Effects of ecological roofs in water quality: an experimental study over a humid tropical climate

Yan Ranny Machado Gomes (yanr.machado@gmail.com)
Federal University of Pernambuco: Universidade Federal de Pernambuco https://orcid.org/0000-0002-2375-541X
Sylvana Melo dos Santos
Federal University of Pernambuco: Universidade Federal de Pernambuco
Patrícia Martins Torres de Macedo
Federal University of Pernambuco: Universidade Federal de Pernambuco

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Abstract

Although ecological roofs (vegetated or non-vegetated) provide many benefits, it can also leach substances such as nutrients and metals that can affect downstream aquatic ecosystems. Recife has a legislation requiring the installation of green roofs under certain conditions. Therefore, this work aims to investigate the rainwater quality from ecological roofs in Recife using local species in a tropical and humid climate. Using four test cells of 1m² (one non-vegetated filled with expanded clay aggregate, two vegetated with cactus “Coroa-de-Frade” and grass “Grama Esmeralda”, and one control roof) we analyzed thirteen water quality variables regarding irrigation parameters: pH, electrical conductivity, turbidity, nitrate, ammonia, phosphate, bicarbonate, carbonate, calcium, magnesium, sulfate, potassium, boron, sodium, and sodium adsorption ratio. We simulated rain events controlling its intensity and analyzed a sample of natural rainwater event. All roofs neutralized the pH. Control and clay roofs were source of bicarbonate and calcium, responsible for more alkaline effluents. Carbonate and ammonia were below the recommended limits for irrigation purposes for all roofs. Green roofs were source of NO3-, NH4 + and B-. All roofs were neither source or sink for sulphate and chloride for all analyzed samples. Regarding the natural rainwater experiment, only green roof with Coroa-de-Frade exceeded the recommend irrigation parameters for potassium and phosphate. A post-treatment is required for irrigation purposes being recommended a first-flush system followed by a filter with sand and activated carbon.

1. Introduction

Impervious surfaces increase due to populational growth can modify the hydrologic cycle and increase in runoff which can lead to urban floods. In recent years, stormwater management strategies have been developed to mitigate urban flooding (Gill et al. 2007). Among these practices, ecological roofs (Versini et al. 2015) can help to mitigate the impacts of impervious surface area growth by retaining and detaining stormwater and subsequently evapotranspiration or infiltration excess water.

A green roof consists of several components, including the water proofing membranes, drainage material, filter layer, substrate, and vegetation (Hashemi et al. 2015). Each component has its role for the overall performance. Due to numerous benefits, green and brown roofs, which differentiate only by the presence or absence of vegetation, are being applied in many countries. Benefits include the increase in thermal comfort (Santos et al. 2019), mitigating the urban heat island effect (Razzaghmanesh et al. 2016), noise reduction (Connelly and Hodgson 2013), air quality improvement (Yang et al. 2008), contribution to the landscape and recreational and habitat functions (Williams et al. 2014).

Despite ecological roofs have benefits, it is not consensus regarding the water quality issue, which could become either source or sink of runoff pollutants (Wang et al. 2017). The runoff water quality of ecological roofs is a result of substrate and vegetation establishment, microbial activity, roof age, meteorological conditions and seasons, irrigation water quality and atmospheric deposition (Berndtsson 2010; Harper et al. 2015; Hashemi et al. 2015; Karczmarczyk et al. 2018; Akther et al. 2020). Due to several structural designs, substrate, and vegetation combinations, it is important to better understand optimal configuration considering local hydrological variables.

Following a global trend for green infrastructure incentive policies (Liberalesso et al. 2020) some cities in Brazil regulate the construction of green roofs including Recife in the Pernambuco State, Northeast Brazil (Law No. 18112, 2015).

Even though Brazil gradually advances in green roofs legislation, still lack studies regarding their impacts. Particularly, legislation in Brazil requires the strict separation of sewage and rainwater into two networks. Rainwater runoff is not treated before reaching rivers. In case of green roofs acting as source of pollutants, they can contaminate water bodies (Karczmarczyk et al. 2018).

Some studies have already investigated the influence of green roofs in Brazil (Vieira et al. 2013; Noya et al. 2017; Santos et al. 2019; Castro et al. 2020). Specially in a tropical climate, extensive green roof vegetation species need to endure a hot environment, high solar exposure, and wind. One way to guarantee technical feasibility is to use percolated water to irrigate the system itself. Therefore, this study aims to investigate the effects of ecological roofs in water quality in a humid tropical climate and assess use of runoff water for irrigation purposes.

2. Material And Methods

2.1. Study Area

The city of Recife is located in the Pernambuco State, Northeast Brazil. The city has low thermal amplitude and is under a humid tropical climate (type AS’ under the Köppen-Geiger climate classification) with the rainy season from April to July.

Four experimental units of ecological roofs were built in the Federal University of Pernambuco (8.0549º S e 34.9527º W). All experimental units were built with dimensions of 1.30 m x 1.30 m (useful area of 1m^2) at a height of 2.75 m above soil. Roofs were properly waterproofed following Brazilian Technical Standards test for infiltration in buildings (ABNT 2013). Three ecological roofs were settled: one green roof covered with substrate and a cactus locally called “Coroa-de-Frade” (*Melocactus zehntneri*), which survives in poor nutrient, water scarcity and high temperature conditions (Fig. 1a); one green roof covered with substrate and a grass vegetation locally called “Grama Esmeralda” (*Zoysia japonica*), which has more ramified roots and covers the whole soil (Fig. 1b); one brown roof only covered with expanded clay aggregate (Fig. 1c). The remaining of four roofs is a control roof (Fig. 1d) to compare results from the three ecological roofs. All roofs except the control roof have a drainage bed followed by a 10 cm sand layer to favor water percolation.

2.2. Experiment setup

To conduct this research a rainfall simulator system was built as showed in Fig. 2. A well that supplies the engineering center in the University was used as water source of the experiment. The reservoir (01) of 500 L was filled using groundwater and then pumped to the system using a water pump (03) of 0.55 KW. To control the flow rate in the system, a hydrometer (04) and a manometer (05) were used. To properly simulate rainfall, sprinklers (07) with a 360º water irrigation angle were placed upside down in the center of each roof. Polyethylene containers (08) were used to harvest runoff water at each simulation.

The amount of water flow in the rainfall simulation system was controlled using a water valve (02). A linear correlation between pressure and water discharge was obtained. In this way, it was possible to maintain the same rainfall Intensity throughout all simulated experiments. It is important to note that our system has significant hydraulic losses. Then, for each roof the same pressure has different water discharge. For this reason, linear regressions were calculated for each roof individually using three data points each.

Using the intensity-duration-frequency equation (IDF) of Recife (Prefeitura do Recife, 2016), we identified rainfall intensities and chose the 5 return periods to simulate in the experiment. This value corresponds to approximately 163 mm/h. This return period is consistent for urban micro-drainage devices.

