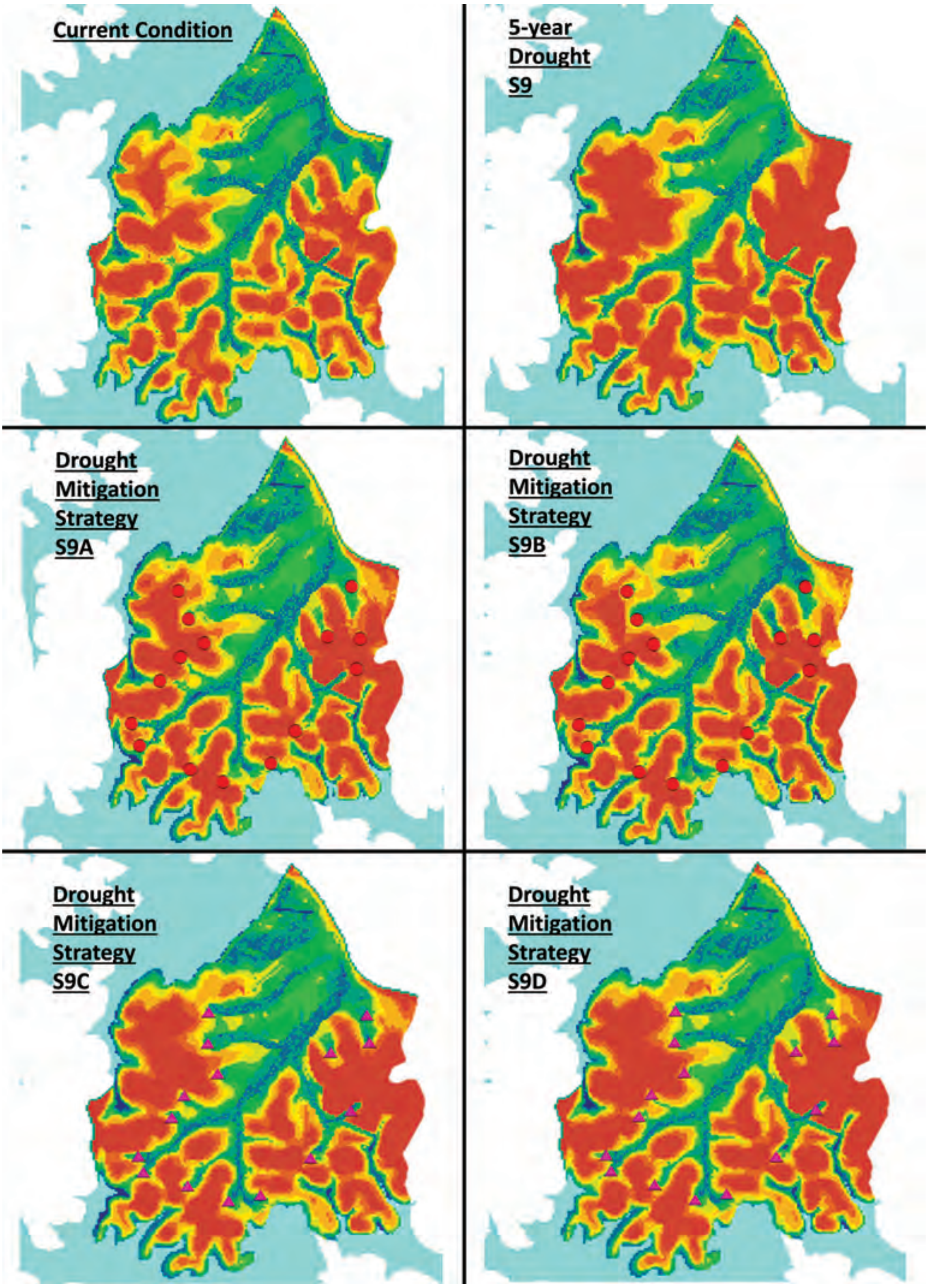


Fig. 8. Simulated groundwater table maps: Current vs. Scenarios 9, 9A, 9B, 9C, 9D.

