A METHOD FOR THE CONSISTENT AND UNIFORM EVALUATION OF STORMWATER BMPs

Authored by: Thomas R. Adams, P.E.
Robert A. Strong Jr.
Vortechnics, Inc.
www.vortechnics.com

1. ABSTRACT

This paper introduces a method for evaluating stormwater quality inlets while supporting the rationale that rainfall intensity is the governing factor affecting runoff quality. A system manufactured by Vortechnics is used as an example of a stormwater water quality inlet sized in accordance with rainfall intensity.

2. RUNOFF QUALITY

As a design parameter, the first-flush concept has been the most practiced, and most questioned, criterion used by engineers. Quantifying runoff remains a daunting challenge due to the extreme variability in rainfall events, pollutant loading, and surface conditions among other factors. Advocates of using the first flush concept as a design parameter have typically attempted to quantify it as the first 0.5 inch (13mm) or inch (25mm) or other depth of precipitation. Others have preferred to quantify it as depth of runoff as opposed to precipitation.

The following discussion will show that rainfall intensity, not depth, may be the most appropriate design parameter for evaluating runoff quality. Although the first-flush concept holds some legitimacy, many studies have shown that "concentration profiles for particle-associated pollutants often display a discharge pattern more complex than a simple 'first-flush'" (University of Texas, 1993). Studies by Hoffman et al. (1985) revealed that runoff concentrations for hydrocarbons, lead, and suspended solids "generally followed the trend of rainfall intensity." Harrison and Wilson (1985) confirmed these findings by reporting that "the temporal variation of concentrations of particle associated pollutants was more complex (than a first-flush) and related to rainfall intensity and the flushing of sediment through drainage systems."

A particulate washoff model presented by Sartor and Boyd (1972) utilizes rainfall intensity to predict sediment washoff from impervious surfaces. The model is given by:

$$N = N_o (1-e^{-krt}) \qquad (2.1)$$

where,

N = street sediment washoff (gm/curb-m)
N_o= initial street sediment load, prior to the rain event (gm/curb-m)
e = exponential constant (2.718)
k = proportionality constant (/mm)
r = rain intensity (mm/hr)
t = rain duration (hr)

The proportionality constant, k, is a subjective variable chosen by the model user. For the model to produce reliable results, the proportionality constant should be calibrated at the intended site. Sartor and Boyd maintain that the proportionality constant is only slightly dependent on street texture and condition and independent of rain intensity and particle size. Their recommended k-value of 0.18/mm is intended to produce 90 percent washoff of the sediment load from the street surface in 1 hour during a 13 mm/hr rainfall event. Many analysts have criticized their value for k claiming that it exaggerates washoff quantities. Vladimir Novotny has proposed much smaller values for k, specifically 0.026/mm for fine particles (<45 micron) and 0.01/mm for medium sized particles (100 to 250 micron). Studies by Jewell et al. (1980) and Alley (1981) also found considerable variation for k values and both recommend local calibration (Pitt, 1987).

While the model incorporates both rainfall intensity and duration into its estimation, it doesn't directly relate buildup and washoff of sediments to rainfall intensity. To exclusively account for the effect of rainfall intensity on washoff quantities, Novotny & Chesters (1981) developed the so-called availability factor (A). The purpose of the factor is to isolate the quantity of sediments available for washoff given the relative energy of rainfall. The availability factor is given by:

$$A = 0.057 + 0.04\,(r)^{1.1} \qquad (2.2)$$

where,

r = rainfall intensity (mm/hr)

The product of the availability factor and the initial sediment loading amount (N_O) yields the total available sediment load susceptible to washoff at a given rainfall intensity. The Sartor & Boyd model can then be shown by:

$$N = AN_o\,(1-e^{-krt}) \qquad (2.3)$$

For all intensities greater than or equal to 18 mm/hr , the availability factor is equal to 1.0 (hence, all sediments are available to washoff). Popular runoff models STORM and SWMM both utilize the factor for calculating the available sediment loads (Pitt, 1987).

3. ANALYSIS

The following analysis was developed so that direct comparisons can be made between stormwater quality BMPs. Modeling two or more stormwater quality BMPs under similar runoff conditions and comparing their performance will allow engineers to make appropriate decisions with respect to a site's stormwater treatment needs. Requirements for the analysis include a description of a rainfall event, a classification of surface constituents, a locally calibrated or assumed value of k, and performance data for a specific BMP.

