A plan for conversion of stormwater to groundwater recharge on the Utah Valley University main campus, Orem, Utah

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Abstract. At the present time the vast majority of the stormwater generated on the Main Campus of Utah Valley University is exported to Utah Lake, which is only 1.4 miles from campus. Although there is a large boulder-lined detention pond on campus, it is used only as a holding pond before the stormwater is exported. The objective of this study was to determine what percentage of the average annual stormwater and the stormwater generated by a 100-year 24-hour precipitation event could be retained on campus and used for groundwater recharge by constructing a series of French drains. It was determined that the Main Campus could be divided into 33 watersheds that currently export stormwater (72.8% of the surface area) and 28 additional self-contained watersheds. Using the NRCS Runoff Curve Method, it was determined that the Main Campus exports 0.4998 ac·ft of stormwater annually and would export 23.2969 ac·ft of stormwater following a 100-year 24-hour precipitation event, while the self-contained watersheds capture 0.0330 ac·ft annually and would capture 2.7913 ac·ft following a 100-year 24-hour event. The construction of nine French drains (including subsurface expansion of the existing detention pond with discontinuation of pumping) with a combined surface area of 0.9260 ac would convert to groundwater recharge 0.1402 ac·ft annually (28.1% of current export) and 6.2083 ac·ft following a 100-year 24-hour precipitation event (26.6% of current export). Further reduction of stormwater export could not be accomplished without disruption to current paved areas or other built infrastructure.

1. Introduction

The Main Campus of Utah Valley University covers approximately 211 acres in Orem, Utah (see Fig. 1). At the present time the vast majority of the stormwater generated on the Main Campus is exported to Utah Lake, which is only 1.4 miles from campus. Although there is a large boulder-lined detention pond on campus, it is used only as a holding pond before the stormwater is exported (see Fig. 2). The objective of this study was to determine what percentage of the average annual stormwater and the stormwater generated by a 100-year 24-hour precipitation event could be retained on campus and used for groundwater recharge by constructing a series of boulder-lined retention ponds, also known as French drains. (Note that a detention pond is intended to hold water temporarily, while a retention pond is intended to hold water indefinitely until the water evaporates or infiltrates into the underlying soil. Due to the high water table in Orem, Utah, any downward infiltration results in groundwater recharge.)

The objectives were addressed by asking the following questions:

1) How is the campus divided into watersheds?

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2) What is the volume of surface runoff that would be generated in each watershed from a 100-year 24-hour precipitation event?

3) What is the average annual volume of surface runoff from each watershed?

4) What would be the location and dimensions of the French drains required to retain all of the stormwater generated in a 100-year 24-hour precipitation event?

5) Could the current detention pond be converted into a French drain simply by discontinuing pumping water out of the pond?

