STORM WATER DRAINAGE AND EFFLUENT DISPOSAL

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Contents

Summary

Due to increasing urbanization, accelerating the demolition of forest lands, and the growing use of chemicals, storm water carries large quantities of sediment and pollutants. If untreated, the storm water pollutes the receiving natural water bodies, such as lakes, streams, rivers and seas on the one hand, and diminishes the volumetric capacity of lakes and the discharge capacity of streams and rivers, on the other hand. Therefore, the drainage of storm water has to be designed taking into account the pollution potential of the storm water. Different methods of disposal of the effluent either on land, in rivers or in seas are discussed, and considerations for the design of such disposal works are presented.

1. Introduction

At the global level, the growth rate of human population is exponentially on the rise. To meet increasing demands for food, shelter and water, humanity's limited natural resources are under continual stress. For increasing food production, heavy fertilizer doses are being applied. The case is similar to the demand for shelter, which in many instances, has been achieved by denuding the land. To improve living standards for a large portion of the global population, recent times have witnessed a phase of rapid industrialization.

Eccentric concerns for profit have led to the ignoring of the proper treatment of urban waste products before their disposal to either the land or a natural water body. This has led to the instability of many natural water bodies, which have not only dramatically shrunk, but the water they contain has become non-potable. This shrinkage has been due either to an excessive input of sediments eroded from deforested lands, or due to growth of weeds in water bodies. Sufficient food for encouraging the growth of aquatic weeds is available in the form of phosphorus and nitrogen in the surface runoff emanating from agricultural fields, or from untreated effluents. In addition to widely known culprits such as plastic bags, eroded sediments have often been a contributing factor for choking the drains carrying surface runoff to water bodies, thus leading to overflows (see chapters *Hydraulic Structures in Urban Drainage Systems; Hydraulics of Two-phase Flow: Water and Sediment*).

Under the national combined sewer overflow (CSO) policy formulated by the US Environmental Protection Agency (EPA), more than nine hundred cities in the US will no longer be able to discharge untreated sewerage and storm water effluent into lakes, rivers, and streams, according to Mealey. To meet the present day needs of society, it is essential to address the issues related to storm water drainage and effluent disposal. It is expected that a consideration of these issues may help with the management of storm water drainage and effluent disposal practices to improve the standard of living (see chapter *Hydraulics and Sustainable Wastewater Disposal in Rural Communities*).

2. Characteristics of Storm Water and Sewage Effluent

Prior to presenting any discussion regarding the characteristics of storm water and sewage effluent, it is desirable to be apprised of certain commonly used terms in the literature.

- Sewage refers to the liquid conveyed by a sewer. It may consist of any single type, or a mixture of liquid wastes, such as sanitary or domestic sewage, industrial waste, storm sewerage, infiltration due to leakage from groundwater, and inflows. Inflows occur only during runoff events and enter sewers through cracks in manholes, open clean-outs, perforated manhole covers, roof drains, or basement sumps connected to the sewers.
- Sanitary sewage originates from dwelling units, business buildings, or institutions.
- Industrial waste is the liquid waste product of industrial processes, such as dyeing and paper making.
- Sewerage system refers to the collection of wastewater from occupied areas and its conveyance to some point of disposal.
- Sewage treatment aims to treat the sewage to render it less offensive.
- Sewage disposal applies to the act of disposing of sewage, which is the focus of this article.

It must be emphasized here that sewage or effluent characteristics can vary widely, depending on the sources of sewerage. During a storm period, there can be a dilution of the sewage strength, but at the same time the volumetric load on the treatment units can be increased, if the storm water is also conveyed through sewers. It is also possible that leachate from solid waste disposal sites may enter the storm runoff collector system, and could greatly influence the characteristics of the sewage. Thus, it is possible to expect variations in the effluent characteristics with spatial and time scales.

Table 1 refers to some of the important sewage characteristics of a domestic waste from the US according to Steel and McGhee, while Table 2 refers to some of the water quality characteristics, which may be of importance when an effluent is disposed of and introduced into the environment.