3.1 SELECTING A RAINFALL EVENT

The first step to applying the Sartor & Boyd model is to describe a rainfall event in terms of intensity and duration (i.e. draw a hyetograph). Using a regional design storm (i.e. SCS Storm) for the site being modeled would be one alternative; using an actual storm that typifies the desired parameters is another alternative and the approach adopted for this discussion. Storms that maintain 6-month storm intensities or greater are recommended because they represent a threshold upon which sediment transport becomes significant. This analysis will use an actual rainfall event that occurred on January 20, 1995 in Southeast Cumberland County, Maine. This storm was a 6-month storm in terms of peak intensities (see Fig. 3.1).

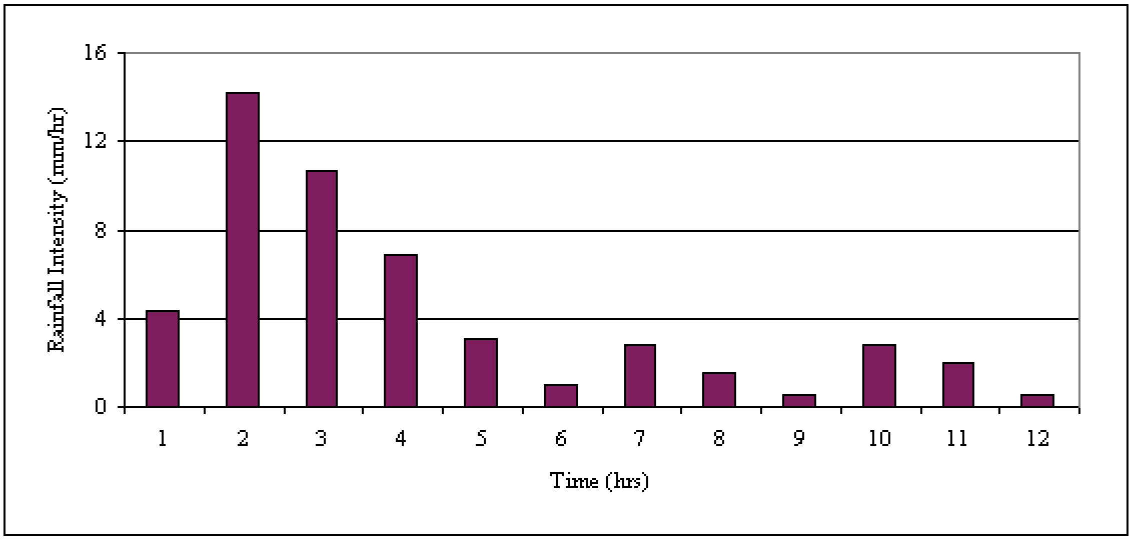

Figure 3.1 Rainfall Hyetograph For A January 20, 1995 Event In Southeast Cumberland County, Maine

3.2 SURFACE CONSTITUENTS

To evaluate how a BMP would perform at a certain site, the surface constituents must be described in both quantitative and qualitative terms. The Sartor & Boyd model requires the sediment load (N_O) be quantified in terms of mass per linear measure. Since this analysis will focus only on the percentage of sediment mobilized, the selection of N_O (e.g. initial sediment load) is inconsequential. The composition or quality of the initial sediment load must be described, preferably in the form of a particle gradation curve. Countless particle size distributions have been conducted on sediments from roadways, parking lots and other areas subjected to vehicular traffic and stormwater runoff. Physical properties of sediment unquestionably vary from site to site. For accurate results, a particle gradation curve should be performed at the site being modeled. For qualifying the sediment load in this analysis, we will use a particle gradation curve produced by Pitt (1979) for the San Francisco Bay area (Fig. 3.2).