2.3. Runoff Water Quality Monitoring

Three experiments were conducted in the study:

• During consecutive days, rainfall was simulated using the intensity and duration chosen (5 years return period for 5 minutes duration). Water samples were collected from the reservoir (01) to identify the prior water quality condition and compare with runoff water. A two-day dry period antecedent to experiments was respected to prevent interferences in results.

• A non-simulated rainfall (natural) event was collected. Samples were taken and analyzed right after the rainfall cessation.

• Water was sampled in three different times within the same experiment. The same 5-year return period and 5 minutes duration experiment were chosen for this analysis. The water was sampled at: the first water percolated through the roof, at the 2-and-a-half-minute mark, at the 5-minute mark until the last water was percolated. These timestamps were chosen respecting water detention time of all roofs.

The fieldwork was conducted from June to July 2019. All water samples were analyzed at the Water Quality Laboratory of the Ecological Roofs Research Group and 16 water variables were obtained according to Table 1. pH and electric conductivity were analyzed in loco using the multi parameter water quality monitor Multi 350I from WTW. Turbidity was measured through the Hanna Instruments HI 93703 turbidimeter. All other water quality measures were obtained using the photocolorimetric method (AT100PBII by Alfakit). The sodium adsorption ratio (SAR) was calculated using Eq. 1 and values are expressed in $(\text{mmolcL}^{-1})^{1/2}$. To guarantee precision in estimates, triplicate samples for each variable were obtained and mean of three values considered the true value. In case of discrepancy between data, the outlier was discarded and mean obtained with the remaining two values.

Water quality variable	Analysis method	Measurement Unity
Electric conductivity	Multi parameter water quality monitor	dSm^{-1}
Calcium and Magnesium	Titration	$mgL^{-1}Ca^{2+}$ $mgL^{-1}Mg^{2+}$
Sodium	Flame Photometry	$mgL^{-1}Na^{+}$
Carbonate and Bicarbonate	Titration	$mgL^{-1}CO_3^{-2}$ $mgL^{-1}HCO_3^{-}$
Chloride	Titration with silver nitrate	$mgL^{-1}Cl^{-}$
Sulfate	Barium chloride	$mgL^{-1}SO_4$
N-Nitrate	NTD	$mgL^{-1}N - NO_3$
N-Ammoniacal	Indophenol Blue Dye	$mgL^{-1}N - NH_3$
P-Phosphate	Vanado Molybdate	$mgL^{-1}PO_4$
Potassium	Sodium tetraphenyl borate	$mgL^{-1}K$
Boron	Curcumin	$mgL^{-1}B$
pH	Multi parameter water quality monitor	$(mmol_c L^{-1})^{1/2}$.
SAR	Equation	$(mmol_c L^{-1})^{1/2}$.
Turbidity	Turbidimeter	NTU
SAR = sodium adsorption ratio | NTU = Nephelometric Turbidity Unit | NTD: N-(1- naphtile)-ethylenediamine.		

Table 1

Analyzed water quality variables and respective calculation methodologies

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{\mathrm{Ca}^{+2} + \mathrm{Mg}^{+2}}{2}}}$$

(1)

To evaluate the possibility of using the drained water from the green roof to irrigate the roof itself we compare whether all results follow the recommendations presented in the publication of the Brazilian Agricultural Research Corporation – EMBRAPA on the “Water quality for irrigation” (Almeida 2010). The only water variable not included in the recommended thresholds list is turbidity, however we chose to measure it as it is a good indicator of substrate carrying. Only relevant plots cited in results and discussion section are presented in this paper.

3. Results And Discussion

3.1. Water simulation system calibration

Figure 3 show results for the pressure and water discharge regression. Calculated minimum Rainfall Intensity (pressure equals to zero) varies between 68 mm/h and 114 mm/h for the grass roof and control roof, respectively. However, empirically, we noticed that minimum pressure to generate water flow in the system considering hydraulic losses varied 2 to 2.5 meters of water gauge (mwg). Under these conditions, we chose a rainfall simulation of 5 minutes using the IDF (Prefeitura do Recife 2016) as reported in the methodology section.

Naturally, the low possibility of choosing the intensity of precipitation duration is a limitation in the designed rainfall simulation system. The elevation of the reservoir above the level of the simulation system could be a solution to this issue, where the water pump would feed the reservoir and no longer the simulation system directly. As we are testing extreme rainfalls (for 5 minutes duration) this would represent the worst-case scenario regarding lixiviate nutrients, as extreme rainfall is associated with leaching more nutrients (Berndtson 2010).

3.2. Water simulation system calibration

All samples showed an increase in pH for both natural and simulated scenarios (Fig. 4). The control roof showed the highest pH value 7.70 ± 0.12 (mean ± standard deviation). This may have been due to the dissolution of alkaline substances related to the cement and the waterproofing material of the slab, especially calcium carbonate. Lima (2012) evaluated the water quality in cisterns also built with cement, she observed that the younger the cistern, the higher the alkalinity levels.

The experimental roofs in this study were built in less than 2 years of the conducted experiment, therefore we can attribute the increase in pH to the roof age. In the studied ecological roofs, the presence of the substrate and vegetation minimized this effect. Among the green roofs the results were quite similar, a pH of 7.38 ± 0.24 for the grass and 7.33 ± 0.24 for the cactus. As for the brown roof, results of 7.50 ± 0.29 were obtained. Carbonates and Bicarbonates results are correlated with pH effect, as they are substances present in cement, especially in the form of calcium bicarbonate ($CaCO_3$), derived from limestone rocks. In all analyzed samples we could not detect presence of carbonate. However, the bicarbonate in control roof (34.2 mg/L ± 4.5 mg/L) and expanded clay (25.5 mg/L ± 4.6 mg/L) showed increase in its concentration. Cactus (13.6 mg/L ± 2.2 mg/L) and Grass green roof (11.2 mg/L ± 1.9 mg/L) showed similar bicarbonate concentrations and overall performed as sink for bicarbonate. In control and expanded clay roofs, the contact of water with the cemented surface of the slab probably promoted the dissolution of these ions. On green roofs, due to the presence of vegetation and substrate layers, this contact was reduced, resulting in lower bicarbonate concentrations. Results for Calcium measures also corroborate with the hypothesis that calcium carbonate may be the cause of the presence of alkalinity in the samples. Control roof showed increase in Calcium, followed by the expanded clay aggregate roof.

Overall, pH neutralization is beneficial for all green roofs. The results agree with studies using different substrates and vegetations present in the literature (Razzaghmanesh et al. 2014; Vijayaraghavan and Joshi 2014; Buffam et al. 2016). In studies in the semi-arid region of Pernambuco, neutral-alkaline pH results were also found (Farias 2012; Lima 2013; Silva 2017). Comparing to the irrigation recommendation levels for the studied variables by Almeida (2010), all roofs met the pH (between 6 and 8.5), bicarbonate (maximum of 10 meq/L, *i.e.*, 610 mg /L) and calcium (maximum of 30 meq/L, *i.e.*, 1063.8 mg /L) thresholds.