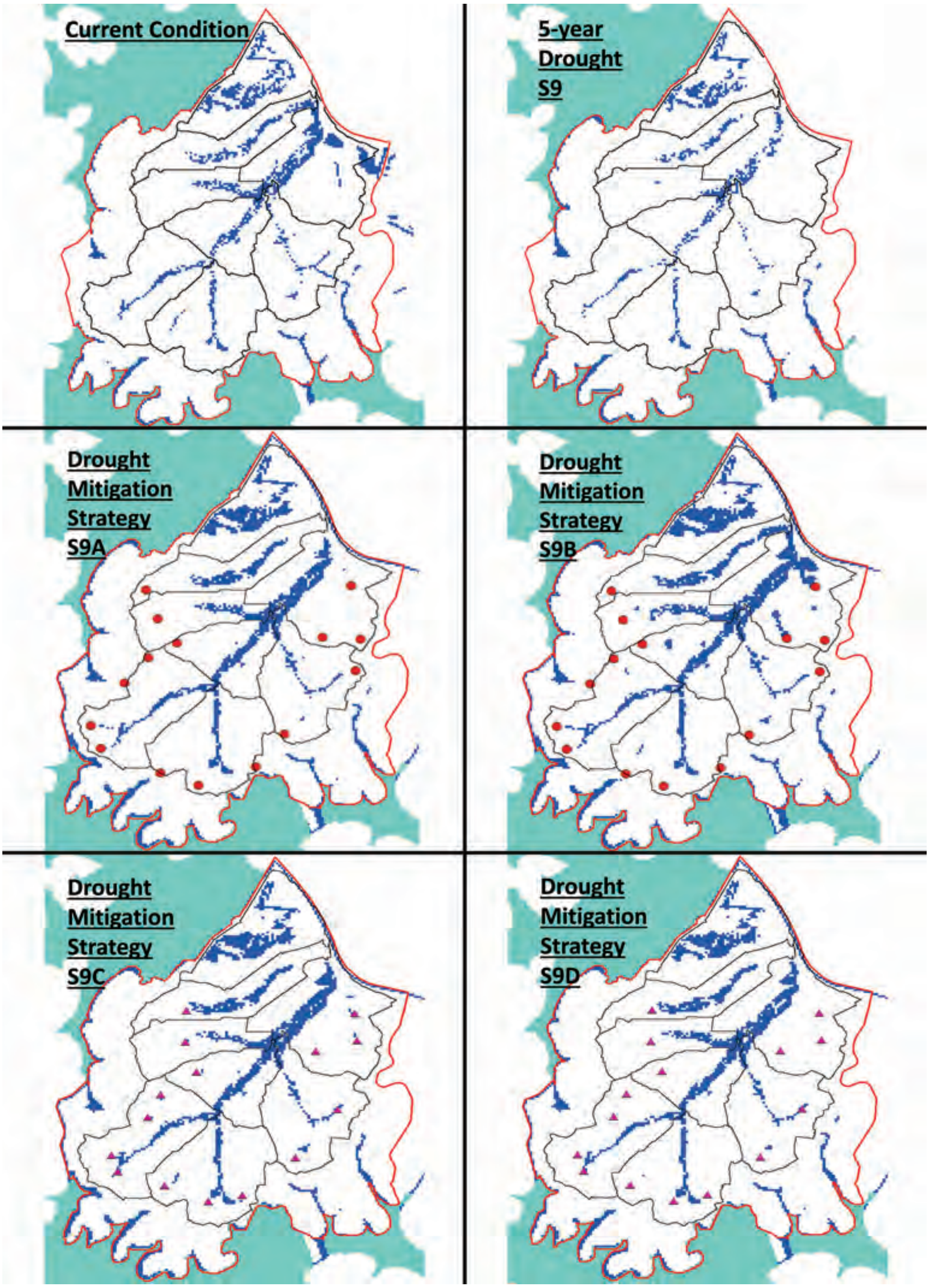


Fig. 9. Simulated surface water maps: Current vs. Scenarios 9, 9A, 9B, 9C, 9D.