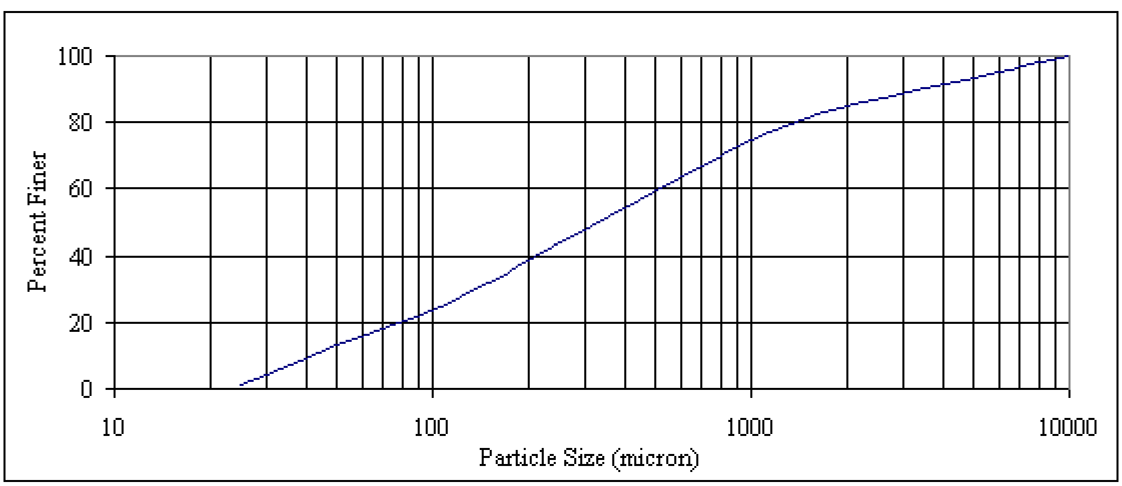

Figure 3.2 Particle Size Distribution of Street Refuse Before Sweeping (Pitt, 1979)

3.3 SEDIMENT TRANSPORT

Sediment transport certainly varies widely. Figure 3.3 displays two curves showing the cumulative percentage of sediment washed from the surface by the storm shown in Fig. 3.1 (See data in Appendix A). One curve was produced using Novotny's proportionality constant, 0.026/mm for fine particles. The other curve was created using the average of Sartor & Boyd's value (0.18/mm) and Novotny's value (0.026/mm), that is 0.103/mm. Both transport curves were formed by applying rainfall intensities (from Fig. 3.1) to the Sartor & Boyd model for the entire 11.5 hours of the storm. The availability factor was incorporated at each 1-hour interval so that only the solids fraction susceptible to washoff was considered.

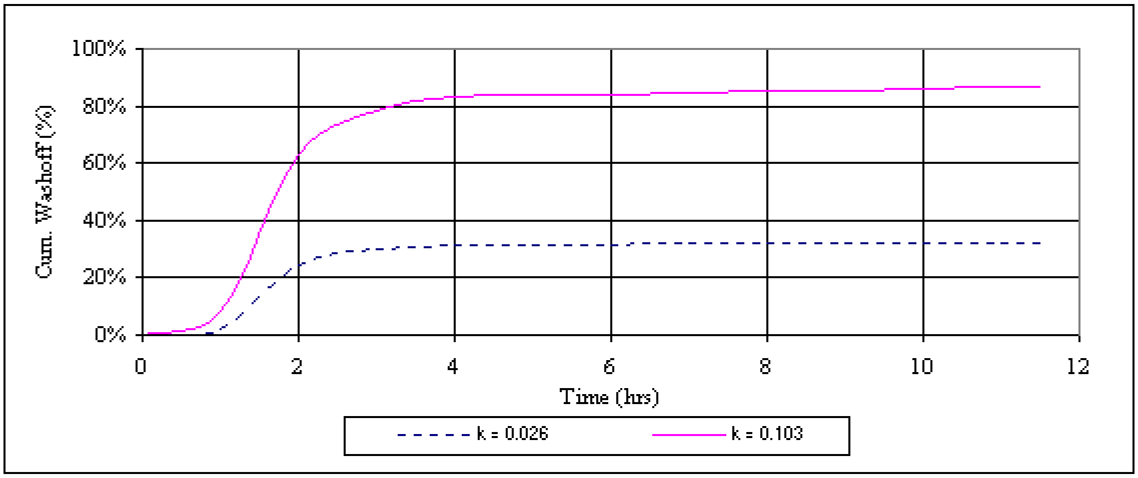

Figure 3.3 Sediment Washoff for A 6-Month Storm in Southeast Cumberland County, Maine

The variation in the two curves demonstrates how influential the proportionality constant is to the model. Observing the curve formed when k is equal to 0.026/mm, one can see that the storm washed off a total of 33.3% of the available sediment from the surface. The model indicates that intensities were not significant enough to washoff the remaining 66.6%. When k was set equal to 0.103/mm, the model predicted 87% washoff of available sediments.

