Research progress of the non-point source pollution-based rainwater treatment technologies for urban and agricultural

Jianguang Wang[1,2,3*], Shiyi Li[1,3], Haifeng Fang[1,3], Shengjie Fu[1,3], Feng Ying[1,3], Xiaohu Lin[1,3]

[1] Huadong Engineering Corporation Limited of Power China, Hangzhou, China,
[2] National Engineering Laboratory for Advanced Municipal Wastewater Treatment and Reuse Technology, Beijing University of Technology, Beijing 100124, P. R. China
[3] Huadong eco-environmental Engineering Research Institute of Zhejiang Province

Abstract. Currently, the treatment of point source pollution has been basically com-pleted, and the development of non-point source pollution(NPP) has become a new threat to natural water. Unlike point source pollution, NPP is much more complex than point source pollution in terms of treatment difficulty and treatment measures. Therefore, NPP has gradually become the focus of researchers' attention. This paper mainly reviews the current research status on the governance of NPP, precisely urban source and agricultural source pollution governance. In addition, the article reviews the treatment measures of NPP at the present stage, from source treatment, process blocking and end-of-pipe treatment. This thesis provides a more comprehensive overview of NPP treatment measures, which can provide a reference for further research and development of engineering practices on NPP.

1. Introduction

With the accelerated urbanization process, polluted runoff has become the main factor that endangers the water quality of urban rivers and lakes. Polluted runoff belongs to non-point source pollution(NPP) and has a high pollution index, espe-cially the initial rainwater even exceeds the pollution level of urban domestic sewage to the environment[1, 2]. Runoff pollution(RP) is divided into the urban source and agricultural source pollution. Urban source RP occurs in cities due to the weakened permeability of the subsurface and the formation of polluted rain-water by rainfall scouring; agricultural source RP refers to polluted rainwater formed by residual pesticides, fertilizers, and farming manure by rainfall scour-ing[3]. NPP can be divided into source control, migration control, and end-of-pipe treatmen[4]. Source control is to reduce the runoff volume by improving the per-meability of the subsurface on the one hand and to reduce the pollutant content in the runoff by reducing the pollutants on the subsurface on the other hand; mi-gration control is achieved by building storage facilities; end-of-pipe treatment is to discharge after centralized treatment using wastewater treatment facilities.

In contrast to other reviews that discuss single RP control techniques, this review provides an overview of the current research status on NPP and various measures for NPP treatment to provide a basis for further research and NPP treatment.

2. The study of runoff pollution characteristics

Studying RP characteristics is the basis for carrying out treatment. Based on many studies, the RP characteristics generally agreed upon by researchers can be summarized as the following six points[1, 5].

(1) Having the dual characteristics of the non-point and point pollution

Pollutants accumulate in the dry season and enter natural water with precipitation in the rainy season, which has the characteristics of non-point discharge; pollut-ed rainwater enters the urban drainage system and is transported to sewage plants or is discharged directly, which also has the characteristics of point pollution.

(2) The spatial and temporal distribution of pollution sources is discrete and heterogeneous

Pollutants are distributed over the entire catchment area or on the subsurface and are affected by various deterministic and random factors, showing the characteristics of uneven distribution.

(3) Complexity and variability of pollution components

The composition of pollutants in runoff of different regions is affected by many factors, such as pollution source distribution, surrounding land use condi-tions, atmospheric pollution conditions, rainfall characteristics, cleaning condi-tions, and urban treatment level, showing complex and variable characteristics.

(4) Spatial and temporal variability of pollution load

*wang_jg7@hdec.com

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

Many factors influence urban surface runoff, and the spatial and temporal var-iability of pollution load is large. This variation is manifested in different land use functional areas with different runoff pollution loads and in the wide varia-tion of runoff pollution loads in different fields in the same area.

(5) Difficulty in monitoring

Due to the above characteristics of urban surface runoff and the randomness of rainfall events, there are many difficulties in field monitoring runoff pollution, which is laborious and time-consuming.

(6) Systematic control strategy

The randomness of urban surface RP is inconvenient to be controlled by con-ventional point pollution treatment, and a multi-angle, multi-level, multi-link system control strategy should be adopted.

