Civil & Mineral Engineering
UNIVERSITY OF TORONTO

Enhanced Hydrological Regulating Services by Meadow Restoration Supported by Rainfall Simulation Tests

Author: Ke Qin

Instructed by: Prof. Jennifer Drake

Submitted to: Toronto and Region Conservation Authority & Parks Canada

April 13, 2022

1. Background and Objectives

The Gatineau Hydro Corridor stretching across the City of Scarborough was constructed in the 1920s to connect downtown Toronto to the hydroelectric power plants in Quebec's Gatineau region (TRCA, 2019a). The Scarborough Centre Butterfly Trail (SCBT), a part of the Gatineau Hydro Corridor, revitalized in 2015 with restored meadow habitats and improved trails, received great success in providing multiple ecosystem services and a sustainable transportation approach (TRCA, 2019a). Its success supports the Gatineau Hydro Corridor Revitalization Project, which aims to restore 200 ha of meadow habitats and complete a linear multi-use trail over 16 km along the Gatineau Hydro Corridor connecting downtown Toronto and the Rouge National Urban Park (TRCA, 2019b). The project will integrate existing greenspace and transportation networks across eastern Toronto to form a multi-use trail and complete a meadow restoration project named The Meadoway (TRCA, 2019a).

One possible outcome of meadow restoration efforts may be an improvement in the hydrological regulating service provided by the ecosystem along the hydro corridor. We hypothesize that the complex root systems of the restored meadows will improve stormwater retention and reduce peak runoff rates by supporting more infiltration of stormwater. However, the results of in-situ double-ring infiltration tests conducted in 2020 field season failed to identify any significantly different near-saturated infiltration capacities of lands with different vegetation covers. Although double-ring infiltrometers are an accepted method for measuring soil infiltration, it is unclear how well this method captures the effect of vegetation types on infiltration rates. This report presents the methodology and results of rainfall simulation tests used to further explore the role of vegetation on infiltration and water balances.

The objectives of this study were to:

(1) Develop a method to simulate rainfall on undisturbed vegetated soil samples,

(2) Evaluate the hypothesis that native meadows generate less runoff than turf lands,

(3) Compare the water balances of a still-establishing meadow and an established cultural meadow.

2. Methodology

2.1. Field Sampling

Five pairs of undisturbed vegetated soil samples were each collected from Section 4 of The Meadoway in the restored meadow and turf buffer (Table 1). The terms “turf land” and “buffer area” are used interchangeably in this report. The restored meadow was covered with native plants, while the buffer area was covered with turfgrasses. When possible, sampling locations were selected to overlap with the double-ring infiltration tests conducted in 2020. Two additional vegetated soil samples were collected from a cultural meadow in the Rouge National Urban Park (RNUP), located approximately 12 km northeast of Section 4. The RNUP cultural meadow is located within the South Slope and was planted with native grasses and wildflowers in 2009 (TRCA, 2019b), making it several years older than the restored meadow of Section 4 which was restored in 2015 (TRCA, 2019b). The sampling dates are listed in Table 1 and sampling locations are presented in Figure 1.

Table 1. The sampling dates of paired samples from the restored meadow, the turf land, and the cultural land

Date	Land Type	Location ID	Original Weight (kg)
Jul. 29, 2021	Restored Meadow	3	7.92
	Turf Land	8	6.60
Aug. 10, 2021	Restored Meadow	2	5.92
	Turf Land	6	7.46
Aug. 30, 2021	Restored Meadow	1	5.86
	Turf Land	5	5.57
Sept. 10, 2021	Restored Meadow	4	7.20
	Turf Land	7	8.10
Sept. 29, 2021	Restored Meadow	5	9.87
	Turf Land	4	9.05
Oct. 28, 2021	Cultural Meadow	1	8.40
		2	7.09

Before collecting soil-vegetation samples, three cone index measurements were taken using a ELE International proving ring penetrometer (ELE International, n.d.) to check if the soil was similar to the overall conditions observed in 2020. Once a location was selected, plant stems and grass blades were trimmed using a pair of shear scissors. The soil cutter (Figure 2) from the Jumbo 4 Expo Rainfall Simulator (Conservation Demonstrations, n.d.) (Figure 3) was used to collect a 7 in. (width) × 9 in. (length) × 5.5 in. (height) undisturbed vegetated soil samples. The soil cutter was placed on the ground and covered by a thick wood block. A rubber mallet was used to hit the woodblock and carefully push the cutter into the soil vertically. Once the woodblock was flush with the ground surface, it was removed to avoid any soil compression, and a rubber hammer was used to hit at the edge of the cutter until the top of the cutter was at the same level as the soil surface. Soil samples collected on Aug. 10th and 30th experienced significant shrinking during rainfall, causing ponding and preventing runoff measurement. Thus, afterwards, soil samples were collected with a surface about 1 cm above the soil cutter edge so that the soil surface could be flush with the cutter edge when shrinking occurred. Then, a shovel was used to dig around the cutter and take out the complete soil sample. A flat-bladed knife was used to flatten the bottom of the soil sample. Any operations that disturbed the soil from its original conditions or caused soil loss were avoided. If there was any apparent evidence of soil compression, disturbance, or loss, the sample was discarded, and a new one was collected following the correct procedure. Once a good soil sample was taken out, a metal grid was placed and assembled at the bottom of the cutter to hold the soil. The soil sample was then transported to the laboratory for rainfall simulation tests. Immediately after collected soil samples were transported back to the laboratory, they were weighed to obtain original weights in field conditions (Table 1).