3.4 EVALUATING A BMP

The final phase of the analysis is to select a BMP and establish removal efficiencies for uniform particle sizes for a range of flow rates. The Vortechs™ Stormwater Treatment System will be used to demonstrate the application of this analysis. The Vortechs System (see Fig. 3.4), designed and manufactured by Vortechnics, Inc., provides physical treatment for stormwater runoff. Attributes of the system include a unique swirl concentrator, which promotes particle settling, accompanied by a surge control feature to contain floatables and maintain quiescent flow conditions.

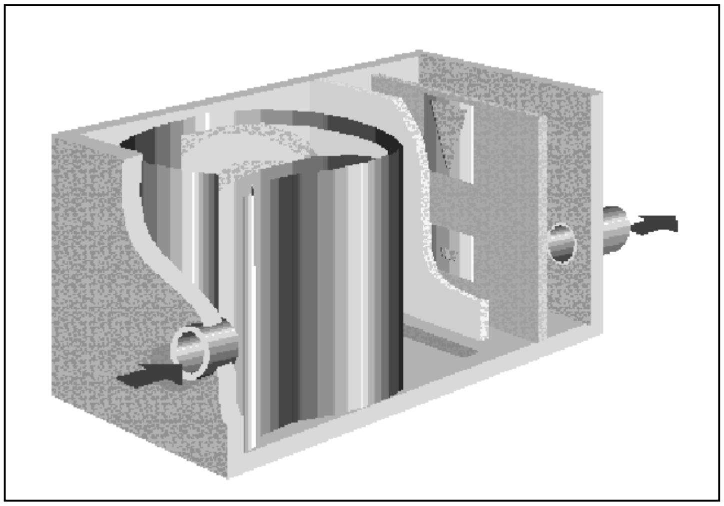

Fig. 3. 4 Vortechs™ Stormwater Treatment System - Cutaway View

A testing program initiated in June 1996 has enabled Vortechnics to document removal efficiencies for uniform particle sizes at varying operating rates. Operating rate for the Vortechs System is flow per unit of swirl concentrator surface area. Almost any BMP operating rate can be represented in similar fashion. Figure 3.5 shows performance data for the Vortechs System.

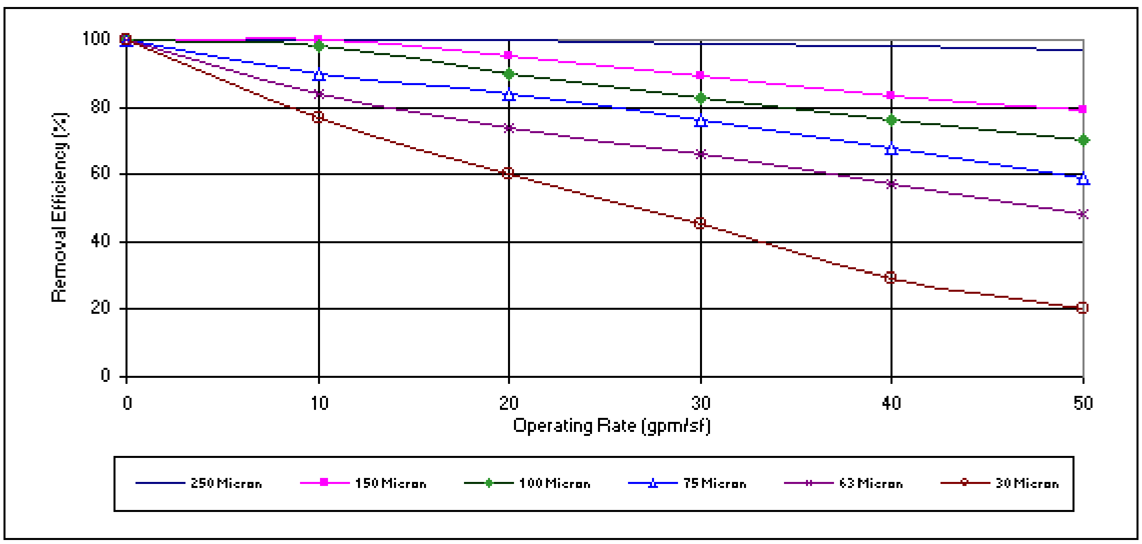

Figure 3.5 Uniform Particle Removal Efficiency for Vortechs™ System

To determine the level of performance the system will achieve given the nature of street sediment and rainfall, it is presumed that finer sediments are mobilized before larger sediments during a rainfall event. The supposition is that a particle with less mass requires less force to be mobilized than a larger particle. The incremental intensity growth typical of most rainfall events suggests that finer sediments are mobilized during the early stages of an event and larger sediments are mobilized during the subsequent, more intense stages.

