Recommended Locations for Water Level Data Loggers to Infer the Time-Dependent Snowy River Discharge North of Floating Islands

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March 25, 2018

To date, the Fort Stanton Cave Study Project (FSCSP) has deployed pressure-reading data loggers along Snowy River in depressions in the river bed for the primary purpose of obtaining a history of water presence in the river as it goes through stages of flooding and dry out. The loggers sense water presence and depth via recording pressure. These data are post-processed with comparisons to ambient air pressure within the passage (obtained from separate loggers placed well above the maximum water height in the passage) to determine water depth at the logger location. While this gives a good record of the timing of floodings and dry outs, the specific locations chosen are not very well suited for inferring discharge (volumetric flow rate) from water depth (stage) even when cross sections of the river bed and slope are obtained. The reason for this is that a good discharge inference requires a relatively uniform cross section and slope over a length greater than several river widths. Pools are not good locations for this. In addition, we are not allowed to walk in Snowy River when the water is present, and there are no walkable routes along the river bank, so obtaining discharge directly (by hand) via flow meters is not an option. And at this time, we do not have automated flow meters and batteries that can measure discharge over the several years that is typical for a wet-dry cycle. Hence, discharge inference loggers may be our best option for determining discharge vs. time at various locations along Snowy River.

To determine suitable locations in which to place depth loggers for discharge inference, hydrologists Anne Tillery, Johanna Blake, and Scott Christensen were consulted to obtain guidance on the desired characteristics of a stretch of stream. In addition, a brief review of the literature was made. Discharge in a stream is a function of stream cross sectional area, wetted perimeter, slope, friction factor, and flow regime (laminar or turbulent). The friction factor is a function of the roughness relative to the stream depth and flow regime. The flow velocity of Snowy River is fairly low (about 0.10 m/s at Turtle Junction), but the river is deep enough there (about 0.2 m) that the flow is moderately turbulent (Re is about 1×10^4). It probably is moderately turbulent throughout most of its course. Hence, the Manning Equation is suitable for estimating discharge.

Available photos and videos of Snowy River passages were reviewed to find sections which were fairly straight and uniform. The well-lit passage shots by Pete Lindsley from SRN03 through SRN12 were reviewed. FSCSP expedition reports were also reviewed, but the full set of surveyor photos was not reviewed. In addition, the videos of Snowy River by Jim Cox from Crystal Creek (SRN80) to Mt Airy (SRS300) were reviewed. Jim Cox's videos are an excellent resource in general, and in particular they show that there are very few places where Snowy River is straight, uniform, and smooth. The videos also show that the plan view maps of Snowy River (and original sketches) are not sufficient for determining good locations for discharge inference loggers. Photos and videos are needed. Nonetheless, from inspection of the videos and other photos a set of locations that appear suitable for discharge inference was chosen.

Figure 1 shows the locations of the proposed discharge inference sites (blue circles). In addition, the figure shows the locations of existing FSCSP loggers (red circles) that are mostly located in pools. BLM loggers are also shown (green circles). Talon Newton, Lewis Land, and Lala Darrah performed some hydrological studies in the dry Snowy River in September 2009 and made river bed cross section measurements at seven locations (Newton 2009). They identified historic water level lines (Snowy River Formation Top (SRFT), Water Line 1 (WL1), and Water Line 2 (WL2)) that will be useful in inferring past flow rates. They did not measure the slopes of these waterlines, which would be needed for discharge inference. These cross section locations are also shown in Figure 1 (short magenta lines). Photos near the SRS78-SRS92 series of cross sections were not found; this area is called "The Sidewalk", so it also may be sufficiently uniform for placement of a discharge inference logger. Figure 2 shows an additional pair of proposed locations upstream and downstream of the Mount Airy collapse complex.