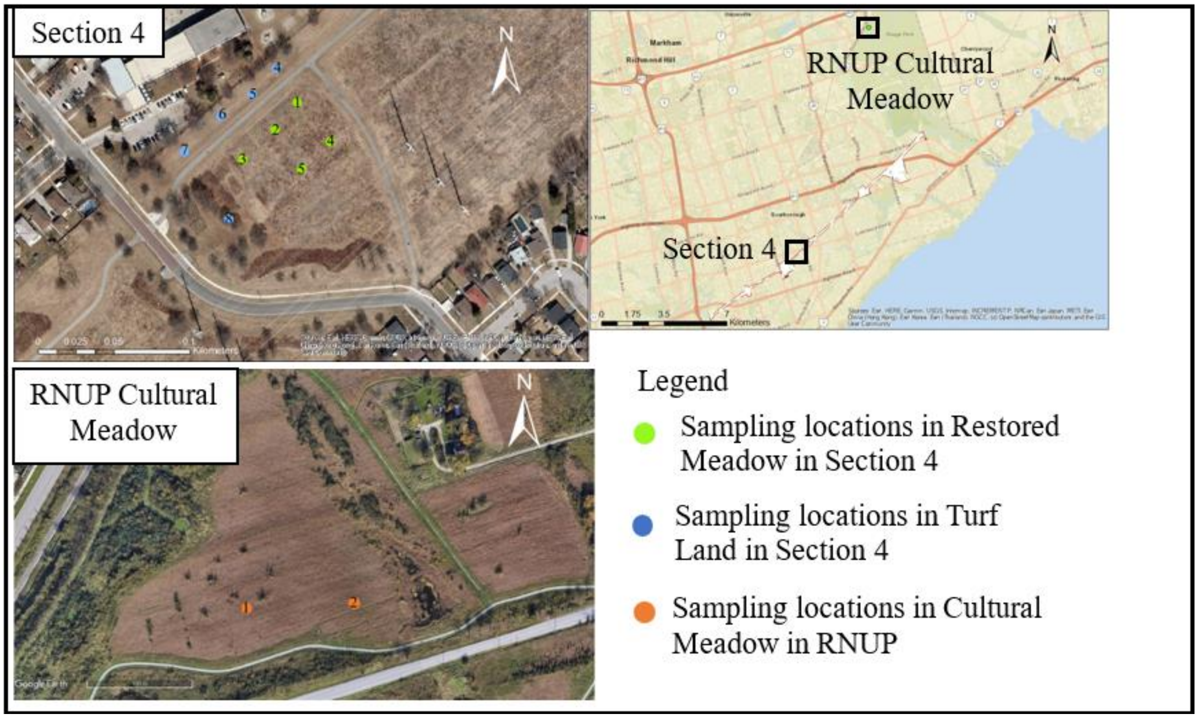


Figure 1. Soil sampling locations for rainfall simulation tests in restored meadow, turf land, and cultural meadow.

Figure 2. Collecting undisturbed vegetated soil samples using a soil cutter.

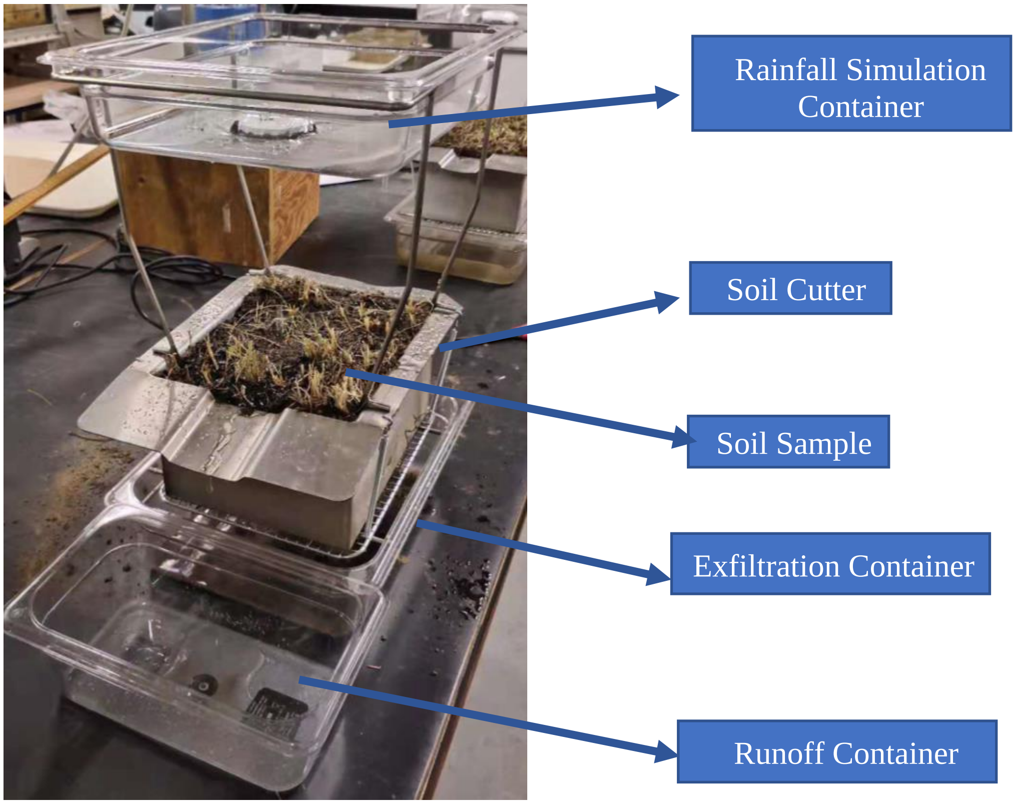


Figure 3. Rainfall Simulation Kit.

2.2. Rainfall Simulation Tests

The 2006 Toronto Wet Weather Flow Management Guidelines Intensity-Duration-Frequency (IDF) curves were applied to calculate rainfall depths for 10-minute storms of return periods 2, 5, 10, 25, 50 and 100. These return periods were selected because (1) City of Toronto has adopted the 100-year storm as the level of protection for properties against surface flooding (City of Toronto, 2006), and (2) post-development peak flows of a development site located within the Highland Creek watershed, where Section 4 of the Meadoway is located, should be controlled to pre-development levels for all storms up to and including the 100-year storm (i.e. 2, 5, 10, 25, 50 and 100-year storms) (City of Toronto, 2006). The rainfall intensity was multiplied by the rainfall duration (10 minutes) and multiplied by the basal area of the rainfall simulation container (23 cm × 28 cm) to calculate the volume of rainwater used in each test. The information of designed rainfall events with different return periods is summarized in Table 2.

