Improving the Viability of Stormwater Harvesting through Rudimentary Real Time Control

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Abstract: Stormwater Harvesting (SWH) to alleviate water scarcity is often hindered by the lack of suitable available storage in urban areas. This research aimed to discover an economically viable strategy of storing runoff in existing stormwater ponds with the assistance of rudimentary Real Time Control (RTC) techniques to increase the effective storage capacity. The Diep River sub-catchment situated in the southern suburbs of Cape Town, South Africa, that has several stormwater ponds that were largely constructed for the purposes of flood mitigation, was used as a case study. Six SWH scenarios utilising three distinct RTC strategies coupled with two alternative water demand alternatives were simulated with the aid of 10 years' of historical rainfall data with a view to determining the unit cost of supplying selected developments with non-potable water. The use of RTC to increase the effective storage of the ponds was shown to improve the volumetric yield without significantly impairing the flood mitigation provided by the system at a cost that was comparable to what the local residents were already paying for potable water. This finding is important as it suggests a cost-effective way of overcoming one of the greatest limitations associated with stormwater harvesting.

1. Introduction

South Africa is facing increasing concerns over the security of its water resources as population growth—overwhelmingly concentrated in urban areas—has pushed water demand to the limits of sustainability with the existing, surface-water based systems [1–3]. This, together with the additional threat of climate change, has resulted in a growing interest in alternative water resources to supplement the existing supplies. Stormwater, in particular, has been identified as a viable supplementary water resource owing to its relative abundance in urban areas, but a practical obstacle to Stormwater Harvesting (SWH) is long-term storage [2,4]. Since stormwater flows are intermittent, SWH systems require facilities that can store large enough volumes of the collected runoff to ensure that they can deliver a reasonably reliable water supply during dry periods [5,6].

Historically, stormwater ponds were constructed to attenuate the stormwater flows associated with large storm events (e.g., 1 in 10 years or larger) by providing temporary storage for runoff [7,8]. Since events of this magnitude seldom occur, they commonly have unutilised storage potential [9,10]. Mitchell et al. [5] have shown that this unutilised storage can potentially be used to store runoff for distribution without impairing their existing functionality or incurring a significant space penalty. Whilst many existing ponds are located in unsuitable areas or individually have insufficient storage capacities for the purpose of SWH on their own, urban catchments typically contain many of them [11–13] and it may thus be possible to provide suitable storage by managing them as a group through the use of Real Time Control (RTC) techniques. In this context, RTC refers to the opening and

closing of the outlets of the stormwater ponds as well as the operation of the stormwater extraction pumps in accordance with set operating rules. It is becoming a popular method to reduce redundant storage within drainage systems [14–16].

This study thus aimed to discover whether it was economically viable to use Real Time Control (RTC) techniques with low complexity to facilitate the harvesting of stormwater from a number of existing stormwater ponds in an urban catchment without impairing their ability to alleviate downstream flood risks. A typical urban catchment in the City of Cape Town (CoCT), South Africa, with multiple existing stormwater ponds was selected as a feasibility case study. The study modelled six SWH scenarios utilising three distinct RTC strategies coupled with two alternative water demand alternatives with a view to supplying selected developments with non-potable water.

2. The Modelled Catchment

The catchment that was modelled in this study, the Diep River sub-catchment, forms part of the greater Sand River catchment (Figure 1) [17]. The catchment covers an area of some 2000 ha and is home to about 41,000 people [18]. It experiences seasonal rainfall with warm, dry summers and mild, wet winters [19]. Due to its position on the slopes of the Table Mountain range, the average annual rainfall varies from 800 to 1400 mm/year. depending on the location, which is far greater than the average annual rainfall of the CoCT of around 515 mm/year. [20]. There is a semi-natural *vlei* (a shallow, minor lake), called 'Little Princess Vlei (LPV)', which acts a retention pond located at the most downstream point of the catchment. It is steeped in cultural and ecological significance [21–23].
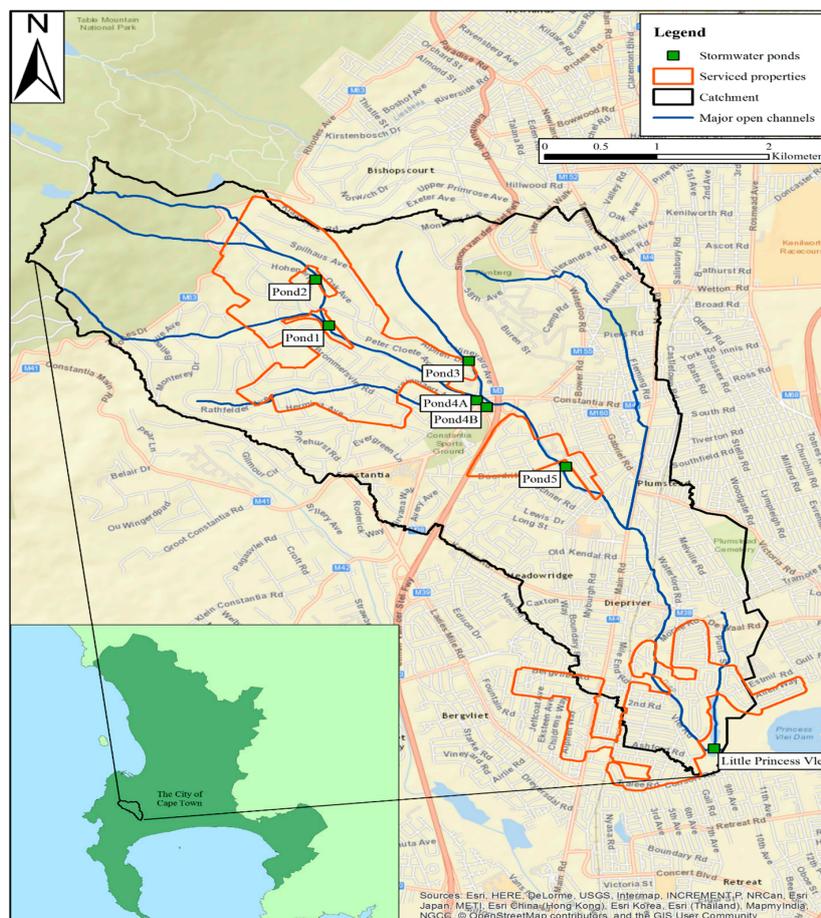