It is not possible for the three ions (carbonate, bicarbonate, and hydroxides) to coexist in the same sample, as the bicarbonate reacts with the hydroxide. Whenever a sample has a pH between 4.5 and 8.3 (all samples are in this pH range) the alkalinity is only due to the presence of bicarbonate, explaining the absence of carbonate ion in our results. This effect is due to the balance between carbon dioxide, carbonate, and bicarbonate in the sample.

All roofs revealed to be neither source nor sink of magnesium, except for Coroa-de-Frade which was able to absorb part of magnesium (10,12 mg/L ± 2,86 mg/L to 4,70 mg/L ± 1,14 mg/L). Overall, all roofs recorded magnesium concentration values below the recommended irrigation limit of 486 mg/L by Almeida (2010).

3.3. N-Ammoniacal, N-Nitrate and Phosphate

Regarding nutrients, for most of the analysis N-ammoniacal was kept below the detection level (0.1 mg/L). 6 samples out of 30 was detected N-ammoniacal, with a maximum value of 0.6, below the Almeida (2010) recommended threshold of mg/L. As inflow water for all tests was below detection level, in these 6 samples roofs acted as sources in a non-clear pattern. The green roof containing the Coroa-de-Frade vegetation acted as source of N-nitrate (Fig. 5a) and Phosphate (Fig. 5b).

Considering N-nitrate, the green roof with Coroa-de-Frade obtained the highest values (6.43 mg/L ± 2.95 mg/L) and in one of the tests (10.30 mg/L) it exceeded the established limit. for nitrate by Almeida (2010) of 10 mg/L (Fig. 5). The green roof with Grass and expanded clay obtained the same means of 1.16 mg/L and deviations of 0.45 mg /L and 0.79 mg/L, respectively. On the control roof, there were no major changes in the concentration of the outflow (0.78 mg/L ± 0.69 mg /L) to the inflow (0.73 mg/L ± 0.85 mg/L). There is a more significant increase in nitrate concentrations for the simulated events compared to natural rainfall, even though the concentrations of N-nitrate in the inflows are similar. This may have occurred due to the intensity of simulated rain compared to natural rain, allowing for higher nitrate leach. In fact, Berndtson (2010) indicate that intense rainfall is responsible for higher concentrations of nitrogen and phosphorus species than less intense rainfall, although other factors may influence these results.

For the analysis of natural rain, the roof with Grass was also found to be above the recommended threshold. On 26th June and 27th June, the concentration on the inflow water were 3.00 mg/L and 2.20 mg/L, respectively, both above the recommended limit. In studies of the semiarid region, the green roofs studied were also sources of phosphorus (Farias, 2012; Lima, 2013; Silva, 2017), with all their effluents above the limit established by Almeida (2010). The reason for the green roof with Coroa-de-Frade leached the highest concentrations of ammoniacal-N, N-nitrate and phosphate was probably because the substrate used was rich in nutrients. The cactus species was not using all the available nutrient resulting in leaching at the observed levels. The use of a substrate in lower quantity of nutrients would be an alternative to reduce the concentrations of nitrogen and phosphorus compounds in the effluents.

Future analyzes are needed to verify whether the amount of leached nutrients has stabilized, since nutrient concentrations are higher for newly constructed roofs and decrease over time (Todorov et al. 2018).

3.4. Turbidity and electric conductivity

For the Turbidity, according to Fig. 6a, we notice that the green roof with Coroa-de-Frade obtained the highest values for the simulated events (277.7 NTU ± 39.2 NTU), followed by the expanded clay roof (17.5 NTU ± 13.5 NTU), by the grass roof (12.7 NTU ± 5.3 NTU) and the control roof (4.2 NTU ± 4.9 NTU). For better visualization of the results, the y axis of Fig. 6a is in logarithmic scale. Turbidity is associated with the type of substrate (Morgan et al. 2011) and the roof age, as young roofs may carry more fine particles. All roofs have the same substrate. Thus, the greater turbidity from the cactus roof can be explained by the higher soil exposure, facilitating the transport of sediments and by the shape of the vegetation's roots, since they are not as ramified as that of the grass ones. The turbidity for the event with natural rain was lower than the average of the simulated events (less expressive in the control roof), probably because the intensity of the simulated rain is greater than the natural rain.

Regarding electric conductivity, in the experiments for the simulated rain, only the green roofs decreased the electric conductivity (EC), and the roof with Coroa-de-Frade had the highest removal efficiency. The inverse effect was noticed for the natural rainfall analyzed. All roofs increased EC, with the greatest increase in the Grass roof (Fig. 6b). Only the EC of the green roofs, when using the average values of the simulated experiments, are within the parameters of Almeida (2010) which has a maximum value of 300 mS/cm. For the experiment using natural rain, all roofs are in accordance with the parameters for irrigation.

3.5. Chloride, sodium, and RAS

All roofs were neither sources nor retained chloride, maintaining all outflow concentrations inside standard deviation of inflow samples. Chloride inflow concentration mean was 60.70, while outflow means varied from 57.40 to 59.44.

Sodium and RAS values were found to be much lower the limits established by Almeida (2010) of 919.6 mg /L and 15 $(\mathrm{mmol_c L^{-1}})^{1/2}$, respectively, for all roofs studied. Silva (2010) found similar results for green roofs, from 19.1 mg/L to 20.9 mg/L of sodium and 1.4 $(\mathrm{mmol_c L^{-1}})^{1/2}$ to 2.3 $(\mathrm{mmol_c L^{-1}})^{1/2}$. This is indicative of the absence of sodicity in the soil, a factor that could decrease hydraulic conductivity and affect vegetation growth and water retention.

Regarding potassium (Fig. 7a), the effluents from the brown roof with expanded clay (1.30 mg/L ± 0.75 mg/L), the control effluent (1.22 mg/L ± 0.53 mg/L) and the Grass roof (1.37 mg/L ± 0.88 mg/L) were below the limit recommended by Almeida (2010) of 2 mg/L. The effluents from the green roof with Coroa-de-Frade obtained an average of potassium samples approximately 5 times higher than the recommended limit for irrigation (10.94 ± 1.49). Silva (2017) found values between 18.0 mg/L and 18.8 mg/L for effluents from the green roofs of both cactus species, Babosa and Coroa-de-Frade, in the semi-arid region of Pernambuco State.

The well water used for the simulated rainfall analysis contained high levels of sulfate compared to natural rainwater. The presence of these sulfate concentrations in well water may be due to the decomposition of soils and rocks present in the aquifer such as gypsum ($CaSO_4$) and magnesium sulfate ($MgSO_4$). Sulfate analysis of natural rainwater resulted in values below the detection level (0.1 mg/L). The green roof with Frade's Crown was a source of sulfate (Fig. 7b) both for the simulated experiments and for the one with natural rain, the others did not show such significant differences in relation to the initial concentrations. The green roof with Coroa-de-Frade was a source of sulfate for all experiments analyzed. According to Almeida (2010), the maximum recommended limit for sulfate is 960.6 mg/L, so all samples were within the recommended values for irrigation.