Table 2. Simulated rainfall events with 2-, 5-, 10-, 25-, 50-, and 100-year return periods.

Return Period (year)	Rainfall Duration (min)	Rainfall Intensity (mm/hr)	Rainfall Volume (mL)	Pump Revolution Rate (RPM)
2	10	88.2	947	17
5	10	131.8	1415	25
10	10	162.3	1742	30
25	10	189.5	2034	36
50	10	224.3	2408	42
100	10	250.3	2687	47

A rainfall simulation container was placed upon the soil cutter, from which synthetic 'rainfall' drained out through the small holes (1.73 mm) onto the surface of the vegetated soil. The Fisher Scientific GP1000 peristaltic pump (Fisher Scientific, n.d.) was used to control rainfall intensities by adjusting the revolution rate. During rainfall events, surface runoff flowed out through an outlet into the runoff container, and subsurface discharge percolated from the bottom of the soil sample was collected in the exfiltration container. Tap water was supplied to the rainfall simulation container at a constant rate with the pump set to match the desired rainfall intensity.

Before conducting rainfall simulation tests, soil samples were saturated and left drain overnight to reach the field capacity. To saturate the sample, rainfall was applied at an intensity of 84 mm/h (90 mL/min) until surface runoff and exfiltration rates stabilized. This typically took 30 minutes. The 30-min rainfall intensity was less than the designed 2-year rainfall to avoid any unintended alterations of soil structure. Then, the sample was left to drain overnight for at least 12 hours to reach the field capacity.

On the next day, the saturated sample was re-weighed. Then, the rainfall simulation kit was assembled, and the rainwater volume of the first event with a 2-year return period was measured using 1000 mL graduated cylinders and transferred in a bucket. The peristaltic pump was used to pump water from the bucket into the levelled rainfall simulation container at the desired rate. At the end of the rainfall simulation, any water remaining in the tubing or the bucket was poured manually into the rainfall simulation container. Once water stopped draining from the rain simulation container, it was flipped over, and any remaining water was poured directly onto the soil surface. When the rainfall ended, the weight of the soil sample plus the weight of the soil cutter was measured immediately to calculate the amount of water retained by the soil. The runoff collected in the runoff container and the exfiltration collected in the exfiltration container was measured for volume, respectively. All data were recorded in a Microsoft Excel sheet for analysis. The soil sample was then left to drain for at least 10 minutes until percolation water stopped draining from the bottom. The sample was re-weighed, and then the next rainfall event (e.g. 5-year) was applied. The simulated rainfall events were conducted in the same way and in order of increasing rainfall intensity. Rainfall simulation tests on paired buffer and meadow samples were conducted on the same day to avoid possible effects of the changes in soil characteristics due to biodegradation or drought with time.

2.3. Mini Disk Infiltrometer Tests

After rainfall simulation tests were completed on each sample, the sample was left until percolation water stopped draining from the base of the sample. Subsequently, three infiltration tests were conducted on each soil sample using the mini-disk infiltrometer (METER ENVIRONMENT, n.d.). Measurements were spaced evenly over the soil surface and away from the edge of the soil cutter to eliminate the effects of no-flow boundary, which was likely to reduce the infiltration rate. The mini-disk infiltrometer is a very robust tool to measure the saturated hydraulic conductivity of soils at a location. It consists of an upper chamber filled with water to control the suction rate by adjusting the position of a suction control tube, and a lower chamber, which is labeled like a graduated cylinder where water drains out from the bottom into the soil.

To begin a test, the upper chamber was filled with water and the suction control tube was adjusted at an appropriate level to provide the suction rate suitable for the soil. A greater suction rate decreased the infiltration rate, and a suction rate of 2 cm was suggested for most soils (METER Group, n.d.). In the tests, a suction rate of 2 cm was applied for most of the soils, while the suction rate was adjusted to 1 cm for some soil samples with low infiltration rates. Then, the lower chamber was filled with water, and a stainless-steel disk was replaced at the bottom. The water volume in the lower chamber was recorded every 10 seconds during the first 3 minutes of the test and then every 30 seconds after 3 minutes. Once the incremental infiltration rate became stable, it was assumed that the infiltration capacity was reached, and the test was stopped. The saturated hydraulic conductivity of each soil sample was calculated using the Microsoft Excel spreadsheet (www.decagon.com/macro) provided by the manufacturer of the mini-disk infiltrometer.

2.4. Calculation and Analysis

The volume of water collected in the runoff container (V_{runoff}) and the exfiltration container ($V_{exfiltration}$) was converted into the ratio to the total precipitation (P) in each simulated rainfall event as R_{runoff} and $R_{exfiltration}$. The volume of water retained by the soil sample ($V_{retained}$) was calculated based on the increased mass of the soil sample after each test, which was also converted into the ratio to the total precipitation as $R_{retained}$. The following equations were used:

$$R_{runoff} = \frac{V_{runoff}}{P}$$

$$R_{exfiltration} = \frac{V_{exfiltration}}{P}$$

$$V_{retained} = \frac{M_{sa} - M_{sb}}{\rho_w}$$

$$R_{retained} = \frac{V_{retained}}{P}$$

where:

- M_{sb} is the mass of soil sample plus the soil cutter before the rainfall event,
- M_{sa} is the mass of soil sample plus the soil cutter after the rainfall event,
- ρ_w is the density of water,
- V_{runoff}, $V_{exfiltration}$, and $V_{retained}$ are the volume of runoff, the volume of exfiltration, and the volume of water retained in the soil, respectively,
- P is the volume of total precipitation of the rainfall event.

R_{runoff} and $R_{exfiltration}$, and $R_{retained}$ of each simulated rainfall event upon each soil sample were calculated. For rainfall events with a specific return period, the mean of R_{runoff}, $R_{exfiltration}$, and $R_{retained}$ of all soil samples from each type of land (e.g., restored meadow, turf land, and cultural meadow) was calculated. In addition, non-parametric Wilcoxon tests were conducted to assess potential differences in the R_{runoff}, $R_{exfiltration}$, and $R_{retained}$ of soil samples between the restored meadow, the turf land, and the cultural meadow.

