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DESIGNING A POND AND EVALUATING ITS IMPACT UPON STORM-WATER QUALITY AND FLOW: A CASE STUDY IN RURAL AUSTRALIA

PROJEKTOWANIE ZBIORNIKA WODNEGO I OCENA JEGO WPŁYWU NA JAKOŚĆ I PRZEPŁYW WÓD DESZCZOWYCH: STUDIUM PRZYPADKU AUSTRALIJSKICH OBSZARÓW WIEJSKICH

Abstract: Storm-water management is a common concern in rural catchments where development-related growth causes increases of storm-water flows. Greater magnitude and frequency of storm-water create greater challenges for mitigating storm-water damage and improving water quality. The concept of Blue-Green Infrastructure (BGI) as a solution incorporates a wide range of applicable components with the aim of minimizing the effect of catchment development on flow regimes without changing the watershed morphology. BGI components manage storm-water by decreasing impermeable cover and expanding natural and semi-natural systems to store water or recharge and filter storm-water into the ground. In this paper, guidelines for designing a pond as a component of BGI are provided and, configuration and size of the pond are determined. Moreover, the impacts of the designed pond on storm-water peak flow and quality are assessed for the Tarwin catchment, State of Victoria, Australia. The results indicate that the introduction of the pond would have reduced outfall inflow by 94 % and would have achieved the reduction of 88.3, 75.5 and 50.7 % for total suspended solids, total phosphorus, and total nitrogen respectively, during the extreme weather event in June 2012.

Keywords: Blue-Green Infrastructure, MUSIC, PCSWMM, pond, sustainable development goals

Introduction

Wetlands are complex ecosystems that provide many ecological, biological, and hydrologic functions. They improve water quality, operating as active filters that remove sediment and nutrients from surface and ground water [1]. Nutrient removal occurs via plant uptake, adsorption into sediments and deposition of particles such as organic matter. Sediment removal occurs because the flat topography and vegetation of wetlands slows down water flow, allowing deposition to occur. The abilities of wetlands to recycle nutrients in these ways make them the most biologically productive ecosystems that provide habitat for wildlife and many specialized species [2].

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Another important, but often over-looked benefit of wetlands, is their capacity to accept excess surface water runoff during heavy rainfall events and therefore protect other landscape elements from the effects of flooding. Wetlands can act as a buffer, provisionally storing storm-water and discharging it gradually over time, thus decreasing peak flows, damping extreme flood events, and protecting downstream or surrounding regions from damage. They can also trap sediments and decrease erosion by damping wave action and slowing water flows [1].

However, in Australia, a large proportion of wetlands have been destroyed or degraded since human settlement. Two main factors are to blame; the first is agricultural development and urban expansion and the second is the associated construction of flood mitigation measures such as levees. For example, two-thirds of Victoria's wetlands have been drained or degraded (amounting to around 4,000 wetlands and 191,000 hectares) [3]. Those that remain and which are not protected by legislation (for example, in declared national parks) or by international treaties (RAMSAR) continue to be under threat. In fact, until a few decades ago, wetlands were considered as a nuisance that inhibited the agricultural productivity of regions, and their removal (draining) was sanctioned and encouraged [3].

The widespread establishment of structural flood mitigation measures across Australia had a significant impact on wetlands because such practices altered the natural flow of water. Levees were constructed along major river systems to control flooding, but in practice, they were not effective and probably made flooding worse [4-7]. These modifications to natural aquatic systems reduced the capacity of floodplains to absorb flood water, decreased their capacity to moderate water quality, altered the behaviour of major floods, increased stream flows during floods and increased sedimentation [8]. Moreover, all the environmental problems associated with isolated estuarine systems such as changes in water chemistry, the growth of aquatic weeds, and physical damage to riverine communities, are consequences of aquatic system modifications [8].

Today, however, wetlands in Australia are identified as amongst the most valuable ecological environments [7]. Therefore, significant attempts have been made towards their restoration and conservation, as well as to the construction of new wetlands and ponds [4-8] in order to compensate for those that have been damaged or lost.

Here, we present the introduction of a designed pond as part of a broader Blue Green Infrastructure (BGI) strategy to reduce flooding and nutrients in a case study site. BGI is a system of natural and semi-natural landscape components that (could) create a sustainable network of blue (water based) and green (landscape based) elements that mitigate flood while at the same time providing many of the functions of natural wetlands [9-12]. BGI is potentially a straightforward and environmentally friendly solution to storm-water impacts that can be integrated with rural and regional development plans. The elements of an interconnected BGI system may consist of different blue and green bodies such as bio-retention cells, infiltration trenches, wetlands/ponds, green and blue roofs, rain-gardens, and others.

In this paper, we design a pond and model its necessary design parameters as one BGI element that is analogous to a wetland in form and function. We then investigate the impacts of the designed pond on the storm-water peak flow reduction and quality improvement of a hydraulic system, as part of a broader BGI system, during a heavy rainfall event in the Tarwin catchment of Victoria, Australia where agricultural development has substantially altered natural hydrological responses. The paper quantifies the efficiency of the designed pond to remove Total Suspended Solids (TSS), Total Phosphorus (TP), and Total Nitrogen (TN) in runoff from adjacent agricultural areas as well as reduce peak flow to mitigate flooding. We then discuss the opportunities for local implementation of BGI solutions to achieve specific flood and water quality objectives.

Case study

The impacts of the introduction of a designed pond were tested in a flood-prone case study site - the Tarwin catchment located in the South Gippsland, Victoria, Australia (Fig. 1). At this location, it is possible to encounter extreme weather events on a regular basis that result in flooding and for which detailed meteorological and hydrological data exists. We used as a reference a recent heavy rainfall and significant flood event in June 2012. This was the most recent damaging flood event in the region and therefore it was selected as the focus of this study.

Wetland loss in the Tarwin catchment (Gippsland region) has been significant since human settlement [13]. Due to agricultural development, this regional area has lost 86 % of native vegetation. Clearing still continues, and the remaining native vegetation is in a degraded state [14].