Sulfate (which also obtained values below the detection level of 0.1 mg/L) and nitrate are substances that contribute to acid rain, as they can produce sulfuric (H_2SO_4) and nitric acids in an aqueous medium. (HNO_3). The low concentration of these ions contributed to a more neutral pH of the rain of 6.4. According to the studies analyzed by Hashemi et al. (2015) normally the rain pH is between 5 and 6. Studies in the dry period are necessary to evaluate the effect of these variables.

No boron levels (Fig. 7c) above the lower limit of quantification (0.1 mg/L) were detected in natural rainfall, the brown roof with expanded clay and the control roof. As in the experiments using simulated rain. In agreement with Ferrans et al. (2018) the green roofs were sources of Boron, being more pronounced in the one that contains Coroa-de-Frade as vegetation. The presence of Boron is associated with the composition of the substrate and in Coroa-de-Frade to the low degree of assimilation by the vegetation. The higher concentration of boron in the simulated experiments was possibly due to the presence of boron-containing aquifer rocks, as groundwater was used for simulated. Silva (2017) found values far above Sulfates in his analyzes (2685 mg/L to 3050 mg/L) and values below Boron (0.6 mg/L to 0.9 mg/L) than those found in the presented study.

3.6. Temporal discretization of a single event

Figure 7 shows the main results of the temporal discretization sampling in a single event experiment. The cactus green roof was the one that showed the greatest changes with the collection of samples at different times, especially there was a more expressive decrease in the variables: N-ammoniacal, calcium and potassium. Variables that exceeded the recommended parameters for irrigation (Almeida 2010) using natural rainfall were phosphate and potassium. This experiment by sampling at different times of the same precipitation event indicates that a device for the disposal of first waters would be an alternative to mitigate the leaching effects of potassium but not phosphate. The first water disposal device is a sanitary barrier that diverts the first waters of each rain to discard the waters that wash the atmosphere and the catchment surface. This type of device has proven to be very efficient (Carvalho et al. 2018).

Silva (2017) developed a filter containing sand and activated carbon that was able to decrease the phosphate levels of effluents from green roofs containing the two types of cactuses: Coroa-de-Frade and Babosa. Thus, a treatment system containing a first water diverter and a sand and activated carbon filter could keep all parameters in the recommendation levels of Almeida (2010) and should be further investigated.

4. Conclusion

All roofs neutralized the pH of the runoff water. The control and expanded clay roofs had this effect more attenuated by the possible dissolution of calcium carbonate from the cement and waterproofing present in the slab, this effect was attenuated in the other roofs by the substrate and vegetation layers.

Green roofs were sources of nitrate, ammonia, and boron. On the other hand, all roofs retained sulfate and chloride. Only the cactus green roof exceeded the parameters for potassium and phosphate.

The experiment with rainwater compared to the recommended limits for water for irrigation purposes,

Considering only the natural rainfall experiment, all the analyzed water quality variables from the grass green roof, the brown roof with expanded clay aggregate and the control roof, fit into the recommended limits. In this way, the system is water self-sufficient in the context of water quality. As for the cactus green roof, phosphate and potassium were outside the limits established for irrigation, requiring a subsequent treatment for use for irrigation.

Considering the possible forms of treatment and the results of the analysis by sampling at different times of the same precipitation event, a series system with a first water diverter and a sand filter with activated carbon are good alternatives to mitigate the phosphate concentration. and potassium and makes them suitable for use in irrigation. The efficiency of this system should be further investigated and test application feasibility.

Declarations

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Conflicts of interest

The authors declare no conflicts of interest.

Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Availability of data and material

Not applicable

Code availability

Not applicable

Authors' contributions

Y. G. and S. S. conceived of the presented idea. Y. G. wrote the manuscript. Y. G. performed the laboratory analysis. Y. G. and S.S. analyzed the results. P. M. and S. S. coordinated the construction of the experimental units. S. S. reviewed and wrote the final draft of the manuscript.

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References

1. ABNT: Brazilian Association of Technical Standards (2013) NBR 15575-3. Housing buildings — Performance. Part 3: Requirements for flooring systems. Rio de Janeiro, p 42
2. Akther A, He J, Chu A, Duin BV (2020) Chemical leaching behaviour of a full-scale green roof in a cold and semi-arid climate. Ecol Eng 147(15). https://doi.org/10.1016/j.ecoleng.2020.105768
3. Almeida AO (2010) Water quality for irrigation. Cruz das Almas/BA: EMBRAPA (in Portuguese)
4. Berndtsson JC (2010) Green roof performance towards management of runoff water quantity and quality: A review. Ecol Eng 36(4):351–360. https://doi.org/10.1016/j.ecoleng.2009.12.014
5. Buffam I, Mitchell ME, Durtsche RD (2016) Environmental drivers of seasonal variation in green roof runoff water quality. Ecol Eng 91:506–514. https://doi.org/10.1016/j.ecoleng.2016.02.044
6. Carvalho JRS, Luz J, Santos SM, Gavazza S (2018) A PVC-pipe device as a sanitary barrier for improving rainwater quality for drinking purposes in the Brazilian semiarid region. J Water Health 163:391–402. https://doi.org/10.2166/wh.2018.208
7. Castro AS, Goldenfum JA, Silveira AL, DallAgnol ALB, Loebens L, Demarco CF, Leandro D, Nadaleti WC, Quadro MS (2020) The analysis of green roof's runoff volumes and its water quality in an experimental study in Porto Alegre, Southern Brazil. Environ Sci Pollut Res 27:9520–9534. https://doi.org/10.1007/s11356-019-06777-5
8. Connelly M, Hodgson M (2013) Experimental investigation of the sound transmission of vegetated roofs. Appl Acoust 74(10):1136–1143. https://doi.org/10.1016/j.apacoust.2013.04.003
9. Farias MM (2012) Aproveitamento de águas de chuva por telhados: aspectos quantitativos e qualitativos. Dissertation, Federal University of Pernambuco (in Portuguese)
10. Ferrans P, Rey CV, Pérez G, Rodríguez JP, Díaz-Granados M (2018) Effect of Green Roof Configuration and Hydrological Variables on Runoff Water Quantity and Quality. Water 10(7):960. https://doi.org/10.3390/w10070960
11. Gill SE, Handley JF, Ennos R, Pauleit S (2007) Adapting Cities for Climate Change: The Role of the Green Infrastructure. Built Environ 33(1):115–133. https://doi.org/10.2148/benv.33.1.115
12. Harper GE, Limmer MA, Showalter WE, Burken JG (2015) Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA. Ecol Eng 78C:127–133. https://doi.org/10.1016/j.ecoleng.2014.06.004
13. Hashemi SSG, Mahmud HB, Ashraf MA (2015) Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review. Renew Sust Energ Rev 52:669–679. https://doi.org/10.1016/j.rser.2015.07.163

