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CATCHMENT WATER QUALITY MANAGEMENT PLANNING FOR SUSTAINABLE DEVELOPMENT OF TIDAL AREAS†

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ABSTRACT

Controlling the water quality of a freshwater reservoir that has been created by a tidal land reclamation project is never easy and presents great challenges to engineers and administrators. One of the major factors affecting the water quality of a freshwater reservoir created by tidal area development is pollution entering from catchment areas through rivers and streams. Pollution in a catchment is classified by two sources, point source and nonpoint source (NPS) pollution. Point source pollution must be eliminated by adopting cutting-edge treatment technologies, while NPS pollution is controlled and managed effectively by adopting best management practices (BMPs) in both rural and urban areas for a sustainable development of tidal areas. About 70% of total pollution is NPS pollution and strategies and policies need to be adopted to counter this. NPS pollution is mostly generated and transported by rainfall runoff and groundwater. It is very important to make every effort to minimize runoff during rainfall to reduce NPS pollution. Both runoff and groundwater qualities can be controlled and managed successfully by applying BMPs, enforcing strict legal requirements and supporting participatory catchment management activities. Principles of natural attenuation mechanisms must be applied together with BMPs to ensure the fast and effective decomposition and transformation of the pollutants removed by BMPs. In addition to technological approaches, systematic support for ongoing education, incentives, and legal enforcement of antipollution laws can all help to encourage participatory catchment management activities. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: catchment; water quality; point source pollution; NPS pollution; tidal area

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RÉSUMÉ

Le contrôle de la qualité de l'eau d'un réservoir d'eau douce qui a été créé au cours de la remise en état des terres en zones d'estran n'est jamais facile et présente de grands défis pour les ingénieurs et les administrateurs. L'un des principaux facteurs affectant la qualité de l'eau de tels réservoirs d'eau douce est la pollution par les rivières et les ruisseaux. La pollution dans un bassin versant est classée en pollution ponctuelle et en pollution diffuse. La pollution ponctuelle doit être éliminée par l'adoption de technologies de traitement de pointe alors que la pollution diffuse est contrôlée et gérée efficacement par l'adoption de meilleures pratiques de gestion (PGB) dans les zones rurales et urbaines. Environ 70% de la pollution totale est la pollution diffuse et doit être contrée par des stratégies et des politiques adaptées. La pollution diffuse est principalement produite et transportée par le ruissellement des eaux météoriques et souterraines. Il est très important de ne ménager aucun effort pour minimiser le ruissellement lors des pluies afin de réduire la pollution diffuse. La qualité des eaux de ruissellement et souterraines peut être contrôlée et gérée avec succès par l'application des PGB, l'application d'exigences légales strictes et en soutenant des actions participatives de gestion des bassins. Les principes des mécanismes d'atténuation naturelle doivent être appliqués conjointement avec des PGB afin d'assurer la décomposition rapide et efficace et la transformation des polluants enlevés par des PGB. En plus des approches technologiques, un soutien systématique à la formation continue, les incitations, le renforcement et l'application des lois antipollution peuvent contribuer à encourager les activités participatives de gestion des bassins versants. Copyright © 2013 John Wiley & Sons, Ltd.

MOTS CLÉS: bassin versant; qualité de l'eau; pollution ponctuelle; pollution diffuse; zone d'estran

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†Gestion de la qualité de l´eau à l'échelle d'un bassin versant pour la planification et le développement durable des zones d'estran.

INTRODUCTION

Tidal area reclamation projects are generally pursued where the demand for land needed for industry and agriculture is high. Such projects necessarily accompany the construction of sea dikes and freshwater reservoirs at the mouth of a river. As environmental concerns among citizens and civil activists increase, water quality management of the freshwater reservoirs becomes one of the key elements in the success of a tidal area reclamation project. The water quality of freshwater reservoirs created by tidal area reclamation projects is affected by many factors: pollution from catchment areas through runoff, a reservoir's primary production mostly by photosynthesis, dry and wet deposition from the air, and natural attenuation processes in streams and reservoirs. Organic sediment at the bottom of a reservoir may also play an important role in the deterioration of water quality if it exists in large quantities (United States Environmental Protection Agency (USEPA), 1993; Ki *et al.*, 2010). Of these factors, inhibiting pollution from a catchment area is considered critical in controlling freshwater reservoir water quality.