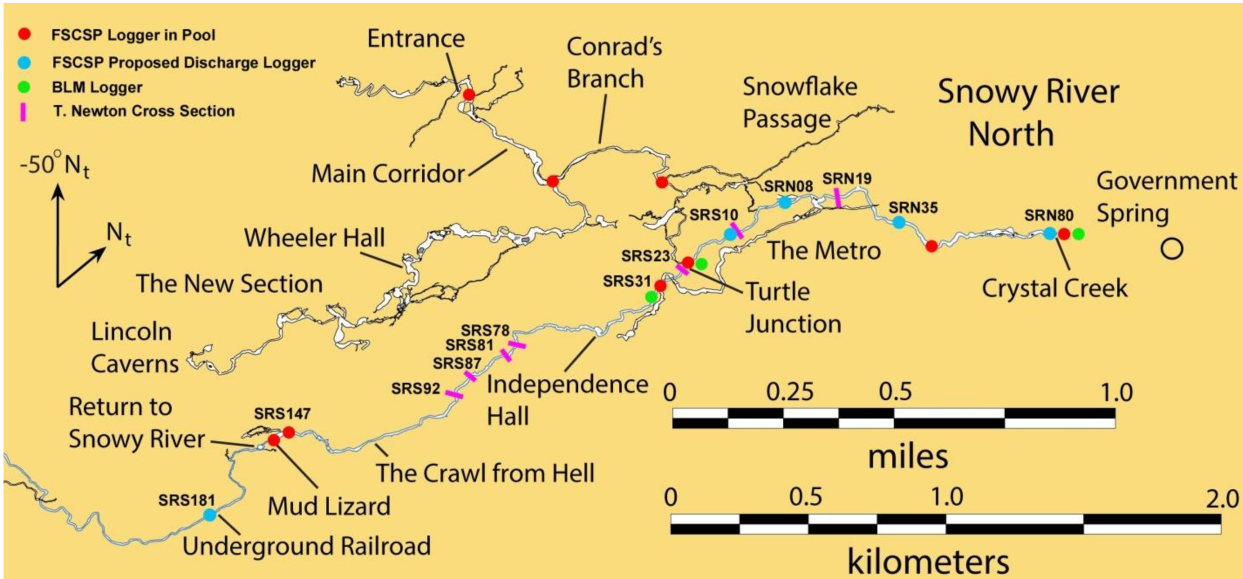

Figure 1. Fort Stanton Cave with existing and proposed logger locations north of Mt Airy. Map is rotated 50 deg. Water flows from left to right. Talon Newton cross section locations also shown (Sept. 2009).

Figure 2. Proposed logger locations before and after Mt. Airy region.

Table 1 lists the proposed inference loggers and the rationale for their placement, and Table 2 lists Talon Newton's cross section locations. Primarily, we are interested in whether the discharge increases or decreases as the water flows towards Crystal Creek and Government Spring. This would indicate sources or sinks below the river bed or seeping in from the banks that we are not able to observe when the river is flowing. Of particular interest is making measurements upstream and downstream from regions of cave complexity, such as Mount Airy, Turtle Junction, Starry Night Passage (SRS01), and the end of Snowflake and Metro Passages.

Table 1. Proposed discharge-inference data loggers (south to north, i.e. downhill).

Station	**Location**	**Rationale**
SRS317	Eggshell Trail	Just upstream of Mt Airy
SRS270	Near Mt Airy	Just downstream of Mt Airy, compare with SRS317
SRS181	Underground Railroad	Upstream of the Mud Lizard collapse
SRS010	Near Turtle Junction	Just north of Turtle Junction to compare with measured discharge at TJ and calibrate Manning's "n" for discharge inference
SRN80	Crystal Creek Falls	Direct measurement via critical flow, just before Crystal Creek Spring
SRN35	Snowy River North midway	Just north of Metro and Sewer Pipe ends to see if sub-rubble flow goes from these passages into Snowy River or into Crystal Creek Spring
SRN08	Window Passage	Just north of Priority 7 and Starry Night Passage to see if sub-rubble flow is under these passages

Table 2. Talon Newton's cross sections of Sept 28-29, 2009 (south to north, i.e. downhill).