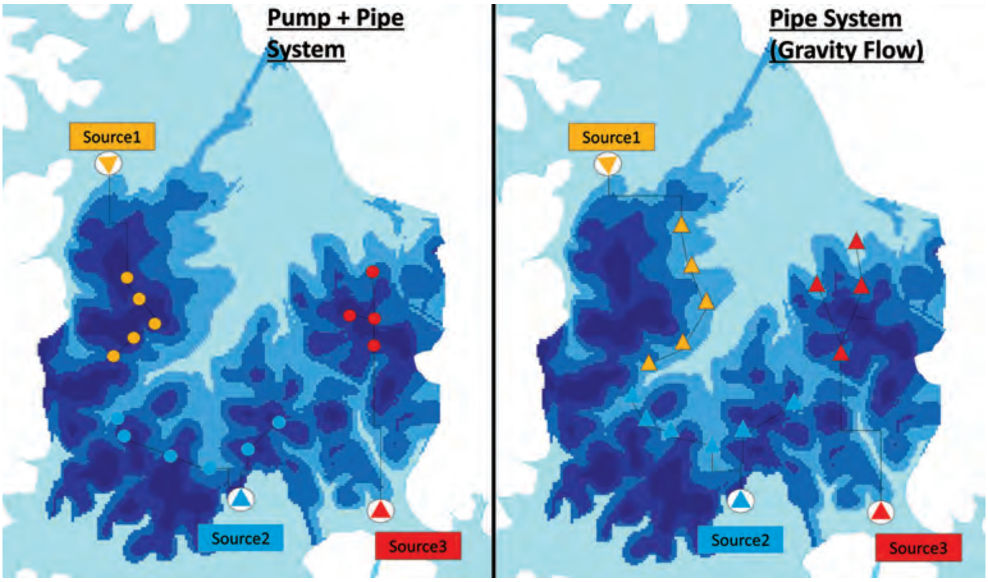


Fig.10. Proposed drought mitigation management systems: Pump+Pipe System vs. Pipe System.

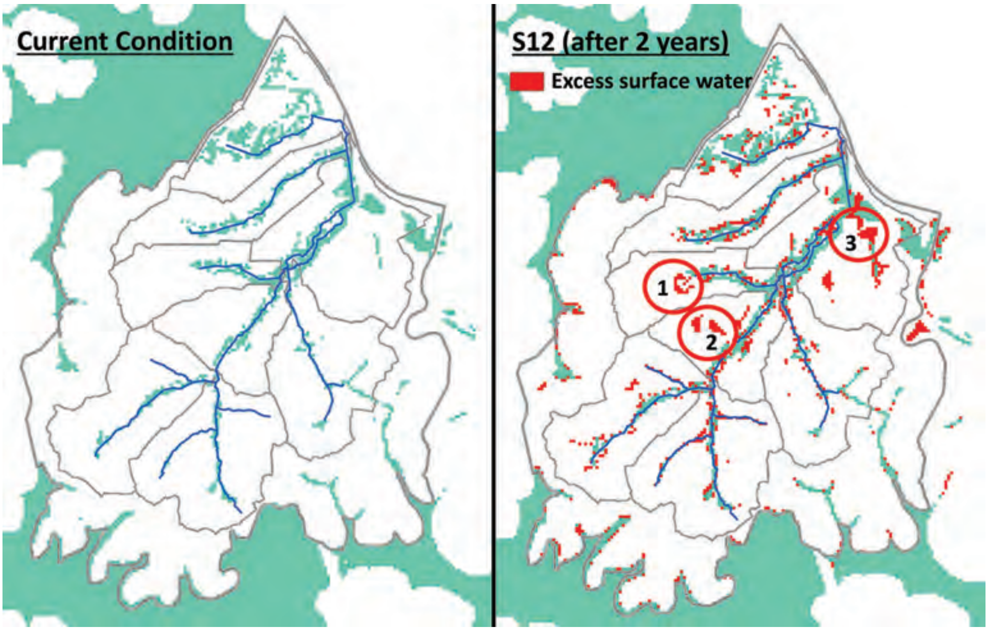
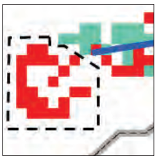
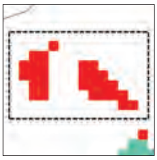
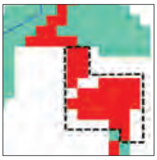
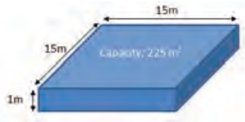
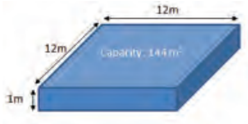
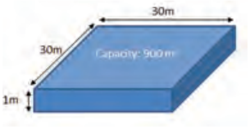