A catchment is an important physiographic property that affects the quantity and quality of runoff. Catchments vary widely depending on the size of a river. In general, the larger the catchment, the greater the runoff and the greater the point and nonpoint (diffuse) pollution expected. Of all the many pollutants, sediment, nitrogen (N) and phosphorus (P) are mostly responsible for aquatic habitat deterioration, algal blooming, and eutrophication, and considered the most important factors in the management of water quality and aquatic ecosystems. These pollution sources may be categorized into four groups: wastewater treatment plants (WWTPs), agriculture, developed urban areas and forests. The proportion of N and P loadings from the four pollution sources in Maryland and Virginia, in the USA, are shown in Table I (Batiuk and Koroncai, 2009a, 2009b).

Table I shows that non-point source (NPS) pollution from agriculture, forests and developed urban areas contributes 74–75% of N and 80–82% of P to total pollution loadings. The Korean government estimated that the proportion of NPS pollution to total pollution was about 35–50% before 2007 but will increase by as much as 70% by 2015 as point source pollution is treated and reduced in WWTPs (Ministry of Environment (MOE), 2006). It means that even if point source pollution is well treated, the goal of freshwater reservoir water quality management at the mouth of a river may be doomed to fail if NPS pollution is not effectively managed by means of catchment water quality management. The objective of this paper is to briefly describe the principles, strategies, and effects of land use on runoff quality required to prudently manage catchment area water quality.

AN EXAMPLE OF FRESHWATER RESERVOIR MANAGEMENT

Most of the freshwater reservoirs formed by tidal land reclamation projects in Korea have experienced serious water quality problems since their formation. A typical example is Lake Sihwa. The lake's water quality degradation could not be arrested and the government had to abandon maintaining a freshwater reservoir simply because point and NPS pollution from the lake's catchment area was not treated or managed effectively. The lake is no longer a freshwater lake because seawater regularly circulates through tidal gates. However, the limited seawater circulation through the tidal gates cannot improve the water quality enough to meet water quality standards. It is because the tidal gates are located at a remote corner of the sea dike and the circulation is not sufficient to mix and replace polluted freshwater with seawater, especially in the upper area of the lake. One way of increasing seawater circulation and improving the water quality is to build new tidal gates in the middle of the dike. And the Korean government decided to build a large tidal electric power plant instead of tidal gates to generate electricity and increase seawater circulation. It cost more than US$3 billion. The power plant was completed in August 2011 and the average chemical oxygen demand (COD) of the lake is expected to improve from 3.7 to 2 mg l^{-1} which is the quality mandated for water-friendly activities such as boating and water skiing in Korea (Seok, 2011; Yoon, 2011).

One of the objectives of this tidal land reclamation project was to supply fresh water to adjacent industrial and agricultural areas by forming a freshwater reservoir. But because of failure in catchment water quality management, the reservoir can no longer be used as a source of freshwater supply. If no alternative freshwater source is found, the project could be an environmental disaster. This is a typical example of

Table I. Proportion (%) of N and P loadings from the four sources in Maryland (Md) and Virginia (Va), USA

	Nitrogen (%)				Phosphorus (%)			
State	WWTP	Agriculture	Urban area	Forest	WWTP	Agriculture	Urban area	Forest
Md	25	36	29	10	20	39	33	8
Va	26	38	20	16	18	50	18	14

freshwater reservoir quality failure caused mainly by poor catchment water quality management. The water quality management failures in Sihwa freshwater lake and other large rivers in Korea have caused the Ministry of Environment (MOE) (2004) to develop a nationwide and comprehensive total maximum daily load (TMDL) policy as a tool for catchment water quality management. The TMDL began in 2004 in the catchment of the Nakdong River and has been expanded to the catchments of four major rivers in Korea. Under the TMDL, all pollution sources are tightly managed and controlled to reduce waste loads to water bodies and improve water quality. The TMDL could be a typical and successful catchment management tool and be referred as an example for catchment management of a new tidal area development project.