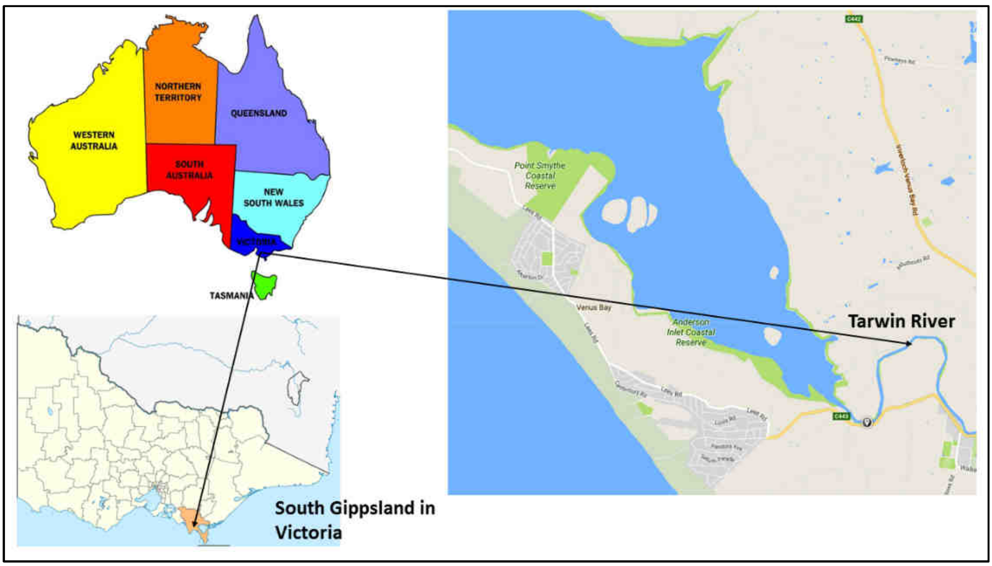

Fig. 1. Tarwin River located in South Gippsland, Victoria, Australia [15]

Due to structural flood mitigation measures, the study area has lost a significant portion of its wetlands. The Tarwin Lower region and the nearby deltas are protected from small floods (nuisance flooding) and storm surges by the broad system of levees along the lower part of the catchment. These levees were generally constructed by private landowners in response to “Drainage Area” declaration from the early 1940s through to late 1960s, in order to control flooding of the Tarwin River and Anderson Inlet [16]. However, these levees are usually over-topped by large floods and large storm surges and are therefore not effective. As the existing structures are very old (built from 1940-1980) and there is little evidence they have been maintained since construction, a study into feasible, alternative flood mitigation measures is vital, especially as climate change and sea level rise are potential issues into the future [16-18].

An introduction to the proposed pond

The proposed pond is an impoundment area used to provisionally store storm-water runoff and control downstream discharge, thereby decreasing downstream flooding and erosion, as well as improve runoff pollutant removal. This pond is comparable to lakes as there is always a permanent body of water. Extra temporary storage is provided above the permanent level, during extreme rainfall events. After the rainfall, the water level slowly returns to its normal level. Figure 2 shows the proposed pond system layout [19].

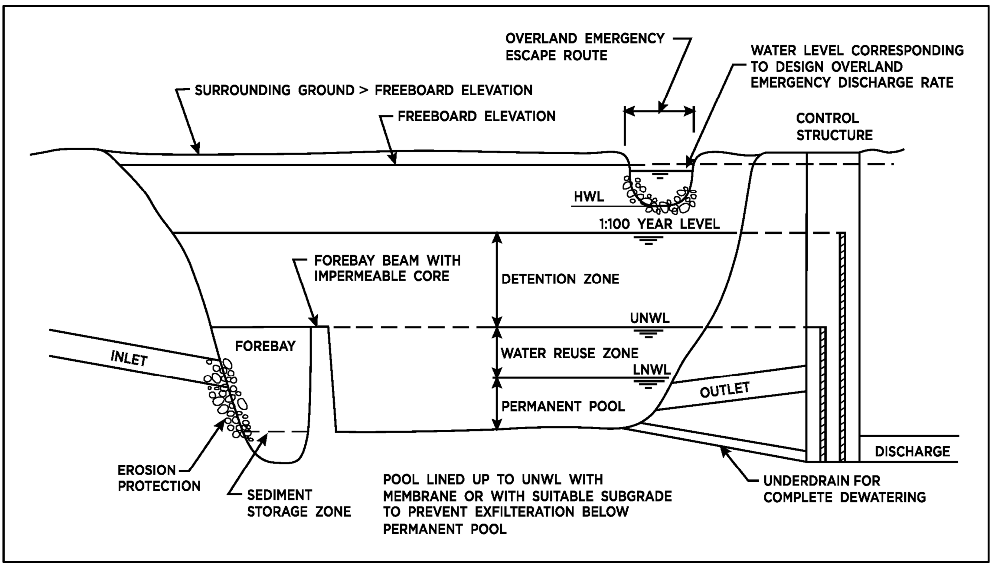

Fig. 2. Section view of the proposed pond [19]

The proposed pond includes a permanent pool, detention storage, an extended detention zone, and a minimum free-board. The permanent pool holds a permanent volume of water and acts as a buffer; it decreases the velocity of the storm-water inflowing to the pond and traps contaminants. The permanent water elevation in the designed pond is defined as the Permanent Water Level (PWL) or Normal Water Level (NWL). The NWL is not fixed if water is re-used for irrigation; it varies between a Lower (L) NWL and an Upper (U) NWL. When the water level in the pond surpasses the (U) NWL, discharge to receiving water or a downstream drainage system starts, and the re-use finishes when the water level has fallen to the (L) NWL (Fig. 2). Detention storage is a temporary storage with the main purpose of quantity control by attenuating runoff. It represents the storage area between the NWL and the 100-year level. Extended detention zone is referred to as active storage, which is mainly designed for storm-water volume control. It represents the temporary storage between the NWL and the High Water Level (HWL). A minimum free-board is planned above the water level that relates to the policy of the overland emergency discharge rate [19].

