

SCS-CN-based Simulation of Pollutants Removal

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Abstract

This paper explores the potential of the Soil Conservation Service Curve Number (SCS-CN) approach in water quality modeling of kinetic wastewater treatment process using the experimentally derived pan evaporation data. Parameter CN is found to be dependent on evaporation and abstraction as well in addition to the influent concentration. For very low or very high values of influent concentration, CN exhibited an asymptotic variation approaching hundred and zero, respectively. Using the data on source water quality and removal, it is possible to compute CN and subsequently, the removal quality at an abstraction well.

Keywords: Water quality; BOD; COD; Cd and Cr; Kinetic coefficient

Introduction

The runoff curve number (also called a curve number or simply CN) is an empirical parameter used in hydrology for estimating direct runoff or infiltration from rainfall-excess. The method is simple to use and requires basic descriptive inputs that are converted to numeric values for estimation of direct runoff volume from the watershed [1]. CN that is descriptive of runoff potential of watershed which is widely preferred by hydrologists, engineers and watershed managers as an independent simple watershed model, as well as the runoff estimation component in many complex watershed models such as AGNPS [2], and SWAT [3]. Recently, Mishra et al. [4] and Ojha [5] illustrated the SCS-CN analogy in metal partitioning and water quality modeling of River Bank Filtration (RBF) system, respectively. An example of such an engineering index or parameter is the Curve Number (CN), there also exists a need for an improved alternative to the exponentially decaying function describing a first-order process, which is commonly assumed. An example is the concept of the Soil Conservation Service Curve Number method (Soil Conservation Service 1956), which is a generalization of the first-order rainfall-runoff process [6]. These works indicate the potential of CN approach in different wastewater treatment systems. Therefore, one of the objectives of the present work is to explore the use of CN approach in describing the removal of various water quality parameters. The paper begins with a background on CN approach and develops a link between kinetic coefficient, residence time, and CN.

Materials and Methodology

The first study site is located in Roorkee, Uttarakhand (India), at 29°52' N latitude and 77°53' E longitude and at an altitude of 268 m above mean sea level. The area has a humid tropical climate with normal annual rainfall of 1068 mm of which about 903 mm falls during the pre-monsoon months (July to August). The maximum temperature during the summer is about 45°C and minimum can lower to 4°C or sometimes even up to 0°C. The second study site at NALCO Ltd. located at Nalco-Nagar in Angul district of Odisha (India) lies between 20° 31' N and 21° 40' N latitude and 84° 15' E and 85° 23' E longitude. The altitude is between 564 and 1187 metres and average annual precipitation 1,421 mm, average summer temperature 47°C (117°F), average winter temperature 10°C (50°F).

Experiments were carried out on evaporator pans (green house environment) Sooknah and Wilkie [7] placed on the roof of the Department of Civil Engineering, Indian Institute of Technology, Roorkee (Uttarakhand) during pre-monsoon season (8 April 2010 to

09 May 2010) for municipal and, from 10 April 2011 to 8 July 2011 for industrial wastewater. The municipal untreated wastewater was collected randomly from different drains (near Sabji Mandi, Ramnagar, Ganeshpur, and IIT Roorkee campus of Roorkee city); Industrial wastewater (about 10 litres of wastewater carried from (NALCO) Angul Odisha; from storage ponds and same quality (and the same quantity) wastewater was prepared at IIT Roorkee in laboratory as industrial wastewater. Three evaporation pans each made of iron, having capacity of 292 L of water and diameter of 120.7 cm and depth 25 cm were installed. One pan contained water hyacinth (*Eichhornia crassipes* (Mart.) Solms L.), second water chestnut (*Trapanatans* L.), and third without plant (control) treatment. Selected plants of seven to ten propagules were placed in the first and second pans.

