RUNOFF CURVE NUMBER METHOD: BEYOND THE HANDBOOK

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Abstract: The behavior of rainfall-runoff systems in terms of the Curve Number method is described, including findings that have become apparent and/or appreciated since the original development in the mid-1950s; not all of which are shown in current versions of the primary reference, NEH-4. These include the following: different modes of application of the method; basic general patterns of rainfall-runoff at variance with the CN equation; sensitivity information; the basic intractability of the method with infiltration-based systems; limitations in the role of prior rainfall; difficulties in the hydrologic descriptions of soils; CN variation with season and land use; and wide spread application to continuous models as a soil moisture budgeting device.

INTRODUCTION

The Natural Resources Conservation Service (NRCS) and the Agricultural Research Service (ARS), both agencies of the U.S. Department of Agriculture formed a joint work group in 1990 to assess the state of the Curve Number method and to chart it's future development. The need for the work group resulted from questions and concerns about the method, its unique role in applied hydrology, and how it was being used and the recognition of the need to provide guidance for reanalysis and clarification of the procedure (Woodward 1991). A number of goals and objectives were developed including: reevaluating the procedure, improving the documentation, updating the primary reference document (NEH-4), developing a data base, standardizing the procedure for developing curve numbers from data, etc.

It became apparent that much of the difficulty surrounding the procedure was attributable to the presentation in the National Engineering Handbook (NEH-4). Thus an early task was to rewrite those portions of the NEH-4 pertaining to the procedure. Problems identified ranged from incorrect and misleading statements to incomplete documentation. For example it was incorrectly stated that S includes I_a, whereas it can be easily shown mathematically that S does not include I_a. Fortunately this is only significant for continuous simulation. Another example was Table 4-1 that related 5-day antecedent rainfall to antecedent moisture condition (AMC) for a local situation. This was not intended to have nationwide application, though it was widely treated as such. Several "Folklore" beliefs concerning Curve Numbers could also be attributed to problems with documentation. An example of such is that the Curve Number Runoff Equation is an infiltration equation.

In rewriting the Curve Number portions of NEH-4, the work group agreed that they must agree with concepts expressed, references will be included and the result must be technically defensible. The results of the updating include such items as:

1) Reference to Antecedent Moisture Condition (AMC) was removed and the terminology changed to Antecedent Runoff Condition (ARC). Variability of the curve numbers and event runoff is incorporated by considering the curve number as a random variable and the ARC-I and ARC-III conditions as bounds on the distribution.
2) Reiteration of desirability of locally determined curve numbers was made. Although this was part of the original documentation in NEH-4, local calibration has been seldom pursued.
3) Explicit expression of Curve Number runoff equation was made as a transformation of rainfall frequency distribution to runoff frequency distribution. This too was demonstrated in the original documentation.
4) Expression of ARC-I and ARC-III as measures of dispersion about the central tendency (ARC II). This is a corollary of treating the CN as a random variable.
5) Mathematical proof and demonstration that S does not include I_a.
6) The chapters are posted on the World Wide Web as approved. http://www.wcc.nrcs.usda.gov/water/quality/wst.html

As the work progressed several other areas of need became evident. These were 1) to reconsider the hydrologic soils classifications recognizing the vastly expanded database available today and the capabilities of modern computers, 2) to reevaluate the use of $I_a = 0.2S$, and 3) to reconsider the tables of curve numbers in terms of the expanded rainfall-runoff database available (Agricultural Research Service 1995). There was also considerable concern about the possibility of regional and seasonal variation of curve numbers (Hjelmfelt et al 2001).

ORDERED PAIRS AND ASYMPTOTES

One of the goals of the work group was to standardize the procedure for calculating a curve number for a watershed from rainfall-runoff data. The accepted handbook method was to plot the annual series of rainfall-runoff on a scatter diagram and select the curve number that best fit the data. This method doesn't make use of the many storms that were not the largest annual events.

The runoff curve number equation is often used to transform a rainfall frequency distribution into a runoff frequency distribution. That is, for example, the 100-year rainfall is used to determine the 100-year runoff, etc. This practice, called frequency matching leads to the idea of ordered pairs (Hjelmfelt 1980). Hawkins (1993) followed this idea by sorting the rainfall and runoff depths separately and re-aligning them on a rank order basis creating new sets of rainfall-runoff pairs. These might be thought of as having equal return periods with the individual runoffs not necessarily associated with the original causative rainfall.