Methodology

A flow diagram of the design approach and modelling the impacts of the designed pond on storm-water quantity and quality is shown in Figure 3; this diagram comprises five main steps shown by different colours. Defining the pond criteria is the first step (yellow). Design criteria are defined to meet specific requirements. In the second step (green), the size of the pond is calculated with the help of the Personal Computer Storm Water Management Model (PCSWMM) software package and local adjustment factors [20]. In step three (blue), based on the calculated size of the pond from the previous step and the criteria defined in step one, the impact of the pond on storm-water peak flow (quantity) is modelled in PCSWMM. Step four (grey) includes modelling of the designed pond (again based on its size determined in step two and its defined criteria in step one) in Model for Urban Storm-water Improvement Conceptualization (MUSIC) for assessing the pond's impacts on TSS, TN, and TP reduction (quality) [21]. Finally, the results of the introduction of the designed pond to the case study are evaluated in step five shown in red.

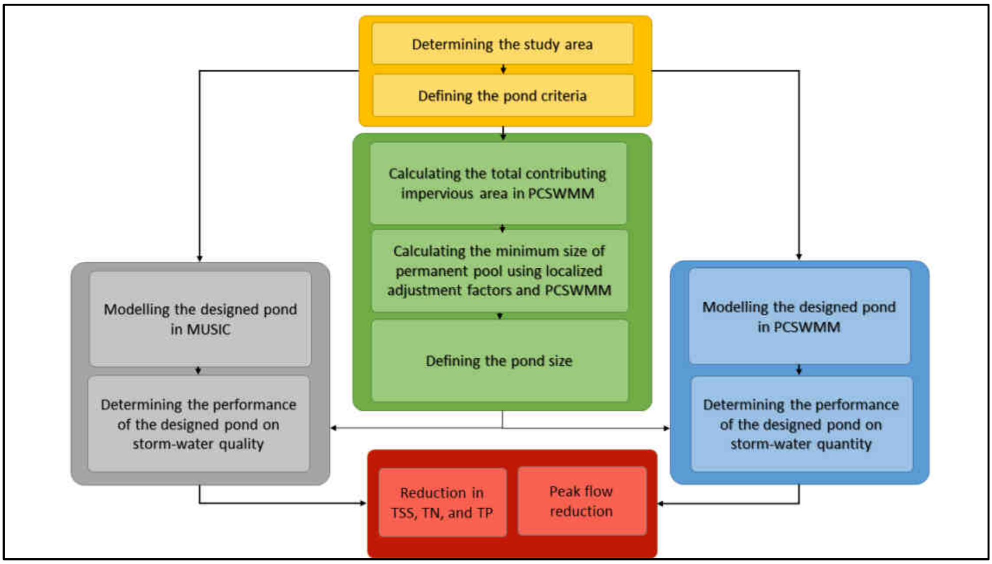

Fig. 3. Typical steps of designing the proposed pond and determining its performance on storm-water quality and quantity at a case study site. (1) Yellow: defining the criteria phase, (2) Green: pond sizing phase, (3) Blue: PCSWMM modelling for water quantity, (4) Grey: MUSIC modelling for water quality, and (5) Red: results

Defining pond criteria

The main goal of a pond is to supply interim storage of storm-water for flooding control, water quality improvement, and sometimes, to reduce runoff and to facilitate storm-water re-use prior to discharge. In order to reduce the peak flows and nutrient loads, a pond was designed for the Tarwin catchment. Typical pond design criteria for Victoria are defined by Melbourne Water (Victoria's principal statutory water authority) and their criteria have been applied in this study with consideration for site-specific characteristics. The pond design criteria, as defined by Melbourne Water are [22]:

1. most conservative storage for 1:100-year storage volume
2. 85 % removal of TSS for particles size ≥ 125 μm
3. Side slope ratio for the pond sides is 3:1
4. Length to width ratio is 3:1
5. Minimum depth of permanent pool is 2 m
6. Maximum depth from the top of water reuse zone to the 100-year line is 1.5 m for ponds subject to reuse or withdrawal for irrigation
7. Maximum depth from top of 100-year line to overland escape route is 2 m
8. Minimum free-board of 0.30 m

In order to design a pond that can accommodate a 1:100 year rainfall event in the Tarwin catchment, site-specific information is needed. The Tarwin catchment DEM layer, sub-catchment imperviousness area, adjustment factor, Mean Annual Rainfall (MAR), and estimated peak flow are Tarwin-specific variables that were fed into the model to calculate the size of the pond. Details on how these case study-based variables were used are fully described in the defining pond size section below.

Defining pond size

We used PCSWMM and local adjustment factors to calculate the pond size. This section describes the steps involved in more detail.

Calculating total contributing impervious area in PCSWMM

Using the Watershed Delineation Tool (WDT) in PCSWMM, sub-catchments, as well as junctions and conduits were created for the case study area. According to PCSWMM, sub-catchments (green patches in Figure 4) are hydrologic units of land whose topography and drainage system elements direct surface runoff to a single discharge point. Junctions (blue dots) are drainage system nodes where links join together. Physically they can represent the confluence of natural surface channels or pipe connection fittings. Conduits (red and yellow lines) are pipes or channels that move water from one node to another in the conveyance system. Outfalls (red triangles (OF)) are terminal nodes of the drainage system used to define final downstream boundaries. This type of discretization needs a Digital Elevation Model (DEM) layer. The Gippsland DEM layer was used for creating sub-catchments including junctions and conduits. WDT is a built-in tool available in PCSWMM that can be utilized to determine sub-catchments. In addition, the WDT generates an entirely interconnected node and link model and allocates the sub-catchment flow lengths and slopes. For the WDT to run correctly, all layers were projected in Popular Visualization CRS Mercator coordinate system.