To establish the flow rate at which the Vortechs System was performing during each interval, it's necessary to correlate rainfall intensity to flow rate and operating rate. If this was an actual site and the acreage and land description was provided, it might be appropriate to use the Rational Method (if less than 100 acres) to determine the flow rate to the system. The flow rate could then be correlated to the system's operating rate. Vortechnics' sizing criteria state that a 2-month storm (approximate intensity

= 12 mm/hr, for SE Cumberland County, Maine) should operate a Vortechs System at *no greater than* 24 gpm per sq. ft. (16 lps/sqm). It follows that if a 12 mm/hr rainfall intensity operates the system at 24 gpm/sq. ft., then a 1 mm/hr rainfall intensity will operate it at no greater than 2 gpm/sq. ft and a 2 mm/hr rainfall at 4 gpm/sq. ft. and so on. (A complete description of Vortechs System sizing criteria is available from Vortechnics Technical Bulletin No. 3).

3.5 PREDICTING BMP PERFORMANCE

Evaluating the performance of the Vortechs System will entail using Figures 3.2, 3.3 and 3.5 in combination. This evaluation will use the curve based on Novotny's k-value of 0.026/mm. From the curve in Figure 3.3, observe that approximately 3% of the total available sediment had washed from the surface after one-hour of rainfall. On the premise that finer particles are mobilized first, that 3% is presumed to represent the finest fraction of the initial sediment load. Therefore from Fig. 3.2, about 3% of the sediment load consists of particles about 30-microns or smaller and this is the portion that the model predicts will be mobilized in that first hour. The average intensity during that interval was 4 mm/hr and the operating rate was 8 gpm/sq. ft. From Figure 3.5 we see that the Vortechs System removes 80% of the 30-micron sized particles at 8 gpm/sq. ft. Therefore, at the 1-hour mark, the system was operating at 80% efficiency.

Similarly, at the 2-hour mark, which represented the peak of the storm, 25% of the total available sediment had washed off the surface according to Fig. 3.3. Fig. 3.2 indicates 25% percent of all particles are finer than 100-micron and since the 30-micron and smaller fraction had already been washed from the surface it can be concluded that particles transported in the second hour were in the range of 30 to 100-micron. The average intensity during that interval was 14 mm/hr and the operating rate was approximately 28 gpm per sf. From Figure 3.5 we see that the Vortechs System removes 82% of the 100-micron particles at 28 gpm per sf. Any particles that might remain after the second hour would removed at relatively higher efficiencies by virtue of their larger size and reduced operating rate of the system.

In view of estimates being on the high end of the range (i.e. using the maximum particle size), results will be increasingly accurate with smaller intervals (i.e. 5 to 15 min). Figure 3.6 shows how the Vortechs System performed in the 6-month event evaluating conditions every hour.