Using all the storms in the data set, Hawkins then calculated the curve number for each of the ordered pairs and plotted them against rainfall. Curve number was found to vary with storm depth, but - for most cases – approaches a constant value at higher rainfalls. The curves that result from these plots were then fitted with asymptotic equations to approach this constant CN. The limiting CN that is approached as rainfall approaches infinity is taken as the best fit curve number for the watershed. The procedure is best illustrated by the figures in the following section.

This method of determining a watershed curve number has the advantage of being mathematical and therefore programmable. The results are mostly influenced by the largest events, which is in keeping with the usual intended applications, but all of the data is used. Additionally, the decrease in scatter results in illustrative graphics which are descriptive of the watershed behavior and therefore a valuable tool for analysis. This method appears to give results consistent with the present procedures and CN tables in NEH-4. The curve number work group has adopted this procedure to determine curve numbers from local data in the future.

BEHAVIOR OF RAINFALL-RUNOFF SYSTEMS

The plots described above show several types of CN "behavior". These have been defined by Hawkins (1993) as Complacent, Standard and Violent. The Standard behavior fits the curve number model best; the Violent less so, and the Complacent not at all.

Standard behavior is the most common scenario. The observed CN declines with increasing storm size and then approaches a near constant value with increasingly larger storms. An example of this behavior is shown in Figure 1. About 70% of all watersheds evaluated showed this pattern (Hawkins, 1993). The process of computing CN for small events biases the CN toward high values. This is because CN can be computed only if direct runoff occurs. If the event CN is low, and the event initial abstraction (I_a) is high, no runoff occurs and CN cannot be computed. Only high CNs can be detected with low rainfalls. The plot of CN vs. rainfall displays this bias and the storm magnitude at which the bias becomes insignificant.

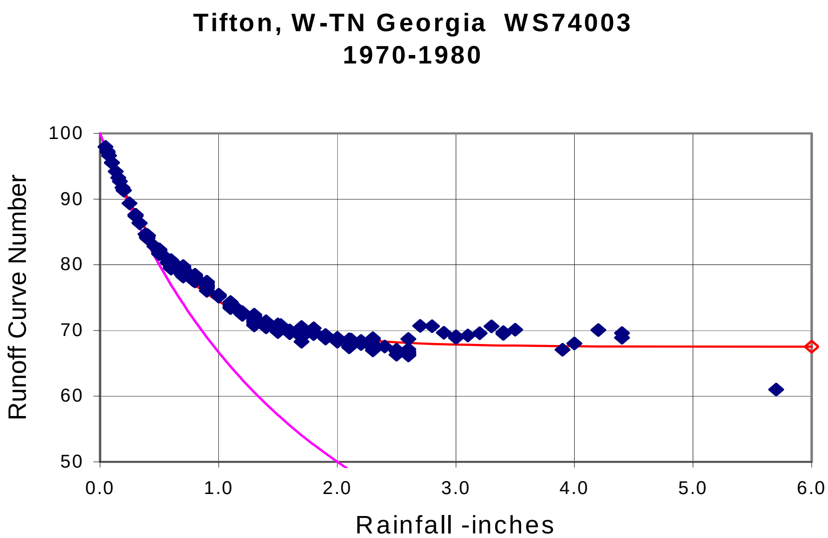

Figure 1. Standard behavior. The asymptotic CN for this example is about 68.

Complacent behavior is defined when the observed CN declines with increasing rainfall and there is no appreciable tendency to achieve a stable value. Curve numbers cannot be safely determined from data that exhibit this pattern. The behavior indicates a partial source area situation where the source area fraction may be quite small. An example of this behavior is shown in Figure 2. There is no easy way of telling if and at what rainfall that the source area or the curve number may change or violent behavior may occur.

