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Mini-review on river eutrophication and bottom improvement techniques, with special emphasis on the Nakdong River

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ABSTRACT

Water quality in rivers is vital to humans and to maintenance of biotic and ecological integrity. During the Four Major Rivers restoration of South Korea, remarkable attempts have been made to decrease external nutrient loads and moveable weirs were designed to discharge silt that may deposit in pools. However, recently eutrophication of the Nakdong River, which was limited to the lower reaches, is seen to be spreading upstream. The reduction of external nutrient loads to rivers is a long-term goal that is unlikely to lead to reductions in algal blooms for many years because of the time required to implement effective land management strategies. It would therefore be desirable to implement complementary strategies. Regulating the amount of water released is effective at preventing algae blooms in weir pools; so, the relationship between discharge, stratification and bloom formation should be understood in this regard. However, pollutants are likely to accumulate in the riverbed upstream from release points. Thus, to control phosphorus levels, total phosphorus density should be lowered by applying in-river techniques as well. As many ecosystem properties are controlled by multiple processes, simultaneous river bottom improvement techniques, such as combined dissolved oxygen supply and nutrient inactivation, are likely to be effective. The purpose of this review is to present a series of technological approaches that can be used to improve the river bottom area and hence sediment nutrient release, and to illustrate the application of these techniques to the Nakdong River.

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Introduction

Eutrophication is the enrichment of water bodies by nutrients, especially compounds of nitrogen (N) and phosphorus (P), causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms and the quality of the water concerned. The component most sensitive to eutrophication is benthic algae, whereas benthic fauna is sensitive to oxygen depletion caused by increased loads of oxygen-consuming substances (organic matter and ammonium) from point sources along the river.

After an initial debate on which nutrient is primarily responsible for limiting productivity in lakes and rivers, known as the limiting nutrient controversy, freshwater
scientists have largely concentrated on P as a key element in controlling eutrophication (Huffman, 1988; Ansari et al., 2011). That is why successful cases of eutrophication control in freshwaters involve reduction of P inputs, primarily from external sources, and additionally the internal recycling of P from sediments (Withers and Jarvie, 2008; Ansari et al., 2011).

For many years it was believed that streams and rivers are insensitive to nutrient inputs due to factors such as light availability, greater rate of atmospheric exchange due to shallow depth and a short hydraulic retention time, restricting the effects of nutrient enrichment on algal growth in rivers (Smith, 2003). The past view that rivers uniformly have high resistance to eutrophication is being challenged by recent studies demonstrating high phytoplankton biomass in some river systems (Smith, 2003; Caraco et al., 2006). As hydraulic retention times and volumes of water increase, streams and rivers behave more like lakes and reservoirs (Goodwin, 2011).

Many rivers have experienced anthropogenic changes in morphology, such as building of weirs, dams and bank engineering structures that can cause changes in water flow (Magilligan and Nislow, 2005; Kim et al., 2007b). These modifications can create large zones of ‘dead’ water where phytoplankton blooms have been observed (Maier et al., 2001; Liu et al., 2012). Changes in runoff regime, water temperature and associated physico-chemical alterations, as a result of climate change, climate instability, further land use change and modifications to the hydrologic cycle, are also expected to exacerbate eutrophication (Dodds et al., 1997; Alexander and Smith, 2006; Ansari et al., 2011; Jarvis et al., 2013).

Over the past few decades, many watershed nonpoint source projects have reported little or in some cases no net improvement of P loss reduction, even after best management practice implementation (Alexander and Smith, 2006). For example, after drastic reduction in river water P concentrations have been achieved through P source mitigation, ecological improvements have not occurred and in some instants, nuisance algal growth has actually increased. Large uncertainties remain over the main drivers of eutrophication in rivers (Dodds, 2007).

