Modeling Sewer Effluent Design Discharge with System Dynamics Technique

*+S.O. Ojoawo, #O.S Olaniyan and #A.A. Adegbola

*Department of Civil Engineering,
NMAM Institute of Technology, Nitte - 574110,
Udupi District, Karnataka State, India

#Department of Civil Engineering,
Ladoke Akintola University of Technology,
P.M.B 4000, Ogbomoso, Nigeria

+Corresponding Author; Email: soojoawo@lautech.edu.ng

Abstract

One of the crucial factors in sewage management systems is the Design discharge of sewer effluents. This study has applied the principles of System Dynamics (SD) for the modeling of sewer effluents design discharge in NMAM Institute of Technology, Nitte Campus. Rational Formular (RF) and Lloyed Davis Formular (LDF) methods were both employed. The equations were coded in the Visual Basic computer Language and processed using Stella 9.0 software. Input parameters were: population (P), Catchment Area (A), per capita water supply (WS), sewage flow (SF), average annual rainfall (AAR), impermeability coefficient for the area (I), and the time of concentration (t_c). Results showed that the maximum Dry Weather Flow (DWF) in the RF and LDF methods were 111 and 103 litres/sec respectively. The optimum effluents design discharge obtained for the RF and LDF methods were however 637 litres/sec and 617 litres/sec respectively. The DWF/WWF ratio was found as 1:4. The study therefore recommends the use of Rational Formular and combined sewer system for effluents in the study area.

Keywords: *System Dynamics, Modeling, Sewer Effluents, Design Discharge*

1.0 Introduction

System Dynamics (SD) is a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems [1]. SD is a well-established methodology for studying and managing complex feedback systems, based on system thinking [2]. SD modeling has a wide practical application. It has been used to address various feedback systems, including the environmental management [3], [4], [5], [6], [7], [8], [9], [10]. It requires constructing the unique *''causal loop diagrams''* or *''stock and flow diagram''* to form a system dynamics model for applications. The development processes in SD models had been documented [11], [12], [13], [14], [15].

On the use of SD in waste management, [16] explored the analysis of the New York State solid waste system. Also, [17] further employed a SD model to capture the dynamic nature of interactions among the various components in the urban solid waste management system, while [18] developed a methodology to incorporate qualitative variables such as voluntary recycling participation and regulation impact quantitatively. The model provides a platform for examination of various structural and policy alternatives for sustainable solid waste management. Other previous applications in different topical areas are collated in SD Review [19].

The representations of SD elements are simple. In addition [20] established that system dynamics methodology is based on the feedback concept of control theory and the feedback loops simulate dynamic behaviour. Two basic building blocks in system dynamics studies are stock or level and flow or rate. Stock variables, denoted by rectangles, are state variables and stocks represent accumulation in the system. Valve symbols stand for flow variables. The rate of change in the stock variables and flows represent the activities and decision function in the system. Converters, represented by circles, are intermediate variables used for miscellaneous calculations. The connectors which are indicated by simple arrows symbolize cause and effect links within the model structure [20].

The simulation of SD scenarios is usually being accomplished with the Stella software package. Stella is iconographic software that uses intuitively assembled basic building blocks such as stocks, flows, and converters to simulate the dynamic processes of a system. Apart from Stella, Vensim is software with a user-friendly interface for most computer SD model simulation applications [2]. These model development procedures are designed based on a visualization process that allows model builders to conceptualize, document, simulate, and analyze models of dynamic systems. They offer a flexible way for building a variety of simulation models from causal loops or stock and flow. The dynamic relationships between the elements, including variables, parameters, and their linkages, can be created onto the interface using user-friendly visual tools. The feedback loops associated with these employed variables can be visualized at every step throughout the modeling process. Simulation runs are carried out entirely along the prescribed timeline.

The paper looks at the application of the flexible and versatile SD in optimizing the sewer effluents at NMAM Institute of Technology Campus, Nitte, Udupi District, India. The direct relationships between the population, water supply, sewage flow, rainfall intensity and the design discharge were studied with the SD technique.