To determine the volume required for the permanent pool, it is necessary to calculate the total imperviousness contributing area. This was done by selecting the sub-catchments that contribute to the pond. According to Figure 4, sub-catchments 1-31 (highlighted in blue) have a contribution to the designed pond based on the water direction. Having the data about impervious ratio [%] and area for all contributing sub-catchments, the contributing sub-catchment imperviousness area was calculated using equation:

$$C = \sum_{i=1}^{i=n} A_i I_i = 277{,}827.72 \text{ m}^2 \quad (1)$$

where C represents the contributing sub-catchment imperviousness area, A is the area of each contributing sub-catchment, I is the % impervious ratio of each contributing sub-catchment, and n is the number of contributing sub-catchments.

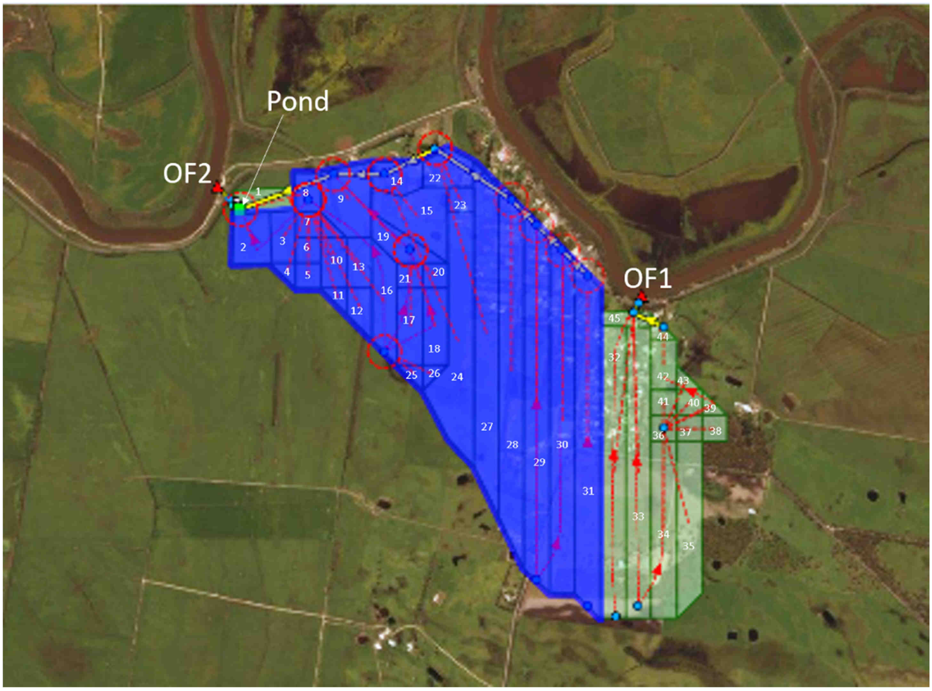

Fig. 4. Total contributing sub-catchment area (sub-catchments 1-31) to the proposed pond in the Tarwin catchment, Victoria, Australia

Determining the minimum volume of the permanent pool

In order to design the pond elements associated with the peak flow reduction and water quality function of the system, a reference site was selected for which detailed performance curves were derived for different configurations (e.g. area, extended detention depth and permanent pool volume) of a range of storm-water treatment measures. Melbourne was selected as the reference site. Estimated pollutant reduction from simulations for a pond component with different configurations for this reference site are presented in Figure 5. The curves shown in Figure 5 describe the TSS, TP, and TN removal performance expected for a pond in Melbourne. The curves were derived assuming the systems receive direct runoff (i.e. no other BGI elements upstream) and the outflow from the system is via an overflow weir. These curves can then be adapted using the adjustment factors for application at different sites across Victoria [22]. So, hydrologic regions within Victoria were defined such that within each region the adjustment factor relationship was consistent.

An equation for each region was developed that could be applied anywhere within that region (i.e. sub-regions).

Melbourne Water analyzed the importance of different meteorological and geographical factors and their impact on adjustment factors [22]. Their analysis was confined to factors for which data are available (from the Australian Bureau of Meteorology) and included MAR, site elevation, a measure of seasonal distribution of rainfall and rain-days, and geographical location. They concluded that the most significant influencing factor was MAR because the inclusion of other factors such as rain-days seasonality, rainfall seasonality and elevation did not appear to improve the estimation of the adjustment factors used in the analysis. Thus, a set of equations that only requires local MAR data has been developed, to define the adjustment factors. This method is based on determining different hydrologic design regions within Victoria with adjustment factors for ponds. A required treatment area derived for the reference site (Melbourne) can therefore be converted into an equivalent treatment area that will achieve the same level of treatment elsewhere in Victoria [22].

Modelling results indicated that the regional equations derived for the five state-wide hydrologic regions fall within a ±10 % band. Thus, by adopting adjustment factors that are 1.1 times (i.e. +10 %) that predicted by these equations, it is expected that the predicted size of storm-water treatment measures using this method will provide adequate sizes for the treatment performance required with a high degree of certainty (i.e. they may be slightly conservatively designed). This preserves the opportunity for designers to adopt a more rigorous approach if desired. The recommended constants and equations for calculating the suitable adjustment factors of a pond for Victoria are summarized in Table 1.