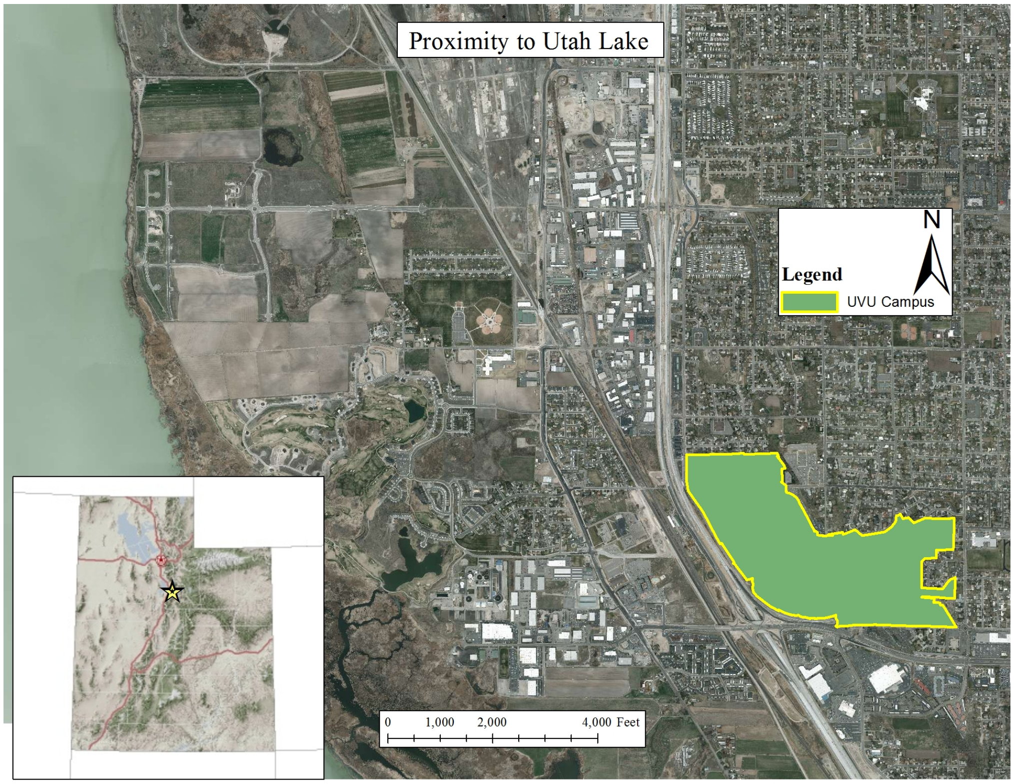

Figure 1. The vast majority of the stormwater generated on the Utah Valley University Main Campus is exported to Utah Lake, which is only 1.4 miles from campus.

2. Methods

2.1 Calculation of Volume of Surface Runoff

The Main Campus was divided into watersheds by walking the campus with a hand level and noting the locations of the storm drains. The volume of surface runoff that would be generated on each watershed by a particular precipitation event was calculated using the Runoff Curve Method (NRCS 2004). According to this method, runoff is calculated using the empirical formula

$$V_r = \frac{(P - I_a)^2}{(P - I_a + S)} \qquad (1)$$

where V_r is runoff in inches, P is precipitation in inches, I_a is the initial abstraction (surface storage, interception and infiltration prior to runoff), and S is defined by

$$S = \frac{1000}{CN} - 10 \qquad (2)$$

where the curve number CN depends upon the land use and Hydrologic Soil Group. (The Hydrologic Soil Groups are defined by infiltration rates of <0.05 in h^{-1} (Group D), 0.05-0.15 in h^{-1} (Group C), 0.15-0.30 in h^{-1} (Group B) and >0.3 in h^{-1} (Group A) (NRCS 2004)). Runoff in inches is then multiplied by watershed area in acres to obtain volume of runoff from a watershed in acre-feet. Where a watershed contains multiple land uses and Hydrologic Soil Groups, the volume of runoff is calculated separately for each region of the watershed and then summed to obtain the total volume of runoff. The initial abstraction I_a can be approximated as

$$I_a = 0.2S \tag{3}$$

so that Eq. (1) becomes

$$V_r = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{4}$$

but in which $V_r = 0$ when $P \leq I_a = 0.2S$.