2.0 Methodology

(a) The study area

Nitte is a Village in Karkal Taluk in Udupi District of Karnataka State, India. It is located 30 km towards East from District head quarters Udupi, 10 km from Karkal and 336 km from the State capital Bangalore. The study area's elevation/altitude is 20 meters above sea level. Udupi district experiences a typical maritime climate with an average temperature of 26.5°C. The district gets highest annual rainfall in Karnataka state, about 4000 mm [21]. In this coastal district, bulk of the rainfall i.e. over 85% occurs during monsoon season. The temporal variation of rainfall is confined to 3 to 4 months in a year. The rainfall increases from west to east with co-efficient of variability ranging from 18.7 to 18.9%. The Map of Udupi District showing Nitte, the study area is in Figure 1 while Figure 2 shows the Layout Plan of NMAMIT Campus.

Figure 1: Map of Udupi District of Karnataka State

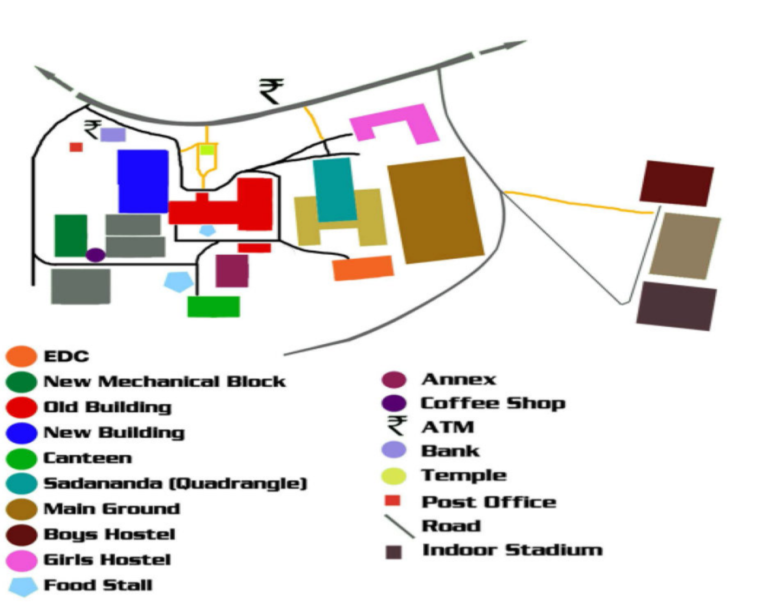

Figure 2: Layout Plan of NMAMIT Campus

(b) Design parameters

The following are the design parameters employed in the SD model for the Design Discharge (*Q*) and Effluent (*E*): Population (*P*), Catchment Area (*A*), Impervious Area (*Ai*), Per capita water supply (*WS*), Sewage Flow (*SF*), Wet Weather Flow (*WWF*), Dry Weather Flow (DWF), Average Annual Rainfall (*AAR*), Rainfall Intensity (*Ri*), Sewage % from water supply (*75*), Average Impermeability, Coefficient for the area (*I*), Time of concentration (t_c), and the Ri constants (*a and b*) as defined by the US Ministry of Health.

(c) The Governing equations and basic relationships

The Governing equations [22] applied for the optimization include the:

(i) Rational Formular (RF), **WWF = 28AIRi** …………………………. *(1)*

(ii) US Ministry of Health Formula, $\mathbf{Ri = 25.4a/(t_c + b)}$ ...……………. *(2)*

(iii) Lloyed Davis Formular (LDF), $\mathbf{WWF = [Ri/6t_c].Ai}$ ……………....*(3)*

The applied basic relationships are:

(i) **SF = 0.75 * WS** ……………………………..…………………. *(4)*

(ii) **DWF = P * SF** ……………………….…………….……………. *(5)*

(iii) **Q = WWF + (2 * DWF)** ……………………………………......... *(6)*

Estimated Population of people generating wastewater on NMAMIT Campus between 2010/2011 and 2013/2014 session are as shown on Table 1.