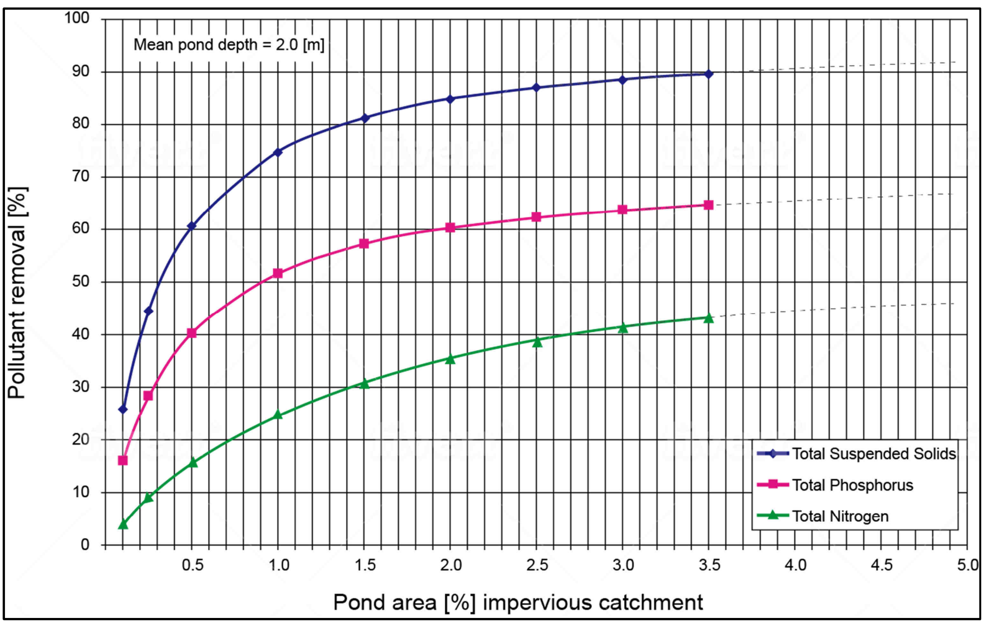

Fig. 5. Performance of ponds in removing TSS, TP and TN in Melbourne [20]

Table 1

Greater Victoria adjustment factors for a pond [20]

Region	Pond
Northern	1.85 (MAR) + 0.151
Western Plains	1.91 (MAR) – 0.105
South Coast	1.84 (MAR) – 0.160
Great Dividing Range	2.20 (MAR) – 0.340
Gippsland	2.28 (MAR) – 0.227

Based on Figure 5, the minimum area of the reference permanent pool needs to be 2 % of the contributing impervious area to meet best practice objectives (85 % of TSS removal) (equation 2):

$$A_r = 0.02 \cdot C = 5{,}556.55 \text{ m}^2 \quad (2)$$

where A_r is the minimum area of the reference permanent pool and C is the contributing sub-catchment imperviousness area.

The adjustment factor for the Gippsland region is calculated using the pond adjustment equation for the Gippsland region in Table 1. Therefore, the minimum permanent pool area for a development in Gippsland with MAR of 850 [mm], is calculated as follows:

$$A_g = A_r \cdot A_f = 9{,}507.30 \text{ m}^2 \quad (3)$$

where A_g is the minimum area of the pond permanent pool for Gippsland, A_r is the minimum area of the pond permanent pool for the reference, and A_f is the pond adjustment factor for Gippsland region.

Therefore, the minimum volume of the permanent pool for the proposed pond with the depth of 2 m is about 19,015 m^3.

Using the storage pond calculator tool of PCSWMM, the storage volume required to match a specified peak flow is estimated. The design outflow is typically governed by local requirements and needs consultation with the municipality for their specific needs. These should typically not exceed pre-development rates, which in Victoria range from 0.13 to 3.84 m^3/s [22].

By determining the total inflow m^3/s for June 2012, the size of the pond can be calculated. The maximum design outflow is set at 0.8 m^3/s. The volume required for the pond is determined using the Storage Pond Calculator tool (about 21,000 m^3).

Table 2

Calculation of the storage curve for available surface area in the Tarwin catchment, Victoria, Australia

Depth [m]	Length [m]	Width [m]	Area [m^2]	Volume [m^3]
0.00	156.90	52.30	8,205.87	0.00
1.00	159.90	55.30	8,842.47	8,374.77
2.00	162.90	58.30	9,497.07	19,018.14
2.20	163.50	58.90	9,630.15	21,218.27
3.80	168.30	63.70	10,720.71	40,903.31
4.10	169.20	64.60	10,930.32	45,021.08

Given length and width data, we used Python programming language version 2.7 (with Numpy and Pandas packages) to find available surface area for a given depth using the pond design criteria (for a pond of rectangular shape with constant side slope). The base length and width were changed iteratively until the pool volume was reached. The overflow depth was changed iteratively until the pool volume plus additional storage required was reached. The volumes and areas were calculated at intermediate depths including free-board level. The results are shown in Table 2.

Modelling the designed pond in PCSWMM

Two modelling techniques (PCSWMM and MUSIC) were used to assess the impacts of the designed pond on storm-water quality and quantity in the study area. These models are well-established and used extensively all over the world [20, 21]. They are particularly pertinent and useful for the case study within this paper, and generally other locations in Australia, because they utilize parameters for which data is readily available.

PCSWMM was used for the hydraulic modelling of the area with the designed pond. Having the information about size and physical configuration of the pond (calculated in step two of the methodology), rainfall data for an extreme event during June 2012, area and characteristics of sub-catchments, imperviousness ratio, slope, and using the dynamic wave routing method for simulation, the pond was modelled in PCSWMM to assess its performance with respect to peak flow reduction.

Dynamic wave routing can account for channel storage, backwater, entrance/exit losses, flow reversal, and pressurized flow. Because it couples together the solution for both water levels at nodes and flow in conduits it can be applied to any general network layout, even those containing multiple downstream diversions and loops. It is the method of choice for systems subjected to significant backwater effects due to downstream flow restrictions and with flow regulation via weirs and orifices. This generality comes at a price of having to use much smaller time steps, on the order of a minute or less (PCSWMM will automatically reduce the user-defined maximum time step as needed to maintain numerical stability) [20].

An unlimited number of upstream and downstream links (conduits, pumps, weirs, orifices) can be connected to any non-outfall node (junction or storage node) when using the dynamic wave routing method in PCSWMM. In dynamic wave routing, flow reversals are possible (depending on the head difference) thus any connected conduit, weir or orifice may be considered "leaving" a junction if the conditions are right at any particular time step during the simulation [20].

Modelling the designed pond in MUSIC

Analysis of the impacts of the designed pond with respect to storm-water treatment (quality) was performed using MUSIC. MUSIC is a decision support tool for storm-water managers, which helps them to plan and design appropriate storm-water management systems for catchments. It simulates pollution removal through storm-water management systems such as ponds, wetlands, bio-retention and harvesting [21].