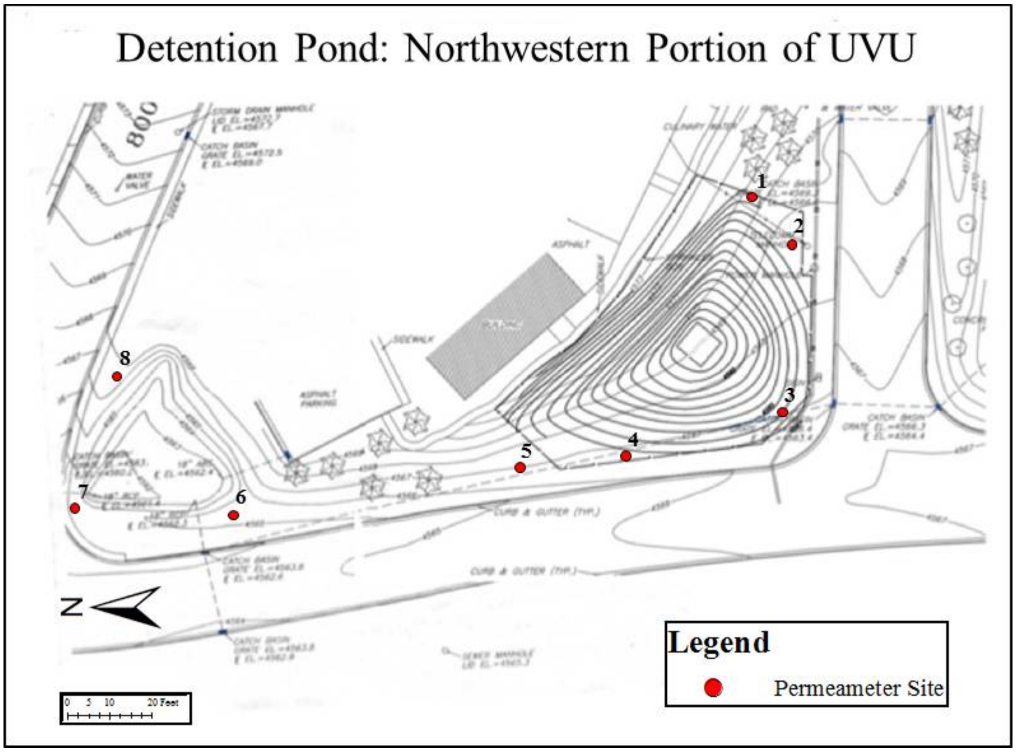

Figure 2. A boulder-lined detention pond is used currently only as a holding pond before the stormwater is exported. However, with subsurface expansion and the discontinuation of pumping, the same pond could convert all of the stormwater generated by a 100-year 24-hour precipitation event into groundwater recharge. Figure modified from King Engineering (2010).

The land-use proportions of each watershed were estimated by aerial photography from Google Earth as taken on June 17, 2010, but were modified based on recent campus construction. The Hydrologic Soil Groups were determined from the NRCS Web Soil Survey (NRCS 2012). The Web Soil Survey could not be relied upon as a sole source of information because the scale of mapping was larger than the scale of interest of this study. Moreover, although the thickness of construction fill was reported to be negligible everywhere on campus (Young 2012), it was uncertain whether construction and the addition of construction fill throughout campus had a significant impact on hydraulic conductivity. Therefore, the validity of the use of the Web Soil Survey to identify Hydrologic Soil Groups was verified by measuring the field-saturated hydraulic conductivity at eight sites near the detention pond (see Fig. 2) using the Model 2800K1 Guelph Permeameter (SoilMoisture Equipment, Inc.). Saturated hydraulic conductivities were determined by the semi-empirical formula

$$K = 35.17(0.0041R_2 - 0.0054R_1) \tag{5}$$

where K is hydraulic conductivity (cm min^{-1}), and R_1 and R_2 are the steady-state rates of fall (cm min^{-1}) of the water level in the permeameter reservoir at heads of 5 cm and 10 cm, respectively (Elrick and Reynolds 1986; SoilMoisture Equipment 1986). Saturated hydraulic conductivities were measured in augured holes 6 cm in diameter and 15 cm deep.

For each watershed, the average annual volume of surface runoff was calculated, as well as the volume of surface runoff that would be generated by a 100-year 24-hour precipitation event. A 100-year 24-hour precipitation event in Orem, Utah, is estimated at 2.38" of precipitation (NOAA-NWS 2012). The average annual precipitation in Orem is 13.26" (NOAA-NCDC 2012). The average annual surface runoff was calculated by summing the runoff that would be produced by the average daily precipitation for each day throughout the year. According to Eqs. (2) – (3), typical pavement (CN = 98 (NRCS 2004)) has sufficient cracks and depressions that surface runoff will occur only when the precipitation exceeds 0.041". The average daily precipitation in Orem, Utah, equals 0.05" on 59 days of the year, equals 0.06" on 14 days of the year and never exceeds 0.06" (NOAA-NCDC 2012), so that surface runoff occurs on average on only 73 days of the year, even on paved surfaces.

2.2 Determination of Sizes and Locations of Retention Ponds

The minimum size of a rectangular retention pond required to contain all of the stormwater generated by a 100-year 24-hour precipitation event and the time required for the retention pond to empty following the precipitation event was calculated using the procedure described in the appendix. It was assumed that stormwater entered the retention pond at a uniform rate Q_{in} given by $Q_{in} = V_r/\Delta t$, where $\Delta t = 24$ h. It was also assumed that the retention pond simultaneously drained into the surrounding soil at a flux equal to the saturated hydraulic conductivity K. (This assumption is equivalent to the assumption of unit hydraulic gradient, which is also equivalent to the assumption of a constant infiltration rate for a given Hydrologic Soil Group.) The hydraulic conductivities were chosen as the mid-range for each Hydrologic Soil Group as follows: Hydrologic Soil Group A: K = 0.025 in h^{-1}, Hydrologic Soil Group B: K = 0.1 in h^{-1}, Hydrologic Soil Group C: K = 0.225 in h^{-1}, Hydrologic Soil Group D: K = 0.4 in h^{-1}. The minimum size was chosen as the size that would completely fill in exactly 24 hours. The depth of the pond was chosen as the depth to the water table as given in the Web Soil Survey (NRCS 2012), and the width and length were varied to achieve the required size. The time to fill the complex shape of the existing detention pond was calculated by approximating the detention pond by a stack of 10 vertical cylinders with base and top of arbitrary shape (based upon the 10 1-foot contour lines that define the pond (see Fig. 2)) and using the procedure described in the appendix.