Ho and Wong [8] recommended a water depth close to the length of the plant roots for water hyacinth and water chestnut used for wastewater treatment. This increases the chance of contact between the plant roots and the wastewater. Therefore, the reactors in the current study had a water depth of 20 cm to fully cover the root zone. The initial concentrations of COD, BOD, Cd, and Cr in the sample municipal wastewater were 98 mg/L, 72 mg/L, 8.6 µg/L, and 6.2 µg/L and 156 mg/L, 76 mg/L, 5.4 µg/L, and 11.1 µg/L, respectively.

The evaporator pans pH was kept between 5.8 and 7.5; water was exposed to the ambient air in open containers during the whole experimental period. The initial pH of the diluted pan constituents was kept between 5.7 and 5.9 with the help of sulphuric acid and distilled water. During the experiments, the overall average water sample temperature was 20.5° to 26.7°C, which is the optimum range for plant growth, i.e. 26° to 35°C.

Water hyacinth and water chestnut were collected from natural pond near Salempur village and Asafnagar Jhal, respectively. They were cleaned and placed in nutrient rich water (for seven to eight days) to encourage growth and to ensure that the plants were healthy before placing them in untreated waste water. The nutrients rich water

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Received January 19, 2015; **Accepted** March 09, 2015; **Published** April 01, 2015

Citation: Narain S, Mishra SK, Ojha CSP, Biftu TW (2015) SCS-CN-based Simulation of Pollutants Removal. J Civil Environ Eng 5: 168. doi:10.4172/2165-784X.1000168

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consisted of Huttener's solution [9].

After eight days of incubation, plants' propagules (a vegetative structure that gets detached from the plant and gives rise to a new plant) were selected with following characteristics: water hyacinth-four to seven leaves, about 15 to 20 cm height, and root length 17 to 21 cm and water chestnut- 15 to 20 leaves, 25 to 27 cm height and root length 5 to 7 cm. Wastewater was kept stagnant in the pan during the whole experimental period and was neither treated with aeration nor replenished. Temperature, pH, Dissolved Oxygen (DO), EC, and TDS were observed daily by multi-parameter meter (HACH/sension-125 and HQ30d). Evaporation (E) of waste water in the pan without plants and Evapotranspiration (ET) of the waste water with aquatic plants, i.e. water hyacinth and water chestnut, were measured by measuring cylinder (capacity 2 lit., equivalent to 2 mm). Since the surface area of the pan is known, it is possible to measure the volume of the waste water loss in terms of depths of E and ET. The four parameters COD, BOD, Cd, and Cr were observed at 5 day interval till 50 days for municipal wastewater and natural ponds and till 120 days for industrial (NALCO) wastewater.

Water quality was analyzed [10] using instruments like Atomic Absorption Spectrophotometer (AAS), Inductive Couple Plasma Mass Spectrometry (IC-PMS), HACH/2400, HACH/5000 spectrophotometer, and sension-125 multi-parameter meter and HQ30d Portable Multi-parameter.

The evaporator pans contained the wastewater and aquatic plants. Weather stations were used to monitor the meteorological data, electronic digital instruments for measurement of water quality parameters. Digital planimeter was used to measure the leaf area index. Notably, the use of digital instruments minimizes the human error and makes the measurements easy.

Curve Number Approach

The runoff curve number is based on the hydrologic soil group, land use, treatment and hydrologic condition. The basic assumption of the SCS curve number method is that, for a single storm, the ratio of actual soil retention after runoff begins to potential maximum retention is equal to the ratio of direct runoff to available rainfall and it forms the basis of the SCS-CN methodology. Expressed mathematically,

$$\frac{Q}{P - I_a} = \frac{P - I_a}{(P - I_a) + S} \quad (1)$$

where, Q is runoff (L); P is rainfall (L); S is the potential maximum soil moisture retention after runoff begins (L); I_a is the initial abstraction (L) or the amount of water before runoff begins, such as infiltration, interception. $I_a=0.2S$ is frequently practiced. The SCS-CN method describes a rainfall (P) and runoff (Q) relationship. I_a (initial abstraction) is used to get better a estimate of input as $P - I_a$ in place of P. The parameter S is mapped on to CN as follows:

$$S = \left(\frac{1000}{CN} \right) - 10 \quad (2)$$

In Eqs. (1) and (2), S represents the potential storage and CN stands for curve number and is related with infiltration rate, antecedent moisture, hydrologic condition etc. Some researchers (for example, some researcher reported that I_a was not a part of the SCS-CN model in its initial formulation, but with the development, it was included, for convenience and simplicity reasons, as a fixed ratio of I_a to S. The relationship was however justified on the basis of measurements for watersheds of less than 10 acres, despite a considerable scatter in the

resulting I_a -S plot. Because of this large variability, $I_a=0.2S$ relationship has been focus of discussion and modification since its inception. For example, Aron et al. [11] suggested $\lambda \leq 0.1$ and Golding [12] provided λ values for urban watersheds depending on Curve Number (CN) as $\lambda=0.075$ for $CN \leq 70$, $\lambda=0.1$ for $70 < CN \leq 80$, and $\lambda=0.15$ for $80 < CN \leq 90$. Hjelmfelt [13] pointed out that many storm and landscape factors interact to define the initial abstraction. For analogy, if the input to any reactor or unit is known, abstraction may not be relevant in water quality modelling and it is emphasized with respect to removal of impurities through aquatic plants.

Pollutants Removal through Aquatic Plants

Exponential variation analysis of first order kinetics model

The first order kinetics is widely used in the water quality modeling. With this in view, it is intended to describe the removal of pollutants in the system using a first order kinetics model as follows

It is seen that the effluent quality C_e can be related to influent water quality C_o as,

$$C_e = C_o \exp(-kt) \quad (3)$$

where, C_e =pollutants conc. after time (t), C_o =initial pollutants concentration, k =temperature dependent first order reaction rate constant (d^{-1}), and t =hydraulic residence time (d). The temperature dependent rate constant is calculated from the rate constant for 20°C and the correction factor which accounts for temperature deviations from 20°C.

In Equation (3), the kinetic co-efficient (k) is obtained as follow:

Let the input load be $Q_0 C_0$ at $t=0$. After one day, the load in the pan will be $(Q_0 - Q_1) C_1$. It is noted that after day 1, there will be changes in Q as well as C. The amount Q_1 will be transpired by the plants; thus Q will change to $Q - Q_1$. Similarly, C will change to C_1 . It is assumed that the change in the quality will be exponential. Thus, $(Q_0 - Q_1) C_1$ will be equal to,

$$(Q_0 - Q_1) C_1 = (Q_1 \times 0) + (Q_0 - Q_1) C_0 \exp(-k) \quad (4)$$

$$\text{or } C_1 = C_0 \exp(-kt) \quad (5)$$

Similarly at second day, the quality C_2 can be computed. If Q_2 is the lost water between day 1 and 2, one can write the following mass balance equation

$$(Q_0 - Q_1 - Q_2) C_2 = (Q_2 \times 0) + (Q_0 - Q_1 - Q_2) C_0 \exp(-kt) \exp(-kt) \quad (6)$$

$$\text{or } C_2 = C_0 \exp(-2kt) \quad (7)$$

Thus after time t, equation (7) can be generalized as

$$C_t = C_0 \exp(-kt) \quad (8)$$

Temperature effect

Temperature effects are considered in greater detail by Stowell et al. [14], and Technobagalous [15]. Because of the adverse effect of temperature on aquatic plants, their use should be limited to the more temperate climate where the changes in both the water and air temperature between summer and winter are within a limited range. Cattail systems however, have been used in Canada the year round with great success.