Figure 1. The Diep River sub-catchment and outline of properties that are serviced by the SWH scenarios (After ESRI et al. [24]).

Between 1970 and 1980, the Diep River sub-catchment experienced extensive urban development. This resulted in greatly increased flood peaks which the existing stormwater network did not have the capacity to handle, leading to several serious flooding events. To mitigate this, the CoCT constructed six detention ponds along the Diep River and its upstream tributaries that were designed to alleviate floods up to the 1 in 20-year flood event [25].

For this study, it was assumed that all of the existing detention ponds could be modified to retain runoff by controlling the outlets. All ponds were then modelled as on-line (i.e., positioned directly in-line with their providing watercourse) open storage facilities without impermeable linings. This meant that the ponds would be susceptible to water losses through evaporation and infiltration—with an average modelled loss of volume of 18%. The modelled storage volume of each pond was further divided into: dead storage, active storage, and flood mitigation storage (Figure 2). Dead storage represents the permanent volume of storage in the pond used for water treatment purposes as well as to uphold the aesthetic value of the pond; active storage is the volume of water that can be distributed; whilst flood mitigation storage is the additional volume of the pond allocated over-and-above spare active volume capacity to attenuate storm events. The types of ponds as well as the parameters used in the model are listed in Table 1.
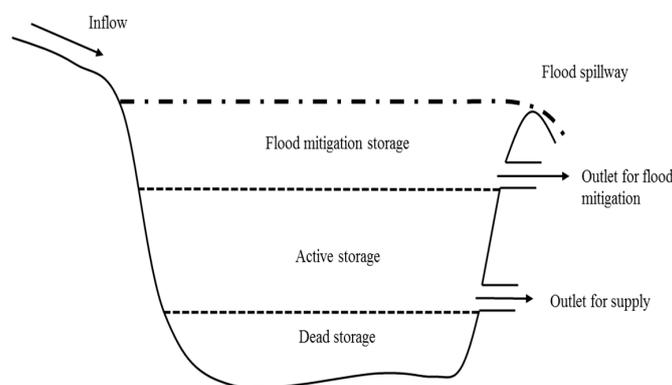

Figure 2. Conceptual design of an open storage stormwater harvesting system (After Mitchell et al. [5]).

Table 1. Description of the existing stormwater ponds in the Diep River sub-catchment.

Storage Facility	Little Princess Vlei	Pond 1	Pond 2	Pond 3	Pond 4B	Pond 5
Pond type (Existing)	Retention	Detention	Detention	Detention	Detention	Detention
Harvestable volume (m³) (Modelled)	22,300	18,500	11,900	4700	8900	3800
Dead storage depth (m) (Modelled)	1.2	3.3	1.8	1.8	1.2	1.2
Active storage depth (m)	2	5.5	6.6	3	2.9	1.8
Maximum pond depth (m) (Existing)	3.72	6.5	8.1	4.4	4.25	2.3

3. Stormwater Harvesting Scenarios

Only six SWH scenarios (Figure 3) were modelled in this study. These comprised three basic RTC strategies (A–C), each with two different non-potable water demand alternatives (WDA) (1 & 2).
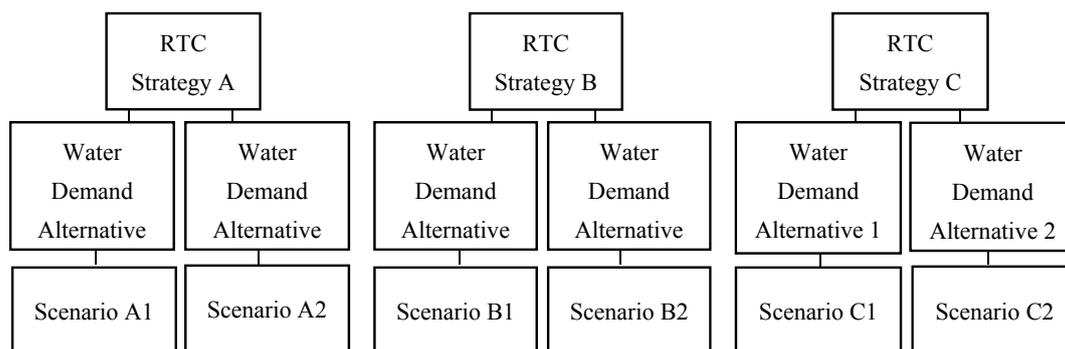
Figure 3. The six SWH Scenarios—RTC Strategy and Water Demand Alternative (WDA)—modelled.