14. Karczmarczyk A, Bus A, Baryła A (2018) Water Bodies? Water 10:199. https://doi.org/10.3390/w10020199. Phosphate Leaching from Green Roof Substrates - Can Green Roofs Pollute Urban
15. Law, No (2015) 18112, Regulates for the Improvement of the Environmental Quality of Buildings by Requiring the Installation of the “green Roof” and Other Measures (In Portuguese). Recife, Pernambuco, Brazil. Retrieved from. http://leismunicipa.is/cjeuk
16. Liberalesso T, Cruz CO, Silva CM, Manso M (2020) Green infrastructure and public policies: An international review of green roofs and green walls incentives. Land use policy 96:104693. http://doi.org/10.1016/j.landusepol.2020.104693
17. Lima JCAL (2012) Avaliação do desempenho de dispositivo de desvio das primeiras águas de chuva utilizado em cisternas no semiárido pernambucano. Dissertation, Federal University of Pernambuco (in Portuguese)
18. Morgan S, Alyaseri I, Retzlaff W (2011) Suspended Solids in and Turbidity of Runoff from Green Roofs. Int J Phytoremediation 13(S1):179–193. http://doi.org/10.1080/15226514.2011.568547
19. Noya MG, Cuquel FL, Schafer G, Armindoc RA (2017) Substrates for cultivating herbaceous perennial plants in extensive green roofs. Ecol Eng 102:662–669. https://doi.org/10.1016/j.ecoleng.2017.02.042
20. Prefeitura do Recife (2016) Study and Design of the Recife Stormwater Management Plan – PDDR. Document available at the Urban Maintenance and Cleaning Company from Recife (EMLURB)
21. Razzaghmanesh M, Beecham S, Kazemi F (2014) Impact of green roofs on stormwater quality in a South Australian urban environment. Sci Total Environ 470–471C:651–659. http://doi.org/10.1016/j.scitotenv.2013.10.047
22. Razzaghmanesh M, Beecham S, Salemi T (2016) The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. Urban For Urban Green 15:89–102. https://doi.org/10.1016/j.ufug.2015.11.013
23. Santos SM, Silva JFF, Santos GC, Macedo PMT, Gavazza S (2019) Integrating conventional and green roofs for mitigating thermal discomfort and water scarcity in urban areas. J Clean Prod 219:639–648. https://doi.org/10.1016/j.jclepro.2019.01.068
24. Silva TF (2017) Tecnologia alternativa em drenagem urbana: telhado verde. Dissertation, Federal University of Pernambuco (in Portuguese)
25. Todorov D, Driscoll CT, Todorova S, Montesdeoca M (2018) Water quality function of an extensive vegetated roof. Sci Total Environ 625:928–939. https://doi.org/10.1016/j.scitotenv.2017.12.085
26. Versini P-A, Jouve P, Ramier D, Berthier E, Gouvello (2016) Use of green roofs to solve storm water issues at the basin scale – Study in the Hauts-de-Seine County (France). Urban Water J 13(4):372–381. https://doi.org/10.1080/1573062X.2014.993993
27. Vieira NL, Queiroz TM, Fagundes MC, Dallacort R (2013) Potential of utilization of rainwater excess for irrigation of green roofs in Mato Grosso. Brasil Engenharia Agrícola 33(4):857–864. https://doi.org/10.1590/S0100-69162013000400024

28. Vijayaraghavan K, Joshi UM Can green roof act as a sink for contaminants? A methodological study to evaluate runoff quality from green roofs (2014).Environ Pollut194:121–129. http://doi.org/10.1016/j.envpol.2014.07.021
29. Wang H, Qin J, Hu Y (2017) Are green roofs a source or sink of runoff pollutants? Ecol Eng 107:65–70. https://doi.org/10.1016/j.ecoleng.2017.06.035
30. Williams NSG, Lundholm JT, MacIvor JS (2014) FORUM: Do green roofs help urban biodiversity conservation? J Appl Ecol 51:1643–1649. https://doi.org/10.1111/1365-2664.12333
31. Yang J, Yu Q, Gong P (2008) Quantifying air pollution removal by green roofs in Chicago. Atmos Environ 42(31):7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003

Figures

(a) Cactus “Coroa-de-Frade”

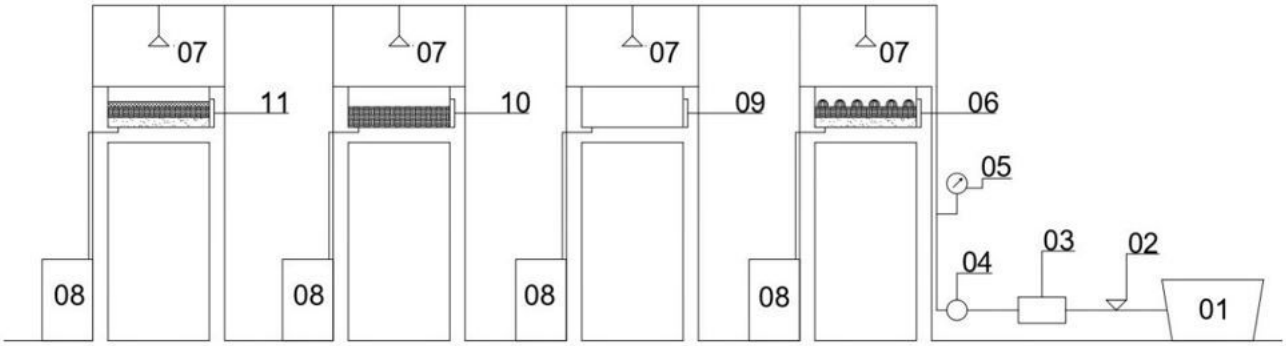
(b) Grass “Grama Esmeralda”