3. Runoff pollution research status

The following four main areas are covered throughout the decades of domestic and international research on RP.

3.1 Basic tests of pollutant sources, components, and concentrations in RP

Studies have shown that RP pollutants are mainly derived from traffic source emissions, pollutants in precipitation, and atmospheric deposition. Pollutant evaluation indicators include suspended particulate matter (SS), heavy metals, mineral oils, total phosphorus (TP), nitrogenous compounds (NH_3, NO_X^-) chlo-rides, and organic substances such as polycyclic aromatic hydrocarbons. The general representative evaluation indexes are SS, COD, TP, NH_3, and total nitro-gen[6].

3.2 Study of RP load, influencing factors, and prediction models

Pollution load is an essential concept in runoff pollution studies. Therefore, studying pollution load and the prediction models have become critical issues in roadway RP. Due to the difficulty of runoff monitoring, researchers have tried to establish mathematical models that can predict RP load by analyzing the factors affecting RP based on monitoring several field runoff events. The Study shows that RP is related to geographical features, atmospheric pollution status, rainfall amount and intensity. However, there are controversies regarding the effects of traffic volume, pre-sunny daytime, and watershed area on pollution loads, and different studies even get contradictory conclusions. Based on identifying factors influencing RP, the researchers use mathematical methods to establish mathemat-ical models for predicting runoff pollution loads.

3.3 Study of pollutant accumulation, flushing patterns, and runoff water quality models

In addition to monitoring RP areas, the researchers investigate the mechanism of pollutant accumulation and flushing. Based on hydrological and hydraulic mod-els, researchers have added RP elements to urban drainage models and applied them in urban drainage system planning, RP load calculation, and analysis of the impact on natural water. The classic models are the SWMM model[7], STORM developed by the American Society of Engineers[8], MOUSE model developed by the Danish Hydraulic Research Center[9], and Infoworks CS model developed by a British company[8], which have been widely used and achieved good results in urban drainage system planning, design, treatment, and nonpoint source pollution control.

3.4 Research on urban RP control measures

Developed countries have generally recognized the seriousness of urban RP and started to control it. Among them, the most famous is the Best Management Prac-tices (BMPs) developed in the United States, which include all methods, measures, or operational procedures, including non-engineering management, engineering measures, and maintenance procedures[10]. The study showed that vegetation control, wet detention basins, infiltration systems, and wetlands are practical measures that can significantly reduce the pollution load of pavement runoff and its impact on natural water[11]. The vegetated channels have a good retention effect on heavy metals in pavement runoff, especially in the ionic state, and their removal efficiencies for Zn, Pb, Ni, and Cr are 62%, 57%, 51%, and 43 %[12].

4. Research status on urban runoff pollution control measures

4.1 In-situ treatment

The self-purification ability of rivers and lakes can realize the natural purifica-tion of polluted rainwater from the confluence. Most cities containing water sys-tems collect polluted rainwater through rainwater pipes and then discharge it directly into water systems, bringing more significant environmental pressure to rivers and lakes. The self-purification capacity of rivers and lakes is limited, and the self-purification capacity of rivers and lakes will be far exceeded if polluted rainwater is continuously collected. Therefore, the existence of urban rainwater discharging directly into rivers is very likely to cause pollution, and the mainte-nance time is short through treatment, which is a way to treat the symptoms but not the root cause[13]. In-situ treatment methods are no longer suitable for the current environmental quality needs.

4.2 Wastewater plant treatment

4.2.1Urban wastewater treatment plant treatment

Retaining and conveying pollut-ed rainwater to wastewater treatment plants(WWTPs) is an effective treatment method. Sewage plants adopt different treatment methods on rainy and sunny days, ensuring the water quality of sewage treatment on sunny days and treating polluted rainwater on rainy days[14]. However, as the core infrastructure for treat-ing urban domestic sewage, WWTPs are more challenging to handle a large amount of polluted rainwater in the rising domestic sewage generation. Polluted rainwater has different types and concentrations of pollutants compared with domestic sewage, and polluted rainwater will significantly impact the treatment process of WWTPs during the rainy period. In addition, rainwater pipeline trans-portation improves operating costs and easily triggers secondary pollution. Based on the above, many places have established larger rainwater treatment plants for treating polluted rainwater.