Table 1: The Estimated Population of NMAMIT Campus

Year/Session	*Estimated Population of Boarders*	*Estimated Population of Non-Boarders*	*Total Estimated population on campus*
2010/2011	1, 015	5, 258	6, 273
2011/2012	1, 699	4, 742	6, 441
2012/2013	1, 885	5, 069	6, 954
2013/2014	2, 156	5, 219	7, 375

From Table 1 which shows the estimated population on campus, the boarders include all who are fully resident in the Hostels and Quarters (*Staff and Students*), while the non-boarder estimates cover Staff, Students and Guests who generate wastewater as they spend only the working hours (*9am to 5pm daily*) on campus.

(d) Model development

According to the Bureau of Indian Standards (IS 1172:1993) the water demands for institutions are 135 litres per capita per day (hostel) and 45 litres per capita per day (non-boarders). These were taken into consideration in the application of equations (1) to (6) above to develop the model. The model equations were coded in the Visual Basic language. The variables were either defined or quantified as key elements of the model. As soon as the parameters and the initial values for the State Variables (Stocks) were specified, the model became definitively determined through the program. STELLA 9.0 software and simulation package was employed in the development of the stock flow diagram of the system. The principles of SD were applied to determine the interrelationships of P with the WS and sewage flow. Causal loops indicating the linkage of P, SF, I and t_c to Q were developed. Figure 3 shows the STELLA flow diagram of the model.

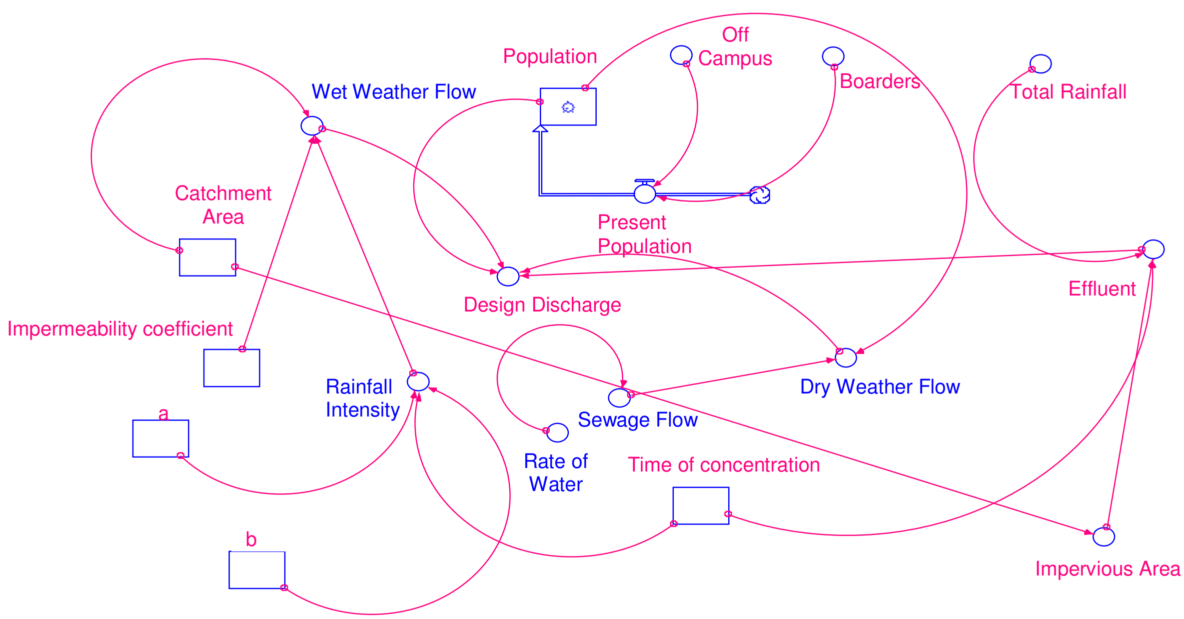

Figure 3: The Stella Flow diagram of the design

The figure connects the key variables of population to the main output which is the Design Discharge, Q. The Rational Formular (RF) and Lloyed Davis Formular (LDF) were alternately employed in the design discharge optimization, hinged basically on P. The flexibility of the model is strongly hinged on P; negative P designed using LDF, while the positive P used RF. The model validation is considered necessary so as to compare the model results with historical data, and to check whether the model generates plausible behaviour. The developed model was validated by applying it in solving the practical problems of various Q values, using data from the study area until the optimized Q value is obtained.