Locations for the proposed retention ponds were chosen based on the following criteria:

1) Retention ponds were to be constructed only on current grassy areas so that there would be no disruption of current paved areas or other built infrastructure.

2) A retention pond had to be located in a watershed so that, given the current drainage pattern, all surface runoff would drain toward that retention pond.

3. Results

3.1 Volumes of Surface Runoff

The Main Campus was divided into 33 watersheds that export stormwater (72.8% of campus surface area) and 28 self-contained watersheds (27.2% of campus surface area) (see Fig. 3 and Tables 1-2). Self-contained watersheds capture stormwater in fountains, grassy depressions, small French drains or sumps. The majority of campus land use was found to be pavement or buildings (65.2% of surface area) with the remainder being lawns in good condition (34.8% of surface area). The lawns were found to be about equally divided between Hydrologic Soil Group A (38.3%) and Soil Group B (34.7%) with lesser amounts in Soil Group C (6.6%) and Soil Group D (20.4%) (see Fig. 4). The average hydraulic conductivity K (excluding one outlier) measured in an area mapped as Hydrologic Soil Group C (see Figs. 2, 4) was $K = 0.14$ in/h (see Table 3), so that the mapped Hydrologic Soil Groups were regarded as accurate. Therefore, the curve numbers were chosen as $CN = 98$ (pavement), $CN = 80$ (lawn in Soil Group D), $CN = 74$ (lawn in Soil Group C), $CN = 61$ (lawn in Soil Group B), and $CN = 39$ (lawn in Soil Group A). Based on the above, it was determined that the Main Campus exports 0.4998 ac·ft of stormwater annually and would export 23.2969 ac·ft of stormwater following a 100-year 24-hour precipitation event, while the self-contained watersheds capture 0.0330 ac·ft annually and would capture 2.7913 ac·ft following a 100-year 24-hour event.

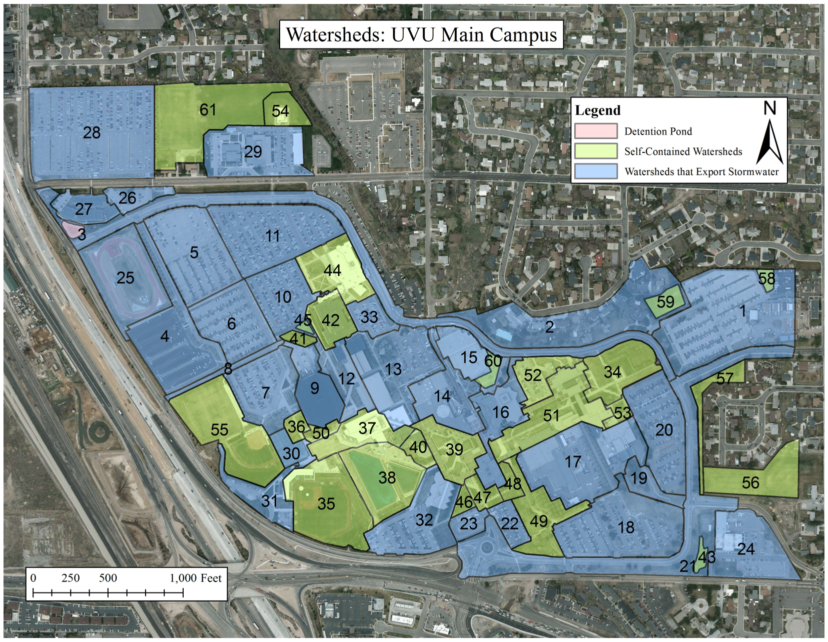

Figure 3. The UVU Main Campus was divided into 33 watersheds that export stormwater and 28 self-contained watersheds.

Table 1. Runoff generated in a 100-year 24-hour precipitation event and average annual runoff in current watersheds that export stormwater.