Due to the longitudinal nature of rivers, management problems that arise are frequently more difficult to deal with than in lakes (Wehr and Descy, 1998). For instance, flow regulation has practical attractions, such as reducing economic losses due to flooding and allowing water control for other purposes, such as irrigation and recreation. However, the morphological alterations may lead to alterations in ecological patterns and system behaviors, i.e., phytoplankton proliferation (Kim et al., 2007b).

Main consequences of river eutrophication

As many municipalities rely on rivers for drinking water, excess nutrients can result in increased water treatment costs, mainly by shortening filter run at water treatment plants. Algal and cyanobacterial blooms can cause taste and odor problems, and increase toxin levels in river water (e.g., the Murray–Darling River system in Australia, Maier et al., 2001; Davis and Koop, 2006). Algal blooms can also interfere with recreational uses such as boating, swimming, fishing and tourism due to increased phytoplankton, periphyton, and/or macrophyte biomass (Murdock and Dodds, 2007). Eutrophication of large rivers discharging into the sea has also had serious effects on the water quality of coastal regions, through increases in nutrient loading and changes in nutrient ratios (Wehr and Descy, 1998).

Control of river eutrophication

Linking land use practices to in-stream nutrient concentrations, including both point and nonpoint sources of nutrients, will be necessary to control eutrophication (Dodds, 2006; Jarvie et al., 2012). Effluent from human sewage and livestock-handling facilities can be treated with existing tertiary treatment methods (e.g., denitrification facilities, P precipitation) to reduce N and P loads to lotic waters (McIntyre et al., 2003; Garnier et al., 2005). However, nonpoint sources of nutrients such as atmospheric deposition and runoff from cropland remain difficult to control (Fry et al., 2011). Particularly, for large catchments with nutrient inputs coming predominantly from diffuse sources, significant reductions in the nutrient load would require large-scale modification of land-use practices, such as riparian buffer strips, cropland terracing and the use of only the necessary amounts of fertilizer, and this will be effective only as a long-term goal (Liu et al., 2012).

Controlling sediment nutrient inputs, with modification of nutrient loads from the catchment, speeds up the recovery of eutrophic systems. Environmentalists have contended that discharge and temperature through navigation dams and channelization in the Mississippi were the most likely controlling factors of algal biomass (Wehr and Descy, 1998). Such conditions are common in most large rivers of the world and it is not always straightforward to make conclusions about the primary causes of eutrophication. Information on the ecological relevance of the supply and how it is modified by in-stream processes is needed for accurate targeting of source reduction strategies in catchments (Withers and Jarvie, 2008).

Case of South Korea

Since seasonal variation of rainfall is very large in Eastern Asia, many locks and dams have been or are being built. Besides, natural lakes in South Korea are limited in number and generally quite small. As a result, reservoirs and regulated rivers are the major sources of freshwater for the society. For instance, about 10 million residents rely on the Nakdong River for their water supply. Before the recent extensive restoration of the river, the flow was highly regulated by multi-purpose dams in the major tributaries and an estuary barrage, which were constructed in the mouth of the river to ensure efficient use of water resources (Kim et al., 2007a). As to the quality, blue green algae and diatom bloom in the winter have repeatedly occurred in the lower Nakdong River since 1992 (Ha et al., 1999; Joo and Kim, 2001).

In South Korea, repeated flooding and droughts have caused human casualties, ecosystem loss and habitat degradation, property damage and forced displacement of riverine residents. To solve such problems, the Korean government completed the so-called ‘four major river project’ at the end of 2012. The main purposes of the project were obtaining water
resources and managing water quality through building 16 weirs along the four major rivers: the Han, Nakdong, Geum and Yeongsan Rivers (Fig. 1).

The weirs are designed to be movable so as to discharge silt that is deposited on the riverbed over time and to control the amount of water according to weather conditions. The project involved construction of 1281 sewage treatment facilities and 233 total phosphorus treatment facilities. It was stated that the water quality of the main stream will be improved to Biochemical Oxygen Demand less than 3 mg/L by expanding sewage treatment facilities and establishing green algae reduction facilities (Cha et al., 2011). To control nonpoint sources, best management practices, including riparian buffer and wetland protection and smart use of fertilizers in agriculture are being implemented (Zheng and Paul, 2007).

