USING DISCHARGE AND PRECIPITATION TO ESTIMATE RUNOFF COFFICIENTS ON TITAN. J. P. Kay and G. C. Collins, Wheaton College, Physics & Astronomy Dept. (26 East Main St., Norton, MA 02766, USA) kay_jonathan@wheatonma.edu.

Introduction: Branching valley networks have been observed on Saturn's moon Titan, primarily near the Huygens landing site [1] as well as near the south pole [2-4]. These valley networks were likely formed by fluvial erosion in the form of liquid methane eroding the surface. We develop a model that links minimum surface discharge and expected surface precipitation to attempt to bracket the runoff coefficient on the surface of Titan.

A common way to relate peak discharge in a stream basin to rainfall intensity is

$$Q_p = ciA \quad (1)$$

where Q_p is the peak discharge, i is the rainfall intensity, and A is the basin area. The scaling coefficient c is non-dimensional and accounts for infiltration and evaporation of the precipitated liquid. The coefficient c varies between locations with different drainage areas, topography, and substrates, and is usually in the range of 0.1 to 0.9 on the Earth. In their study of stream discharge on Titan, Perron *et al.* [4] assumed c = 1 for simplicity and used estimates of Q_p and A to get i. Without a good way to estimate c on Titan, we would like to attempt to bracket its possible values by using independent measures of i, Q_p and A.

The only location on Titan with good current "ground truth" available is the Huygens landing site. The basin drainage area for the Huygens site is about 800,000 m^2 [5]. With this value in hand for A, we now pursue values of Q_p and i.

Rainfall Modeling: Ground based observations have shown that the Titan atmosphere produces variable, probably convective, large clouds [6-7]. These clouds are observed mostly at the mid-latitudes and over the south pole. Given the short lifetime of the observed clouds (1-8 hours) it is believed that large amounts of liquid methane are raining out onto the surface during intense storm events.

Several models have been created to explain cloud formation on Titan. *Hueso & Sánchez-Lavega* [8] created a model that incorporated aerosol particles as cloud condensation nuclei. These aerosol particles allowed their models to form the mid-latitude clouds that we have noticed from the ground. The clouds formed in the middle troposphere under 90% relative humidity. Their models suggest it is possible to condense a lot of precipitable droplets (12 - 190 kg/m^2) in a brief period of time, 3.5 hours. Typically the storms dissipated in 5-8 hours, and were similar to microbursts on the Earth. This model could overestimate the rainfall rate due to their assumption of 100% efficiency of rain drop formation, forming drops up to 5 mm.

Barth & Rafkin [9] have adjusted a model that incorporates the Regional Atmospheric Modeling System (which combines several terrestrial weather codes) for use on Titan and cloud formation composed of methane and ethane. The *Barth & Rafkin* model tests the perfect drop formation efficiency and finds similar accumulation numbers to the *Hueso & Sánchez-Lavega* model, but it also tests lower efficiencies and finds smaller accumulations. The amount of accumulated material is also a function of the relative humidity: the higher the humidity the higher the accumulated rainfall. The range of rainfall accumulation that they were able to find depended on the humidity percentage, but for a 60% relative humidity they were able to generate between 80 and 130 kg/m^2 of ground accumulation over the course of five hours.

The two models that were discussed show an accumulation rate consistent with storms that produce flash floods on the Earth. These are short duration storms that rain out a lot of material. Using the amount of condensed material from the cloud models it is possible to estimate a rainfall rate. We have used the following expression to estimate the rainfall rates based on the expected total accumulation,

$$i = \frac{V_t m_s}{\rho h} \quad (2)$$

where i is the effective rainfall in cm/h, V_t is the terminal velocity of a particle on Titan (5.76 km/h) [10], m_s is the amount of precipitating material per square meter in the air column, h is the height of the column, and ρ is the density of liquid methane, 450 kg/m^3.