3. Results and Discussion

The means of runoff to precipitation ratio (R_{runoff}), exfiltration to precipitation ratio ($R_{exfiltration}$), and retained water to precipitation ratio ($R_{retained}$) for soil samples from the restored meadow, the turf land, and the cultural meadow in simulated rainfall events with different return periods are summarized in Table 3. The R_{runoff}, $R_{exfiltration}$, and $R_{retained}$ of each soil sample in each simulated rainfall test are plotted in Appendix. The weight of soil samples during rainfall events with increasing return periods is plotted in Figure 4. Almost no surface runoff was generated from all soil samples for some tests (i.e., meadow 2 VS. turf land 6, meadow 1 VS. turf land 5). These samples exhibited great shrinkage when exposed to the simulated rainwater. Consequently, although water was observed pooling on the sample surface during the tests, it was unable to flow into the runoff collection container. In the fourth and fifth rainfall simulation tests, soil samples were collected with an extra thickness of about 1 cm to mitigate the effect of soil shrinking. Therefore, the data of rainfall simulation tests on the second and third pairs of samples was excluded from analysis.

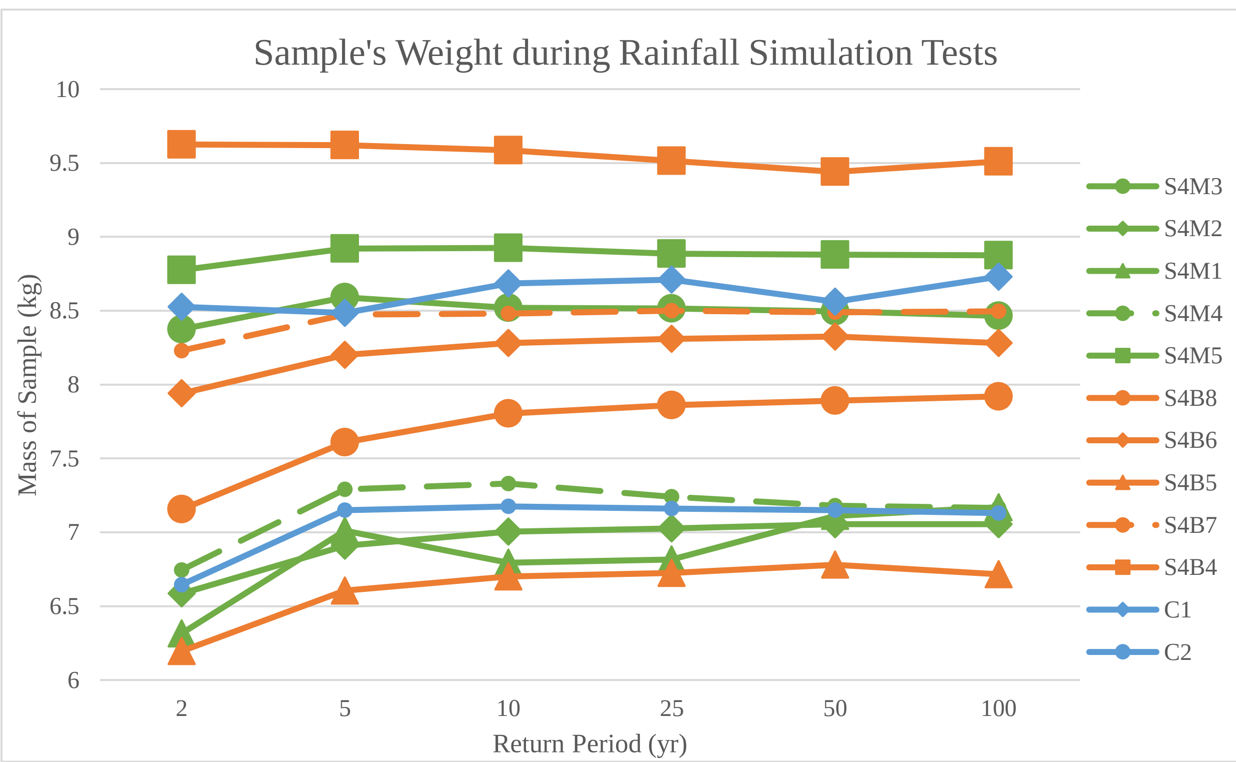


Figure 4. Sample's weight during rainfall events with increasing return periods.

In the successful tests, the turfgrass samples generated much more surface runoff than the restored meadow and the cultural meadow (错误!未找到引用源。). An example of the results of rainfall simulation tests and water balance analysis on the samples taken from the restored meadow and the turf land on Jul. 29, 2021 is presented in Figure . A small amount of surface runoff occasionally occurred in the restored meadow in 5-, 10-, 25-, and 50-year rainfall events. In addition, as rainfall intensity increased with greater return periods, the surface runoff ratio of the turf land increased gradually from 1.1% to 31.6%. This indicates that as rainfall intensity increased, the land had a smaller capacity to infiltrate water and a greater chance to generate runoff. The cultural meadow generated no surface runoff in all rainfall events. Both the restored meadow and the cultural meadow had a greater capacity to infiltrate rainfall and mitigate surface runoff compared with the turf land. The results of Wilcoxon tests showed that the turf land had a significantly greater surface runoff ratio and a significantly smaller exfiltration ratio than the restored meadow and the cultural meadow (Table 4).