PARAMETER	*Weak*	*Medium*	*Strong*
Total suspended solids	100	200	350
Volatile suspended solids	75	135	210
BOD (Bio-oxygen demand)	700	200	400
COD (Carbon oxygen demand)	175	300	600
TOC (Total organic content)	100	200	400
Ammonia–N (Nitrogen)	5	10	20
Organic-N (Nitrate, Nitrite)	8	20	40
PO_4-P (Phosphate, Phosphor)	7	10	20

Table 1. Typical domestic sewage characteristics, mg/L

CATEGORY	*Characteristics, Examples*
Physical	Specific conductance, color, turbidity, pH, total hardness
Major cations	Calcium, magnesium, sodium, potassium
Major anions and others	Carbonates, bicarbonates, sulfate, chloride, nitrate, silica
Nutrients	All forms of phosphates, inorganic nitrogen, total kjeldahl nitrogen, silica
Wastes	Dissolved oxygen, biochemical oxygen demand, total organic carbon, chemical oxygen demand, phenol
Heavy metals and elements	Iron. manganese, copper, zinc, lead, nickel, cadmium, chromium, arsenic, mercury
Pesticides, herbicides, and other compounds	DDT, methoxychlor, heptachlor, aldrin, chlordane, dieldrin, lindane, etc., light and heavy petroleum products
Biological	Total coliforms
Others	Alpha emitters, beta emitters

Table 2. List of important water quality characteristics

Industrial waste, containing solid substances, or objects which might plug conduits or damage pumping equipment, usually requires primary treatment prior to its entry into the sewer system. These substances include ash, cinders, sand, mud, straw shavings, metal, glass, rags, feathers, tar, plastics, wood, hair, fleshing, chemical residues, etc., and can also be found in sanitary or domestic sewage.

3. Sewage Treatment Processes

A sewage treatment process may generally be classified as primary, secondary, or tertiary, as follows:

- Primary treatment is physical in nature. Thus, the quality of an effluent from a primary treatment unit will be different from the quality of effluent from secondary or tertiary treatments.
- Secondary treatment is biological in nature.
- Tertiary treatment is adopted to achieve higher quality effluents.

The quality of effluent from these treatment operations may further depend on the treatment efficiencies of these systems. Table 3 indicates typical efficiencies to be encountered in these treatment processes, according to the CPHEEO (Central Public Health and Environmental Engineering Organization, India).

Process		Percentage reduction		
		SS	BOD	Total coliforms
1.	Primary treatment (sedimentation)	45-60	30-45	40-60
2.	Chemical treatment	60-80	45-65	60-90
3.	Secondary treatment			
	Standard trickling filters	75-85	70-90	80-90
	High-rate trickling filters			
	–Single stage	75-85	75-80	80-90
	–Two stage	90-95	90-95	90-96
	Activated sludge plants	85-95	85-95	90-96
	Stabilization ponds			
	–Single cell	80-90	90-95	90-95
	–Double cell	90-95	95-97	95-98

Table 3. Efficiency of different treatment options

To add a further dimension to the quality of the effluent, dissolved atmospheric pollutants and nutrients leaching from irrigated fields are expected to be found in it. Thus, it is essential that the quality of the effluent should be ascertained before taking any decision regarding its disposal. It is equally important to model or monitor the post-disposal quality of the effluent (see *Eutrophication*).

4. Hydraulics of Drainage Networks

The design of drainage systems essentially involves routing of flow due to a design storm. This process is very similar to flood routing. Drainage networks can be tree-type or looped. Generally, these networks possess a complex multiply-connected loop structure.

Equations 1 and 2 below, the governing equations for flow in a drain, are one-dimensional in nature, and are known as the Saint Venant equations (see chapter *Fluid Mechanics*).

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}-q=0 \quad (1)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (Q^2/A)}{\partial x}+g\,A\frac{\partial h}{\partial x}-g\,A\left(S_0-S_f\right)=0 \quad (2)$$

where t = time, x = distance, A = wetted cross-sectional area, Q = discharge, q = lateral inflow or outflow distributed along the x-axis of the channel, g = acceleration due to gravity, h = flow depth, S_0 = bed slope and S_f = friction slope, which may be evaluated using a uniform, steady-flow empirical resistance equation, such as Manning's equation, as described under Design Aspects in Section 5 below and elsewhere (see chapter *Fluid Mechanics in Pipelines*).