3.0 Results and Discussion

The SD model outputs for the 2 methods are as presented in Figures 4 to 8 (RF method outputs) and Figures 9 to 13 (LDF outputs). From the RF outputs, it is observed that population increase is directly related to Q and DWF. The RI and the WWF are kept constant under the DWF condition. The design discharge is a function of the time of concentration. This explains the reason why its value is noted to be generally lower at the DWF when time of concentration reduces. Both Q and E are directly proportional all through the RF method. In LDF scenario however, it is only the RI, DWF and WWF relationships which are directly proportional, where DWF increases with the time.

The optimum DWF and WWF in the RF were 111 and 412 litres/sec, while in the LDF they were 103 and 412 litres/sec respectively. The optimum effluent design discharge according to the RF from the model is 637 litres/sec while from the LDF it was 617 litres/sec. Considering the ratios, in the RF the DWF/WWF ratio gives (111/412) which is 1:3.7 while in the LDF the ratio is (103/412) which is 1:4. Since this ratio is not very large, it is preferable to use a combine sewer system for the study area.

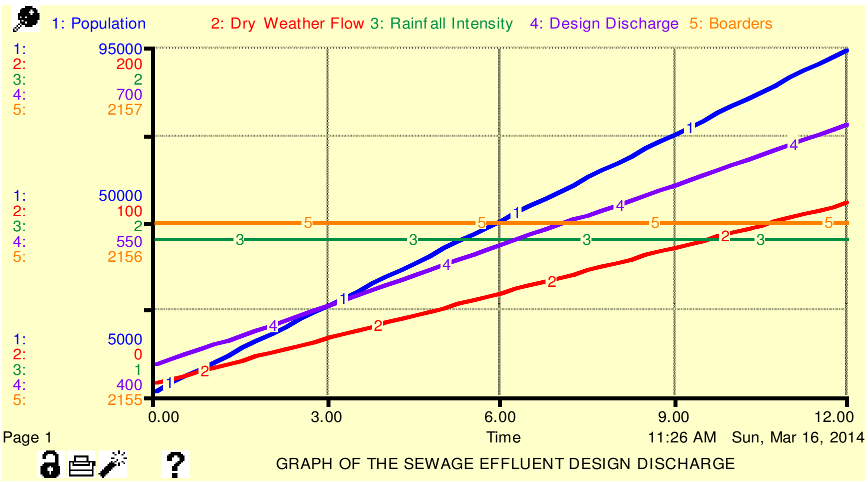

Figure 4: The graph relating design discharge and the key input parameters in RF method