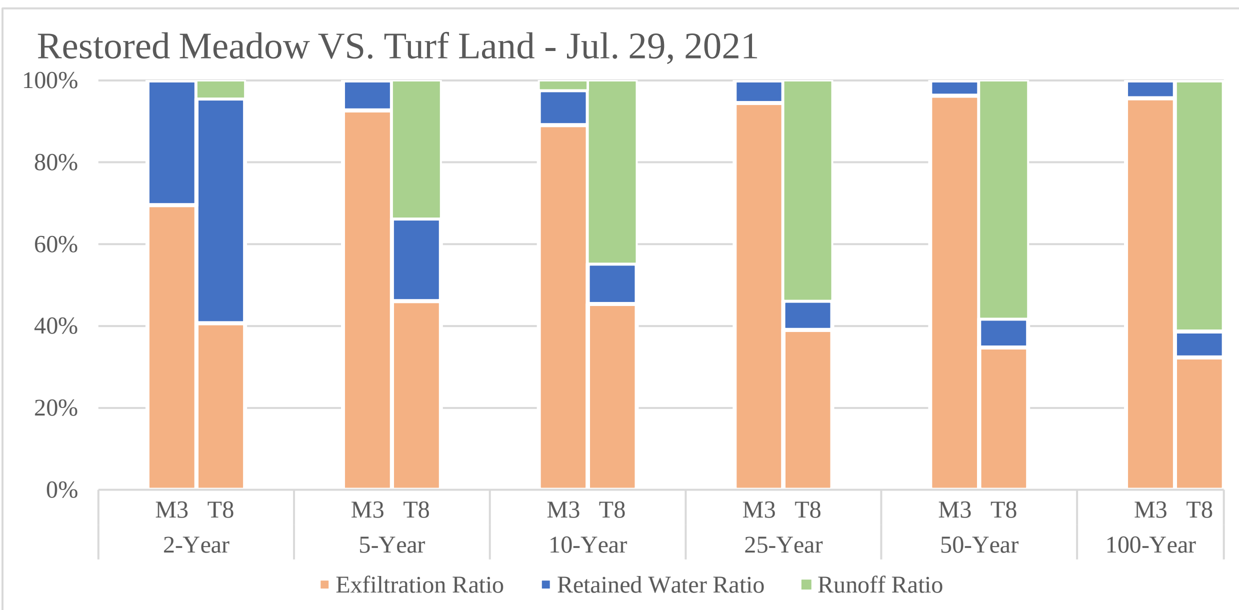


Figure 5. The results of water balance analysis of rainfall simulation tests: runoff ratio, exfiltration ratio, and retained water ratio of restored meadow VS. turf land sampled on Jul. 29, 2021.

Table 3. The runoff ratio, exfiltration ratio, and retained water ratio of soil samples from restored meadow, turf land, and cultural meadow in rainfall events with return periods of 2, 5, 10, 25, 50, and 100 years.

Return Period (year)	Runoff Ratio (%)			Exfiltration Ratio (%)			Retained Water Ratio (%)		
	Restored Meadow	Turf Land	Cultural Meadow	Restored Meadow	Turf Land	Cultural Meadow	Restored Meadow	Turf Land	Cultural Meadow
2	0.00	1.1	0.00	55	61	53	45	38	47
5	1.6	7.9	0.00	86	75	81	12	12	19
10	3.5	11	0.00	87	82	90	10	7.3	10
25	4.6	24	0.00	88	70	94	7.3	6.8	6.2
50	0.30	25	0.00	94	70	92	5.7	5.7	8.2
100	0.00	32	0.00	95	61	95	5.0	7.5	4.6

Table 4. A summary of p-values of Wilcoxon tests on runoff ratios, exfiltration ratios, and retained water ratios between different land types.

Parameter	Runoff Ratio		Exfiltration Ratio		Retained Water Ratio	
Land Type	Restored Meadow	Turf Land	Restored Meadow	Turf Land	Restored Meadow	Turf Land
Restored Meadow	-	1.3E-4	-	0.0017	-	1.0
Cultural Meadow	0.054	6.0E-5	1.0	0.0017	0.99	0.99

The saturated hydraulic conductivity of each sample from the restored meadow, the turf land, and the cultural meadow ranged from 3.10 to 9.82 cm/h (Table), which within the range for the textural class of sandy loam (Pachepsky & Park, 2015). Although rainfall simulation tests showed that the turf land had a greater tendency to generate runoff than the restored meadow and the cultural meadow, this hydrologic behaviour could not be predicted based on samples' saturated hydraulic conductivities. The saturated hydraulic conductivity is an important measurement to estimate the infiltration in the water balance analysis of lands (Post & Owens, 2020). The results of this study suggest that the saturated hydraulic conductivity measurement cannot be interpreted solely to characterize the hydrological response of different land types to storms.

Table 5. The cone index and saturated hydraulic conductivities of soil samples from the restored meadow, the turf land, and the cultural meadow.

Cover	ID No.	Cone Index (psi)	2020 $K_{in-situ}$* (cm/h)	$K_{mini\ disk}$ (cm/h)	Average $K_{mini\ disk}$ (cm/h)
Restored Meadow	1	102	2.4	6.15	5.66
Restored Meadow	2	93	3.6	4.04	
Restored Meadow	3	111	2.4	5.70	
Restored Meadow	4	88	2.4	8.85	
Restored Meadow	5	99	4.8	3.57	
Turf	5	154	3.6	6.82	7.06
Turf	4	131	1.8	3.10	
Turf	6	107	7.2	7.38	
Turf	7	108	3.6	9.82	
Turf	8	133	3.6	8.18	
Cultural Meadow	1	71	-	3.39	4.65
Cultural Meadow	2	39	-	5.91	

*2020 $K_{in-situ}$ is the infiltration capacity measured by double-ring infiltromteter

4. Conclusion

The rainfall simulation tests were successfully conducted on undisturbed vegetated soil samples collected from the restored meadow and the turf land in Section 4 in The Meadoway as well as the cultural meadow in the RNUP. The results of the water balance analysis showed that the turf land had a much greater tendency to generate surface runoff than the restored meadow and the cultural meadow. As rainfall intensity increased, the turf land infiltrated less rainfall and generated more runoff, increasing flood risks. Both the restored and cultural meadows had a great capacity to infiltrate rainfall and mitigate surface runoff even during 50-year and 100-year rainfall events with significant rainfall intensities. In conclusion, the restoration of native meadows can enhance the hydrological regulating functions of urban greenspace by flood control.