Flow-routing models, which are based on Equations (1) and (2), are called dynamic routing models. Simplified models, based on Equation (1) and various simplifications of Equation (2), are also available, as cited by Singh. Kinematic wave models are based on the consideration of only the fourth term of Equation (2), which amounts to assuming that the momentum of unsteady flow is the same as that of steady, uniform flow as described by Manning's equation (see chapters *Fluids at Rest and in Motion; Hydraulic Methods and Modeling*).

Diffusion wave models are based on the consideration of only the third and fourth terms of Equation (2). This amounts to assuming that the inertia in unsteady flow is negligible compared with other effects. It is obvious that dynamic routing models are more complex than the simplified routing models, but their range of application is wider. The advent of high-speed computers has made the development of dynamic routing models feasible and their application popular.

Equations (1) and (2) constitute a set of quasi-linear hyperbolic partial differential equations. Many explicit and implicit finite difference models for flow routing based on Equations (1) and (2) have been developed in the past, according to Abbott (see chapter *Hydroinformatics*), Cunge and co-workers, and Chaudhry and Singh. Of these modeling methods, Preissmann's implicit scheme is probably the most popular. In this method, the partial differential terms are discretized using finite difference analogs as given in Equations (3), (4) and (5) below:

$$\frac{\partial f}{\partial t} = \frac{f_i^{j+1} + f_{i+1}^{j+1} - f_i^{j} - f_{i+1}^{j}}{2\Delta t} \tag{3}$$

$$\frac{\partial f}{\partial x} = \frac{\theta(f_{i+1}^{j+1} - f_i^{j+1}) + (1-\theta)(f_{i+1}^{j} - f_i^{j})}{\Delta x} \tag{4}$$

$$f = \frac{\theta(f_{i+1}^{j+1} + f_i^{j+1}) + (1-\theta)(f_{i+1}^{j} + f_i^{j})}{2} \tag{5}$$

where f is any variable, Δt = computational time step, Δx = distance step, and θ = implicit weighting parameter. Superscript j indicates values at time level t and superscript $j + 1$ indicates values at time level $t + \Delta t$. Subscript i indicates values at node i and subscript $i + 1$ indicates values at node $i + 1$. Substitution of Equations (3) to (5) in Equations (1) and (2) results in two algebraic equations for node i in four unknowns: values of discharge and flow area at nodes i and $i + 1$ at time level $t + \Delta t$.

Finite difference equations can be written in a similar way for all nodes $i = 1, N\text{-}1$, where N = the total number of nodes into which the channel is divided. These $2(N\text{-}1)$ equations along with two boundary conditions, one at the upstream end and the other at the downstream end, constitute a system of $2N$ equations needed for determining the $2N$ unknowns.

These are a set of $2N$ non-linear equations, which can be solved using the Newton-Raphson iteration method. While applying this method, a matrix of size $2N \times 2N$ needs to be inverted during each iteration. For a single channel system, the matrix is well structured (block-bidiagonal structure) and a very efficient double sweep method can be applied for solving the matrix equation as described by Cunge and co-workers.

Applications of finite difference or finite element analogs to channel networks have been attempted by several investigators such as Tucchi, Akan and Yen, Barkau and co-workers, Choi and Molinas, Nguyen and Kawano, and Sen and Garg. Drainage networks are basically designed to insure that the entire runoff should be quickly and safely disposed of into the adjoining river. Precipitation from a floodplain depends on the nature of the surface of the floodplain. A higher percentage of paved surfaces will lead to greater runoff than from an agricultural field or park of the same area. These considerations already exist in the rational formula for runoff estimation (see chapter *Hydraulic Methods and Modeling*).