Within each RTC strategy, a stormwater pond could perform one of three roles: (i) storage and harvesting of runoff; (ii) storage of runoff only; or (iii) not used for SWH. Stored runoff was only extracted from ponds whose role was storage and harvesting. Ponds whose role was just storage were only used to store runoff which was subsequently released to a downstream storage and harvesting pond according to various rules. Ponds that were not used within a particular SWH system were not retrofitted in any way; i.e., these ponds maintained their existing function which is to attenuate peak flows. The study modelled each RTC strategy under two separate residential non-potable water demand conditions: WDA 1, which modelled only toilet flushing; and WDA 2, which modelled toilet flushing, clothes washing and lawn irrigation.

Assuming that LPV, the most downstream pond in the catchment, was always to be used for the storage and harvesting of runoff, there are 243 different possible RTC strategies that could be devised from the combination of pond roles and the existing stormwater ponds. Many of these RTC strategies, however, share considerable similarities to one another. Modelling all of them was thus unnecessary as long as the most representative ones were considered. Thus, in an effort to streamline the study and save massively on computational effort, only the three RTC strategies that represented the most extreme options (Figure 4), coupled with two WDAs that in turn represented the likely ends of the spectrum, were modelled. It is possible that these might not include the optimum solution but seeing that this study was primarily looking at the feasibility of RTC for SWH, identifying this was not essential to prove the point.

3.1. RTC Strategy A

RTC Strategy A considered the least possible modification to the existing stormwater ponds, viz. no control on the outlets of any ponds and only one pump in the system situated at LPV. In other words, all ponds maintained their existing function except for LPV which was used for storage and harvesting. This strategy provided the 'benchmark' against which the other alternatives could be judged. The RTC operated under the following rules:

- During periods in which there is a demand for harvested stormwater, if the water level in LPV is above the dead storage depth, the pump is turned on and it extracts water from the pond. If there is no demand for harvested stormwater or the water level in LPV is below the dead storage depth, the pump is turned off.
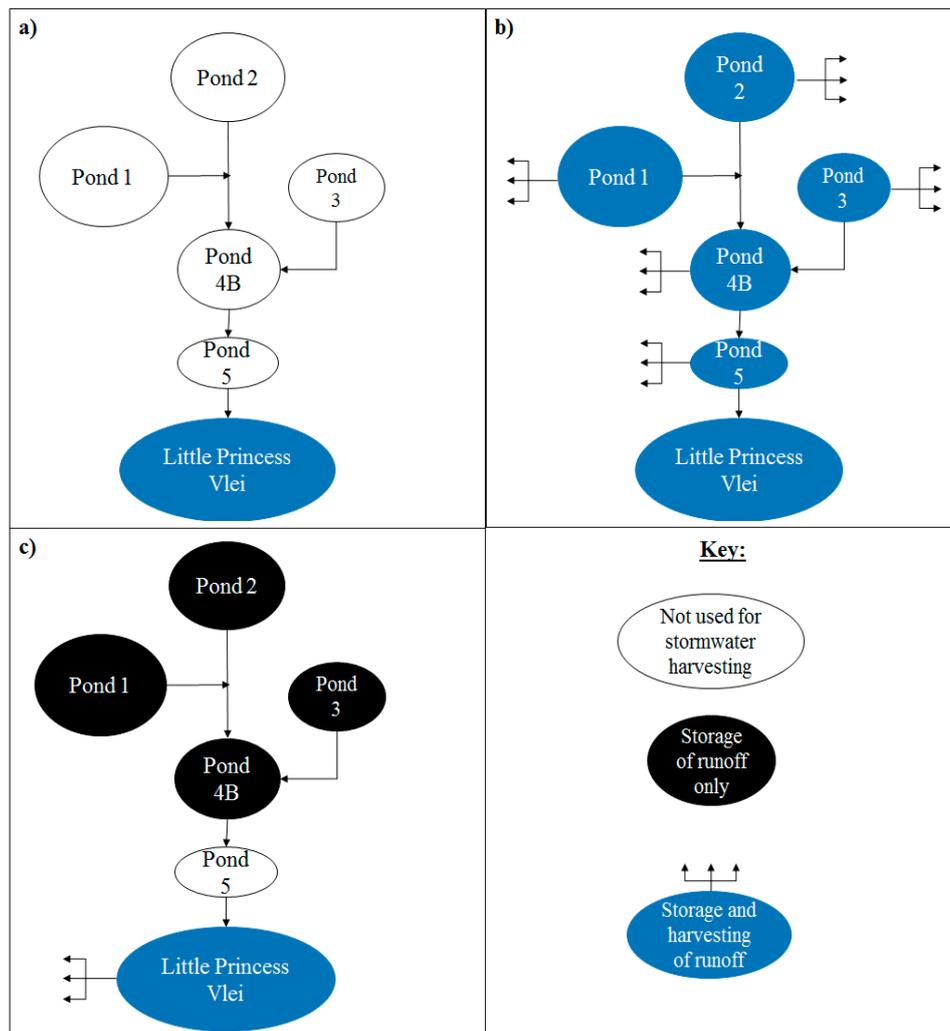
Figure 4. Schematic of RTC options: (**a**) RTC Strategy A; (**b**) RTC Strategy B; (**c**) RTC Strategy C.