Fig. 11. Simulated surface water maps: Current vs Scenario 12 (after 2 years).

Table 4. Proposed flood mitigation management system: retention ponds.

Flood cluster	**1**	**2**	**3**
Map			
Flooded area (m^2)	9,200	11,200	12,800
Flood volume (m^3)	198.34	127.77	859.98
Average depth (m)	0.022	0.011	0.067
Proposed dimension	 	 	
Reduction of flooded area (%)	97.5	98.7	93.0

the growth of trees and even leads to death of the root system. Fig. 11 compares the current surface water area extent with the projected future surface water area extent (after 2 years) resulting from a model simulation of Scenario 12. The excess surface water area, after 2 years, is 36.72 ha with an excess water volume of 73,606 m^3. To mitigate the extent of flooding, and also to promote habitats for fauna, retention ponds with a maximum depth of 1 m, various surface areas and different water volumes are suggested.

To demonstrate the flood mitigation management approach, we focus on three flooded areas as circled in Fig. 11. Three retention ponds in their respective locations are indicated. Detailed information on the flooded areas and retention ponds is summarised in Table 4. The suggested retention ponds appear to reduce the flooding area by more than 90%. As mentioned above, the retention ponds could also promote habitats for fauna if properly designed and managed.

Conclusions

An integrated eco-hydrological model for the Nee Soon freshwater swamp forest has been developed in this study. The surveyed GIS data, including the stream network, the cross-sections and the Digital Elevation Model (DEM), have been incorporated in the model setup. The spatial and temporal variations of LAI and reference ET retrieved from remote sensing data, i.e. the reference ET from MODIS and LAI from GLASS-MODIS, with the aid of the surveyed RD, are 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 have been processed and integrated to calibrate and validate the model parameters.

Twelve scenarios were introduced, being the combinations of various reservoir operating levels and the projected future rainfall resulting from climate change study. Despite rainfall appearing to be the most influential factor for the overall catchment water availability, i.e., the spatial average over the catchment, it is interesting to observe the different contributing factors of both rainfall and reservoir water at sub-catchment levels. The effects of the two inputs differ depending on the locations as can be seen from the hydrological maps. This spatial distribution information is of importance should eco-hydrological management be approached at sub-catchment levels or spatially distributed.

Several possible management strategies are put forth to mitigate severe drought and flood resulting from the projected climate change impacts as simulated in Scenarios 9 and 12. These have yet to be evaluated in terms of cost, engineering feasibility, and biological impacts. Introducing water sources (point sources) in the catchment upstream is a potential strategy to mitigate future drought. Retention ponds could be a simple and effective solution in mitigating flooding and simultaneously promoting habitat for aquatic fauna. Discussion of these two possibilities does not represent a commitment to carry them out, as they must be considered in relation to recommendations from other teams in the study of Nee Soon freshwater swamp forest.