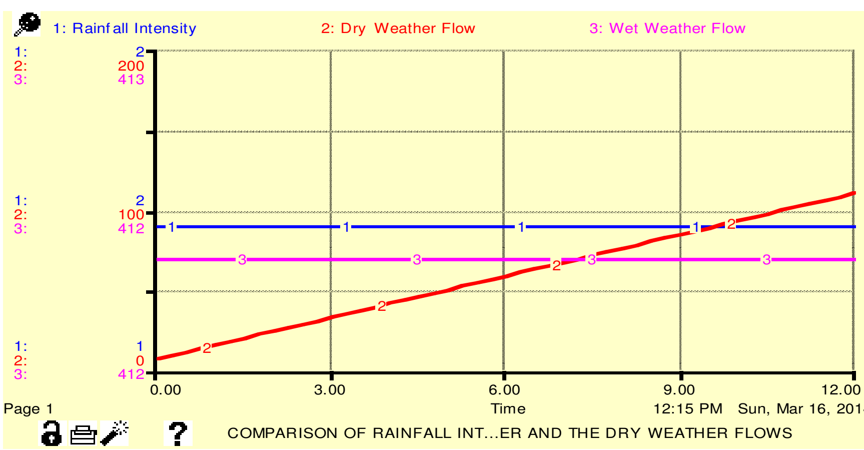

Figure 5: The graph relating Ri, DWF and WWF in RF method

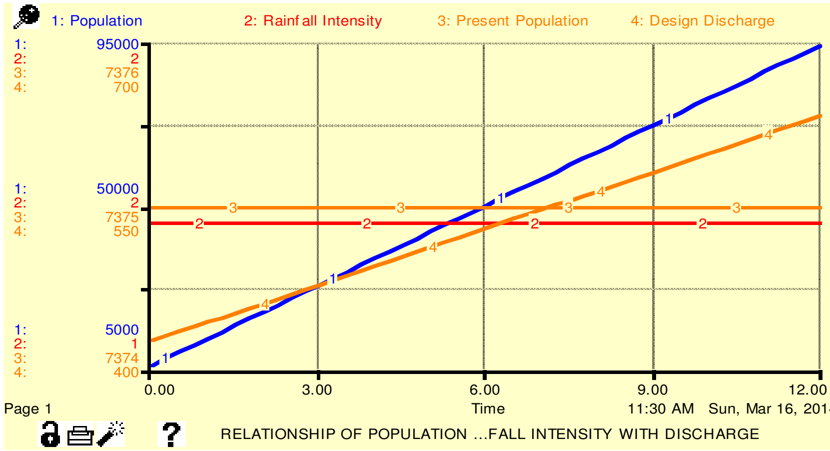

Figure 6: The graph relating Ri, P and Q in RF method

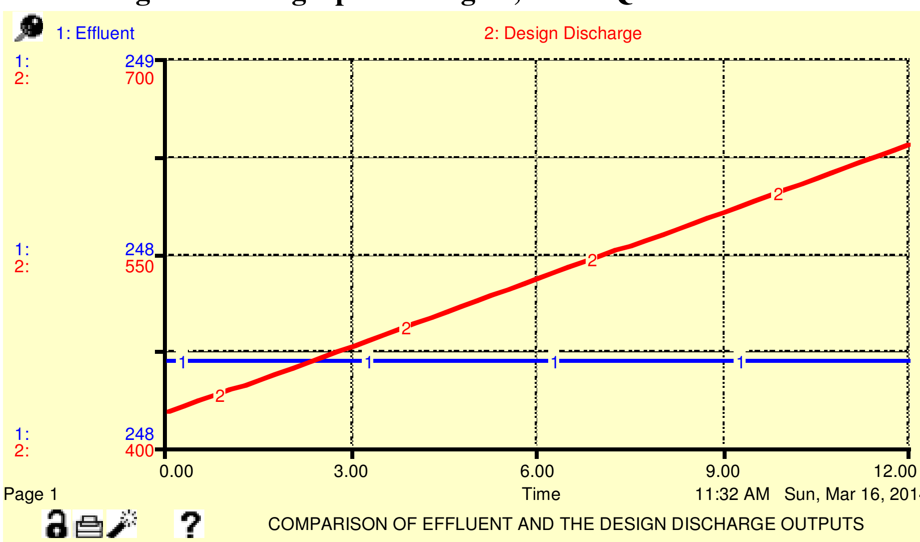