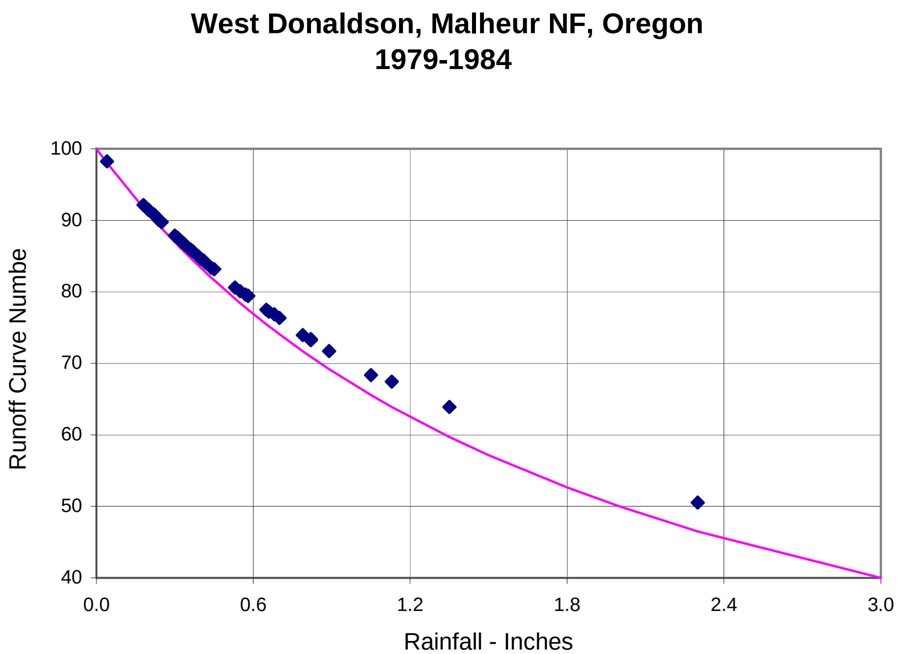

Figure 2. Complacent Behavior**.** No constant CN is determined for this data.

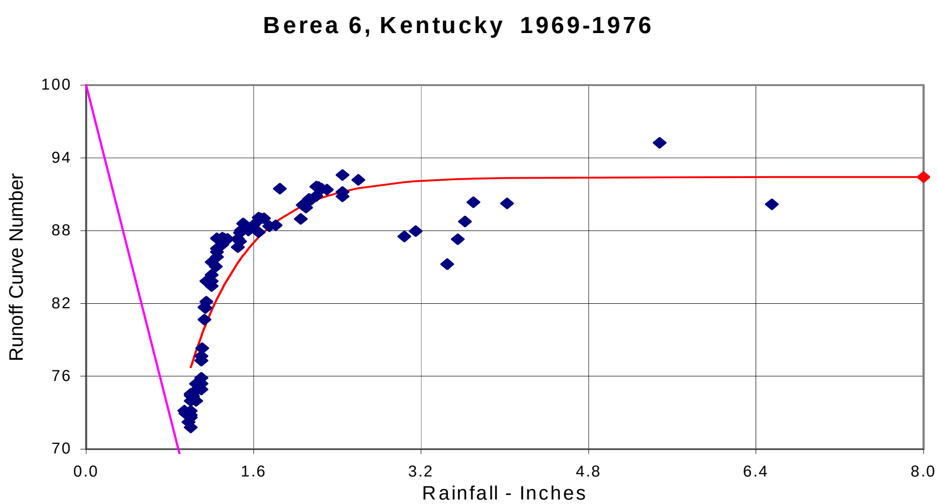

Figure 3. Violent Behavior. The asymptotic CN for this example is about 93**.**

Violent behavior is seen where the observed CN rises suddenly and asymptotically approaches an apparent constant value. This is often accompanied by complacent behavior at lower rainfalls. From a source process standpoint, this could be a threshold process at some critical rainfall depth value. At rainfall above the threshold a high fraction of the rainfall becomes runoff. An example of Violent behavior is shown in Figure 3**.** For this example the threshold rainfall is about 0.80 inches**.**

MODES OF APPLICATION OF THE CN METHOD

The work group recognized three distinctly different modes of application for curve numbers: 1) Determination of runoff volume of a given return period, given total event rainfall for that return period. 2) Determine the direct runoff for individual events. This acknowledges the variation between events and is the basis for the development. 3) Process models, an inferred application as an infiltration model, or a soil moisture-CN relationship, or as a source area distribution.

