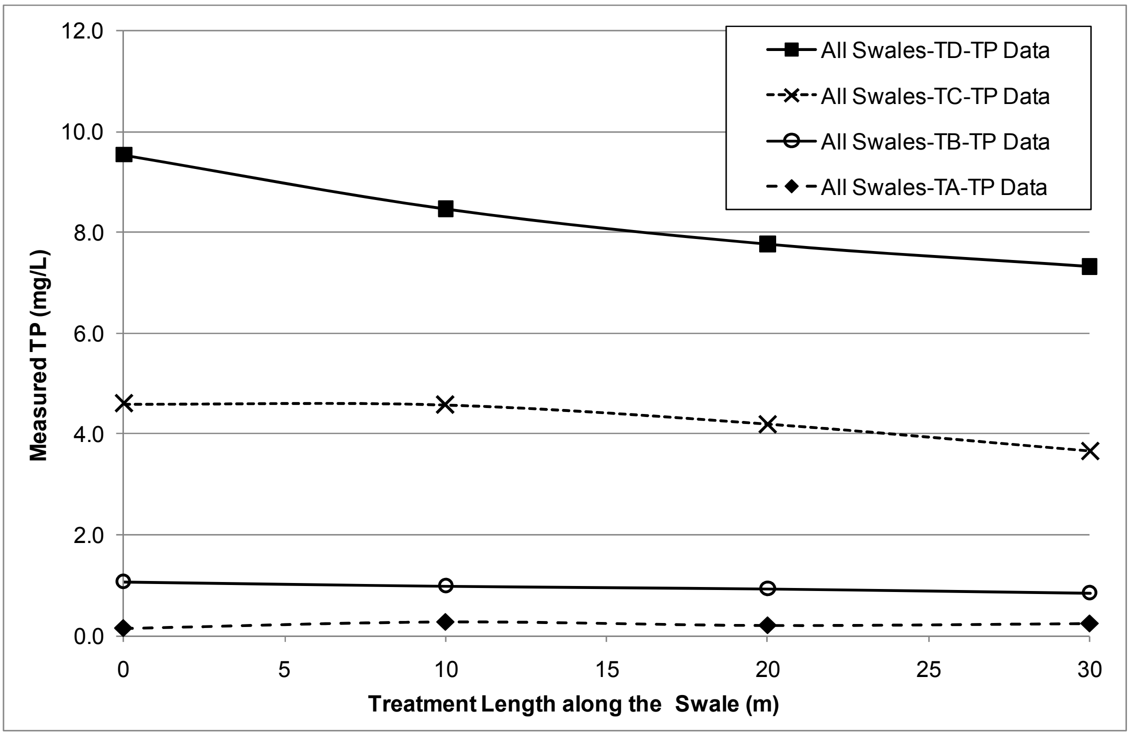
The experimental results demonstrated that the swales were not effective in removing TN from the synthetic stormwater runoff used in the study. This result is in contrast to a number of previous study results (Table 3). However, the sediment reduction achieved in the swales may also result in a reduction in the overall amount of TN leaving the swales as nutrients are known to attach to sediment particles.

The average TP concentrations measured at 10 m intervals along the four swales during the four tests (TA-TD) are shown in Figure 9. The results show that there was between 20% and 23% reduction in measured TP levels between the inlet and the outlet for the TB, TC and TD tests. The uptake of TP along the swale during the simulation experiments may be attributed to several phosphorous trapping mechanisms that can occur when high TP concentrations are present. Other than direct removal of TP onto the surface of grass and soil within the swale, phosphorous from the simulated runoff may have been adsorbed by finer sediments that settled while flowing in the swales. In addition, the high TSS removal rates shown by swales (Figure 4) may have also assisted in the TP removal performance [6]. However, the results in Figure 9 show there was a substantial increase (61%) in the TP levels between the inlet and the outlet for the TA tests. This was presumably due to leaching of phosphorous components along the swales. The residual of the fertilizers that was used in the tested swales to maintain grass growth may have been contributed to this phosphorous leaching.

Figure 9. Average TP concentrations for all study swales measured at 10 m intervals.



Differences in the nutrient removal performance of the swales used in this study, compared to previous study results may be attributed to a number of causes, including the testing conditions under which the experiments were performed. For example, the synthetic nutrients (*i.e.*, chemical reagents) used in this study to replicate runoff nutrients were fully dissolved in the simulated stormwater. Real stormwater runoff also contains nutrients in particulate form and the methodology used in this study did not account for these pollutant types.

6. Conclusions

Four different field swales were tested during 24 standardised synthetic runoff simulation experiments under varying pollutant loading conditions to evaluate their performance in removing TSS, TN and TP from stormwater runoff. Hydraulic reduction capability of the swales was also assessed by flow measurements carried out at the outlet of the swale during some of the experiments.

Flow measurements demonstrated a mean total flow reduction of 52% in the 30 m long swales studied, with a peak flow reduction of 61%. The initial soil moisture content of a swale was shown to affect infiltration rates, total flow volumes and peak discharges. The study results have demonstrated that swales can be used successfully to attenuate peak stormwater flow rates and to substantially reduce runoff volumes to downstream water courses which can significantly improve the quality of stormwater runoff.

The study has shown that swales were effective in reducing the higher TSS concentrations used in the tests. However, the results demonstrate that a swale's TSS removal performance is highly dependent on the inlet concentrations. Results showed that between 50% and 80% of the TSS was generally removed within the first 10 m of the swales. A further 10% to 20% reduction in TSS concentrations can be expected in swales up to 30 m long. The study also demonstrated that swales can be used to treat higher pollution loads typically associated with the "first flush" phenomenon.

The study has found that swales can be used effectively as a primary treatment measure to remove larger sediment from stormwater runoff. The results showed that the first 15 m of the swale length is the most effective in treating the bulk of the TSS. This suggests that the installation of unnecessarily long swales to treat TSS pollutants may not be the optimal solution. The results suggest that swales could be used in a stormwater treatment train as a pre-treatment to prevent clogging in downstream treatment systems.

The study found no reduction in TN levels in any of the four tests that could be attributed to treatment by the swales. This was in contrast to previous study results. However, the study demonstrated a reduction in measured TP levels of between 20% and 23% between the inlet and the outlet for the TB, TC and TD tests. This reduction is within the range of TP removal reported in previous studies. Differences in nutrient removal performance by swales from this study and other studies may be attributed to the differences in testing conditions and pollutant constituents.

The overall study findings suggest that swales can be used effectively to reduce stormwater runoff pollution, particularly runoff with high concentrations of TSS and TP. Selection of swales as a primary stormwater treatment measure could significantly affect the design requirements of downstream treatment systems. The results from this study will assist designers to estimate the appropriate length of swale required to achieve specific TSS and TP pollution reductions in urban stormwater runoff.

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Author Contributions

This study was undertaken as a collaborative research project by the Stormwater Research Group of the University of the Sunshine Coast in Australia. The experimental design of the project was undertaken by Terry Lucke and Neil Tindale. The majority of the experimental field work was conducted by Mohamed Ansaf Kachchu Mohamed with assistance from Terry Lucke and Neil Tindale. The paper was written by all three authors equally.

Conflicts of Interest

The authors declare no conflict of interest.

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