Figure 7: The graph relating E and Q in RF method

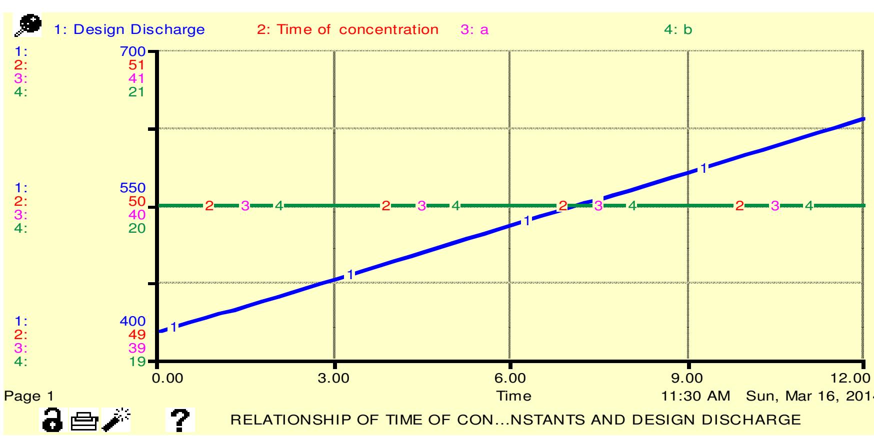

Figure 8: The graph relating Q, t_c and the constants in RF method

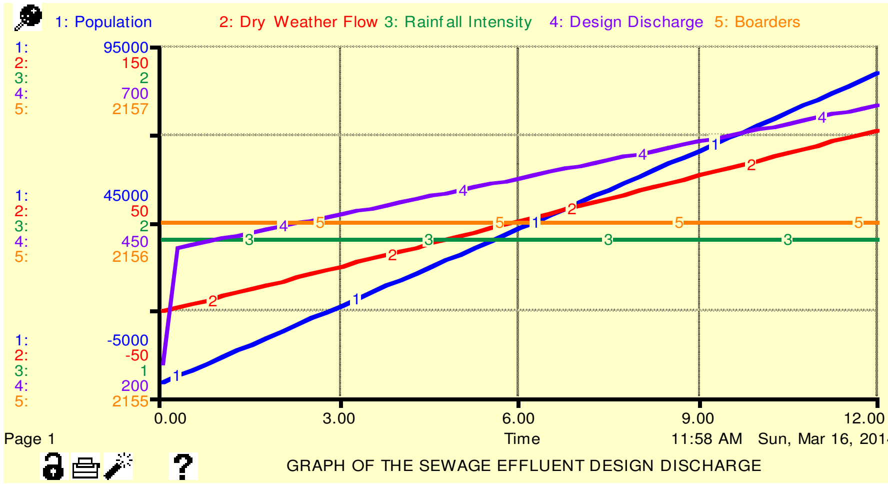

Figure 9:The graph relating design discharge and the key parameters in LDF method