In South Gippsland’s agricultural catchments, the highest catchment nutrient loads come from intensive land uses, which typically occur in flatter landscapes with high rainfall runoff. The study area comprises five types of land use: grazing modified pasture (cattle and other livestock), rural living, conservation environment, and roads. Land use type is seen as the primary factor responsible for changes in sediment and nutrient delivery to the pond.

The major driver of sediment and nutrient delivery to surface water at the catchment scale is intensive land use, in particular, the most intensive land uses of grazing modified pasture. The more intense the land use in terms of nutrient inputs such as fertilizers, the greater the nutrient enrichment in waterways. The land uses of grazing modified pastures-cattle, grazing modified pastures-other livestock, rural living, roads and conservation environment generate the most nutrients at catchment outlets respectively. Grazing modified pastures (cattle and other livestock) contributed the most because of the extent of this land use in South Gippsland catchments [14].

Once the meteorological data (rainfall data per 6 minutes for the year 2012, mean monthly potential evapotranspiration, and the time step of 6-minute for the Tarwin catchment) was entered into the model, the source nodes were defined to reflect the details of the contributing catchments. This involved establishing the type of land use, defining the sub-catchments, splitting the catchments into land types where required, introducing rainfall runoff parameters, and defining pollutant export parameters.

Table 3 depicts the rainfall runoff parameters for the Tarwin catchment. In MUSIC, the default parameter for deep seepage is zero. As rainfall on pervious areas is subject to losses by evapotranspiration from the soil store and deep seepage from the groundwater store, this was set to a default value of zero because we assumed that no runoff was lost by deep seepage from the groundwater store.

Table 4 illustrates Dry Weather Concentrations (DWC) and Event Mean Concentrations (EMC) of the nutrients according to land use. Data were collated by South Gippsland Water for TSS, TN, and TP.

Table 3

Rainfall runoff parameters for the Tarwin catchment, Victoria, Australia

Impervious area properties	
Rainfall threshold [mm/day]	1.00
Pervious area properties	
Soil storage capacity [mm]	120.00
Initial storage [%] of capacity	25.00
Field capacity [mm]	80.00
Infiltration capacity coefficient - a	200.00
Infiltration capacity coefficient - b	1.00
Groundwater properties	
Initial depth [mm]	10.00
Daily recharge rate [%]	25.00
Daily base flow rate [%]	5.00
Deep seepage [%]	0.00

Table 4

DWC and EMC values for different land use types in the Tarwin catchment, Victoria, Australia

Land use	**TSS [g/m^3]**		**TN [g/m^3]**		**TP [g/m^3]**	
	DWC	**EMC**	**DWC**	**EMC**	**DWC**	**EMC**
Grazing modified pasture cattle	10	200	0.30	2.20	0.08	0.50
Grazing modified pasture other livestock	10	150	0.30	2.20	0.04	0.50
Rural living	10	110	0.30	2.00	0.10	0.25
Conservation environment	5	40	0.008	0.90	0.02	0.09
Road	10	100	0.30	2.30	0.10	0.30

Size and physical configuration of the designed pond (calculated in step two of the methodology) and its pollutant removal parameters are shown in Table 5.

Table 5

The designed pond properties in MUSIC

Inlet properties	Low flow by-pass [m^3/s]	0.00
	High flow by-pass [m^3/s]	100.00
Storage properties	Surface area [m^2]	10720.70
	Extended detention depth [m]	1.80
	Permanent pool volume [m^3]	19018.10
	Initial volume [m^3]	0.00
	Vegetation cover [%] of surface area	10.00
	Exfiltration rate [mm/hr]	0.00
	Evaporative loss as [%] of Potential Evapotranspiration (PET)	100.00
Outlet properties	Equivalent pipe diameter [mm]	200.00
	Overflow weir width [m]	1.00
	Notional detention time [hr]	42.90
Advanced properties	Orifice discharge coefficient	0.60
	Weir coefficient	1.70
	Total Suspended Solids [k [m/yr], C^*[g/m^3]]	400.00, 12.00
	Total Phosphorus [k [m/yr], C^*[g/m^3]]	300.00, 0.09
	Total Nitrogen [k [m/yr], C^*[g/m^3]]	40.00, 1.00

Having the information about the size of the pond, area, imperviousness ratio, soil parameters, and DWC and EMC values for TSS, TN, and TP of each land use, as well as the pond's physical configuration and pollutant removal parameters, enabled the treatment analysis in MUSIC.

Results and discussion

Results of the designed pond modelled in PCSWMM and MUSIC on peak flow reduction and water quality improvement are described in this section.

Peak flow reduction

Simulating the rainfall event of June 2012 in the presence of the designed pond shows it has a significant impact on reducing the peak flow at key node OF2, as shown in Figure 6. This figure illustrates the maximum total inflow of the catchment main outfall node (OF2) during the heavy rainfall event in 2012. The red colour curve shows the outfall node maximum total inflow [m^3/s] for the study area without the pond while the green colour depicts the outfall node maximum total inflow [m^3/s] with the designed pond.

Statistics of the catchment outfall inflow including maximum, minimum, mean and total inflow are tabulated in Table 6. They indicate that the introduction of the pond to the case study would have reduced outfall total inflow by 94 % (reduction from 47,540 m^3 to 2,848 m^3) during the extreme weather event of June 2012, thereby largely mitigating flood in the defined sub-catchment area. This is a good result but is to be expected since the outfall node (OF2) is adjacent to the pond and the pond serves to hold all storm-water (Fig. 4). It would be useful to know the capacity of the pond to mitigate subsequent rainfall events. However, that is beyond the scope of this study.