Using this step we were able to determine a rainfall rate between 1.1 - 9.0 cm/h. It is possible that the rainfall was not uniform and at some point in the storm the rate is higher than 9.0 cm/h, but we are interested in the steady-state peak discharge after the storm has gotten going and the stream is filled with fluid.

The results from these two models have shown that during storms on Titan a significant amount of rainfall can accumulate. This rainfall will lead to discharge of liquid methane through stream channels, mobilization of sediment, and erosion of the surface. Such clouds have not been detected over the Huygens landing site to date, so we cannot be sure that such storms happen there, but we have a small base of knowledge right now for the full range of Titan weather throughout the seasonal cycle.

Discharge Modeling: After estimating likely rainfall rates, it is necessary to find an independent method of estimating the minimum discharge to move particles with diameter 50-150 mm. We chose these particle sizes because they were observed as the large particles around the Huygens landing site [1].

The flow velocities neecessary to transport sediment on Titan was studied by *Burr et al.* [11]. To examine the shear velocity u_* needed to transport the large sediments at the Huygens landing site, we rewrite the Shields criterion as

$$u_* = \sqrt{\frac{(\sigma - \rho)gd\theta}{\rho}} \quad (3)$$

where ρ is the density of the liquid, g is the gravitational constant for Titan, d is the particle diameter, and θ is the critical Shields value. For the particle sizes we are interested in examining, the Shields curve displays a constant value of 0.05. We find the shear velocity u_* must lie in the range of 0.064 - 0.11 m/s to transport the sediment observed at the Huygens site.

If we multiply the values that we find for u_* by values for different widths of streams we are finding a minimum flow discharge that can move sediment in our range on Titan.

$$Q_P = \frac{wu_*^3 (8/f_c)^{\frac{1}{2}}}{gS} \quad (4)$$

Where w is stream width, f_c is the Darcy-Weisbach friction factor which we used a value of 0.05, which is consistent with the observed Huygens landing site particle sizes, g is the gravitational constant for Titan, and s is the slope of the channel which we used 0.05.

Values of minimum peak discharge Q_p to move the required sediments are listed in Table 1, and range from 0.628 m^3/s for small grains in narrow channels to 16.682 m^3/s for large grains in wide channels. The choice of the channel width is unfortunately not well constrained. *Perron et al.* [5] acalculated that in a drainage area of 0.8 km^2 you need discharge values as high as 3.3 m^3/s to move the sediments of similar sizes.

We have now found estimates for all of the missing expressions from our original rainfall-discharge relation in equation (1).

Bracketing *c*: For the highest intensity rain from the cloud models ~9.0 cm/h we find low values of c in the range of $0.031 < c < 0.645$. For the lower intensity rain from the models ~1.18 cm/h we find that c spans values in the range of $0.239 < c < 1$, more closely matching the range of typical terrestrial values. For some examples of c values for different materials see table 2.

These results could be telling us one or more of the following: (a) soil at the Huygens landing site is well packed or saturated and does not typically experience intense rainfall at the upper end of events possible on Titan, (b) even larger sediments are dumped on the surface upstream of the Huygens landing site, and the discharge from the valleys becomes very widely distributed at the mouth of the valley, or (c) during rainstorms stream channels in small watersheds are filled to a width beyond the upper limit of 30 m assumed here. Further work is needed to sharpen the ranges of the rainfall and discharge parameters, and more data and data analysis from more areas is necessary to go beyond modeling the Huygens landing site.

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	Channel Width (m)			
Q_p(d)	5	10	20	30
Q_p(0.05)	0.628	1.257	1.885	3.770
Q_p(0.075)	0.991	1.983	2.974	5.948
Q_p(0.1)	1.523	3.046	4.568	9.137
Q_p(0.125)	2.152	4.304	6.457	12.913
Q_p(0.15)	2.780	5.561	8.341	16.682

Table 1- Minimum discharge values needed to move different size sediments in different stream withs.

Material [12]	**c-range**
Dry sandy soil	0.05-0.10
Unconsolidated gravel	0.75

Table 2- Some terrestrial examples of c values