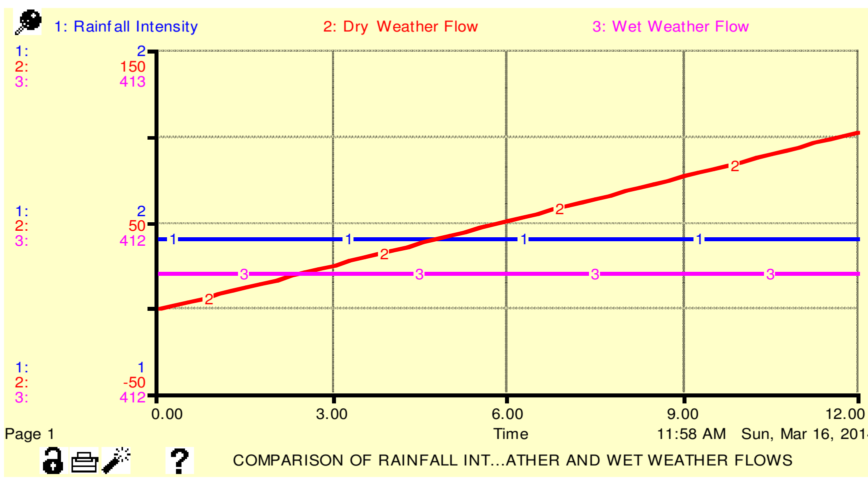

Figure 10: The graph relating Ri, DWF and WWF in LDF method

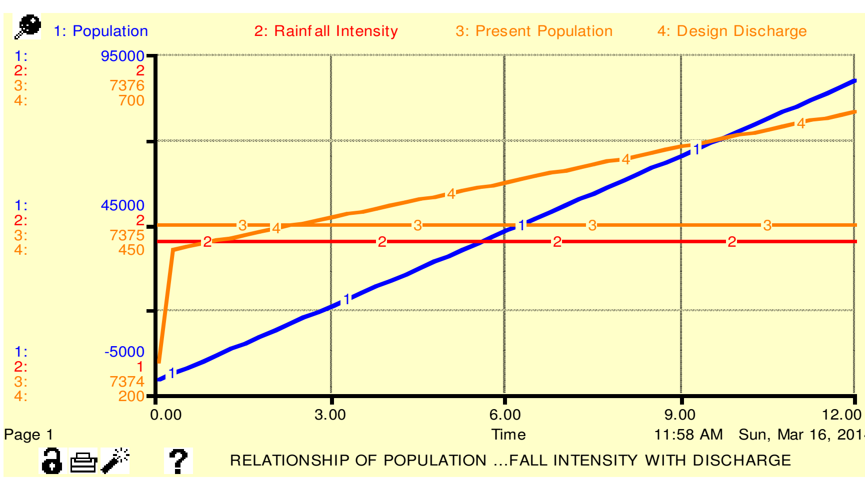

Figure 11: The graph relating Ri, P and Q in LDF method

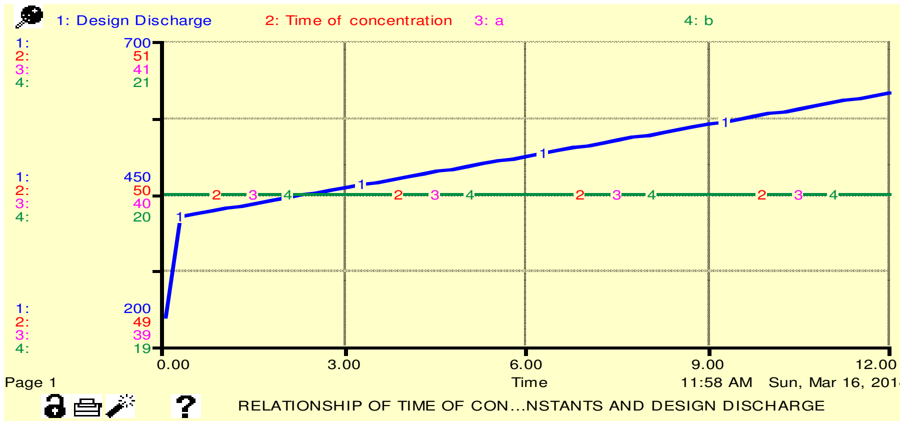

Figure 12: The graph relating Q, t_c and the constants in LDF method

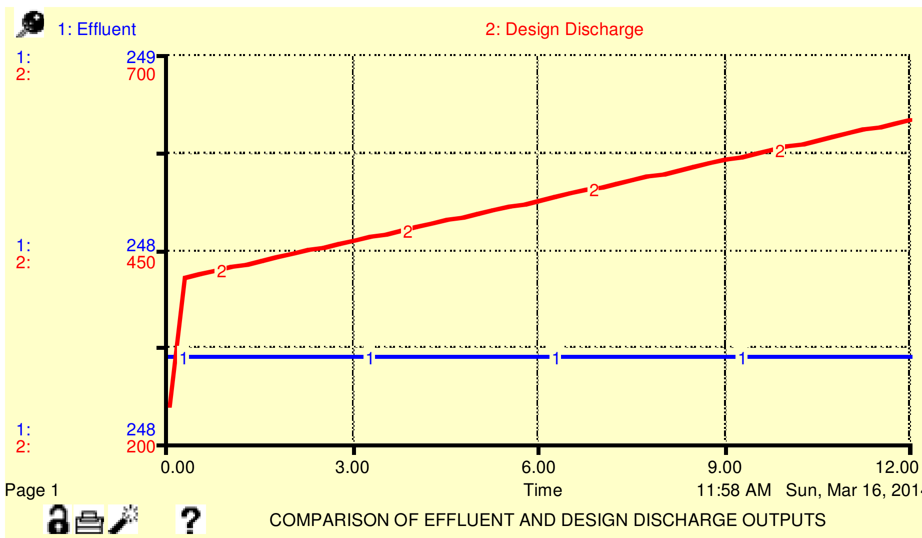

Figure 13: The graph relating E and Q in LDF method

4.0 Conclusion

The study has applied the principles of System Dynamics (SD) for the optimization of sewer effluent design discharge. Rational Formular (RF) and Lloyed Davis Formular (LDF) methods were both employed with the Population status as the determinant input. The optimum DWF and WWF in the RF method were 111 and 412 litres/sec, while in the LDF they were 103 and 412 litres/sec respectively. The optimum effluent design discharge obtained for the RF and LDF methods were 637 litres/sec and 617 litres/sec respectively The DWF/WWF ratio was found as 1:4. The study therefore recommends combine sewer system for the study area.