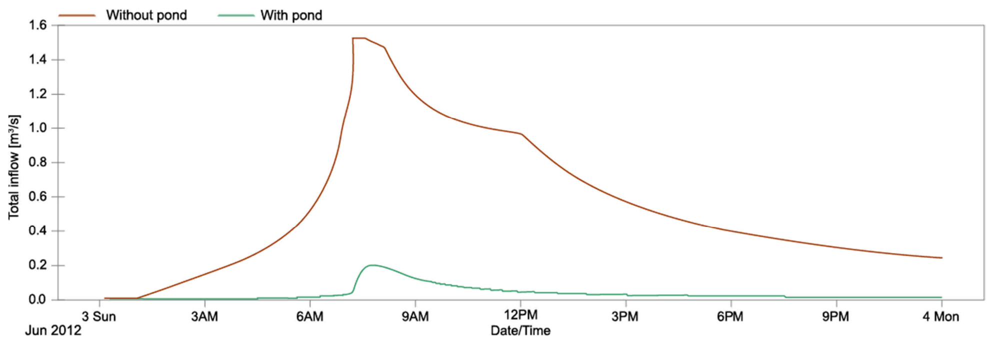

Fig. 6. Comparison of outfall peak inflow with and without pond, Tarwin Catchment, Victoria, Australia

Table 6

Comparison of the maximum, minimum, mean and total inflow of the catchment outfall node with and without the designed pond

Catchment outfall statistics	**Scenario 1: with the designed pond**	**Scenario 2: without the designed pond**
Maximum total inflow [m^3/s]	0.19	1.53
Minimum total inflow [m^3/s]	0.00	0.00
Mean total inflow [m^3/s]	0.03	0.55
Total total inflow [m^3]	2,848.00	47,540.00

Water quality improvement

The results of the storm-water treatment using the designed pond in the Tarwin catchment are shown in Table 7. Based on this table, the designed pond is predicted to remove approximately 88.3 % of TSS loads, 75.5 % of TP loads, and 50.7 % of TN loads. Moreover, the model predicts that approximately 4.5 tons (4,490 kg) of gross pollutants are captured in the designed pond each year. This is the total amount of gross pollutants generated in the catchment.

Table 7

Pond treatment effectiveness on TSS, TP, and TN reduction in the Tarwin catchment, Victoria, Australia

Sediment and nutrient	**Sources**	**Residual load**	**Reduction [%]**
Total Suspended Solids [kg/yr]	21,900.0	2,570.0	88.3
Total Phosphorus [kg/yr]	77.4	19.0	75.5
Total Nitrogen [kg/yr]	441.0	217.0	50.7
Gross Pollutants [kg/yr]	4,490.0	0.0	100.0

Figures 7-9 illustrate the time series graphs of TSS, TP, and TN pollutants in the designed pond respectively. They show inflow and outflow of TSS, TP, and TN concentrations for the designed pond; the time-step chosen for production of the time series graph is a daily interval. Time series graphs present a plot of user-specified data against time and provide a simple way to view the overall performance of a particular treatment node.

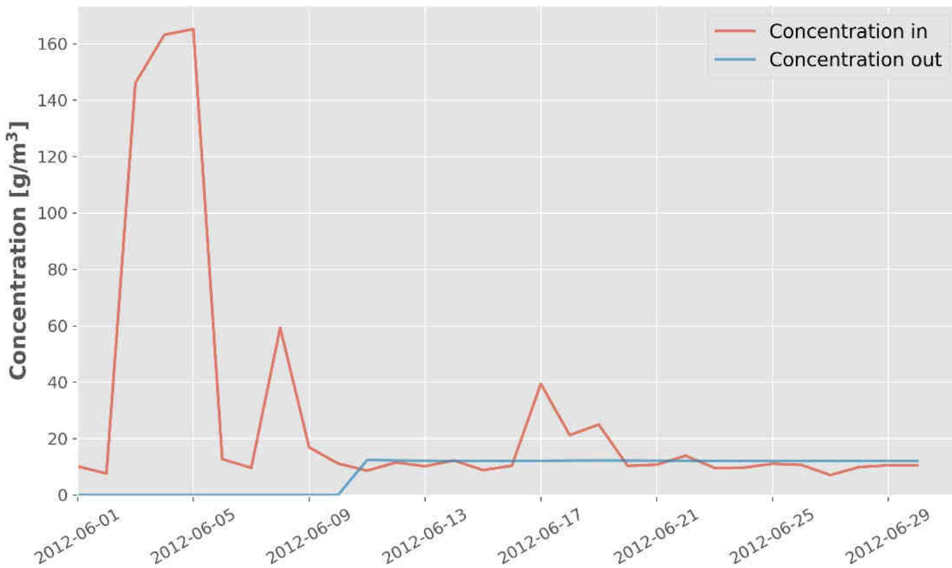

Fig. 7. Time series graphs, Total Suspended Solid for the designed pond, Tarwin catchment, Victoria, Australia

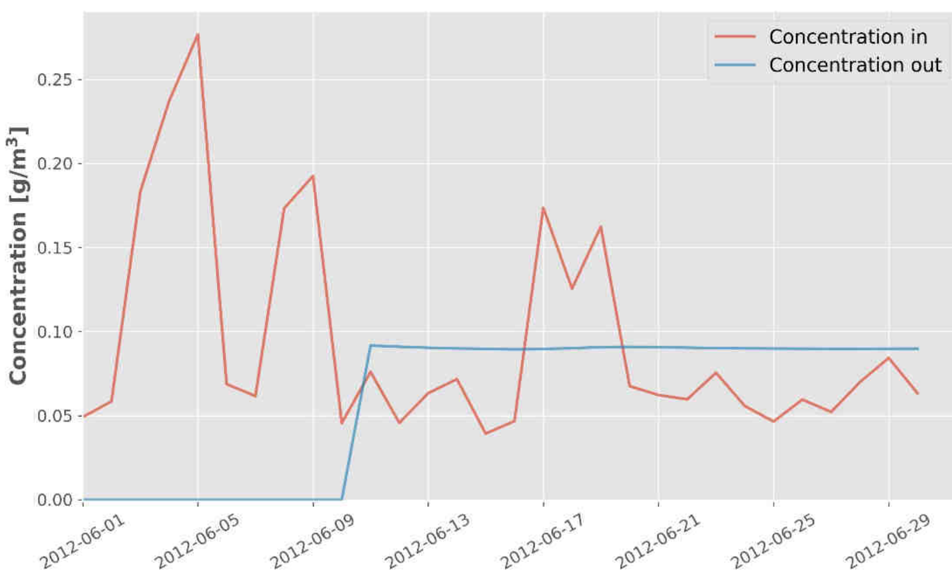

Fig. 8. Time series graphs, Total Phosphorus for the designed pond, Tarwin catchment, Victoria, Australia