Regardless of the significantly different hydrological performances, the restored meadow, the turf land, and the cultural meadow had similar saturated hydraulic conductivities based on mini-disk infiltrometer tests. Therefore, the saturated hydraulic conductivity measurement is not an effective indicator to quantify the enhanced hydrological regulating services of green infrastructures like The Meadoway. In the future, other hydrological experiments, including large-scale rainfall simulation, water balance analysis, and lysimeter tests, should be conducted to evaluate the enhanced hydrological functions of the land.

5. References

Allen, S. M. J., Gough, W. A., & Mohsin, T. (2015). Changes in the frequency of extreme temperature records for Toronto, Ontario, Canada. *Theoretical and Applied Climatology*, *119*(3–4), 481–491. https://doi.org/10.1007/s00704-014-1131-1

Chase, T. N., Pielke Sr., R. A., Kittel, T. G. F., Nemani, R. R., & Running, S. W. (2000). Simulated impacts of historical land cover changes on global climate in northern winter. *Climate Dynamics*, *16*(2–3), 93–105. https://doi.org/10.1007/s003820050007

City of Toronto. (2006). *Wet Weather Flow Management Guidelines*. https://www.toronto.ca/wp-content/uploads/2017/11/9191-wwfm-guidelines-2006-AODA.pdf

Conservation Demonstrations. (n.d.). *Jumbo 4 Expo Rainfall Simulator*. https://www.rainfallsimulator.com/shop/expos/large-expo-rainfall-simulator/

Das, M., & Das, A. (2019). Dynamics of Urbanization and its impact on Urban Ecosystem Services (UESs): A study of a medium size town of West Bengal, Eastern India. *Journal of Urban Management*, *8*(3), 420–434. https://doi.org/https://doi.org/10.1016/j.jum.2019.03.002

ELE International. (n.d.). *Proving Ring Penetrometer*. Retrieved December 26, 2021, from https://www.ele.com/product/proving-ring-penetrometer

Fisher Scientific. (n.d.). *Fisherbrand™ GP1000 General-Purpose Peristaltic Pumps*. Retrieved December 29, 2021, from https://www.fishersci.com/shop/products/fh100-fh100x-general-purpose-peristaltic-pumps-1/13310656

Government of Ontario. (2020). *Provincial Policy Statement, 2020*. https://files.ontario.ca/mmah-provincial-policy-statement-2020-accessible-final-en-2020-02-14.pdf

METER ENVIRONMENT. (n.d.). *MINI DISK INFILTROMETER*. https://www.metergroup.com/environment/products/mini-disk-infiltrometer/

METER Group. (n.d.). *MINI DISK INFILTROMETER*. http://publications.metergroup.com/Manuals/20421_Mini_Disk_Manual_Web.pdf

Ontario Ministry of Finance. (2020). *Ontario Population Projections Update, 2019–2046*. https://www.fin.gov.on.ca/en/economy/demographics/projections/#:~:text=The Greater Toronto Area (GTA,over 9.5 million by 2046.&text=The five other regions are,populations over the projection period.

Pachepsky, Y., & Park, Y. (2015). Saturated hydraulic conductivity of US soils grouped according to textural class and bulk density. *Soil Science Society of America Journal*, *79*(4), 1094–1100. https://doi.org/10.2136/sssaj2015.02.0067

Post, R., & Owens, D. (2020). *Overview of Water Balance Practices in the Greenbelt*. https://www.nvca.on.ca/Shared Documents/Greenbelt Water Balance Report_FINAL_24-Jan-2021.pdf

TRCA. (2013). *Building The Living City: 10-year Strategic Plan 2013-2022*.

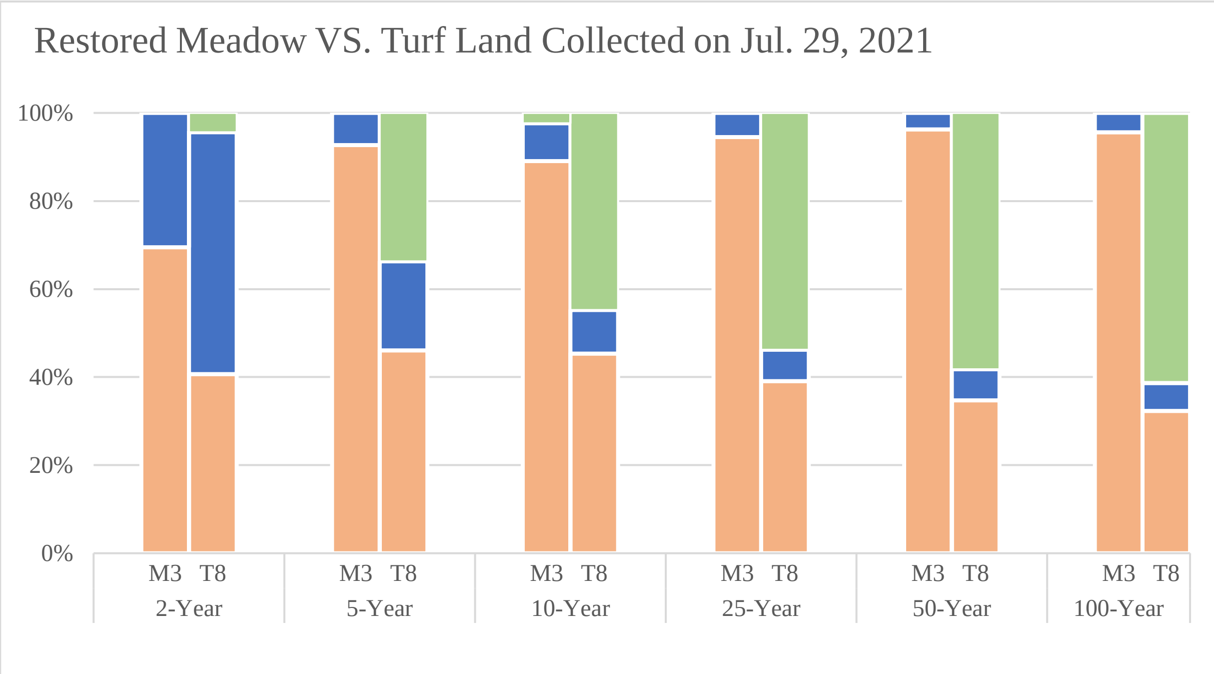
http://www.trca.on.ca/about/strategic-plan.dot