Near	Cross Sect #	Description
SRS92	SRCS#4	10 m downstream from SRS92
SRS87	SRCS#5	At SRS87
SRS81	SRCS#6	10 m upstream from SRS81
SRS78	SRCS#3	3 m downstream from SRS78
SRS23	SRCS#7	At Mud Turtle junction close to where data logger is located
SRS10	SRCS#1	3 m downstream from SRS10
SRN19	SRCS#2	1 m upstream from SRN19

Figure 3 through Figure 8 show photos and local maps of the sections of river bed at the proposed logger locations. The photos show the nature of the river bed. It is not as smooth and uniform as desired, but the existing photos did not show sections that were any better, and most sections were much worse. One major caveat: these sections tend to be a bit wide and shallow, so surface roughness will have a significant effect. But the photos and videos did not show any narrow and deep sections that were straight and uniform. Perhaps when the loggers are deployed, such sections could be found. If so, they could take priority over the proposed locations.

Of special interest is Figure 8. It shows the location of the 3-foot waterfall at Crystal Creek. It can be a suitable location for determining discharge via an equation for flow over a falls. The channel is even somewhat rectangular. It will be important to anchor the logger at this location securely. This location is the terminus of Snowy River just before it joins Crystal Creek, which is fed by a spring at the bottom of the falls (even when Snowy River is dry).

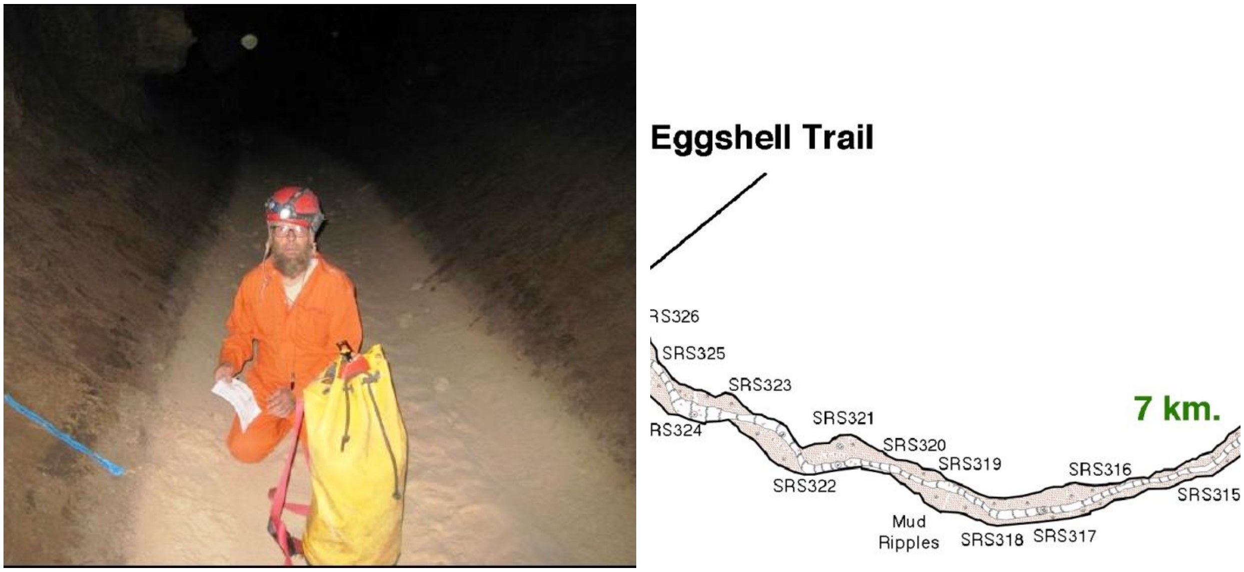

Figure 3. SRS317, Eggshell Trail, D. Davis, photo and map.

Figure 4. SRS270 looking upstream, by J. Cox, photo and map.