Even though great effort was put into the project and a great amount of money was invested to prevent blooming, via the afore-mentioned mechanisms, recently, there have been a number of reports in the press about the occurrence of algae blooms that threaten the mid and upper reaches of the Nakdong River when the water temperature rises, and the scientific community addressed the related issues. Eutrophication of the Nakdong River is seen to be spreading upstream.

Numerous studies on the management and the status of water quality in the Nakdong River since the 1990s have included the phytoplankton community, primary production, ecological studies, water quality and zooplankton, eutrophication and water quality (Lee et al., 2005). Researchers on the Nakdong River hypothesized the possibility of water quality control by flow regulation, i.e., increased dam discharge that may dilute or flush out the abundantly formed population of phytoplankton in the river (Ha et al., 2003; Jeong et al., 2007). Jung et al. (2014) suggested that control of the level and flow of water by the regulation of discharge is important for water quality as well as for the dynamics of aquatic organisms.

Regulating the amount of water released, as is practiced in Australia, would be effective at preventing algae blooms. However, pollutants are likely to accumulate in the riverbed upstream from release points. Thus, in order to control P levels and prevent the occurrence of algae blooms in rivers, the total P density should be lowered by applying in-river techniques as well. River intervention measures in-river are necessary to lessen the symptoms of eutrophication until changes in catchment management practices result in reduced input of nutrients. Oxygenation of stream waters (enhanced microbial activity linked to high organic matter inputs) and associated development of reducing conditions at the sediment-water interface may result in reductive dissolution of iron III phosphates in surface bed sediments and release of highly bio-available soluble reactive phosphorus into the overlying stream water (Withers and Jarvie, 2008).

Thus, along with controlling nutrient inputs to rivers, the capacity of rivers to retain and transform excess nutrients is an important aspect of the maintenance of river water quality to meet biological quality targets and to protect and conserve habitats. The objective of this review is to narrate the experience of some countries on the in-river mechanisms of eutrophication control; to describe promising river bottom area improvement approaches to overcome the problem and finally to suggest appropriate techniques to be implemented for the Nakdong River. The review does not address biological P control processes.

1. Techniques used in some countries to manage river eutrophication

The eutrophication of rivers is considered to be a dominant source of water quality impairment in the United States (Dodds et al., 1997; Reckhow et al., 2005), in the European Community (Lyche-Solheim et al., 2010) and in general for most of the
fresh-water and coastal marine ecosystems in the world (Smith and Schindler, 2009; Chalar et al., 2010). In this part of the review, brief descriptions of some USA, Europe and Australia rivers’ eutrophication status and mechanisms employed to solve the problem are presented.

1.1. USA

Eutrophication occurs widely in large rivers of the United States, perhaps because large rivers integrate such large land areas (Murdock and Dodds, 2007; Zheng and Paul, 2007). In the U.S., total maximum daily loads have been implemented to attain target total P water quality criteria, through the control of both point and non-point sources (Joo and Kim, 2001; Jarvie et al., 2012). Alexander and Smith (2006) reported that total N and total P concentrations have been decreasing slightly in the country, following a reduction in agricultural intensity.

Huffman (1988) presented lower Neuse River management alternatives to control blooms that involved consideration of several hydrologic and environmental factors, including seasonal patterns of discharge and their effect upon available nutrient concentrations. Model results of the study indicated that significant reduction in maximum annual chlorophyll a concentrations might be expected when only point-source phosphorus controls are implemented. Most importantly, the combinations of point and non-point source nutrient controls were very effective in reducing maximum concentrations of blue-green algae. Of the eutrophication control alternatives evaluated in this study, low-flow augmentation was found to be the most effective means of reducing peak chlorophyll a.