The first application, already discussed**,** is the most widely used in engineering and uses the curve number to transform the rainfall frequency distribution into a runoff frequency distribution. It was the reason for the development of the model. The runoff volume that is computed is often overlooked and the peak discharge, which is more frequently the desired value, calculated with a unit hydrograph model and used directly.

The second application, runoff from individual rainfall events, is the basis for the original development, the P vs. Q plots which led to the curve number concept. There is a wide variation of runoff from rainfalls of the same magnitude which forces us to acknowledge that CN varies between storms for a side range of reasons. The original handbook – developed in large part for conditions in the humid east, south, and mid-west - designated "Antecedent Moisture Condition" or AMC as the most significant variable in explaining this. Average condition moisture was called AMC II and applied to the curve number when flooding occurs. Dry conditions (AMC I) applied to the low curve number, and wet conditions (AMC III) applied to the high curve number. This condition is most often determined by prior rainfall since soil moisture conditions are not frequently monitored.

The work group studied the effect of soil moisture on curve number by looking at infiltrometer studies (Van Mullem 1992). Four studies with 162 data pairs on 86 different soils from across the U.S. were used. Although average CN increased from 9% to 40% between the studies from the initial (dry to average condition) test to the wet condition test, no significant relationship was found between soil moisture and CN. The study indicated that the difference in CN that might be related to soil moisture is much less than the variation between ARC I and ARC III. Similarly, Hawkins and Cate (1998) showed for 25 agricultural watersheds that 5-day prior rainfall (AMC5) was the only consistent factor in explaining deviations from the central trend of runoff, but in only in 11 of the 25 cases studied, and at levels far below handbook expectations.

Because prior rainfall explains only part of the variation of CN the terminology has been changed to "Antecedent Runoff Condition" or ARC. More importantly, the ARC I and ARC III conditions have been shown to be the bounds on the distribution of CN. Figure 4 shows the ARC I, II, and III curve numbers plotted on a rainfall-runoff scatter diagram. Figure 5 shows that the ARC I is the 10% exceedance and ARC III is the 90% exceedance for a number of agricultural watersheds (Hjelmfelt et al 1981).

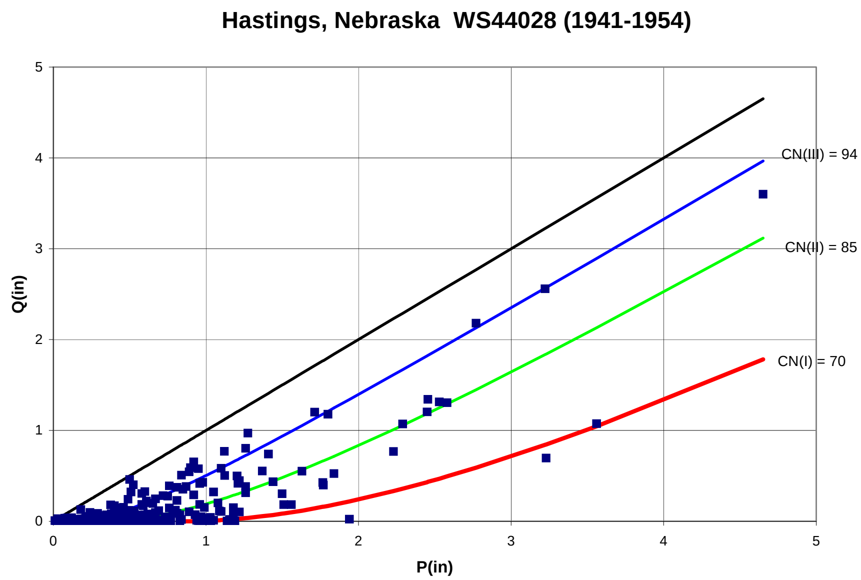

Figure 4. Rainfall-Runoff scatter diagram showing ARC I, II, and III CN.