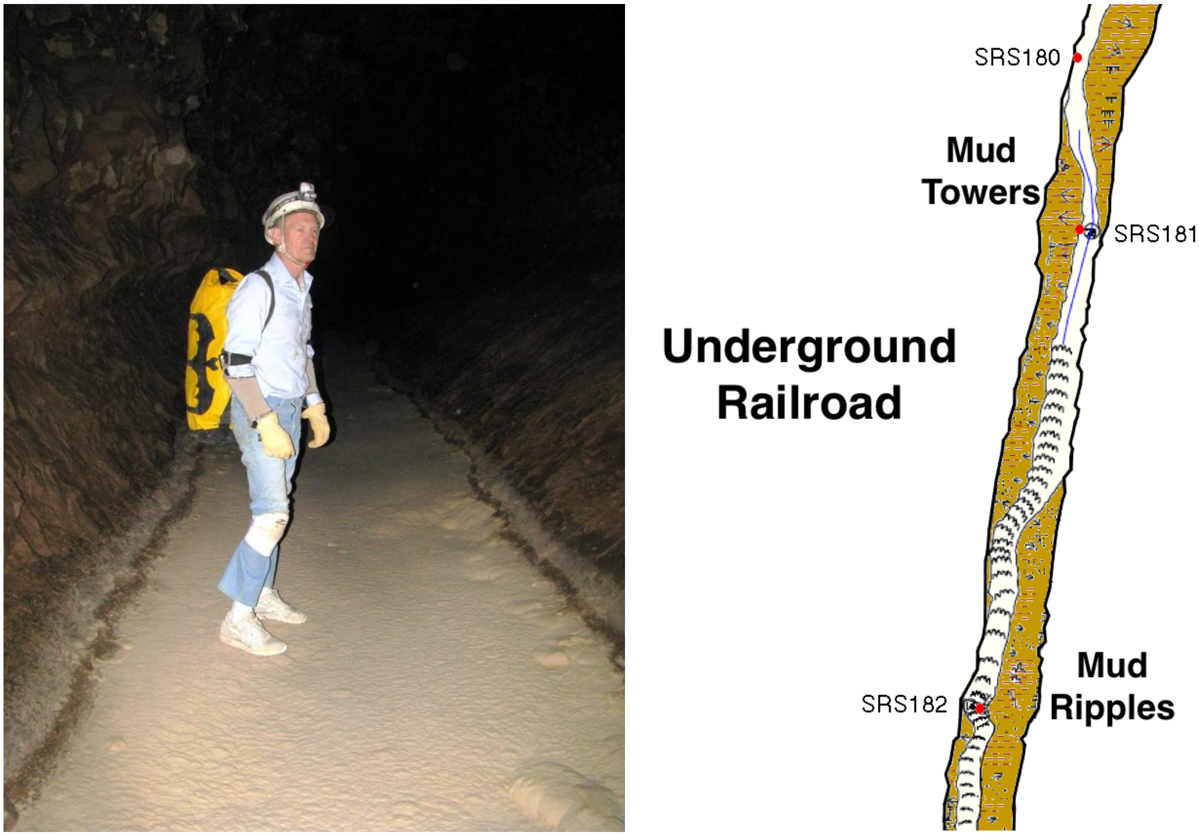

Figure 5. SRS181 looking upstream, Underground Railroad, R. Lipinski by R. Harris, photo and map.

Figure 6. SRN08 looking upstream, by P. Lindsley, photo and map.

Figure 7. SRN35 looking upstream, by J. Cox, photo and map.