3.2. RTC Strategy B

RTC Strategy B investigated the viability of harvesting stormwater in a completely decentralised manner. Each of the catchment's existing ponds was modelled for both storage and harvesting. Harvesting stormwater in this manner maximises the potential for SWH but also costs the most, thus does not necessarily provide the most economical solution. RTC operates both pumps and outlets in each pond except for the outlet at LPV under the following rules:

- Water may be pumped out of every pond in the catchment. Each pond has its own pump, which is operated independently of the other ponds' pumps in the system, based on the local conditions of the pond it serves, i.e., whether there is a demand for harvested stormwater and there is water available above the dead storage level. If there is no demand for harvested stormwater or the water level in a pond is below the pond's dead storage depth, the pump is turned off.
- The pond outlets are opened if the water level in the ponds exceeds their active storage depth; otherwise, the outlets remain closed.

3.3. RTC Strategy C

RTC Strategy C looked at the viability of maximising the storage within the catchment whilst harvesting stormwater in a centralised manner at the most downstream pond in the catchment–LPV. Four of the other ponds; 1, 2, 3 and 4B were modelled as storage ponds only. It was assumed that this

would best represent the benefits of using RTC to improve the viability of SWH as it limited the capital, operational and maintenance costs whilst maximising storage volumes. The RTC control operated under the following rules:

- The outlets of Ponds 1, 2 and 3 are individually opened if the water level of the respective pond exceeds its active storage depth. The outlets of Pond 1, 2, and 3 are also opened if the water level in Pond 4B falls below its dead storage depth whilst the water level of the respective pond exceeds its dead storage depth. The outlets remain closed under all other operating conditions.
- The outlet of Pond 4B is opened if the water level in Pond 4B exceeds its active storage depth. The outlet of Pond 4B is also opened if the water level in LPV falls below the dead storage depth whilst the water level in Pond 4B exceeds its dead storage depth. The outlet remains closed under all other operating conditions.
- During periods in which there is a demand for harvested stormwater, if the water level in LPV is above the dead storage depth, the pump is turned on and water is extracted from the pond. If there is no demand for harvested stormwater or the water level in LPV is below the dead storage depth, the pump is turned off.

3.4. Water Demand Alternatives

Over and above these RTC strategies, as previously mentioned, two separate non-potable residential water demand conditions were modelled in this study. WDA 1 considered the demand for water for flushing toilets only, thus considering the most easily accommodated fraction of the non-potable residential demand per property in the study. WDA 2 modelled the demand for water for toilet flushing, clothes washing and lawn irrigation—thus representing the probable maximum demand for non-potable water in the study. The study focused on non-potable indoor residential demand because in areas that experience winter rainfall, such as Cape Town, using non-potable water such as stormwater for indoor water demand improves the economic viability during periods in which there is no irrigation demand [2]. Treating the water to potable standard and distributing through the existing system was ruled out because reliable on-site advanced treatment was considered too expensive [4] whilst that the cost of pumping the water to the nearest municipal water treatment works, a considerable distance away, was also considered to be too high.

The water demands modelled in this study were derived exclusively from single residential properties (SRPs). For each scenario, the SRPs were selected for their proximity to the harvesting pond/s to minimize the cost of the dual reticulation system that would be required (Figure 1). Mitchell et al. [5] stated that it is acceptable for SWH systems to provide a less reliable level of service than primary potable water supply networks. A less reliable level of service (i.e., poor volumetric reliability) can be a result of attempting to service too many properties (i.e., creating an unrealistically high water demand) that furthermore unnecessarily increases the water distribution infrastructure cost. To prevent this occurring, the water demand that each scenario serviced (i.e., effectively the number of properties) was deliberately limited to ensure around 70% volumetric reliability after considering what could be sustained in-between major storm events that would fully replenish the active storage volume. Some initial modelling of the catchment indicated that events of this magnitude occurred, on average, approximately every 106 days. Based on this approximate value, the number of properties that could be serviced by each scenario ranged between 277 and 1685 properties.

4. Description of Available Data and Modelling Tools

Several modelling tools were used for the study: *SWMM 5* within *PCSWMM 6.2* for the catchment stormwater model [26,27]; *EPANET 2.0* for the water distribution models [28]; and *Microsoft Excel 2016* for the Life-Cycle Cost Analyses (LCCA). The data for these models are summarised in Table 2.

Table 2. Data used to model stormwater harvesting systems.