5. Design Aspects of a Sewerage System

Effluent disposal from households is generally accomplished by means of a sewerage system. A sewerage system consists of either a system of separate sanitary sewers and storm sewers, or a system of combined sewers, or a compound system consisting of sanitary sewers, part-storm sewers, and combined sewers. The combined sewerage system invariably suffers from the disadvantages of sluggish flow during the largest part of the year, leading to deposition of sewage solids and creating foul and offensive conditions. In view of this, the combined system is not normally recommended in modern sewerage design, according to the CPHEEO.

Sanitary sewage is mostly the used water of a community, draining into the sewer system together with some groundwater and a fraction of the storm runoff from the area. Sewers are usually designed for the maximum discharge to meet the requirement of the ultimate development of the area. Population estimates are guided by the anticipated ultimate growth rates, which may differ in different zones of the same town. A design period of thirty years for all sewers is recommended. Population estimates multiplied by per capita sewage flow can give an idea of the load to which the sewer should be designed. In India, sewers are designed for a minimum of 150 liters per capita per day.

Industries and commercial buildings often discharge their liquid waste into the sanitary sewers. Although it is not desirable that industrial wastes should be disposed of in large quantities into municipal sewers, an estimation of these additional loads should be accounted for in the design, if there is no alternative to discharge such wastes separately. Sanitary sewers are not expected to receive storm water. A certain part of the groundwater may also infiltrate into sewers through their joints. This happens particularly when sewers are laid into the groundwater zone. Certain allowances for this should be also be made in the design (see chapter *Groundwater Hydraulics*).

For estimating the flow to be carried in the storm sewer, the intensity of rainfall lasting for the period equal to or greater than the time of concentration should be considered. Among different methods, the rational method is most commonly used for storm runoff estimation. According to this method, the runoff, Q, reaching the sewers is expressed by Equation (6) below:

$$Q = CiA \tag{6}$$

Here C is the coefficient of runoff, i is the intensity of rainfall occurring for a period equal to or greater than the time of concentration, and A is the area of the drainage basin. The coefficient, C, depends on the percentage of imperviousness and the shape of the tributary area, apart from the duration of the storm. The percentage of imperviousness may range from 70 to 90 for commercial and industrial areas, 60 to 75 for residential areas with high density, 35 to 60 for residential areas with low density, and 10 to 20 for sparse and undeveloped areas, as given by the CPHEEO. Steel and McGhee have provided a detailed table for estimation of the runoff coefficient. The intensity of rainfall is related to the duration of storm (see chapter *Probabilistic Methods and Stochastic Hydrology*).

Regional relationships, according to Singh, are used to estimate the intensity of rainfall.

Sewers are normally designed for flows with a free water surface. Also, self-cleansing velocity is an important consideration in design. Self-cleansing velocity is the minimum velocity which insures that the sediments/suspended solids do not deposit and cause nuisance. This velocity is a function of particle size and the specific weight of the suspended solids. Certain typical ranges of this velocity are 0.6 to 0.8 m/sec. Similarly, a limit on the maximum velocity is also imposed, and this value is around 3 m/sec. For the design of sewers, the use of a hydraulic resistance relationship is essential, and for this purpose Manning's formula is widely used, as given in Equation (7):

$$V = \left(\frac{1}{n}\right) R^{0.67}\ S^{0.5}, \qquad (7)$$

with V = flow velocity, n = Manning's roughness coefficient, which ranges between 0.011 to 0.015 for the materials used in constructing sewers, R = hydraulic radius, and S = slope or hydraulic gradient (see chapter *Hydraulic Structures in Urban Drainage Systems*).

From a consideration of ventilation, sewers should not be designed to run full. The head losses occurring in sewer transitions must be considered in the design. To maintain the slope requirement, the vertical drops in sewer alignments are a regular feature. In no case should the hydraulic flow line in larger sewers be higher than the incoming flows, as this would cause flow stoppage/reverse flow into the incoming smaller sewers.

Sewer appurtenances are necessary for the smooth functioning of any sewerage system. These include structures and devices, such as various types of manholes, lamp holes, gully traps, intercepting chambers, flushing tanks, ventilation shafts, catch basins, street inlets, regulators, siphons, grease traps, side-flow weirs, leaping weirs, Venturi flumes and outfall structures. A description of each of these is out of place here, but their details can be obtained elsewhere, for example in textbooks such as authored by Metcalf and Eddy, Fair and Geyer, and others (see chapter *Hydraulic Structures in Urban Drainage Systems*).