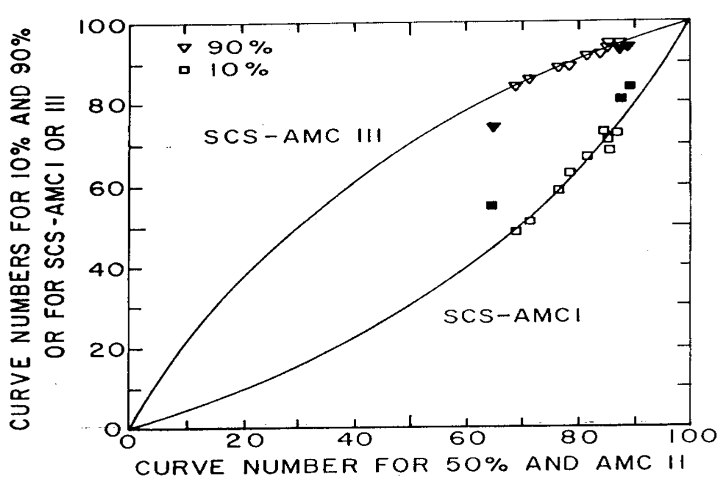

Figure 5. The 10% and 90% exceedance values compared to the ARC I and ARC III curve numbers.

It might be inferred that the curve number model is an infiltration model because in its application it is used to determine runoff incrementally over the duration of the storm for input into a unit hydrograph model. With this use it becomes a surrogate for an infiltration model and this has created much confusion. The model doesn't behave like most infiltration models/equations because the CN losses don't always decline with time or with prior rainfall but may increase when the rain intensity increases (Hawkins 1980). The CN model behavior in this regard is the same as from a partial area saturation model. Also the ultimate steady state rate is zero, it does not approach a steady-state non-zero infiltration rate with time, as do (say) the Horton or Green-Ampt Equations. There doesn't seem to be any consensus as to whether this is the way watershed losses occur. However, the model performs as originally intended, i.e., as an integrator of all the losses from all processes over the watershed. It should be emphasized that the CN model is not a point infiltration model and the difference between rainfall and runoff is better defined as watershed "losses." Watershed indices – such as the curve number – are lumped expressions of net basin performance.

It is also sometimes inferred that the parameter S, defined as the potential maximum retention, is a physical property of the site like a soil moisture storage parameter, and the water in it can be accounted for. This is has not been shown with any certainty. The parameter S (or CN) is a model variable and is only a constant for a particular storm. Although it is related to soil and cover characteristics, it is not an identifiable physical property.

HYDROLOGIC SOIL GROUPS

There has been a vast increase in basic soils property data since Musgrave first proposed the concept of hydrologic soil groups in Handbook of Agriculture (USDA 1955)**.** The data is now available in an electronic database. Modern tools of data mining were explored for analysis of this mass of data. Both neural networks and fuzzy sets were tried with fuzzy sets being adopted. Soil Hydrologic Groups are assigned to soil series and phase of series by soil scientists based upon their interpretation of the published criteria. The soil scientist's interpretation of the published criteria has varied across time and between states or regions. Thus, the hydrologic group criteria are not applied consistently across the United States. This is most evident in the comparison of soils with similar soil hydrologic and physical properties and dissimilar hydrologic group placement.

The Hydrologic Soil Groups are A, B, C, D, and dual groups A/D, B/D and C/D. Soils in hydrologic group **A** have low runoff potential. Soils that have a moderate rate of infiltration when thoroughly wet are in hydrologic group B. Hydrologic group **C** soils that have a slow rate of infiltration rate when thoroughly wet. Soils in hydrologic group **D** have a high runoff potential. Dual Hydrologic Soil Groups (A/D, B/D, and C/D) are given for certain wet soils that could be adequately drained. The first letter applies to the drained and the second to the undrained condition. Soils are assigned to dual groups if the shallow depth to a permanent water table is the sole criteria for assigning a soil to hydrologic group D.

A model or rule based automated system that provides for objective placement of soils into Hydrologic Soil Groups was developed. The fuzzy system model for assigning soils to hydrologic soil groups is based on the published hydrologic group assumptions and criteria. The soil surface is taken to be bare and the soil is not permanently frozen. The soil physical and hydrologic characteristic which make up the hydrologic grouping criteria are the depth to permanent water, depth to a restrictive layer, minimum saturated hydraulic conductivity in the soil's upper 100 cm, and the soil's texture.