4.2.2 Rainwater treatment plant

In China, the polluted rainwater treatment plant concept is less mentioned, and only a few engineering cases can be referred to. Zhou et al.[15] designed a polluted rainwater treatment plant with a treatment scale of 30,000 m^3/d in the comprehensive improvement project of the Wuhan Huxi River. The plant adopts the operation alternating operation mode of treating rainwater in the rainy season and polluted lake water in the dry season. The pri-mary process is a high-efficiency sedimentation tank, which mainly removes SS and TP from polluted rainwater by physicochemical methods.

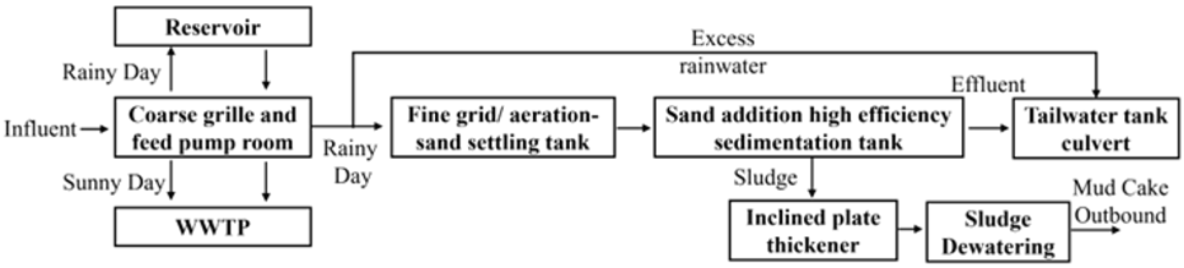

Fig 1 A rainwater treatment plant process[16]

4.3 Artificial wetland process

The artificial wetland method is better for treating low-concentration sewage, especially polluted rainwater. Establishing artificial wetlands in the front section of natural water bodies is a feasible method. For example, Kunming built an arti-ficial wetland at the exit of a river to treat river and canal sewage, the scale of the project is 2000 m^3/d, covering an area of about 16.7 hm^2, and the effluent quality is stable. However, the large footprint of the artificial wetland process also makes it impossible to be widely used.

4.4 Other treatment processes

4.4.1 High-efficiency sedimentation tank+fiber bundle filter tank

Chen et al.[17] studied a polluted rainwater treatment process combining a highly efficient sedi-mentation tank and filter tank, verifying the removal effect of the primary rain-water treatment station on COD_{Cr}, BOD_5, TP, and NH_3-N. The results showed that its treatment efficiency was stable, and the effluent water quality met the stand-ards. However, in the actual operation process, it was also found that the high-efficiency sedimentation tank has high energy consumption and a more compli-cated operation. Meanwhile, the filter tank is more complicated to fill and easy to plate, increasing the operating costs.

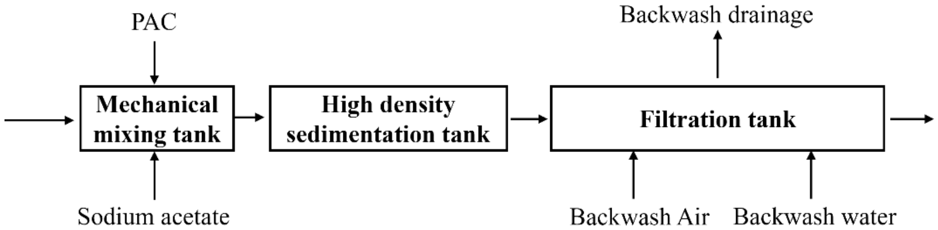

Fig 2 Process chart

4.4.2 Biological aerated filter (BAF)

BAF is a new wastewater treatment technology that combines biological contact oxidation and biofilm method with the functions of efficient removal of contaminants[18]. Hu et al.[19] used BAF as the main treat-ment process for polluted rainwater in the treatment project in the old urban area of Feixi County, Hefei, with the design effluent indexes of NH_3-N $\leqslant$ 2.0 mg/L, COD_{cr} $\leqslant$ 40 mg/L, TP $\leqslant$ 0.3 mg/L, and SS $\leqslant$ 10, and the effluent was discharged into the upstream recharge of Nanchong River. However, the BAF is prone to clogging due to the large SS in the influent water, which increases the backwashing fre-quency, and the resulting backwashing water is also prone to secondary pollu-tion.