Techobanoglous [16] suggests that the performance of aquatic plants treatment systems is temperature dependent. Based on

experimental studies and an analysis of data, it appears that a modified Van't Hoff–Arrhenius temperature relationship, as presented below, can be used to estimate the effect of temperature on wastewater treatment using aquatic system.

$$k_t = k_{20} \theta^{(T-20)} \tag{9}$$

Where, k_t =removal rate constant at water temperature T. d^{-1} , k_{20} =removal rate constant at 20°C, d^{-1} , T=operating water temperature, °C

Based on experimental studies with water hyacinth and emergent plant systems, it has been found that the value of the temperature coefficient is about 1.09. Stowel et al. [14] consider the effect of temperature between 5 to 25°C. However in a tropical climate such in India, the temperature may exceed 25°C and it is not known whether the value of temperature coefficient as 1.09 is unique. Literature [15] also reports adverse effect of temperature on water hyacinth. However, the same is not considered in the present analysis.

The Eq.(3) can write as, [5]

$$\frac{output}{input} = \frac{input}{input + S_0} \tag{10}$$

Here, S_0 is distinguished from S for water quality modelling.

Let ratio of output to input be represented as R. With this, Eq. (10) can be expressed as,

$$R = \frac{output}{input} = \frac{input}{input + S_0} \tag{11}$$

Thus, using Eqs. (10) and (11), we get

$$S_0 = \frac{1-R}{R} input \tag{12}$$

Using Eqs. (2) and (12), one gets Curve Number (CN) as

$$CN = \frac{1000R}{10R + (1-R)input} \tag{13}$$

or

$$CN = \frac{1000R}{10R + (1-R)C_0} = \frac{1000 \exp(-kt)}{10 \exp(-kt) + [1 - \exp(-kt)]C_0} \tag{14}$$

Using Eqs. (2) and (14), we get a relationship between C_e and CN as:

$$C_e = \frac{C_0^2}{(1000 / CN) - 10 + C_0} \tag{15}$$

Most of the equations reported in literature to describe effluent quality fall under this case where, effluent quality C_e is related with influent water quality C_0 as:

$$C_e = C_0 \times a \times \exp(-kt) \tag{16}$$

Therefore,

$$R = \frac{output}{input} = \frac{C_e}{C_0} = a \exp(-kt) \tag{17}$$

$$CN = \frac{1000R}{10R + (1-R)C_0} = \frac{1000 \times a \times \exp(-kt)}{10 \times a \times \exp(-kt) + [1 - a \times \exp(-kt)]C_0} \tag{18}$$

where, a=constant. Thus, depending on a particular type of effluent quality relationship, one can appropriately choose Eq. (14) or Eq. (18).

In the following sections, several variations of Curve Number (CN) with time are shown for different water quality parameters.

Temporal variation of cn for municipal wastewater treated with and without plants

Figures 1-3 represent variation of Curve Number (CN) for water hyacinth, water chestnut and control (without any plant) experiments, respectively. Almost all the variations are exponential in nature with the exception of Figure 2 where two curves are shown in case of BOD. This is because of the two different kinetics coefficients (k) in two distinct regions of time. Ideally, this should be a single curve showing the variation of Curve Number (CN). The interesting observation from these three figures is that the curves for BOD and COD are very close to each other whereas the curves for Cd and Cr are close to each other. This is also reflected from the closeness in k-values for BOD and COD

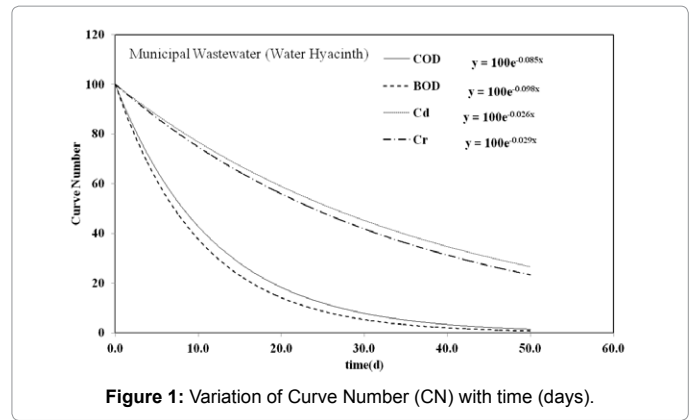


Figure 1: Variation of Curve Number (CN) with time (days).