(c) Expanded Clay Aggregate

(d) Waterproofed slab

Figure 1

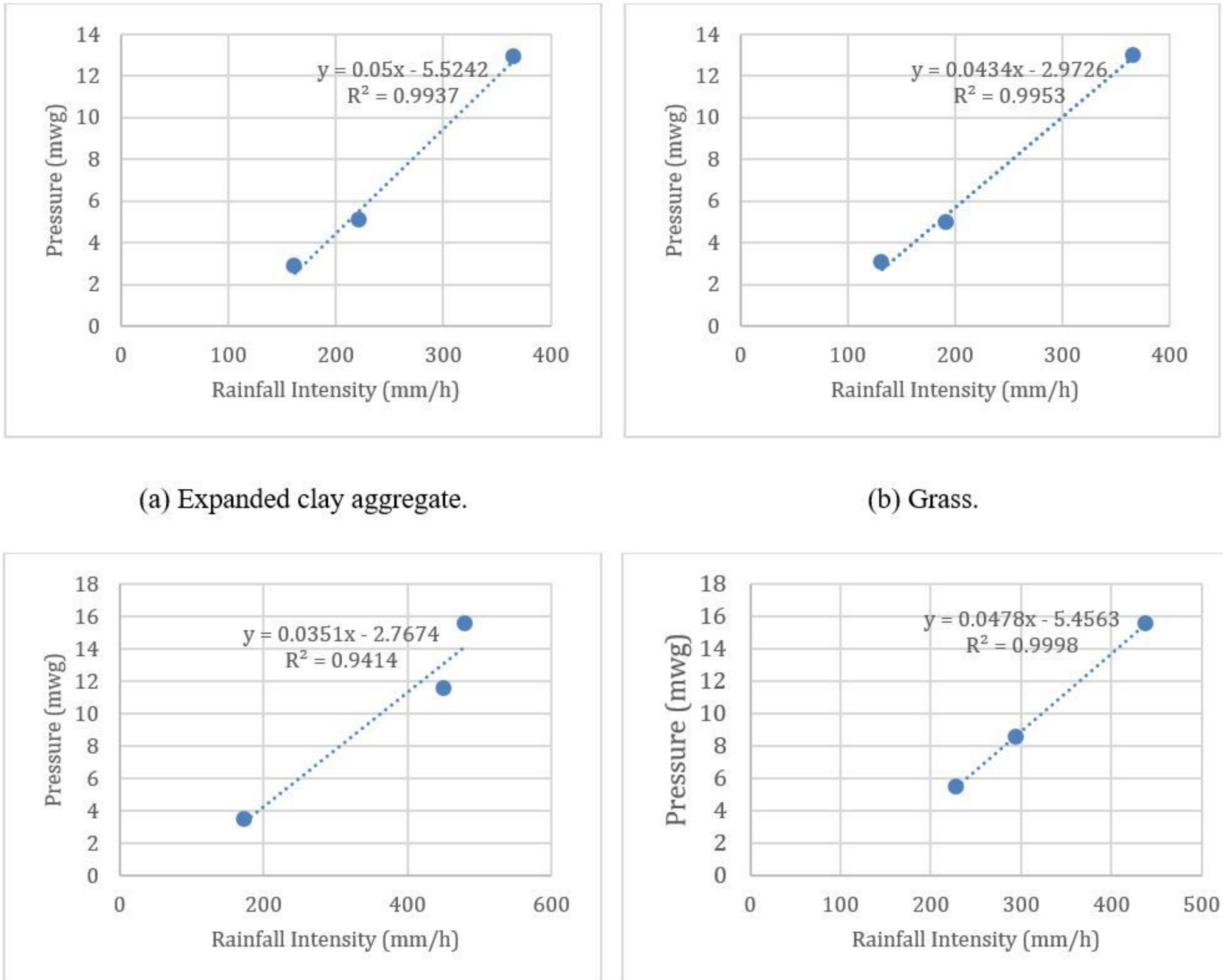
Roof types assessed in the experiment.



01 – water reservoir; 02 – gate valve; 03 – water pump; 04 – hydrometer; 05 – pressure gauge; 06 – cacts green roof; 07 – water sprinklers; 08 – water collection container; 09 – control roof; 10 – brown roof; 11 – grass green roof.

Figure 2

Schematic design of the experiment.



(a) Expanded clay aggregate.

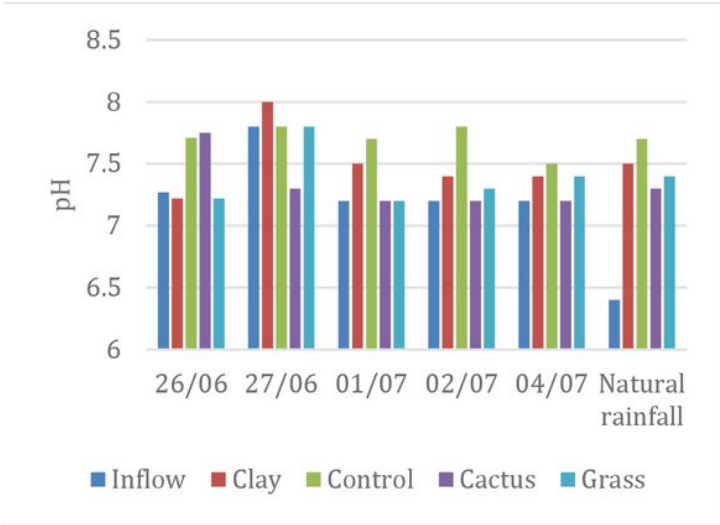
(b) Grass.

(c) Cactus.

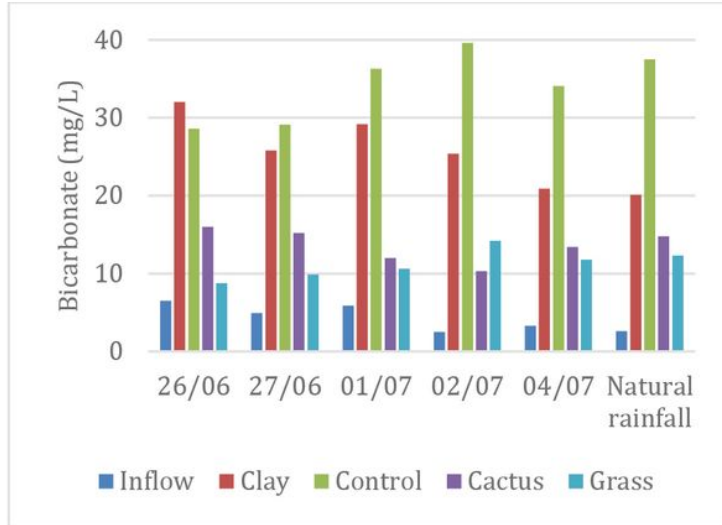
(d) Control.

Figure 3

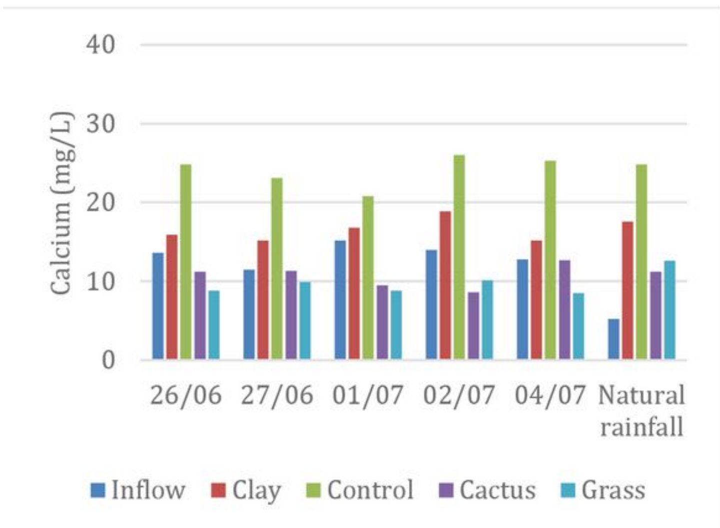
Linear regression from measured pressure and rainfall intensity.