Watershed Identifier[1]	Area (ac)	Land Use	100-Year 24-Hour Event Runoff Volume (ac·ft)	Average Annual Runoff Volume (ac·ft)
1	10.4947	95% paved, 5% Soil B	1.7947	0.0387
2	8.4584	10% paved, 45% Soil A, 45% Soil B	0.2031	0.0033
3	7.9737	97% paved, 3% Soil C	1.4297	0.0309
4	6.3375	100% paved	1.1363	0.0246
5	5.9357	100% paved	1.0642	0.0230
6	4.3359	100% paved	0.7774	0.0168
7	4.3562	100% paved	0.7811	0.0169
8	0.7152	100% paved	0.1282	0.0028
9	2.8241	100% paved	0.5064	0.0110
10	3.7109	100% paved	0.6654	0.0144
11	6.6599	100% paved	1.1941	0.0258
12	2.2895	80% paved, 20% Soil A	0.3284	0.0071
13	6.0539	100% paved	1.0854	0.0235
14	3.2012	90% paved, 10% Soil A	0.5166	0.0112
15	2.7565	90% paved, 10% Soil A	0.4448	0.0096
16	3.2111	95% paved, 5% Soil A	0.5470	0.0118
17	7.4825	90% paved, 10% Soil B	1.2175	0.0261
18	7.1884	85% paved, 15% Soil B	1.1101	0.0237
19	1.2707	10% paved, 90% Soil B	0.0382	0.0005
20	4.9772	100% paved	0.8924	0.0193
21	11.1886	60% paved, 10% Soil A, 30% Soil B	1.2490	0.0260
22	1.1132	100% paved	0.1996	0.0043
23	0.9100	100% paved	0.1632	0.0035
24	4.7102	90% paved, 10% Soil B	0.7664	0.0164
25	5.7649	100% Soil A	0.0000	0.0000
26	1.2055	85% paved, 15% Soil C	0.1919	0.0040
27	1.6878	100% paved	0.3026	0.0065
28	11.9086	100% paved	2.1352	0.0462
29	5.0781	100% paved	0.9105	0.0197
30	1.0425	100% paved	0.1869	0.0040
31	2.3047	60% paved, 40% Soil B	0.2604	0.0054
32	5.0120	90% paved, 10% Soil C	0.8314	0.0175
33	1.3328	100% paved	0.2390	0.0052
Total	153.4919		23.2969	0.4998

[1] See Fig. 3.

Table 2. Runoff generated in a 100-year 24-hour precipitation event and average annual runoff in current self-contained watersheds.

Watershed Identifier[1]	Area (ac)	Land Use	100-Year 24-Hour Event Runoff Volume (ac·ft)	Average Annual Runoff Volume (ac·ft)
34	3.1837	100% Soil B	0.0430	0.0000
35	6.0128	100% Soil D	0.4043	0.0000
36	0.5467	50% Soil A, 50% Soil C	0.0124	0.0000
37	1.9299	100% Soil A	0.0000	0.0000
38	3.8968	Fountain	0.0000	0.0000
39	2.6433	5% Paved, 95% Soil A	0.0237	0.0005
40	0.4676	100% Soil A	0.0000	0.0000
41	0.3679	100% Soil A	0.0000	0.0000
42	1.8746	95% paved, 5% Soil A	0.3193	0.0069
43	0.2803	100% Soil A	0.0000	0.0000
44	3.2868	60% paved, 40% Soil A	0.3536	0.0076
45	0.1260	100% Soil A	0.0000	0.0000
46	0.4060	100% Soil A	0.0000	0.0000
47	0.7870	10% paved, 90% Soil A	0.0141	0.0003
48	0.5761	100% Soil A	0.0000	0.0000
49	3.0864	10% paved, 90% Soil A	0.0553	0.0012
50	0.4405	100% Soil A	0.0000	0.0000
51	4.8065	50% paved, 50% Soil C	0.4634	0.0093
52	1.8129	100% paved	0.3250	0.0070
53	0.5222	5% paved, 95% Soil B	0.0114	0.0001
54	1.2877	100% Soil A	0.0000	0.0000
55	5.8705	60% Soil C, 40% Soil D	0.3172	0.0000
56	3.2747	100% Soil C	0.0442	0.0000
57	1.1990	100% Soil C	0.0162	0.0000
58	0.2859	100% Soil C	0.0039	0.0000
59	0.7552	100% Soil C	0.0102	0.0000
60	0.4542	100% Soil A	0.0000	0.0000
61	7.1254	100% Soil B	0.2875	0.0000
Total	57.3064		2.7913	0.0330

[1] See Fig. 3.