Detail of Data	Source
Sub-hourly rainfall data	It is recommended that stormwater harvesting systems are modelled using a continuous rainfall time series that is greater than ten years in length and has a sub-hourly time step [29–31]. Continuous sub-hourly rainfall data were available for the catchment, but not for a period of ten years or greater. However, three sets of daily rainfall records of at least ten years in length distributed across the catchment were available. These records were temporally disaggregated, based on the descriptive statistics of six-years' worth of sub-hourly rainfall data recorded within the catchment, to a fifteen-minute time step using the computer software *Hyetos* [32,33] followed by *PCSWMM's* rainfall disaggregation tool. Both programs were required as *Hyetos* only disaggregates daily rainfall to an hourly time step whilst *PCSWMM's* disaggregation tool can only disaggregate hourly rainfall to a fifteen-minute time step. Both programs use the Bartlett-Lewis Rectangular Pulse Model [34,35].
Water demand	Monthly water usage data for properties situated in the catchment were obtained from the CoCT. Indoor water demands were estimated from the data using the minimum month method in which the minimum monthly water demand is assumed to represent solely indoor water use [36–38]. Outdoor water demands were estimated using Jacobs & Haarhoff Residential End-Use Model (REUM) [39]. Monthly water demands were converted to daily water demand by dividing the monthly total by 30.4 (average number of days per month). Daily water demands were disaggregated into an hourly time series using typical diurnal patterns for various end-use demands.
Sub-hourly flow data	The flow depths, continuously recorded for a three-year period at a fifteen-minute timestep at a Parshall Flume situated in the middle of the catchment, were obtained from the CoCT. These flow depths were converted into flow rates using the flume's rating curve. Flow data at the catchment's common drainage point were not available.
0.5 m resolution DTM	The Digital Terrain Model (DTM) used to model the topography of the catchment was created from Light Detecting and Ranging (LiDAR) data that were obtained from the CoCT. *'LiDAR is an optical remote-sensing technique that uses laser light to densely sample a surface producing highly accurate x, y, z measurements'* [40].
Catchment soil conditions	The catchment's upper soil layers were identified using Geographical Information System (GIS) data obtained from the CoCT. Infiltration was modelled within *PCSWMM* using the Green-Ampt Infiltration model.
Catchment land use categorisation	The various land-uses situated throughout the catchment were identified using GIS data that was obtained from the CoCT.
Water quality	Water quality data based on monthly grab samples were obtained from the CoCT.
Economic data	Capital, operation and maintenance costs were determined from Bester et al. [41], DoCOGTA [42], Armitage et al. [13], Marchionni et al. [43], as well as recent tender documents (post 2013) and quotes from industry suppliers (post 2015). All costs included Value Added Tax at 14%, whilst a 10% contingency factor was added to all capital costs. Furthermore, all costs were escalated to represent the effective value as of April 2016 using the Contract Price Adjustment Provisions (CPAP) work group indices [44].

4.1. Catchment Stormwater Model

A *SWMM 5* catchment stormwater model was created and calibrated within the program *PCSWMM 6.2*. The model was used to simulate the hydrological and hydraulic behaviour of

runoff within the catchment and its stormwater network for a continuous ten-year period (January 2005—December 2014) using a fifteen-minute time step. Infiltration within the catchment stormwater model was modelled using the Green-Ampt infiltration model [45] whilst evaporation was modelled using the Hargreaves' method [46].

The catchment stormwater model was calibrated using *PCSWMM's* 'SRTC calibration tool'. The calibration accuracy was limited, however, as continuous sub-hourly flow data were only available for a single flow gauge positioned in the middle to upper regions of the catchment. Two rainfall gauges that had continuously recorded rainfall at a five-minute time-step from June 2013 to July 2015 were used to represent this portion of the catchment's rainfall. Thirty-seven storm events were identified from the observed rainfall data, of which two-thirds of these events (22 events) were used for calibration and one-third were used for verification (15 events). In order of importance, the calibration focused on: total runoff, peak flows and visually representing the hydrograph. A summary of the results of the calibration can be found in Tables 3–5. The runoff continuity errors (<0.7%) and routing continuity errors (<0.7%) were deemed to be acceptable.

Table 3. Calibration of total runoff.

Error Function	Observed vs. Calibrated	Observed vs. Verified
Integral Square Error	11.8	17.6
Integral Square Error rating	Fair	Fair
Nash Sutcliff Efficiency	0.81	0.748
R^2	0.83	0.768

Table 4. Calibration of peak flow.

Error Function	Observed vs. Calibrated	Observed vs. Verified
Integral Square Error	19	12
Integral Square Error rating	Fair	Fair
Nash Sutcliff Efficiency	0.764	0.606
R^2	0.825	0.909

Table 5. Calibration of hydrograph.

Error Function	Observed vs. Calibrated	Observed vs. Verified
Integral Square Error	0.715	1.87
Integral Square Error rating	Excellent	Excellent
Nash Sutcliff Efficiency	0.383	0.571
R^2	0.556	0.663

As the catchment's only operating flow gauge was positioned in the middle to upper regions of the catchment, only that portion of the catchment that is upstream of the gauge was calibrated against observed flow data. The initial parameter estimates of the ungauged portion of the catchment were then manually adjusted by the same percentages as those of the gauged portion of the catchment. By the end of the calibration, it was deemed that the model provided a reasonable representation of actual catchment conditions.