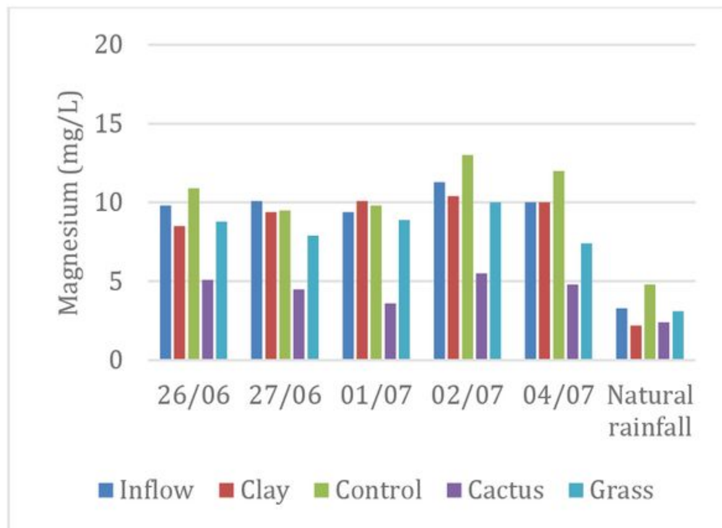
(a) pH



(b) Bicarbonate



(c) Calcium



(d) Magnesium

Figure 4

Water quality results for pH, bicarbonate, calcium, and magnesium

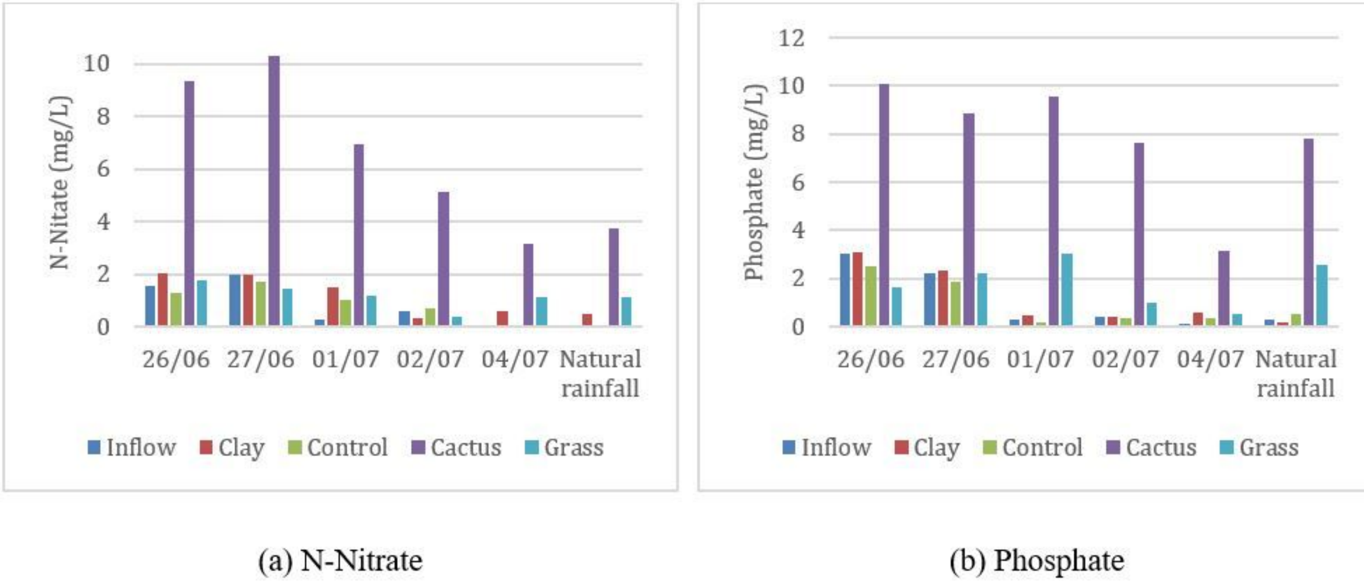


Figure 5

Water quality results for N-Nitrate and Phosphate.

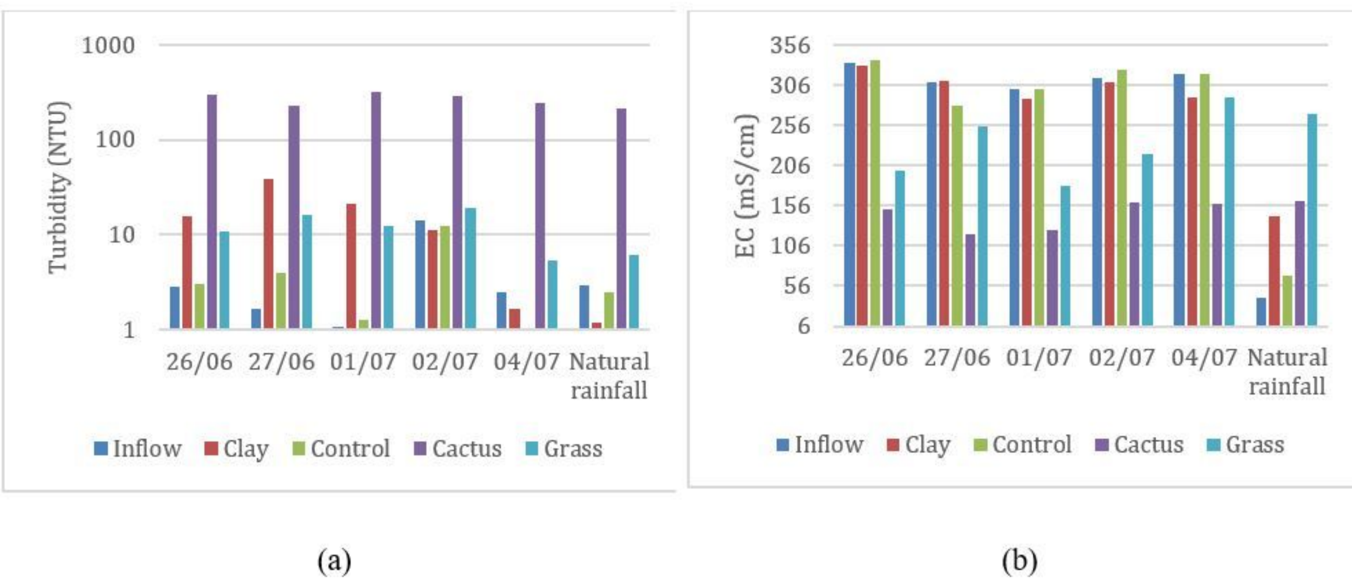
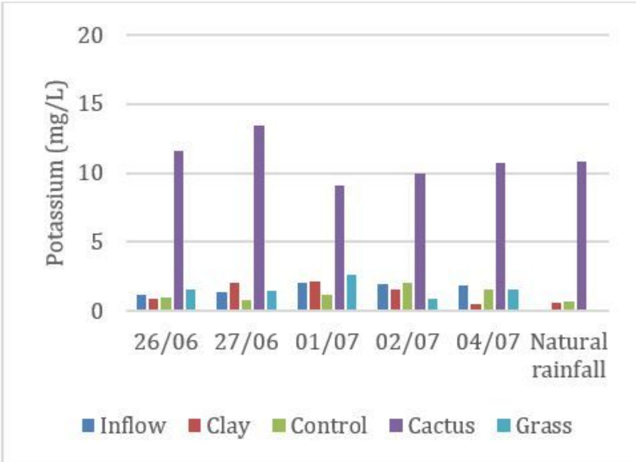
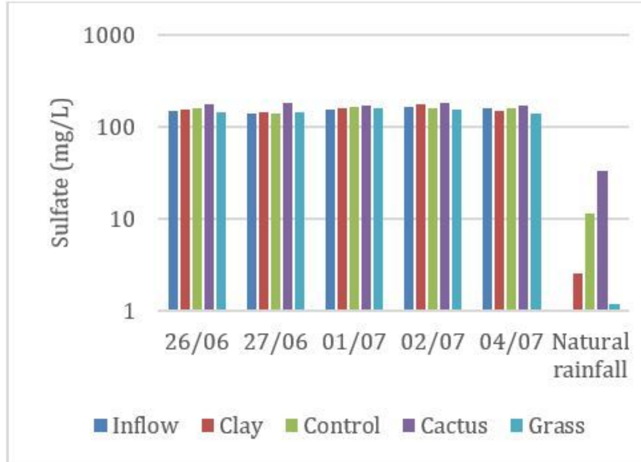