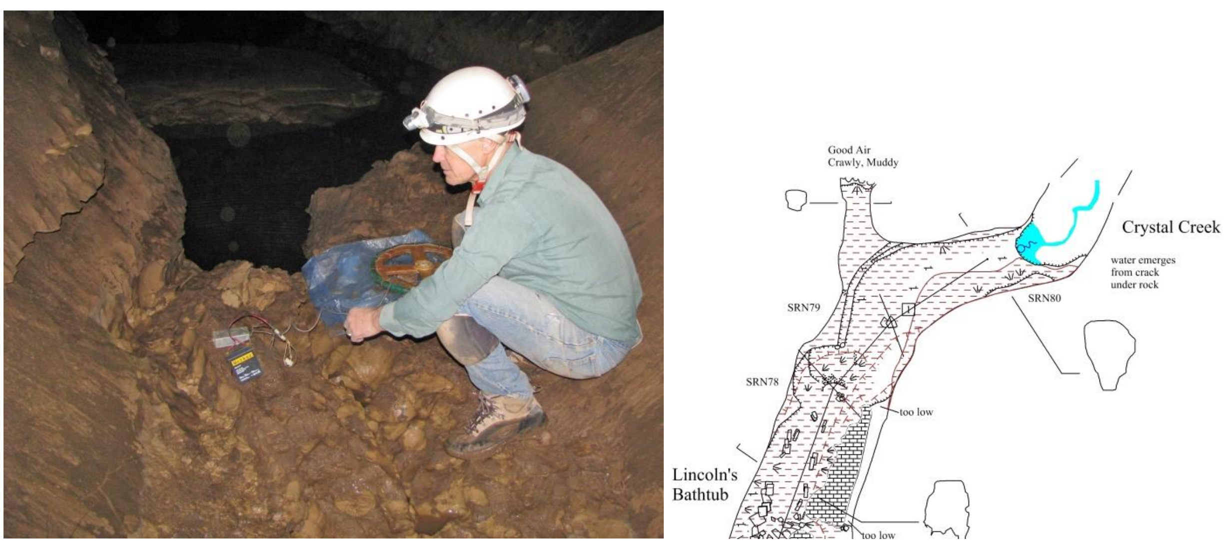

Figure 8. SRN80 looking downstream, Crystal Creek Falls, April 2009, R. Lipinski by J. Cox, photo and map.

Figure 9 shows two views of Crystal Creek taken from the top of the falls above Crystal Creek Spring. The shots were taken in 2005 after a multi-year dry spell, and in 2009 just after Snowy River stopped flowing (note the reflections in the large lake). It will be difficult to obtain discharge measurements in Crystal Creek.

Figure 9. SRN80 Crystal Creek, July 2005 very low water, April 2009 Snowy River barely dry, by J. Cox

Discussion on the Use of the Manning Equation

At Turtle Junction, the discharge of Snowy River was estimated to be 1.6 cu.ft/s (0.0453 m^3/s) at normal flow (FSCSP April-May 2008). A measurement of the cross section and wetted perimeter at that location was made in August 2017 (Lindsley 2017). For the water depth at those flow conditions, the cross section area was 0.455 m^2, and the wetted perimeter is 2.595 m, which is in close agreement with the cross section measured by Newton, et al. The hydraulic radius is thus 0.175 m and the flow velocity is 0.100 m/s. For 0.1 m/s, the Reynolds number is 1.3×10^4, which is moderately turbulent and an appropriate regime for the Manning equation.

The equations below show the Manning equation from 1885 (Kilgore and Cotton 2005; USDA 2007) and hydraulic radius definition:

$$Q = \frac{\alpha}{n} R^{2/3} S^{1/2} A$$

$$R = \frac{A}{P}$$

where

Q = discharge or flow rate (ft^3/s or m^3/s)
α = unit conversion constant depending (1.486 for ft & s, or 1.000 for m & s).
R = hydraulic radius (ft or m)
S = slope of water surface (ft/ft or m/m)
n = Manning's roughness coefficient ($s/ft^{1/3}$ or $s/m^{1/3}$). See note below!
A = water cross section across the river (ft^2 or m^2)
P = perimeter of the river bed (wetted perimeter; it does not include stream top) (ft or m)