Another case is the Forge River, particularly the upper reach, which is often eutrophic during summer and had a documented history of being so for a half century (Swanson et al., 2009). A number of possible remediation measures were proposed to reduce eutrophication in the Forge River. Reducing the primary causes of the eutrophication, which are nitrogen from West Pond and sewage sources, septic systems and cesspools are the best recommended approaches. Options listed for reducing the eutrophication include biological techniques, a variety of dredging approaches, and technological measures. Among the infrastructures, construction of a bubbler aeration network along the bottom of the upper reach of the river and several of the tributaries is believed to supply oxygen to the bottom waters and minimally stir the water column. Such systems are in place in several considerably smaller tributaries than the Forge in New York City (Swanson et al., 2009). Immediate improvements in dissolved oxygen concentrations were observed, along with associated improvements in ecological functioning.

1.2. Australia

In Australia, algal blooms received widespread public attention with the 1991/92 bloom that covered a distance of some 1000 km in the Barwon–Darling River system (Davis and Koop, 2006). The rivers of the Murray–Darling river system are generally slow flowing because of the small bed slope over most reaches. Weirs placed along the rivers to provide water storage resulted in impoundments, which slow the flow even further (Webstera et al., 2000; Mitrovic et al., 2003; Davis and Koop, 2006). It is suggested that probably the most profound anthropogenic influences on Australian rivers have been through flow regulation by a series of dams in the upper catchments of most of the major rivers and weirs in the lowland regions.

The outputs from the eutrophication research conducted over a decade in Australia have provided a range of management actions that are likely to be effective; mainly, nutrient and flow management. Diffuse sources dominate nutrient input to most Australian rivers. Managing internal nutrient sources once the particular mechanisms that govern nutrient release and transport from the sediments in that water body are identified, is also suggested. Aeration of bottom waters using bubble plume devices, if operated with a good understanding of the water body, is believed to break stratification effectively. Alternatively, capping sediments with both passive and chemically active barriers is proposed, including modified clays that bind phosphorus even under strong anoxia.

Stratification in deep storages and shallow weir pools is an important driver for eutrophication because of its profound effect on mobilizing internal sources of nutrients from the sediments. Increased river flows are recommended to break the stratification in weir pools and so remove the advantage that buoyant nuisance species of algae possess, as well as preventing anoxic conditions from becoming established in bottom waters. This technique has been tried with success in some Australian rivers.

Webstera et al. (2000) also studied the causes of cyanobacterial blooms in Maude Weir pool on the Murrumbidgee River (Australia), and four strategies for minimizing the occurrence and severity of cyanobacterial blooms within a weir pool were evaluated, based on manipulation of weir discharges and of physical conditions within the pool. The assessment of these strategies was based partly on the measured behavior of the weir pool and partly on the results of computer simulations of the effects of altered operations. The strategies include setting a minimum (critical) discharge necessary to achieve diurnal mixing, pulsing the discharge, changing the discharge height, and altering the depth of water withdrawal.

Mitrovic et al. (2011) examined the growth of planktonic cyanobacteria in a weir pool on the Lower Darling River. They found that flow releases were effective at mitigating cyanobacterial growth through either the suppression of persistent thermal stratification or through dilution and translocation of cells. The studies suggested testing the effectiveness of flow management strategies to determine which can be successfully implemented under various river conditions and in different locations.

On the other hand, to decrease the incidence and severity of phytoplankton, a full-scale oxygenation plant trial treating 2 km of the Canning River (Western Australia) was installed on the river over the summer of 1999/2000 (Donohue and Van Looij, 2001). The trials proved that oxygenation increased the dissolved oxygen (DO) concentrations in the water column, particularly in the bottom waters where DO concentrations are frequently below a critical level of 3 mg/L. Oxygenation has had a positive impact on nutrient concentrations in the water column and
nitrogen cycling processes. Results of a microbiological study combined with the data analysis indicated that the number of nitrifying microbes increased due to oxygenation (River science report, 2000; Greenop et al., 2001).