The model was applied to 1828 unique soils using data from Kansas, South Dakota, Missouri, Iowa, Wyoming, and Colorado and the correlation between these soils' assigned and modeled hydrologic grouping was analyzed. Table1 shows a detailed comparison by Hydrologic Soil Group between the currently assigned HSG and the modeled HSG. The correlation between the assigned and modeled HSG A and HSG D soils is higher than the correlation between the assigned and modeled HSG B and HSG C soils. There are several reasons for the poorer correlation between the assigned and modeled groups B and C. The first is that of the boundary condition that occurs when a soil has properties that do not fit entirely into a single hydrologic group. In this case, the soil scientist may have placed the soil into one HSG while the model placed the soil into an adjacent group. Groups B and C are the most prone to this error because they are bounded by two groups whereas HSG A and D are only bounded by one group. Another source of correlation inconsistency is that the assigned HSG may be relatively correct but the data in the database may not support the corresponding HSG determination by the model. Finally, correlation inconsistencies can be attributed to the fuzzy modeling of the subjective Hydrologic Soil Group criteria (Hjelmfelt et al 2001).

CURRENT	NUMBER	FUZZY HSG ASSIGNMENT FREQUENCY						
HSG	OF SOILS	A	B	C	D	A/D	B/D	C/D
A	155	***0.903***	0.077	0	0.013	0.006	0	0
B	821	0.248	***0.543***	0.174	0.024	0.006	0.002	0.001
C	405	0.04	0.247	***0.343***	0.309	0.002	0.025	0.035
D	404	0.017	0.05	0.054	***0.636***	0.057	0.104	0.082
A/D	1	0	0	0	0	***0***	1	0
B/D	29	0.103	0.069	0.069	0	0.103	***0.552***	0.103
C/D	13	0	0.077	0.077	0.385	0	0.308	***0.153***

TABLE 1: Correlation frequency between assigned and fuzzy modeled Hydrologic Soil Group

VARIATION OF CN WITH SEASON AND LAND USE

Curve Numbers were derived from rainfall-runoff data for 15 distinct land uses on 177 small watersheds in the United States (Rietz and Hawkins 2000). Curve Numbers for each land use on each watershed were calculated using the asymptotic method and evaluated at the local, regional and national scale. Significant differences at the 5% level were found between the CNs of almost all of the different land uses tested. Significant differences in CN were also found on grazed and ungrazed paired watersheds, and on watersheds that had undergone land use conversions.

The general magnitudes and rank order of the average land use CNs were in general agreement with expected handbook values. Meadows almost always produced the lowest CN at both the local and regional level. Forestland produced the lowest overall average CN at the national level, but also displayed the largest variability. No significant differences could be determined between curve numbers for pasture and rangeland at the regional scale or between row crops and small grain at any scale. Where comparable, pastures usually had higher CNs than meadows. None of these comparisons considered hydrologic soil group or any other soil parameter.

Seasonal variation of CN has also been noted. It is seen more readily in the more humid settings, and is rare in arid and semi-arid watersheds. Where evident it follows a pattern with higher CNs in the dormant season when the ground has less cover and is likely to be wetter, and lower CNs during the summer when the ground is dryer and vegetation is in a high growth stage. Also, the seasonal variation in forest curve numbers may be associated with the leafing stages (Price, 1998).

APPLICATION TO CONTINUOUS MODELS

The curve number is used in hydrologic models to divide rainfall into storm runoff and associated losses. The losses are then added to the soil moisture budget in the model. Rainfall for most of these models is on a daily time-step. Poor results are often obtained because most storms are small, and the CN model does not work well for small events, forcing the model user to increase CN or to devise some other scheme to increase runoff at certain times of the year. Most of these models use the soil moisture budget as an index to vary the CN between ARC I and III. As previously stated the soil moisture should be used to explain only part of this variation.

Most models assume that ARC I is equivalent to wilting point and ARC III is equivalent to field capacity of the soil. This allows the CN for ARC II to be converted to appropriate daily CN. There generally is some procedure for frozen ground and snow melt in each model. However the basic CN technology was not developed for these conditions.

SENSITIVITY

Over a wide range of rainfall depths, the direct runoff Q calculated by the equation is more sensitive to Curve Number than to rainfall depth P. (Hawkins, 1975). This is especially true close to the threshold of runoff. Similarly, hydrograph peaks modeled using CN-derived sequential pulses of rainfall excess are also usually more sensitive to CN than rainfall depth. (Bondelid et al, 1982) The supporting data situation contrasts this order of importance: rainfall is widely measured, studied, analyzed, and reported, but ground truth for Curve Numbers is rare.

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