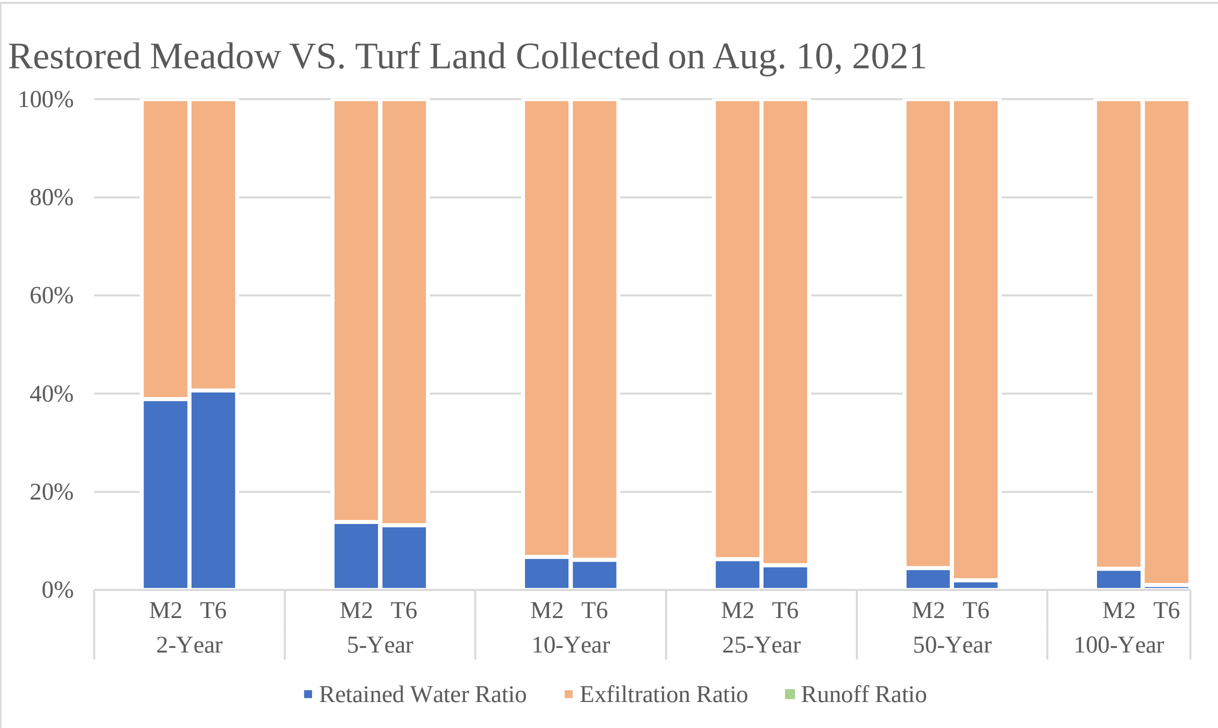
TRCA. (2019a). *Restoration Opportunities Planning Primer*.

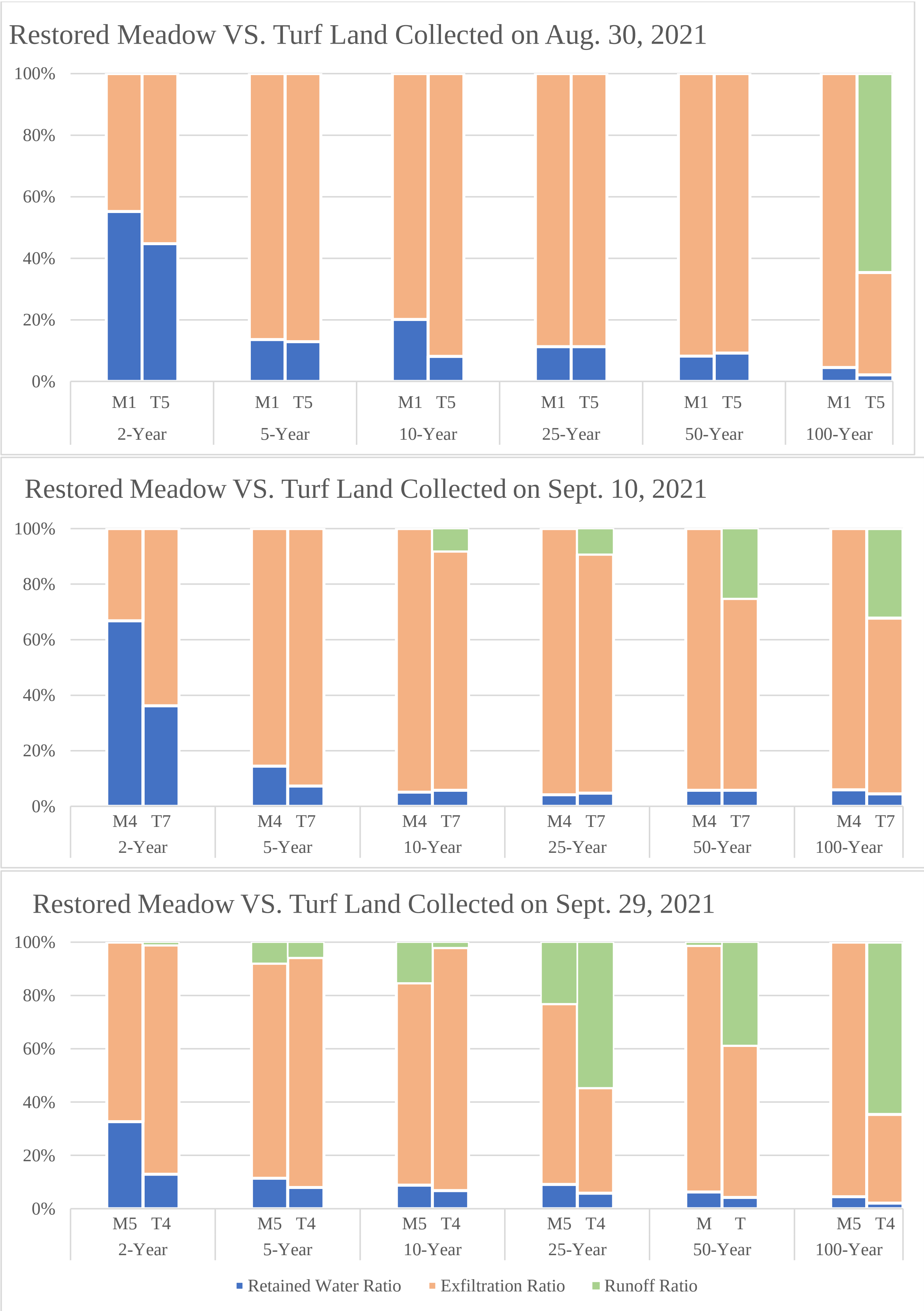
TRCA. (2019b). *The Meadoway & The Multi-use Trail Class Environmental Assessment*.