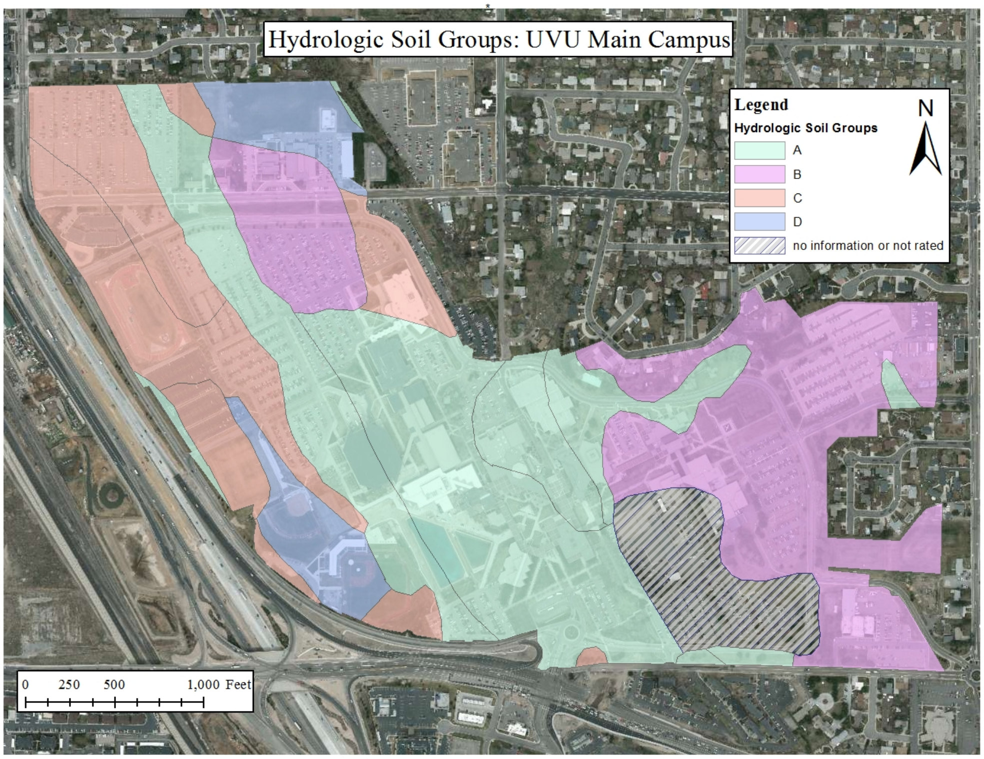

Figure 4. The UVU Main Campus lawns are divided among Hydrologic Soil Groups A (38.3%), B (34.7%), C (6.6%) and D (20.4%).

Table 3. Results of Guelph Permeameter measurements.

Site[1]	Steady-State Rate of Fall at 5 cm Head (cm min^{-1})	Steady-State Rate of Fall at 10 cm Head (cm min^{-1})	Hydraulic Conductivity (in h^{-1})
1	0.1	0.18	0.16
2	0.12	0.2	0.14
3	0.05	0.1	0.11
4	0.12	0.2	0.14
5	0.1	0.18	0.16
6	0.2	0.3	0.12
7	0.2	1.1	2.84*
8	0.15	0.25	0.17
	Average (excluding outlier *)		0.14

[1] See Fig. 2

3.2 Locations and Sizes of Proposed Retention Ponds

It was determined that retention ponds could be placed in nine out of the 33 watersheds that export stormwater (see Fig. 5, Table 4). In the remaining 24 watersheds, there was no place to put a retention pond, either because the entire watershed was in pavement or buildings or because the existing lawn was not at the lowest point of the watershed. For Watershed 16 (see Fig. 5), there was sufficient lawn space to place a retention pond of capacity 0.1385 ac·ft (see Table 4), although the watershed would generate 0.5470 ac·ft of stormwater in a 100-year 24-hour event (see Table 1). For the other eight watersheds, retention ponds could be located with sufficient capacity to accommodate all of the stormwater that would result from a 100-year 24-hour event. The existing cone-shaped detention pond in Watershed 3 (see Figs. 2-3, 5) has a surface footprint of 11,853 ft^2 and would completely fill in 16.5 hours. The detention pond could be expanded below the surface to create a rectangular retention pond that would take 24 hours to fill and which would need a smaller footprint (9120 ft^2) than the present detention pond (see Table 4, Figs. 2-3, 5). The combined surface footprint of the nine retention ponds would be 0.9260 ac (1.4% of the present area in lawns). The construction of the nine retention ponds would convert to groundwater recharge 0.1402 ac·ft annually (28.1% of current export) and 6.2083 ac·ft following a 100-year 24-event (26.6% of current export) (see Table 4). Note that it could take up to 29 days for all retention ponds to completely drain after they were completely filled following a 100-year 24-hour precipitation event (see Table 4).