ACKNOWLEDGEMENTS. This study forms part of the research project “Nee Soon Swamp Forest Biodiversity and Hydrology Baseline Studies—Phase 2” funded by National Parks Board (NParks), Singapore. The authors are also grateful for access to data generously provided by the Public Utilities Board (PUB), Singapore, that helped to make this study possible.

References

Allen, R.G., Pereiro, L.S., Raes, D. & Smith, M. (1998). *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. *FAO Irrigation and Drainage* Paper 56. Rome: FAO.

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., Corlett, R.T., Ho, J.K.I., Kim, D.E., Koh, C.Y., Liong, S.Y., Meier, R., Memory, A., Ramchunder, S.J., Sin, T.M., Siow, H.J.M.P., Sun, Y., Tan, H.H., Tan, S.Y., Tan, H.T.W., Theng, M.T.Y., Wasson, R.J., Yeo, D.C.J. & Ziegler, A.D. (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., 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.

DHI (Danish Hydraulic Institute) (2014). *MIKE SHE, User Manual, Volume 1: User Guide*. Hørsholm: Danish Hydraulic Institute.

Evenhuis, N.L. & Grootaert, P. (2002). Annotated checklist of the Dolichopodidae (Diptera) of Singapore, with new records and descriptions of new species. *Raffles B. Zool.* 50: 301–316.

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.

Liang, S. & Xiao, Z. (2012). Global Land Surface Products: Leaf Area Index Product Data Collection (1985–2010). Data set. Beijing Normal University. doi:10.6050/glass863.3004.db.

Liong, S.Y. & Raghavan, V.S. (2014). *Quarterly Reports on High Resolution Regional Climate Change Impact Study, Vol I, as a part of the Coastal Inundation Risk Map Study for Singapore*. Submitted to the Building and Construction Authority, Govt. of Singapore.

Mu, Q., Zhao, M. & Running, S.W. (2011). Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sens. Environ.* 115: 1781–1800.

Mu, Q., Zhao, M. & Running, S.W. (2013). Algorithm Theoretical Basis Document: MODIS Global Terrestrial Evapotranspiration (ET) Product (NASA MOD16 A2/A3) Collection 5. NASA Headquarters.

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

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.

Reid, R.L. (2015). Engineering for every drop. *Civil Engineering – the Magazine of the American Society of Civil Engineers* 85(10): 46–55.

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.

Tan, H.T.W., Tan, K.-X., Ali bin Ibrahim, Chew, P.T., Chua, K.S., Duistermaat, H., Ganesan, S.K., Goh, M.W.K., Gwee, A.T., Kiew, R., Lee, S.M.L., Leong, P., Lim, J., Lok, A.F.S.L., Loo, A.H.B., Lum, S.K.Y., Morgany Thangavelu, Saifuddin bin Suran, Sim, S., Samsuri Ahmad, Wee, Y.C., Yap, K.F., Yeo, C.K. & Yong, J.W.H. (2008). Seed plants. In: Davison, G.W.H., Ng, P.K.L. & Ho, H.C. (eds) *The Singapore Red Data Book: Threatened plants and animals of Singapore*, 2nd ed., pp. 213–244. Singapore: The Nature Society (Singapore).

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

Watson, D.J. (1947). Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Ann. Bot.* 11: 41–76.

Xiao, Z., Liang S., Wang, J., Chen, P., Yin, X., Zhang, L. & Song, J. (2013). Use of general regression neural networks for generating the GLASS leaf area index product from time series MODIS surface reflectance. *IEEE Trans. Geosci. Remote Sens.* 52(1): 209–223.

Yan, J. & Smith, K.R. (1994). Simulation of integrated surface water and ground water systems – model formulation. *Water Resour. Bull.* 30(5): 1–12.