STRATEGIES FOR CATCHMENT MANAGEMENT

Sources of pollution from a catchment area can be divided into two major categories: point source pollution and NPS pollution. Point source pollution is pollution whose quantity and quality are known or easily measured and analyzed. NPS pollution is pollution whose quantity and quality are not easily measured or analyzed because it is generated and transported mostly by rainfall runoff and groundwater to streams and reservoirs. It is clear that both point source and NPS pollution must be managed properly to successfully ensure the water quality of a freshwater reservoir. Point source pollution in the catchment of a tidal reclamation project can be eliminated or minimized by applying stringent and legally enforceable rules and adopting cutting-edge waste and wastewater treatment systems before the project is completed. However, neither legal nor water treatment systems can easily manage or control NPS pollution. Many factors such as rainfall amounts and intensity, waste collection and cleaning of urban areas, crops, agricultural practices, soil texture, and topography affect NPS pollution (Foster, 1982). Many of these factors are natural phenomena and not easy to control manually. Therefore, reduction of NPS pollution requires a concerted effort by residents, farmers, engineers, experts, and administrators to adopt and implement best management practices (BMPs) to mitigate the effects of natural phenomena (Gale *et al*., 1993). It is concluded at this point that the first and the most important strategy to control catchment pollution is to control point source pollution by adopting the most efficient waste and wastewater treatment technologies and enforcing legal systems.

Catchment management is one of the most important alternatives for controlling NPS pollution from both urban and rural areas. Monitoring and modelling data can play an important role in persuading residents to undertake catchment management activities and in helping them adopt BMPs. It is well accepted that land use is closely related to groundwater quality, which in turn is closely related to stream water quality and, therefore, land use is directly related to stream water quality. Figure 1 shows the relationship between shallow groundwater and adjacent stream water quality (Choi *et al*., 1999). Catchment management begins with proper land use and management of potential pollution sources by BMPs. The ultimate goal of catchment management is to improve catchment water quality and to eventually improve the water quality of the freshwater reservoir created by a tidal reclamation project.

Catchments can be managed effectively and economically by encouraging participatory waste management and technology transfer programs and by establishing administrative systems to support these programs. BMPs are typical examples residents can adopt to reduce NPS pollution. Because NPS pollution is extremely site-specific, it should be kept in mind that it is necessary to experimentally understand the processes and mechanisms that generate and transport NPS pollution before developing detailed NPS pollution control methods and policies. This means that one method can succeed at a particular site, but may not be applied to others. It can take a very long time to enlighten and persuade both residents and public workers in a large catchment area to join catchment management programs voluntarily (United States Environmental Protection Agency (USEPA), 1990). However, it must be understood that it is the most effective strategy and every administrative and technological effort should be exerted to encourage participatory catchment management with the aim of reducing pollution and improving water quality.

EFFECT OF LAND USE ON WATER QUALITY

Pollution from forests

The quality of stream water in natural forests may be considered as 'background' or 'natural' water quality. The concentrations

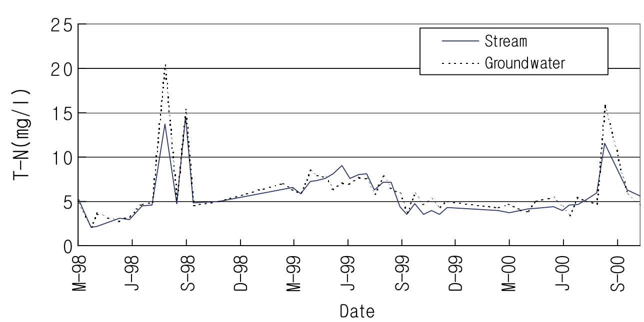

Figure 1. Relationship of total nitrogen (T-N) concentration between shallow groundwater and stream from a mountainous rural catchment in Korea

of NPS pollutants in forest streams might be lower than those in other streams and lakes in tropical and temperate regions. However, pollution from forests in terms of its total daily load might still be large, owing to the large coverage areas of forests; thus, they still can impact water quality management. Logging activities and forest roads must be well controlled and maintained in order to produce the minimum amount of pollution because they are the factors that most strongly influence stream water quality in forests (Irland, 1985; Jeong *et al*., 2001).