### 1.3. Europe

Based on a European main rivers study (Lyche-Solheim et al., 2010), it was found that eutrophication has had major impacts on river ecology in Europe, and that many river sites are far from the good ecological status target for benthic flora and fauna. This is especially found to be true in the middle and lower parts of the large rivers Rhine (European river flowing in France, Austria, Liechtenstein, Netherlands, Germany, Switzerland) and Danube (the EU’s longest and the continent’s second longest), as well as in the whole Po River (Italy) basin, in spite of implementation of extensive nutrient reduction measures. In Scotland, 30% of rivers were reported to fail the good status objective.

In addition to reduction of external nutrient loads from urban waste water and agriculture, a number of internal restoration measures have been tried to speed up recovery of rivers from eutrophication. The most sustainable restoration measures in the long-term are the construction of buffer strips, restoration of wetlands and re-meandering of rivers. The Urban Wastewater Treatment Directive (UWWTD) has enforced considerable improvement in urban wastewater treatment, causing a major decline in nutrients discharged from wastewater plants, in particular from the older EU-15 Member States. Additional national legislation, including bans on P in detergents, has also contributed to this decline. As an increasing proportion of the nutrient load to European waters comes from agriculture, these diffuse nutrient sources are expected to be reduced due to implementation of the Nitrates Directive and adoption of agro-environmental measures under the European Common Agricultural Policy.

### 2. Potential river bottom area improvement techniques

Mass balance studies have shown that P fluxes entering rivers do not correspond with those measured at the reach or catchment outlet, and that P tends to be retained within river systems, particularly under low flows during spring and summer. In-stream P cycling and retention provide a major ecosystem service by transforming and regulating downstream delivery of nutrients (Withers and Jarvie, 2008; Jarvie et al., 2012) and modifying the timing of delivery in a way that reduces ecological impacts to downstream reaches. Thus, the main strategies for in-stream nutrient control are presented here.

#### 2.1. Dissolved oxygen supply/aeration

Dissolved oxygen (DO) is one of the most important parameters affecting environmental aspects of stream behavior. Respiration by aquatic life, biodegradation of organic material in the sediments and a host of the other oxygen-consuming chemical reactions reduce DO. By keeping the hypolimnion from becoming anoxic during stratification, aeration minimizes the release of phosphorus, iron, manganese and sulfides from deep bottom sediments and decreases the build-up of un-decomposed organic matter and oxygen-demanding compounds (e.g., ammonium). Hypolimnetic aeration can also increase the volume of water suitable for habitation by zooplankton and fish, especially coldwater forms.

In the presence of oxygen, soluble phosphates rapidly bind with other minerals, typically iron oxide, and are then no longer available to plants. When oxygen is not available, iron oxides become more soluble and the bound P also enters the water column. A side-stream oxygenation plant is used to improve DO of the Swan Canning River, Australia. This plant uses pure oxygen, the term ‘side-stream’ referring to the fact that de-oxygenated water is pumped out of the river to be oxygenated, and then returned to the river. The technique offers the advantage of large oxygen transfer capacity with minimal disturbance to bottom sediments or stratification, and allows the oxygenated water to be directed to the river bottom where it is most required (River Science, 2000). On the other hand, Jones and Stokes (2004) considered three technologies, namely a U-tube oxygenation device, a Speecone oxygenation device, and a bubble column oxygenation or aeration device to evaluate their capacity for the San Joaquin River (California) DO supply. Based on applicability in different working and flow conditions, they recommended that a demonstration-scale U-tube device be constructed for testing over two years.

#### 2.2. Sediment nutrient inactivation

Phosphorus precipitation by chemical complexing removes phosphorus from the water column and can control algal abundance. Inactivation of phosphorus in sediments can greatly reduce the release of phosphorus from those sediments, minimizing the internal load. This technique is most effective after nutrient loading from the watershed is sufficiently reduced, as it acts only on existing phosphorus reserves, not new ones added post-treatment, and when studies indicate that the primary source of the phosphorus is internal (recycled from river bottom sediments).