6. Effluent Disposal on Land

History records that irrigation with wastewater was practiced in Athens before the birth of Christ, according to Metcalf and Eddy. Sewage farming was used in Germany as early as the sixteenth century, and was common in England until the 1800s. Sewage farming was first introduced in the US in the 1870s. Other countries in Europe and Asia have long histories of applying wastewater to land. More historical information is given by Turk, Wolman, Rafter and Harlin. After the advent of the Industrial Revolution in the eighteenth century, industrial wastewater came to join the streams and rivers, and the need was realized for on-land disposal because of the polluting impact on natural water courses (see *The Uses of River Water and Impacts*).

6.1 Sewage Farming

The present practice of the use of effluents by farmers is due to scarcity of water to meet the irrigation requirements. As the sewage or effluent may have very high biological oxygen demand (BOD) values, say between 2000 to 10 000 mg/L in the case of distillery effluents, it is necessary to apply the effluents with adequate dilution. A desirable practice may be to apply the effluent two to three weeks in advance, before tilling the fields for growing crops. It has been also observed that an application of distillery effluents makes the top surface of the soil hard, which further leads to less percolation of water from rainfall or irrigation.

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Dr. C.S.P. Ojha is with the Department of Civil Engineering, University of Roorkee, Roorkee, India. He obtained the Master of Engineering degree at the Indian Institute of Science, Bangalore, India, with a thesis on the subject of Groundwater Studies. He presented a keynote address at the Institute of Technology, Banaras Hindu University in India, on modeling and monitoring aspects of water pollution in the Ganga River. He also studied groundwater pollution on confined areas.

Professor Vijay Singh was born in 1946 in Agra, India. He obtained the following degrees: B.S. (Engineering and Technology) in 1967 from Pant College of Technology, India; M.S. (Engineering: Hydrology) in 1970 from the University of Guelph, Ontario, Canada; Ph.D. (Civil Engineering: Hydrology and Water Resources) in 1974 from Colorado State University; and D.Sc. (Engineering) in 1998 from the University of the Witwatersrand, Johannesburg, South Africa. He is a registered Professional Engineer and a registered Professional Hydrologist. He currently holds the Arthur K. Barton Endowed Professorship in Civil and Environmental Engineering at Louisiana State University and has had previous faculty appointments at New Mexico Tech, George Washington University and Mississippi State University. He has received more than thirty awards, including Distinguished Service Award (National Research Council of Italy) in 1995; Fulbright Scholar Award in 1997; International Man of the Year Award (International Biographical Center) in 1997; Brij Mohan Distinguished Professor Award in 1999; Distinguished Faculty Award in 1999; Achievement in Academia Award in 1999 (Colorado State University, College of Engineering); James M. Todd Technological Achievement (Louisiana Engineering Society) in 2000; nine book awards; two best paper awards; Teacher of the Year Award and Researcher of the Year Award. He is a Fellow of ASCE, AWRA, IE, IAH, ISAE and IWRS. He has authored nine textbooks, edited twenty-five books, authored thirty book chapters and more than 250 Technical Journal articles and 240 Conference Proceedings Papers and Technical Reports. He is Editor-in-Chief of Water Science and Technology Library Book Series and is Member of nine Journal Editorial Boards. He has organized nine International Conferences and Chaired a number of Conference Sessions, and lectured and given keynote addresses worldwide. He is Senior Vice-President of the American Institute of Hydrology, Vice-President of the Indian Association of Hydrologists and President of the GBS Board, and has served nationally and internationally on committees of professional organizations. Professor Singh's research interest encompass a wide range of topics in surface and subsurface hydrology, watershed hydraulics, irrigation and water quality engineering. He specialized in Kinematic Wave Modeling, Surface Irrigation Hydrodynamics, Watershed Erosion and Sediment Transport, Water Quality Modeling, Modeling of

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