Pollution from upland fields

NPS pollution from upland fields is greater than that from any other agricultural land uses. Many factors, such as rainfall amounts and intensity, crops, agrochemicals, soil texture, slope and slope length, and management and conservation practices, contribute to NPS pollution from upland fields (Foster, 1982). As rural areas develop and young farmers leave for city jobs, elderly farmers tend to use more chemical fertilizers and pesticides to maximize agricultural yields, which increase the number and quantity of potential pollution sources. Many influential factors are not manually controllable and complicate efforts to reduce NPS pollution. Aggressive introduction of agricultural BMPs and supporting administrative policies for BMP adoption must be carried out in tandem with tidal area development planning. It also is clear that without minimizing NPS pollution from upland fields, efforts to control water quality in freshwater reservoirs created by tidal land reclamation projects might be doomed to fail.

Pollution from lowland (paddy) fields

NPS pollution from lowland paddy fields is generally less than that from other land uses (Oh *et al*., 2002). Pollution discharges from paddies tend to increase during the short transplanting season (Hwang *et al*., 2002; Yoon *et al*., 2003). Precise control of irrigation and drainage during this period can significantly reduce NPS pollution discharges to adjacent water bodies. Paddies also might serve as a constructed wetland and often improve the quality of irrigation water, as Table II shows (Oh *et al*., 2002). The hydraulic loading rate of a paddy is 7–8 mm day^{-1} and the depth is generally 3–10 cm, which are lower and shallower than those of common constructed wetlands designed for the treatment of wastewater or storm runoff from rural catchments (Chen *et al*., 1996). It usually results in longer retention time and slower velocity, which improves physical and biological attenuation conditions. A lowland paddy may also provide a good habitat and shelter for small birds such as waders and many other aquatic and wild animals during and after the growing season. Wide and spacious paddy fields created by the development of a tidal area may also provide comfortable shelters for migratory birds, enabling them to avoid the high waves and rapid tidal flows common to tidal areas. Irrigation and drainage canals create good ecological corridors between coastal areas, freshwater reservoirs, and paddy fields. Paddies therefore are considered the best use of land in terms of water quality management. However, if a paddy is large enough, total NPS pollution can adversely impact a reservoir's water quality so tight control of drainage management is required to reduce it.

Table II. NPS pollution loads in a rice paddy during the growing seasons of 1999 and 2000

	1999		2000	
Pollutant	Irrigation load	Discharge load	Irrigation load	Discharge load
T-N (kg ha^{-1})	104	103	94	114
T-P (kg ha^{-1})	3.6	3.5	2.8	3.0
COD (kg ha^{-1})	462	458	501	477

Pollution from rural catchments

With respect to pollution management, a rural catchment is composed of a source, sink and stream. The source is the land where pollution is generated such as fields and paved areas, and the sink is the land where natural attenuation processes reduce the pollution load. Riparian corridors and vegetated filter strips are examples of this. Effective NPS pollution management requires source control first to minimize the generation of pollutants. Then the sink area must be well established and maintained to enhance natural attenuation processes and, thus, maximize the reduction of NPS pollutants discharged from source areas before they enter stream networks. It is important to provide the sink areas with the best environment for infiltration, filtration, deposition, decomposition, nitrification, denitrification, soil incorporation, plant uptake, assimilation by microbes and small animals, as well as other natural attenuation mechanisms. Participatory catchment management by residents is also a key to practicing BMPs and reducing NPS pollution discharge from rural catchments.

Pollution from urban catchments

Urbanized areas produce the greatest amount of pollution and adversely affect the receiving water's quality much more than any other land use. Point source pollution discharged from urban areas and industrial complexes must be eliminated by mechanical treatment systems and NPS pollution must be minimized for successful water quality conservation. Because of the urban storm water runoff's severe adverse impact on the receiving water's quality, the

Environmental Protection Agency (EPA) in the USA has designated urban runoff from cities with a population greater than 100 000 as point source pollution and has asked municipal governments to build sediment basins or other treatment systems to reduce urban NPS pollutants in storm water runoff (Debo and Reese, 1995). Urban storm water runoff not only contains suspended solids, organics, nutrients, and microbes, but also toxic heavy metals and chemical carcinogens (United States Environmental Protection Agency (USEPA), 1995; Characklis and Wiesmer, 1997; Karlsson, 2006). Therefore, the utmost priority in controlling water quality should be given to reducing urban pollution. It is also recommended that tidal land reclamation projects not be planned at the mouth of a river basin where large cities are located because of the huge pollution loads from urbanized and industrialized areas.