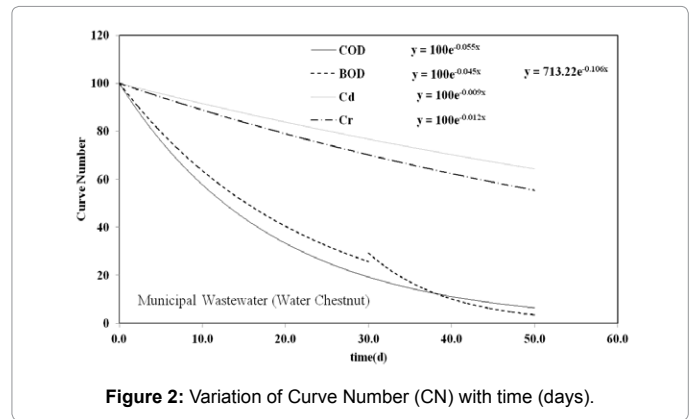


Figure 2: Variation of Curve Number (CN) with time (days).

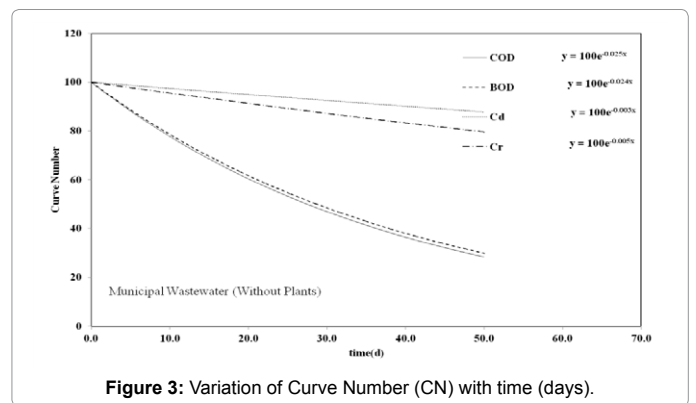
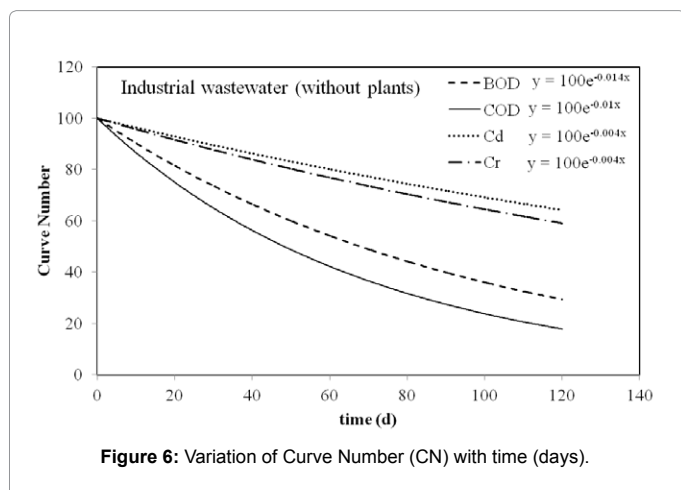
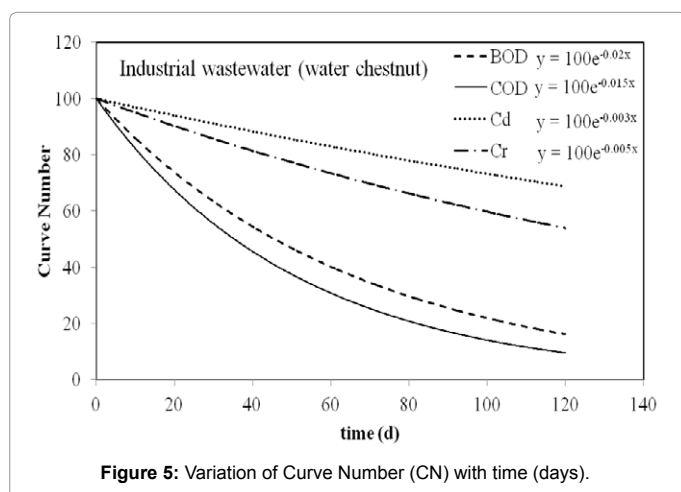
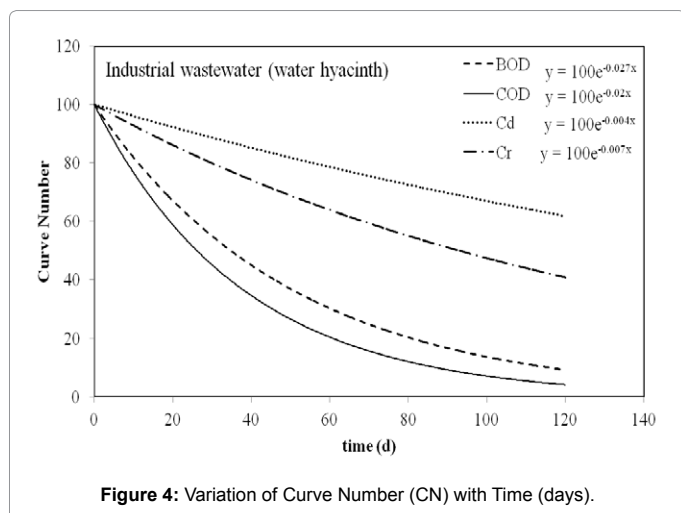