4.4.3 Biological contact oxidation(BCO)

BCO is a process between the activated sludge method and biofilter that can remove contaminants. However, the BCO process also suffers from problems such as long snails, filler mud accumulation, structural damage, and buildup[20]. For the poor biochemical performance of pol-luted rainwater and large fluctuations in water quality and quantity, using the contact oxidation process alone does not give good treatment results and needs to be combined with other processes. Liu et al. studied the highly efficient cyclonic separation/ecological integral BCO method to treat polluted rainwater, and the results showed that the combined treatment unit achieved more than 91.8%, 84.56%, 59.61%, 79.58%, and 67.41% removal of SS, COD, TN, nitrogen, and TN, achieving effective treatment of polluted rainwater[21].

4.4.4 Coagulation and sedimentation

Researchers believe the simplest way to treat rainwater is to use the coagulation-precipitation method. Ren et al. used coagula-tion-ultrafiltration technology to treat rainwater in South China. Using coagula-tion as a pretreatment measure to efficiently remove contaminants by combining with ultrafiltration, the turbidity removal rate turbidity can be improved, and phosphorus can be effectively removed[22]. Ren et al.[23] used PAC as a coagulant to treat polluted rainwater and found that coagulation could remove 50%-60% of COD_{Cr} and 50%-90% of TP from pollutants at optimal dosing levels to achieve better effluent results.

5. Research status on agricultural RP treatment

Common agricultural runoff treatment measures include artificial wetlands, eco-logical ditches, and purification ponds.

5.1 Ecological ditch

The ecological ditch is an ecological interception technology implemented for agricultural runoff rainwater. This technology is mainly through the ecological transformation and functional enhancement of existing drainage ditches or addi-tional construction of ecological engineering, using a combination of physical, chemical, and biological effects to enhance the purification and advanced treat-ment of pollutants. The ecological ditch mainly consists of an engineering part and a plant part. The engineering part refers to the engineering transformation of the ditch walls and bottom on both sides, while the vegetation part stabilizes the slope, fixes the soil, and absorbs and purifies the rainwater. The ecological ditch has the advantages of low cost, good landscape effect, and high ecological bene-fit.

5.2 Purification Ponds

The purification pond is a special aquatic ecosystem composed of dominant plants. The system achieves the purpose of sewage purification through the ad-sorption and sedimentation of aquatic plant communities. Since different plants have different absorption effects on different pollutants due to their physiologi-cal characteristics, the purification pond is developed from one kind of plant to a variety of plants to give full play to the advantages of various plants to achieve the best purification effect.

5.3 Ponding system

The pond system is mainly used for water storage irrigation and retaining initial rainwater runoff by many shallow ponds and ditches in series, with high retention and purification efficiency.

5.4 Buffer Strips

Buffer strips are protected land that use permanent vegetation to hold back pollu-tants or hazardous substances. Buffer strips are a general term for a class of bio-logical treatment measures for water master conservation and NPP control. Buffer strips are also known as riparian buffer strips, vegetated filter strips, riparian buffer strips, vegetated buffer strips, and conservation buffer strips.

6. Conclusion

Currently, the treatment of point source pollution has been basically com-pleted, and the development of NPP has become a new threat to natural water. Unlike point source pollution, NPP is much more complex than point source pollution in terms of treatment difficulty and treatment measures. The RP characteristics should be a prerequisite before carrying out NPP treatment efforts. The NPP can be divided into agricultural sources and urban sources. Agricultural NPP control measures include ecological ditches, purification ponds, ponding systems, and buffer strips. Urban source NPP control measures mainly include in-situ treat-ment, wastewater plant treatment, artificial wetland processes, and other combi-nation processes. This thesis provides a more compre-hensive overview of NPP treatment measures, which can provide a refer-ence for further research and de-velopment of engineering practices on NPP.

Acknowledgments

This work was financially supported by the research on runoff pollution reduc-tion technology and comprehensive efficiency assessment system based on urban pipe network system (KY2022-HS-02-20).