Figure 6

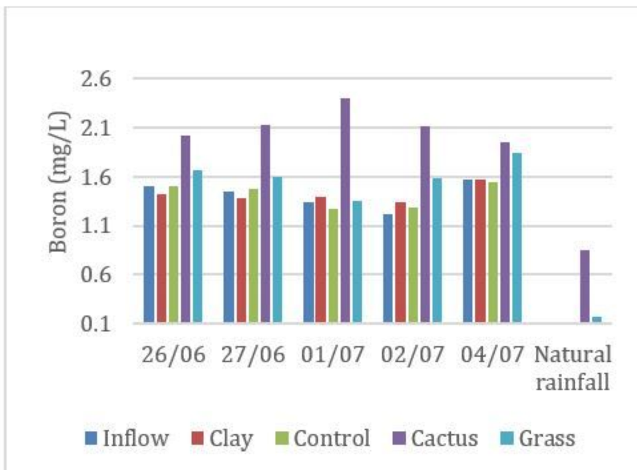
Water quality results for turbidity and electric conductivity.



(a) Potassium



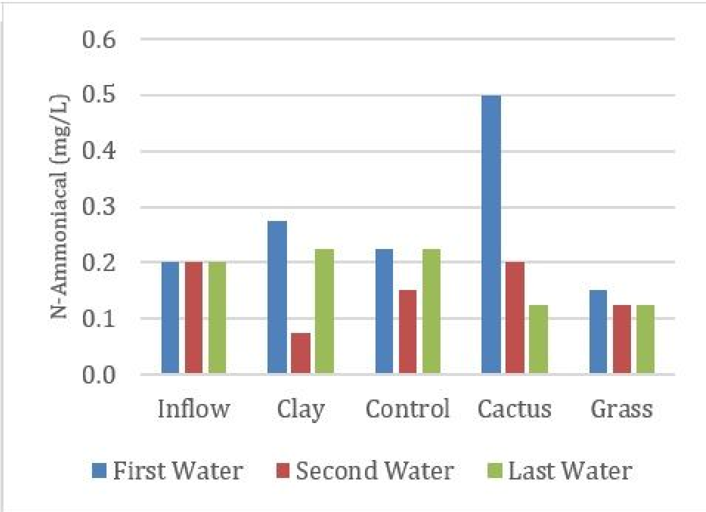
(b) Sulfate



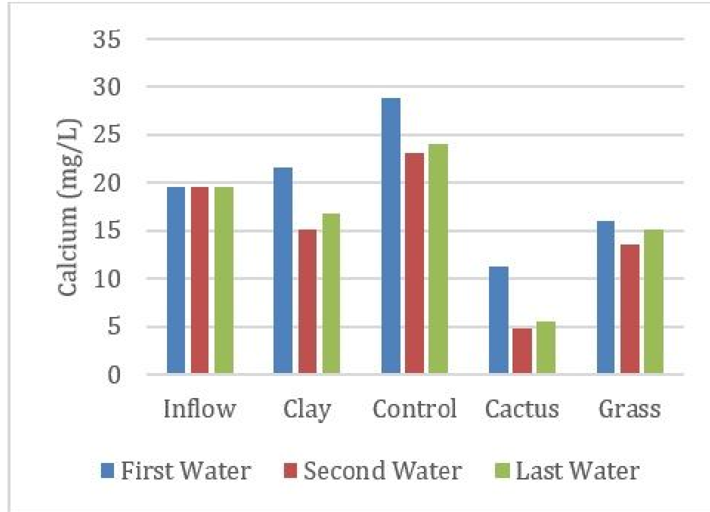
(c) Boron

Figure 7

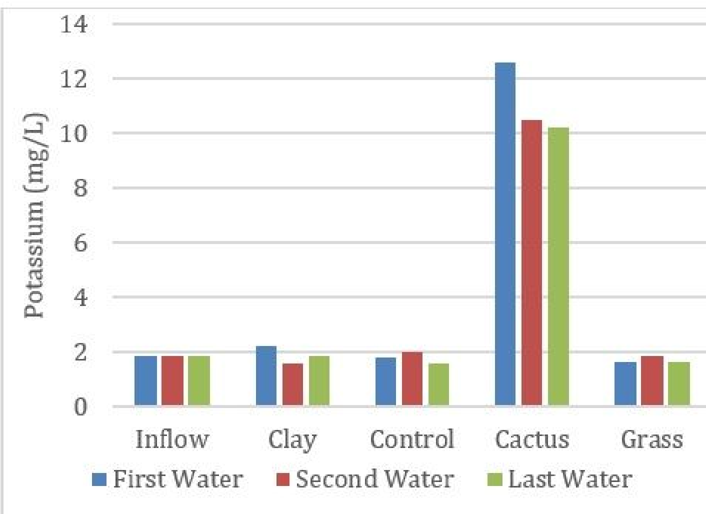
Water quality results for potassium, sulfate, and boron.



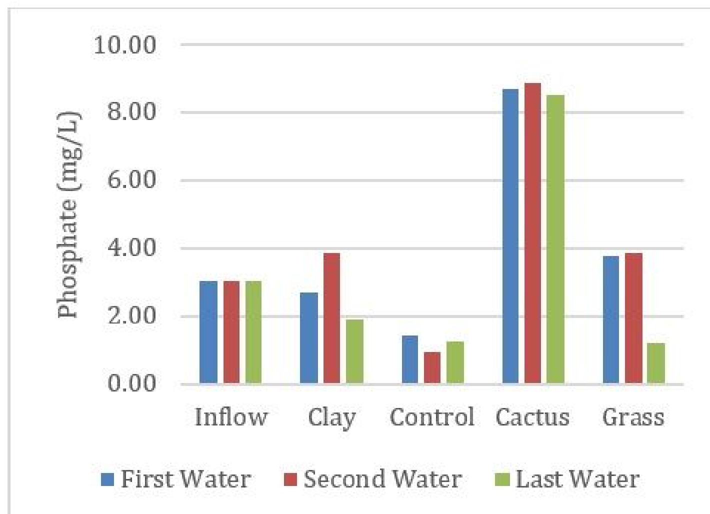
(a) N-Ammoniacal



(b) Calcium



(c) Potassium



(d) Phosphate

Figure 8

Water quality results over time N-ammoniacal, calcium, potassium, and phosphate.