Figure 3: Variation of Curve Number (CN) with time (days).



as well as for Cd and Cr.

In case of control pan experiment without plants, k has a low value, but close for both BOD and COD. This reflects in closeness of BOD and COD based Curve Number (CN) variations with time. It is also possible to relate CN with other variables such as Leaf Area Index. This is however not dealt here for the reason that CN has been linked with

k which, in turn, was related with Leaf Area index and temperature. Thus, all the variables which influence k are likely to influence CN.

Temporal variation of CN for industrial wastewater treated with and without plants

To appreciate the CN variation with time for different water quality parameters, the data of industrial wastewater treatment is also processed in the similar manner as for municipal wastewater. Figures 4-6 represent exponential variations of CN and time for four water quality parameters. Though the proximity between BOD and COD as well as between Cd and Cr is noticed earlier, the gap between BOD and COD is much wider than that observed in case of municipal wastewater, and the same holds true for Cd and Cr for various treatment options with water hyacinth, chestnut, and without plant.

Results and Discussion

Figures 1-6 show different relations of CN with kinetics coefficient (k) for municipal and industrial wastewaters treated with water hyacinth, water chestnut, and without plant, respectively. Curve Number (CN) is seen to have a tendency to decrease with increase in kinetics coefficient with time (t). Thus, to use CN approach, one needs to know the kinetics coefficient (k), possibly from k -Leaf Area Index-temperature relationship, if available. With k known, one can compute quality at any time using expressions relating effluent quality, influent quality, residence time or time t at which quality is desired. Though the separate estimation of CN and its subsequent use for forecasting of water quality may not be preferable, the water quality projections will be the same because of the interrelationship between the two, and it is consistent with the work of Ojha [5].

Summary

This paper showed the applicability of Curve Number (CN) approach in the area of wastewater treatment as it relates the influent quality with the effluent quality. To this end, the work by Ojha [5] was extended, and CN related with kinetics coefficient. The variation of CN can be best modelled in terms of kinetics coefficient, and thus, all the parameters which may influence kinetics coefficient will also influence CN. Alternatively, if relation between CN and the variables affecting kinetics coefficient is available, CN approach can be used for water quality projections.

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