References

[1] Li L Q, Yin C Q, He Q C, et al. Progress of research on pollution sources and discharge characteristics of urban precipitation runoff(in Chinese)[J]. *Advances in Water Science*, 2006(02): 288-294.

[2] Sansalone J J, Cristina C M. First Flush Concepts for Suspended and Dissolved Solids in Small

Impervious Watersheds[J]. *Journal of environmental engineering* (New York, N.Y.), 2004, 130(11): 1301-1314.

[3] Zhao J. Analysis of the current situation and countermeasures of agricultural surface source pollution prevention and control(in Chinese)[J]. *Farm Counselor*, 2022(01): 37-39.

[4] Zhang Y. Research on urban initial rainwater pollution treatment technology(in Chinese)[J]. *Anhui Agronomy Bulletin*, 2020, 26(21): 141-143.

[5] Chen Y C, Li Z P, Li Z C, et al. Urban non-point source pollution and its reduction in the whole process(in Chinese)[J]. *Journal of Soil and Water Conservation*, 2004(03): 133-136.

[6] Chen Y. Research on the characteristics of road non-point source pollution and control technology in Xi'an(in Chinese)[D]. *Chang'an University*, 2011.

[7] Epa U. Modeling of nonpoint source water quality in urban and non-urban areas[J]. 1991.

[8] Zhou Y C. Study on the application of the hydraulic model in the design and management of urban drainage system(in Chinese)[D]. 2008.

[9] B U. Storm water best management practice and detention for water quality,drainage,and CSO management[J]. 1993.

[10] Usepa. Results of the nationwide urban runoff program[J]. *US Environmental Protection Agency*, 1983.

[11] Brunomaestri, Lord B N. Guide for mitigation of highway stormwater runoff pollution[J]. *Science of The Total Environment*, 1987.

[12] Yousef Y A, Hvitved-Jacobsen T, Wanielista M P, et al. Removal of contaminants in highway runoff flowing through swales[J]. *Science of The Total Environment*, 1987, 59: 391-399.

[13] Wu Z B, He F. Application of aquatic plants in wastewater treatment and water quality improvement(in Chinese)[J]. *Botanical Bulletin*, 2003(06): 641-647.

[14] Wang B. Exploring the technical route of urban initial rainwater treatment(in Chinese)[J]. *China Resource Comprehensive Utilization*, 2018, 36(05): 31-32.

[15] Zhou C T, Guo K X, Zhao G Z. Initial stormwater in-situ storage and treatment engineering program(in Chinese)[J]. *Water Purification Technology*, 2020, 39(8): 44-48.

[16] Yang M, Wang B, Zhang F, et al. Design of a rainwater treatment plant around South Lake, Wuhan(in Chinese)[J]. *Water and Wastewater Engineering*, 2021, 57(08): 56-60.

[17] Chen C, Dong Z H. Study of pollutant removal efficiency of initial rainwater treatment stations(in Chinese)[J]. *Shanxi Construction*, 2016, 42(29): 116-117.

[18] Tang S Y, Zhou R J, Zhong H W, et al. Research progress of aeration biofilter technology(in Chinese)[J]. *Modern Chemical*, 2013, 33(2): 24-27.

[19] Hu Y. Process design plan for initial rainwater treatment plant in the old city of Feixi County, Hefei(in Chinese)[J]. *Water Purification Technology*, 2019, 38(07): 47-51.

[20] He S S, Chen C G, Liu H Y, et al. Application of biological contact oxidation process in municipal water supply(in Chinese)[J]. *Water Purification Technology*, 2021, 40(S1): 60-65.

[21] Liu N N, Chi J, Chu Y W, et al. Application study of high-efficiency cyclone separation- ecological inter-gravel contact oxidation combined device to treat initial rainwater runoff(in Chinese)[J]. *Environmental Science and Management*, 2019, 41(09): 1043-1049.

[22] Ren G, Yu Y, Du Y M, et al. Effectiveness of coagulation-ultrafiltration in treating runoff rainwater - an example from South China(in Chinese)[J]. *Environmental Chemistry*, 2015, 34(06): 1142-1149.

[23] Ren Y L, Li M. Experimental study of coagulation treatment of rainwater(in Chinese)[J]. *Environmental Science and Management*, 2015, 40(04): 58-62.