4.2. Water Distribution Models

SWH systems commonly make use of secondary water distribution networks when supplying harvested stormwater to multiple users (i.e., a neighbourhood sized scheme) [47,48]. However, these secondary distribution networks can incur a significant proportion of the total financial cost of a SWH system. Thus, for each scenario, a secondary distribution network supplied by variable speed pumps operating at 75% efficiency was designed with the aid of *EPANET 2.0* in order to establish its likely cost.

The following relaxations were made to the general design criteria recommended by the CSIR [49] for water distribution systems in South Africa:

1. The networks were not designed for fire flow conditions as fire flow would be available from the existing potable water system.
2. The networks were only able to provide a minimum residual head of 15 m during peak demand—chosen because this is the accepted minimum residual head normally allowed in the potable water supply network (during fire flow conditions, i.e., a worst case scenario) [49].

4.3. Treatment of Harvested Stormwater

Water quality data collected by the CoCT for the Diep River indicated highly variable levels of Total Suspended Solids (TSS) (18.9 and 31.4 mg/L, mean and standard deviation, respectively) and *E. coli* (18,629 and 110,994 count/100 mL, mean and standard deviation, respectively) that generally exceeded the acceptable standards for non-potable domestic, recreational and industrial uses specified in DWAF [50–54], the regulatory authority in South Africa. Although TSS removal would occur due to the extended retention time of runoff in the stormwater ponds [16,55], the high levels of *E. coli* suggested that the harvested stormwater would require treatment before distribution. It was decided that harvested stormwater would be best disinfected using an ultraviolet (UV) treatment system to ensure the *E. coli* concentration was reduced to an allowable standard. Chlorination, as a method of disinfection, was avoided as chlorinated water can have harmful effects on plants if the water is used for irrigation purposes. Since the required dose of UV disinfection is dependent on the UV transmittance (UVT) of the water, the harvested stormwater would require filtration beforehand to ensure a consistent quality [4]. The inclusion of slow sand filters—a low cost treatment device requiring relatively low levels of maintenance that can tolerate wide fluctuations in flow range whilst still effectively removing organic matter and mild turbidity [56,57]—was assumed for this purpose. For costing purposes, the slow sand filter and disinfection systems were designed for the peak hourly water demand of the pond and scenario in question. All costs for the sand filters and UV disinfection equipment were obtained from recent tenders or local suppliers respectively.

4.4. Life-Cycle Cost Analysis

An LCCA was performed for each option to establish the effective unit supply cost of SWH and distribution. This only considered direct costs (i.e., capital costs and operational and maintenance expenses), disregarding indirect costs and non-monetary aspects. During an LCCA, it is necessary to convert all costs required to sustain the asset over its lifespan to an equivalent time period. In this study, the estimation of costs was guided by Lampe et al. [58]; Woods-Ballard et al. [11]; WERF [59]; and Armitage et al. [13]. Each LCCA was performed for a fifty-year duration using a real discount factor of 3.25% (Government ten-year bond minus inflation) [60,61]. The life span of each system component was obtained from suppliers where available, alternatively it was based on the recommendations of Armitage et al. [13]. Residual values were calculated using the straight-line depreciation method assuming that each component had zero value at the end of its life-cycle. After the Life Cycle Cost had been determined for each scenario, they were reduced to the Equivalent Annualised Cost (EAC).

4.5. Flood Mitigation Assessment

Degradation of the existing ponds' ability to protect downstream areas from flooding due to SWH would likely mean that additional flood mitigation measures would be required—thereby reducing its economic viability. Thus, the impact that each SWH scenario had on the existing pond system's flood mitigation ability was assessed by comparing the average reduction in peak flow provided by the pond system when used for SWH to the average reduction that is currently provided for the storm events that occurred within the 10-year period of analysis. These were classified by comparing them with the CoCT Intensity-Duration-Frequency (IDF) curves for the catchment. Unfortunately, the record did

not include a 1-in-20 year event—the largest flood event that the existing pond system was designed to attenuate. It was therefore decided to also model the SWH scenarios and existing system under worst-case conditions—i.e., full active storage volume in all ponds and saturated soil conditions—for a design storm with a twenty-year return period. The South African SCS 24-h Type 2 rainfall distribution curve [62] was used for this purpose; the total rainfall depth for the storm specific to the catchment (110.1 mm) was obtained from CoCT data.

5. Results and Discussion

Creating economically viable SWH systems requires reaching an optimal state in which the harvested volume of stormwater is traded off against costs. Whilst harvesting stormwater in a decentralised manner—i.e., harvesting from multiple ponds (Scenarios B1 and B2)—tends to maximise the harvested volume, it also increases the overall cost of the system due to the increased capital, operation, and maintenance costs—particularly associated with the need for multiple treatment works and dual reticulation systems. By contrast, centralised systems—i.e., harvesting from a single pond (Scenarios A1, A2, C1 and C2)—minimise the infrastructure costs but with reduced yield. Figure 5 shows the estimated raw unit cost to supply harvested stormwater for each of the six scenarios considered. Figure 6 shows the estimated average yield. Table 6 gives the total infrastructure cost.