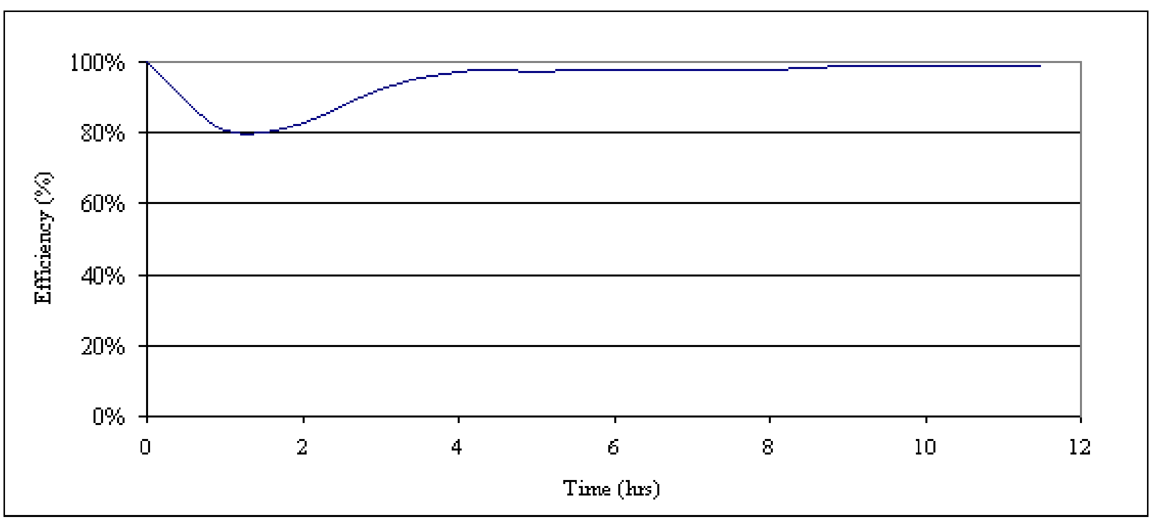

Figure 3.6 Vortechs^{TM} System TSS Removal on January 20, 1995

4. CONCLUSION

With a growing number of so-called BMPs and manufactured products emerging for stormwater quality management, there exists an ever-greater need for a common basis of comparison of the various alternatives.

The approach described in this paper provides such a basis. The key element needed to implement this approach or anything similar to it would be the development of a set of curves such as those shown in Figure 3.5. The units of operating rate may differ. For example, the units might be gpm per sf. (as applied to the Vortechs Systems), detention time, or flow-through velocity. Another key factor is that rainfall intensity must be correlated to operating rate (such as by proportion as in this presentation).

When the time comes that BMPs and stormwater management facilities are provided with a set of completely descriptive curves, such as those described above, comparing them will become a very simple matter. Comparing the curves for one BMP with the curves for another will be straightforward. Some BMPs may exhibit a tendency to exhibit efficiencies that approach zero or even drop below zero at higher rainfall intensities and operating rates. Conventional oil/grit separators (OGSs) are widely suspected of this tendency, but the evidence, to date, that they do has been largely anecdotal and/or inferential. Furthermore, once a set of curves for each BMP is developed, a single curve for each one will be able to be developed, by applying the same model that was presented here in developing Figure 3.6.

The authors believe that this model will make a very significant contribution to the field of stormwater quality management. Currently, that field is notoriously lacking in any standards, design parameters or criteria that should be met and even more lacking in consistent ways to evaluate the measures that are supposed to meet what standards do exist. This model is intended to make evaluations of both conventional and innovative measures much more uniform and consistent. To the extent that it succeeds in doing so, it will further the cause of developing stormwater quality standards and design parameters that are achievable.

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Acronyms:

BMP: Best Management Practice
CFS: Cubic Feet per Second
GPM: Gallons Per Minute
LPM: Litres Per Minute
LPS: Litres Per Second
TSS: Total Suspended Solids

APPENDIX A

Sartor & Boyd Washoff Model: Storm Event - January 20, 1995

	Initial Sediment Load (N_o):	100	(grams per curb-mile)				
Rain Intensity	**Duration**	**A-Factor**	**AN_o**	**N (gm/curb-mi)**		**Cum. % Transported**	
(mm/hr)	**(hr)**			**k = 0.026**	**k = 0.103**	**k = 0.026**	**k = 0.103**
0.0	1.00	0.06	0.0	100.0	100.0	0.0%	0.0%
4.0	1.00	0.24	24.1	97.6	91.9	2.4%	8.1%
14.0	1.00	0.79	72.2	75.6	36.7	24.4%	63.3%
11.0	1.00	0.62	22.6	70.0	21.4	30.0%	78.6%
7.0	1.00	0.40	8.5	68.5	17.0	31.5%	83.0%
3.0	1.00	0.19	3.3	68.3	16.2	31.7%	83.8%
1.0	1.00	0.10	1.6	68.3	16.0	31.7%	84.0%
3.0	1.00	0.19	3.1	68.0	15.2	32.0%	84.8%
2.0	1.00	0.14	2.2	67.9	14.8	32.1%	85.2%
1.0	1.00	0.10	1.4	67.9	14.6	32.1%	85.4%
3.0	1.00	0.19	2.8	67.7	13.9	32.3%	86.1%
2.0	1.00	0.14	2.0	67.6	13.5	32.4%	86.5%
1.0	1.00	0.10	1.3	67.5	13.4	32.5%	86.6%