Side note for non-hydrologists: Typically the roughness factor for fluid flow in a pipe is dimensionless (e.g. Fanning friction factor, Darcy-Weisbach friction factor). But for historical reasons, Manning's "n" is given units of time/length$^{1/3}$. Normally, this would imply that the value of "n" would depend on what units were being used. However, to avoid changing "n", the convention is to change the leading coefficient in Manning's equation (α) instead, even though it is declared to be dimensionless. An easier approach would be to declare the unit conversion coefficient (α) to be 1 $m^{1/3}/s$ and declare "n" to be dimensionless. Then it would be normal for "n" to be the same regardless of units, and it would be obvious that α would be 1.486 $ft^{1/3}/s$ if English units were used (because there are 3.2808 ft/m and the cube root of 3.2808 is 1.486). But that is not the convention. The key point to all this is that the value used for "n" is the same, regardless of what units are used for Manning's equation, but the unit conversion coefficient value must be selected to match the units being used.

Replacing R by A/P gives:

$$Q = \frac{\alpha A^{5/3} S^{1/2}}{n P^{2/3}}$$

The slope can be measured fairly well using the SRFT and WL1 waterlines, and the square root dependence will reduce the effect of errors by two. The area and perimeter can be measured accurately via string and ruler, or lidar, or photogrammetry. The greatest uncertainty will likely be in Manning's roughness coefficient.

Kilgore and Cotton summarize the many salient features of Manning's equation and the roughness coefficient "n". In particular, they note in Section 6.1:

> Manning's roughness is a key parameter needed for determining the relationships between depth, velocity, and slope in a channel. However, for gravel and riprap linings, roughness has been shown to be a function of a variety of factors including flow depth, D_{50}, D_{84}, and friction slope, S_f. A partial list of roughness relationships includes Blodgett (1986a), Limerinos (1970), Anderson, et al. (1970), USACE (1994), Bathurst (1985), and Jarrett (1984). For the conditions encountered in roadside and other small channels, the relationships of Blodgett and Bathurst are adopted for this manual.
>
> Blodgett (1986a) proposed a relationship for Manning's roughness coefficient, n, that is a function of the flow depth and the relative flow depth (d_a/D_{50}) as follows:
>
> $$n = \frac{\alpha d_a^{1/6}}{2.25 + 5.23\log(\frac{d_a}{D_{50}})}$$
>
> where,
>
> n = Manning's roughness coefficient, dimensionless
> d_a = average flow depth in the channel, m (ft)
> D_{50} = median riprap/gravel size, m (ft)
> α = unit conversion constant, 0.319 (SI) and 0.262 (CU) [not the same α as in Manning's eq.]
>
> Equation 6.1 is applicable for the range of conditions where $1.5 \le d_a/D_{50} \le 185$. For small channel applications, relative flow depth should not exceed the upper end of this range.

The size of the river bed bumps, D_{50}, can be obtained from field notes, photos, or photogrammetry, and a typical Snowy River depth is 0.2 m. Table 3 shows the variation in Manning's roughness coefficient for typical Snowy River conditions in a smooth portion of the river. The table shows that if the river bed bumps are characterized, the uncertainty in the discharge inference might be as low as 30%.

Table 3. Manning's "n" for various water depth and Snowy River bed bump diameters, no vegetation.

	d_a (m)			
D_{50} (m)	**0.1**	**0.2**	**0.3**	**0.4**
0.02	0.0368	0.0326	0.0311	0.0302
0.04	0.0502	0.0413	0.0382	0.0366
0.06	0.0637	0.0489	0.0442	0.0417
0.08		0.0563	0.0497	0.0464
0.1		0.0638	0.0550	0.0507
0.12		0.0715	0.0603	0.0549

For the case of the logger at SRS80 (the falls at Crystal Creek), the Manning equation is not appropriate. The discharge over a waterfall can be expressed in the form of a broad-crested weir equation (Dust 2012):

$$Q = C^* g^{1/2} h^{3/2} W$$

where

C^* is a dimensionless discharge coefficient, (approximately 0.2 to 0.5, dependent on upstream conditions),
g is gravitational acceleration (32.2 ft/s^2 or 9.81 m/s^2),
h is the upstream flow depth above the step crest (ft or m), and
W is the channel width (ft or m).

Perhaps the uncertainty in C* can be reduced by further literature search.

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