5.0 References

[1] SDS, The Field of System Dynamics. System Dynamics Society (2011). Accessed online on January 10, 2014 at http://www.systemdynamics.org/what_is_system_dynamics.html

[2] B. Dyson and N. Chang, Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling, Waste Management, 25 (2005), p 669-779.

[3] K. Vizayakumar and P.K.J, Mohapatra, Environmental impact analysis of a coalfield. J. Environ. Manage. 34 (1991), 73–93.
[4] K. Vizayakumar and P.K.J. Mohapatra, Modeling and simulation of environmental impacts of a coalfield: system dynamic approach. J. Environ. Manage. 42 (1993), 59–73.
[5] M. Vezjak, T. Savsek, and E.A. Stuhler, System dynamics of euthrophication processes in lakes. Eur. J. Oper. Res. 109 (1998), 442–451.
[6] A. Ford, Modeling the Environment. Island Press, Washington, DC, USA, 1999.
[7] T.S. Wood and M.L. Shelley, A dynamic model of bioavailability of metals in constructed wetland sediments. Ecol. Eng. 12 (1999), 231–252
[8] M.D. Abbott and R.S. Stanley, Modeling groundwater recharge and flow in a upland fracture bedrock aquifer. Syst. Dynam. Rev. 15 (1999), 163–184.
[9] M.L. Deaton and J.J. Winebrake, Dynamic Modeling of Environmental Systems. Springer-Verlag, New York, USA, 2000.
[10] H.C. Guo, L. Liu, G.H. Huang, G.A., Fuller, R., Zou, and Y.Y. Yin, A system dynamics approach for regional environmental planning and management: a study for Lake Erhai Basin. J. Environ. Manage. 61 (2001), 93–111.
[11] J.W. Forrester, Industrial Dynamics. The MIT Press, Cambridge, Massachusetts, USA, 1961.
[12] J.W. Forrester, Principles of System. Cambridge, Massachusetts, Productivity Press, MA, 1968.
[13] J. Randers, Elements of the System Dynamics Method. Cambridge, Productivity Press, MA, 1980.
[14] G.P Richardson and A.L. Pugh, Introduction to System Dynamics Modeling with DYNAMO. Cambridge, Productivity Press, MA, 1981.
[15] M.A. Sufian, Planning for Urban Solid Waste Management: The Case of Dhaka City. Unpublished M.S. Thesis, Dept. of Farm Power & Machinery, Bangladesh Agricultural University, Mymensingh, December, 2001.
[16] A.N. Mashayekhi, Transition in New York State solid waste system: a dynamic analysis. Syst. Dynam. Rev. 9(1993), 23–48.
[17] V. Sudhir, G. Srinivasan, and V.R. Muraleedharan, Planning for sustainable solid waste in Urban India. Syst. Dynam. Rev. 13 (1997), 223–246.
[18] V. Karavezyris, K. Timpe, and R. Marzi, Application of system dynamics and fuzzy logic to forecasting of municipal solid waste. Math. Comput. Simulat. 60 (2002), 149–158.
[19] M.D. Abbott and R.S. Stanley, Modeling groundwater recharge and flow in a upland fracture bedrock aquifer. Syst. Dynam. Rev. 15 (1999), 163–184.
[20] B.K. Bala, Principles of System Dynamics. Agrotech Publishing Academy, Udaipur, India, 1999.
[21] S.O Ojoawo, The flexibility and Versatility of System dynamics technique in optimization of sewer effluents in NMAMIT Nitte, India. Proceedings of the International Conference on Modeling, Optimization and Computing, held at Kumaracoil, Tamil Nadu State, India, April 2014, pp 217 - 226
[22] B.C. Punmia, A.K. Jain, and A.K Jain, Wastewater Engineering. Laxmi Publications Ltd, New Delhi, 2012, p 30-36.