BASIC PRINCIPLES OF BEST MANAGEMENT PRACTICES (BMPS)

Managing catchment water quality is very complex because it requires knowledge of engineering and scientific fields such as hydrology, point and NPS pollution reduction technologies, groundwater hydrology, soil science and so on. Catchment water quality management assumes that point source pollution is mostly eliminated by adopting cutting-edge treatment technologies. If point source pollution is not properly treated, a freshwater reservoir's water quality cannot be maintained at the required level. And in tandem with point source pollution control, NPS pollution must also be minimized by applying proper BMPs.

NPS pollutants are mostly generated and transported by runoff. The power of runoff is expressed in terms of transport capacity and tractive force. Accordingly, it is important to reduce runoff volume and velocity in order to reduce NPS pollution loads. Many BMPs focus on reducing runoff volume and flow velocity. For example, reducing runoff volume by increasing infiltration; increasing the drag force of residues, grasses, riparian forests or any obstacles existing in watercourses; constructing diversion ditches to cut off inflow from other areas; constructing sediment basins to temporarily store runoff; and building graded structures to smooth the slope of fields and channels, are all intended to reduce either flow velocity or volume or both. Filtered or deposited pollutants can be removed manually or undergo natural decomposition and assimilation processes. Physical, chemical, and biological treatment mechanisms work well to decompose and transform pollutants into nontoxic and ionized materials, or to assimilate them into the bodies of microbes and small animals such as earthworms. Therefore, it is important to create good conditions for natural treatment processes together with BMPs. A sufficient supply of oxygen, good substrates (or soil) for microbial growth, sufficient moisture, and good temperature and nutrient balance (C: N ratio), are the major factors affecting natural treatment processes (Chen *et al*., 1996). Such conditions are well met in riparian corridors and vegetative filter strips and thus, these are typical BMPs used to reduce NPS pollution loads.

In urban areas where the soil surfaces are mostly paved with impermeable materials, the choices for BMPs to reduce runoff volume and velocity are limited. Sediment basins, infiltration ditches, rainfall harvest systems and systems to collect and treat the first flush during a rainfall are good examples of urban BMPs. If a park is well designed and maintained as a runoff retention area, it may function well for reducing urban NPS pollution without jeopardizing its primary function.

Besides the above-mentioned technical approaches to controlling pollution and improving water quality, education, public relations, and legal enforcement can help. Ongoing education and legal enforcement have proven to be the most effective methods (United States Environmental Protection Agency (USEPA), 1990; Gale *et al*., 1993). Point source pollution should be strictly controlled by laws in order to eliminate it. Legal enforcement of NPS pollution control is generally ineffective; however, legal standards to be observed by farmers and citizens can help communities adopt BMPs effectively and follow guidelines to reduce pollution (United States Environmental Protection Agency (USEPA), 1990). Adopting and managing BMPs might entail labor and materials costs. Therefore, it is necessary to formulate policies and systems for government to support residents by means of incentives, educational opportunities, information services, and other benefits.

CONCLUSIONS AND RECOMMENDATIONS

Controlling the water quality of a freshwater reservoir created by a tidal land reclamation project is never easy and presents great challenges to engineers and administrators. One of the major factors affecting the water quality of a freshwater reservoir created by tidal area development is pollution from the catchment area through rivers and streams. Pollution in a catchment area is classified into two sources, point source and NPS pollutions. Point source pollution is eliminated by using cutting-edge treatment technologies and NPS pollution is controlled and managed effectively by adopting BMPs in both rural and urban areas.

NPS pollution is generated, transported and discharged by rainfall runoff and groundwater from the catchment areas to stream systems. It is very important to exert every effort to minimize runoff during rainfall to reduce NPS pollution. Groundwater is one of the major sources of NPS pollution to streams and lakes, so the importance of groundwater management also must be emphasized. Both runoff and groundwater qualities can be controlled and managed successfully by applying BMPs, enforcing strict legal requirements and supporting participatory catchment management activities. Principles of natural attenuation mechanisms must be applied together with BMPs to ensure the fast and effective decomposition and transformation of the pollutants removed by BMPs. Besides the technological approaches to reducing pollution, systematic support for continuous education and incentives can help residents encourage participatory catchment management activities.

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