Table 4. Characteristics of proposed rectangular French drains.

Watershed Identifier[1]	Depth × Width × Length (ft×ft×ft)	Groundwater Recharge: 100-Year 24-Hour Event (ac·ft)	Time to Drain (h)	Average Annual Groundwater Recharge (ac·ft)
1	6.6 × 40 × 270	1.7947	298	0.0387
2	6.6 × 21 × 55	0.2031	182	0.0033
3	6.6 × 95 × 96	1.4297	699	0.0309
12	6.6 × 30 × 63	0.3284	153	0.0071
16	6.6 × 25 × 35	0.1385	141	0.0118
19	6.6 × 15 × 15	0.0382	203	0.0005
21	6.6 × 55 × 174	1.2490	172	0.0260
24	6.6 × 55 × 85	0.7664	297	0.0164
31	5 × 45 × 45	0.2604	221	0.0054
Total		6.2083		0.1402

[1] See Fig. 5.

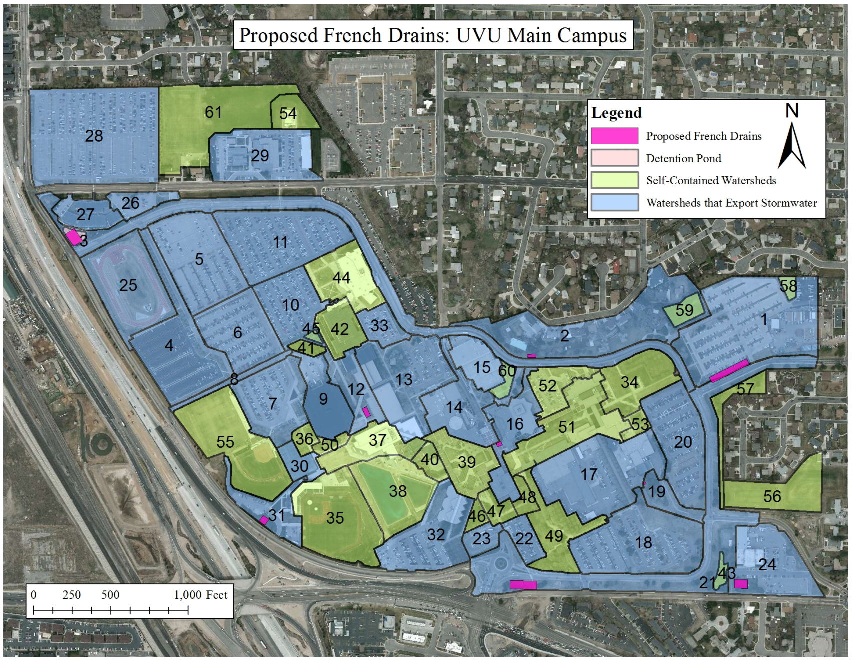

Figure 5. Nine French drains could be constructed, which would convert to groundwater recharge 0.1402 ac·ft annually (28.1% of current export) and 6.2083 ac·ft following a 100-year 24-hour event (26.6% of current export).

4. Recommendations

We are recommending construction on the UVU Main Campus of a series of nine French drains, which would occupy 1.4% of the present area in lawns and which would reduce annual stormwater export by 28.1% and export of stormwater following a 100-year 24-hour precipitation event by 26.6%. Any further reduction in stormwater export would require much more radical changes in campus land use, such as disruption of current paved areas, restoration of vegetation, or creation of artificial wetlands.