Table 6. Annualised cost of each of the stormwater harvesting scenarios.

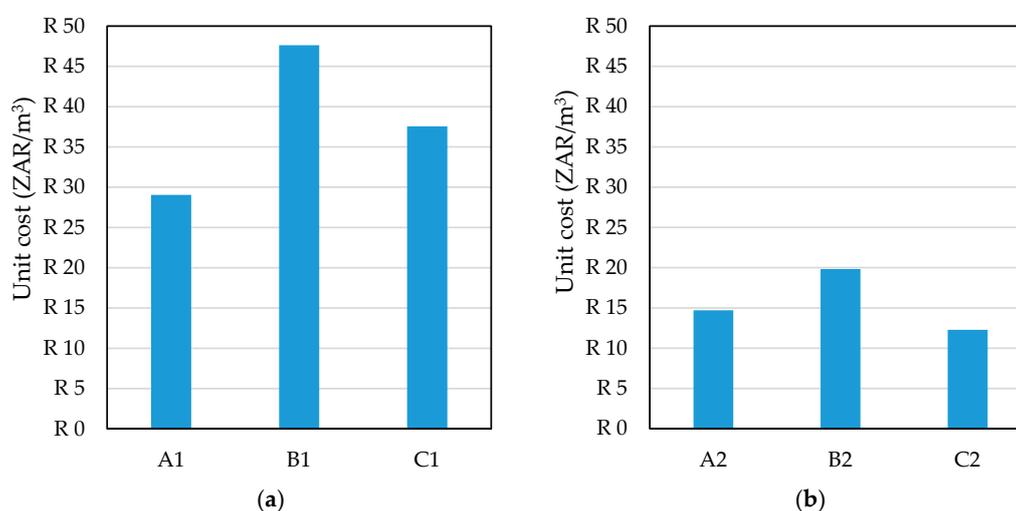| Scenario	Annualised Cost (ZAR/Year)
A2	490,000
C2	768,000
A1	992,000
B2	1,403,000
C1	2,596,000
B1	3,741,000

Figure 5. Comparison of unit cost for each SWH scenario of supplying stormwater for: (**a**) toilet flushing only (WDA 1); and (**b**) toilet flushing, clothes washing and lawn irrigation (WDA 2).
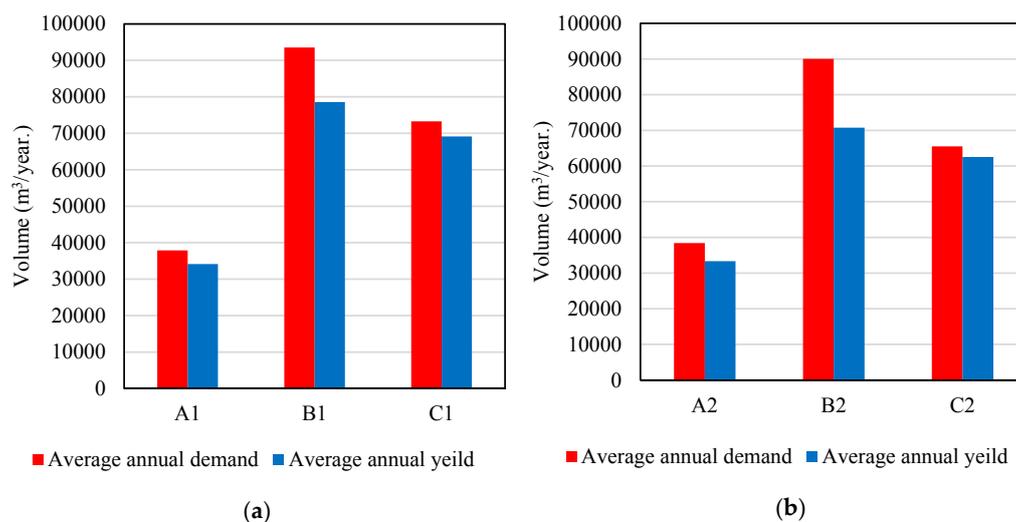
Figure 6. Comparison of annual demand to estimated stormwater yield for each SWH scenario assuming: (**a**) toilet flushing only (WDA 1); and (**b**) toilet flushing, clothes washing and lawn irrigation (WDA 2).

From an economic standpoint, the options that considered WDA 2 (maximum fraction of non-potable demand per property) were clearly more economically viable than those that considered WDA 1 (Figure 5). This was expected as Fisher-Jeffes [4] showed that SWH systems are most likely to be economically viable when supplying areas with a high water demand concentration (i.e., water demand/area) as this limits the extent of the dual water distribution network required—thereby keeping the infrastructure costs down. Each of the three options that modelled WDA 2 indicated a cost per cubic metre to supply harvested stormwater comparable to the typical maximum tariffs (15.81, 23.51 or 29.03 ZAR/m^3 depending on the demand; the CoCT uses a 'rising-block' tariff scheme) that residents within the catchment were being billed by the CoCT for their potable water usage at the time of the study. Comparing Figure 5 with Figure 6, it becomes evident that the lower costs of single, centralised, pump, treatment and distribution systems (Scenarios A1, A2, C1 and C2) essentially outweighs the loss in effective storage when these are compared with the decentralised systems (Scenarios B1 and B2). However, by making use of RTC to distribute storage amongst upstream ponds (Scenario C1 and C2), it is possible to achieve the economic benefits of centralised systems whilst obtaining yields that are comparable to those obtained by decentralised systems.