Chemical precipitation (with aluminum, iron and calcium salts), biological processes that rely on biomass growth (bacteria, algae, plants) or intracellular bacterial polyphosphate accumulation and sorption (activated carbon) have been developed to eliminate P. Metal salts, such as ferric salts and alum, can effectively precipitate phosphorus, but they are generally difficult to handle because of their acidity. Furthermore, the iron or the aluminum phosphorus complex is stable only under oxic conditions, which means that phosphorus may be released from the anoxic sediments of eutrophic waters (Ross et al., 2008).

In recent years considerable attention has been paid, based on economic and environmental concerns, to the investigation of different types of low-cost sorbents, such as alum sludge, red mud, fly ash, calcite, goethite, bimesite, apatite, zeolite and other waste materials (Hamilton et al., 2001). For instance, extensive laboratory experiments and a major field experiment have demonstrated that Phoslock, a modified clay, is capable of reducing dissolved phosphorus (DP) concentrations under a
wide range of pH and DO conditions. A distinguishing feature of Phoslock is its ability to bind DP under the anoxic conditions experienced by many eutrophic waterways (Smith, 2003; Boujelben et al., 2008; Yuana et al., 2009).

In the Canning River, which is partially impounded by the Kent Street Weir during the summer months, sediments are found to be the main source of nitrogen and phosphorus during the summer and anoxia is common. In 2000, a nutrient inactivation trial was conducted by applying Phoslock to an 800 m section. The trial area was separated into three zones: Phoslock treated, Phoslock combined with oxygenation and an untreated control zone. The test demonstrated, for the first time on a large scale, that Phoslock was effective at removing filterable reactive phosphorus (FRP) released from sediments and was also effective at removing FRP from the water column as it settled. The FRP concentrations were reduced by at least 95% in the Phoslock treated areas, until unseasonal rain events flushed the trial area, and Phoslock actively removed FRP after the normal flow conditions returned. The study also showed that Phoslock was not toxic to test species (Smith, 2003).

Recently, Van Oosterhout and Lürling (2013), conducted a laboratory study to examine the lanthanum-modified clay Phoslock’s effectiveness in binding soluble reactive phosphorus (SRP), release of nutrients from this modified clay, its influence on water quality variables (pH, oxygen saturation percent, conductivity and turbidity) and effects on phytoplankton growth. They found that Phoslock has no effect on pH or oxygen saturation. Phoslock addition caused a reduction in the growth of all phytoplankton. Overall, the results of the study indicated Phoslock to be suitable for field applications (Fig. 2).

### 2.3. Flow manipulation

Flow management can decrease residence times of regulated river water, prevent or break down stratification, reduce risks of mobilizing internal sources of nutrients from sediments and sustain low light levels by maintaining turbidity. A more promising approach to managing eutrophication in Australian rivers appears to be flow manipulation (Bormans and Webster, 1997; Webstera et al., 2000; Mitrovic et al., 2011). During flood times, materials are moved through systems rapidly. It is during times of drought and the resulting increased residence time of water in rivers that eutrophication most presents a problem. This is exacerbated in Australia and South Korea by extensive river regulation, which further reduces flows in rivers in times of low precipitation and runoff (Davis and Koop, 2001).

Mitrovic et al. (2003) conducted a study on the Darling River to illustrate links between discharge and the development of persistent stratification. The discharge levels required to suppress the formation of persistent stratification at the study sites were variable because of large differences in channel cross-sectional area. To compensate for this variation, the discharges were converted to flow velocities. The flow velocity and turbulent values sufficient to prevent the development of persistent thermal stratification and concurrent Anabaena circinal growth for all sites were then determined.