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Appendix: Time to Fill and Drain a Retention Pond

Suppose that a rectangular pond of width W, length L and depth D is excavated into a permeable soil of saturated hydraulic conductivity K. Stormwater enters the retention pond at a uniform flow rate $Q_{in} = V_r/\Delta t$, where V_r is the total volume of runoff generated over a time period of interest Δt. As stormwater enters the pond, the pond simultaneously drains into the surrounding soil. The purpose of this appendix is to address the following questions:

1) What is the time required to fill an initially dry rectangular retention pond?
2) What is the total capacity of a rectangular retention pond, which is the sum of the storage capacity (volume of the pond) and the infiltration capacity (volume of water that drains out of the pond while the pond is being filled)?
3) What is the time required to drain a full rectangular pond after stormwater ceases entering the pond?
4) What are the equivalents to the above answers for a retention pond of arbitrary shape?

It is assumed that the flux of water out of the pond is equal to the saturated hydraulic conductivity. This assumption is equivalent to the assumption of unit hydraulic gradient, which is also equivalent to the assumption of a constant infiltration rate for a given Hydrologic Soil Group. Given the above assumption,

$$\frac{dV}{dt} = Q_{in} - KA \tag{A1}$$

where V is the volume of water in the pond and A is the surface area of water in contact with the surrounding soil. The volume V and area A are given by

$$V = WLh(t) \tag{A2}$$

$$A = WL + 2Wh(t) + 2Lh(t) \tag{A3}$$

where $h(t)$ is the height of water in the pond. Substituting Eqs. (A2) and (A3) into (A1) yields the differential equation

$$WL\frac{dh}{dt} = Q_{in} - K[WL + 2(W + L)h(t)]. \tag{A4}$$

Then integrating (A4) from $h(t = 0) = 0$ to $h(t = t_{fill}) = D$ yields

$$t_{fill} = \frac{WL}{2K(W+L)} \ln\left[\frac{Q_{in} - KWL}{Q_{in} - KWL - 2K(W+L)D}\right], \tag{A5}$$

where t_{fill} is the time required to fill the pond. If $\Delta t = t_{fill}$ (the pond completely fills within the time period of interest), then the total capacity C of the pond is given by

$$C = \frac{Q_{in}WL}{2K(W+L)} \ln\left[\frac{Q_{in} - KWL}{Q_{in} - KWL - 2K(W+L)D}\right], \tag{A6}$$

so that

$$IC = C - WLD, \tag{A7}$$

where IC is the infiltration capacity.

The time to drain a completely full rectangular pond, t_{drain}, can be obtained by setting $Q_{in} = 0$ in (A4) and integrating from $h(t = 0) = D$ to $h(t = t_{drain}) = 0$ to yield

$$t_{drain} = \frac{WL}{2K(W+L)} \ln\left[\frac{2D(W+L) + WL}{WL}\right]. \tag{A8}$$

Suppose that the retention pond is now a vertical cylinder with height h and with base and top of arbitrary shape with perimeter P and area A. Then the equivalents to Eqs. (A5) – (A8) are

$$t_{fill} = \frac{A}{KP} \ln\left[\frac{Q_{in} - KA}{Q_{in} - K(A + Ph)}\right], \tag{A9}$$

$$C = \frac{Q_{in}A}{KP} \ln\left[\frac{Q_{in} - KA}{Q_{in} - K(A + Ph)}\right], \tag{A10}$$

$$IC = C - Ah, \tag{A11}$$

$$t_{drain} = \frac{A}{KP} \ln\left[\frac{A + Ph}{A}\right]. \tag{A12}$$

Finally consider an arbitrary cone-shaped pond. Assume that the pond can be approximated by a stack of N vertical cylinders of base and top of arbitrary shape in which the top of one cylinder is wholly contained within the base of the overlying cylinder. If the cylinders are numbered up from the bottom (j = 1 is the bottom cylinder), then

$$t_{fill,1} = \frac{A_1}{KP_1} \ln\left[\frac{Q_{in} - KA_1}{Q_{in} - K(A_1 + P_1h_1)}\right], \tag{A13}$$

and

$$t_{fill,j} = \frac{A_j}{KP_j} \ln\left[\frac{Q_{in} - K(P_{j-1}h_{j-1} + P_{j-2}h_{j-2} + \cdots + P_1h_1 + A_j)}{Q_{in} - K(P_jh_j + P_{j-1}h_{j-1} + \cdots + P_1h_1 + A_j)}\right], \tag{A14}$$

where A_j is the area of the base or top of cylinder j, h_j is the height of cylinder j, P_j is the perimeter of cylinder j, and $t_{fill,j}$ is the time required to fill cylinder j. The time required to fill the entire pond is then

$$t_{fill} = t_{fill,1} + t_{fill,2} + \cdots + t_{fill,N}. \tag{A15}$$

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