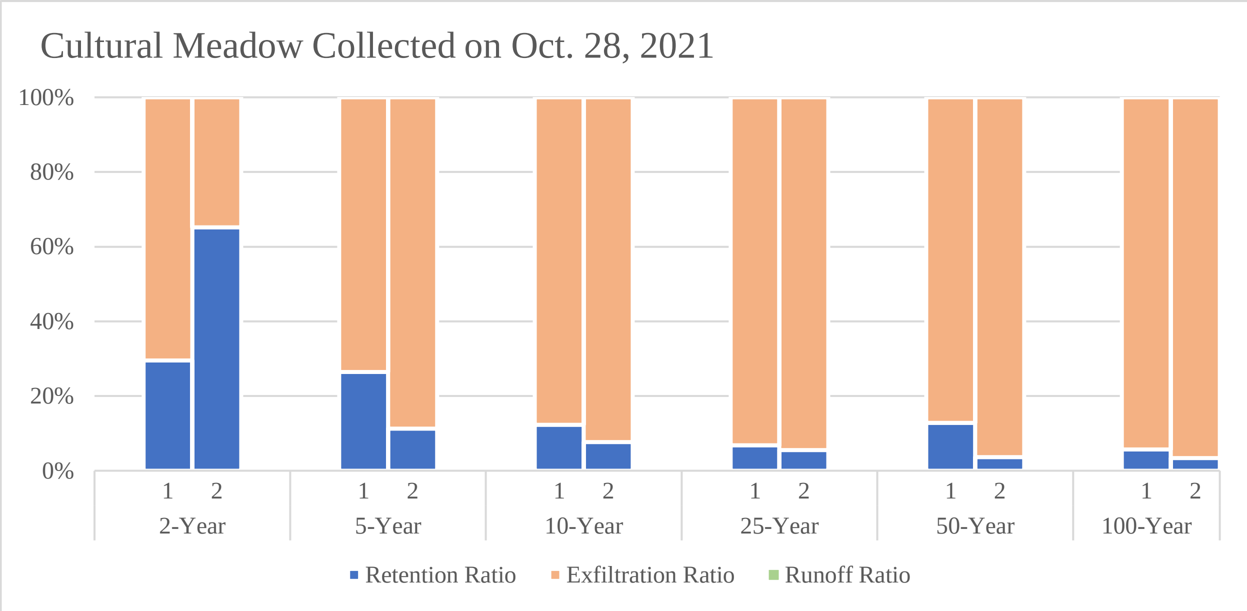
Zang, S., Wu, C., Liu, H., & Na, X. (2011). Impact of urbanization on natural ecosystem service values: A comparative study. *Environmental Monitoring and Assessment*, *179*(1–4), 575–588. https://doi.org/10.1007/s10661-010-1764-1

6. Appendix


Restored Meadow VS. Turf Land Collected on Jul. 29, 2021
100%
80%
60%
40%
20%
0%
M3 T8
2-Year
M3 T8
5-Year
M3 T8
10-Year
M3 T8
25-Year
M3 T8
50-Year
M3 T8
100-Year


Restored Meadow VS. Turf Land Collected on Aug. 10, 2021
100%
80%
60%
40%
20%
0%
M2 T6
2-Year
M2 T6
5-Year
M2 T6
10-Year
M2 T6
25-Year
M2 T6
50-Year
M2 T6
100-Year
Retained Water Ratio
Exfiltration Ratio
Runoff Ratio


Restored Meadow VS. Turf Land Collected on Aug. 30, 2021
100%
80%
60%
40%
20%
0%
M1 T5
2-Year
M1 T5
5-Year
M1 T5
10-Year
M1 T5
25-Year
M1 T5
50-Year
M1 T5
100-Year
Restored Meadow VS. Turf Land Collected on Sept. 10, 2021
100%
80%
60%
40%
20%
0%
M4 T7
2-Year
M4 T7
5-Year
M4 T7
10-Year
M4 T7
25-Year
M4 T7
50-Year
M4 T7
100-Year
Restored Meadow VS. Turf Land Collected on Sept. 29, 2021
100%
80%
60%
40%
20%
0%
M5 T4
2-Year
M5 T4
5-Year
M5 T4
10-Year
M5 T4
25-Year
M T
50-Year
M5 T4
100-Year
Retained Water Ratio
Exfiltration Ratio
Runoff Ratio


Cultural Meadow Collected on Oct. 28, 2021
100%
80%
60%
40%
20%
0%
1 2
2-Year
5-Year
10-Year
25-Year
50-Year
100-Year
Retention Ratio
Exfiltration Ratio
Runoff Ratio