The existing ponds bypass all flows up a certain threshold, beyond which they detain a proportion of the flow to limit the peak flow rate. It is for this reason that Figure 7 shows that the existing system offers a greater average reduction in peak flow for larger events than smaller events. The analysis also, however, indicated that the average reduction in peak flow when the pond system was used for SWH was comparable to what it is for the existing pond system for all events with a return period of one year or greater that occurred over the ten-year period that the systems were modelled. Naturally, the SWH scenarios that made use of RTC strategies that stored or harvested runoff from multiple ponds (i.e., Scenario B1, B2, C1 and C2) significantly reduce smaller event peak flows (i.e., less than a one-year return period). This was because these scenarios were designed to capture all flow events, pond conditions permitting, whereas the existing system bypassed these flows.
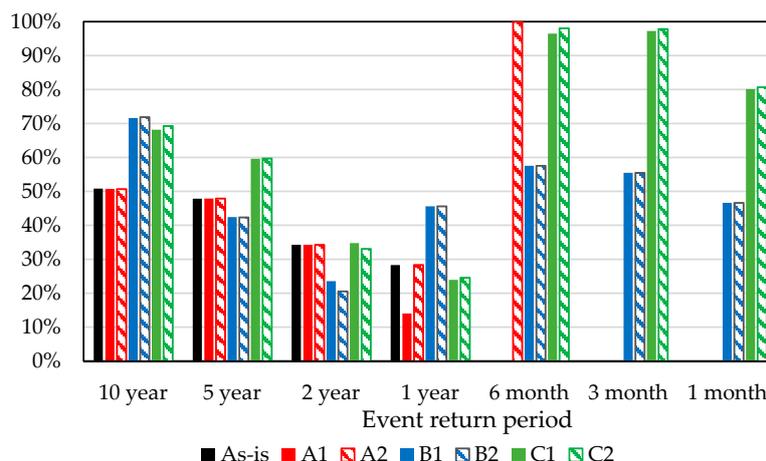
Figure 7. Comparison of the average reduction in peak flow currently provided by the existing pond system to when it is used for SWH over the 10-years of continuous modelling.

The 1-in-20 year flood event analysis compared the percentage change in peak flows downstream of the pond system when it is used for SWH to the existing conditions for a 1-in-20 year event (Table 7). Table 7 shows that centralised systems that did not make use of upstream storage (i.e., Scenario A1 and A2) had no impact on the downstream peak flow. This was to be expected as these scenarios implemented the least obtrusive changes on the existing pond system. Although marginal, the peak flow downstream of the pond systems increased for decentralised systems and centralised systems that used distributed upstream storage (i.e., Scenario B1, B2, C1 and C2). This was because a portion of the ponds that was previously used to attenuate flow was taken up by stored runoff. The increase in peak flow however, was relatively minor in these systems because, whilst the overall system was designed to attenuate storm events up to a 1-in-20 year event, the most upstream ponds (Pond 1, 2 and 3) actually had sufficient storage to handle storms of a greater magnitude [25]. However, this will not generally be the situation in other pond systems.

Table 7. Percentage increase in peak flow downstream of pond system for a 1-in-20 year event for the six SWH scenarios compared with the existing situation.

Scenario	Percentage Increase in Peak Flow
A1	0%
A2	0%
B1	2%
B2	3%
C1	6%
C2	4%

6. Conclusions

As a water-scarce country, South Africa is looking at augmenting its traditional water supplies with alternative water resources. Stormwater is currently a largely unused water resource; however, the limited storage options within urban areas is a problem that needs to be overcome. This study demonstrated that it is possible to secure considerable additional storage capacity within an existing stormwater pond system through the use of rudimentary RTC techniques without significantly impairing the existing ponds ability to mitigate downstream flood risks. Whilst decentralised SWH systems maximise the available storage within a catchment, harvesting stormwater in a centralised manner was shown to be far more economically attractive despite the lower stormwater yields. However, centralised systems that used rudimentary RTC techniques to distribute stored runoff

amongst upstream ponds were able to yield stormwater volumes nearly as large as those obtained offered by decentralised systems at unit costs comparable to a completely centralised system—thus offering a good compromise between the favourable aspects of both approaches. Thus, to conclude, the use of rudimentary RTC techniques to enable existing stormwater ponds to store runoff amongst distributed ponds has the potential to overcome some of the storage limitations associated with SWH in existing urban areas thus making this a viable water source. Additional performance improvements might also be obtained by linking the control of the pond outlets to rainfall prediction data from reliable weather stations to ensure that the ponds are emptied ahead of major flooding events; however, this is the subject of a future study.

Author Contributions: Alastair Rohrer collected the data, carried out the modelling, analysed the results, wrote the first draft of the paper and collaborated with Neil Armitage on the improvements. Neil Armitage conceived the project, provided guidance along the way, and did considerable editorial work on the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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