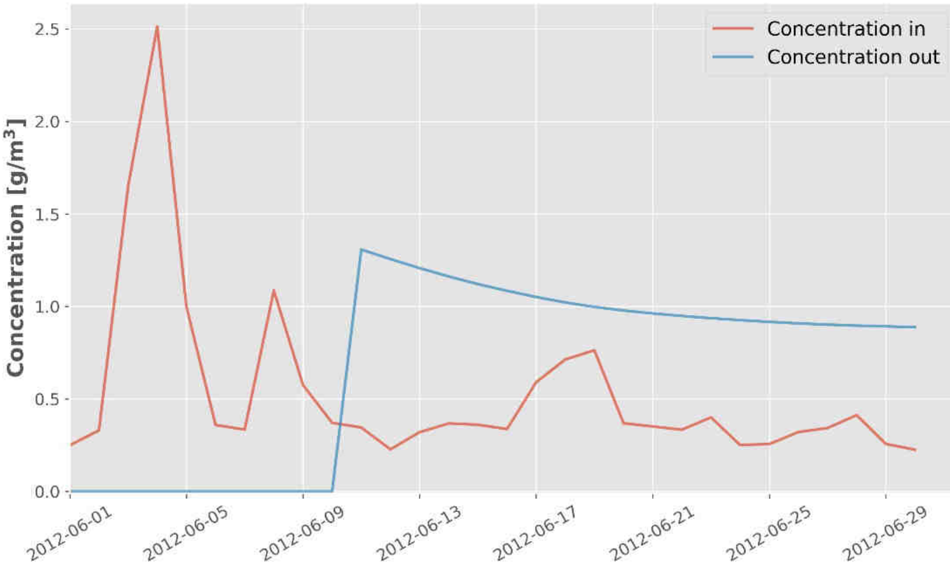

Fig. 9. Time series graphs, Total Nitrogen for the designed pond, Tarwin catchment, Victoria, Australia

The results demonstrated that implementing the designed pond could significantly reduce storm-flow and mass exports of several pollutants in storm-water compared with the current situation. The adaptability of PCSWMM and MUSIC increases the practicality of our approach for many other scenarios and case studies. The results, however, lack other time-dependent changes, especially dynamic activities such as tillage operation and fertilizer application in rural and regional regions.

The designed pond provides a flow management function that protects local properties from flood. Maintenance of a pond is primarily concerned with flow to, and through, the system - this means that simple actions like managing vegetation and removing accumulated sediments and debris will ensure the efficacy of a pond. In the context of a flood-prone rural area, the low-maintenance nature of the pond, together with its low cost and simplicity, make it a viable alternative to the more common (and expensive) hard-infrastructure solutions that are usually implemented, such as levees.

The designed pond also treats runoff by providing extended detention time thereby allowing sedimentation to occur. Management of nutrients in rural and regional areas of Australia is dependent on regulatory frameworks and monitoring systems, which provide triggers for authorities to oblige farmers to change nutrient management practices. This system works relatively well under normal circumstances. But, the system generally fails during extreme weather events because the excess water invariably results in nutrient escape from farmland. The use of the designed pond is an effective and passive solution for control and treatment of runoff in regional and rural areas that is especially useful during the heavy rainfall events when standard systems cannot cope.

Furthermore, the designed pond has the advantage of being purposefully designed and can, therefore, be customized to the case study site and constructed to provide multiple benefits. For example, the permanent body of water component of the pond can be designed to accommodate particular plants and animals so as to provide additional biodiversity benefits. Also, the captured peak-flow water, which would otherwise cause flooding and damage, can be stored and used by farmers for irrigation later. Clearly, a designed pond will not be suitable for every scenario or location and as we have mentioned, an important factor is the efficacy of the pond in the face of repeated rainfall events. But, as part of a suite of mitigation approaches (which might include vegetation buffers and reduced fertilizer use on farms through regulatory approaches and education), ponds are effective and offer the advantage of reducing flood damage as well.

Here, a pond was designed as a stand-alone solution within a rural catchment area. Limitations in terms of size and suitable locations for ponds will inevitably place an upper limit on the possible peak flow and pollution reduction that is possible in a given landscape. However, if ponds are considered as only one BGI element that can be combined with many other blue and green elements in a broader BGI strategy, the potential for broad scale flood and pollution control is much greater. The diversity of BGI elements and the ability to integrate them into a cohesive network means that swales, bio-retention cells and water tanks (among many others) can be introduced where a pond is not feasible and still maintain the integrity of flood control, pollution reduction and excess water storage across a defined area. In a country like Australia, where weather extremes are common, it would, therefore, be possible to mitigate the effects of flood and drought in rural and regional areas using BGI. In the context of climate change, BGI would enhance the resilience of farming communities to more frequent extreme weather events. Finally, the widespread implementation of BGI could go some way to reversing the loss of natural wetlands across regional Australia.

Conclusions

This study demonstrates that the introduction of the designed pond would have largely mitigated peak flow during a recent heavy rainfall event and significantly reduced pollutant load in the resultant runoff from surrounding agricultural land. In addition, it confirms that a pond is an effective BGI component that provides multiple benefits and thus fits well with the concepts of sustainable regional development. The designed pond as a component of a BGI system can likely increase the resilience of farming communities to climate change in this region of Australia. Therefore, this study demonstrates that significant improvements in rural and regional catchment management are possible through storm-water control policies that integrate the use of BGI technologies.

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