Several studies on control of river phytoplankton communities through discharge fluctuation have been conducted in South Korea, such as by Jeong et al. (2007, 2011) and Jung et al. (2014). The results support the necessity of “smart flow control,” which may enable destruction of bloom formation with an adequate pulse of discharge generated by upstream dams or weirs of the river system.

### 2.4. Artificial circulation/destratification

Artificial circulation is a technique that has been used with varying degrees of success for controlling internal nutrient loads and phytoplankton biomass in lakes and reservoirs. The primary objective of destratification for nutrient control is to fully mix the water column and redistribute DO between the surface and bottom waters. This process may thereby encourage nitrification as a preliminary step to denitrification, oxygenation of bottom sediments and a reduction in sediment nutrient release (Hamilton et al., 2001).

A fixed point, artificial destratification trial was conducted in the water column of the Swan–Canning Estuary, over a four week period in 1997. The application of bubble curtains was limited in the upper Swan River Estuary, as stratification was maintained and mixing was inadequate for a flowing system (Hamilton et al., 2001; Swan River Trust Report, 2009). Study on streams and river waters using this technique is limited and destratification seems to be not suitable for flowing waters. Stratification is better removed through flow management.

### 2.5. Dredging

Dredging involves the removal of sediment. It is perhaps best known for its application to increase depth, and the technique does require a containment area to be available where removed sediments are separated from water, and may involve secondary removal of the dried sediment from the containment area for ultimate disposal elsewhere.

Various dredging scenarios are recommended for consideration to relieve the eutrophic conditions of the Forge River. Removing the sills that have grown across the mouths of the tributaries, removing sediment accumulated in the main channel of the river and dredging the entire river are among the dredging options suggested for exploration. Dredging the entire river would be a costly endeavor for which dredge spoil disposal options are few. Additionally, unless the major sources of the nitrogen (cesspools and septic systems) are eliminated, this extensive dredging may need to become a continual undertaking. Also, the Forge has historically been a shallow waterway, rich in organic material. Thus, removing all the sedimentary material would completely alter the ecological functioning of the river (Swanson et al., 2009).

Ohmain et al. (2008) studied the environmental impacts of dredging on Warri River water quality (Nigeria), in 1997/1998. As a result of dredging, the pH of the dredged canal and dissolved oxygen decreased considerably; whereas turbidity and total suspended solid increased rapidly after dredging. However, results of six-month post dredging monitoring of the river water revealed that the water quality improved significantly during this period. The study concluded that the impact of dredging on water quality is localized and short
On the other hand, the Imo State government of Nigeria dredged the Nworie River in view of environmental, health and economic concerns hinging on determinant factors like eutrophication. However, the suspended sediment load and turbidity of the river were increased during the removal of bed or bank material and as a consequence other water quality characteristics were affected (Umunnakwe et al., 2011).

Dredging has been shown to reduce internal loadings in lakes and reservoirs (Fan, 1996; Sondergaard et al., 2000; Fan et al., 2004; Lürling and Faassen, 2012); however, applying this technology is not generally successful in large rivers. It is practiced to remove sediments from ditches, streams, polluted rivers, or estuaries, usually to optimize the flow of water or to ensure adequate water depth for boats or ships, or is an artifact of shellfish harvests (Smith et al., 2006).

3. Summary, with recommendations for the Nakdong River

An important prerequisite for achieving long-term benefits to water quality is a sufficient reduction of the external P loading. All potential external nutrient loads to a river must be assessed to effectively address the nutrient supply, and strong control is recommended. However, since there can be significant nutrient loading from sediments, a reduction of external nutrient loads alone may not be sufficient to attain river quality management. Thus, the suitability and feasibility of different in-stream recovery techniques should be evaluated to counteract the effect of internal nutrient release.

Applying remediation measures simultaneously is found to be effective in reservoir and lake conditions; since combining technologies selected based on model studies minimizes limitations and cancels drawbacks of one by the other (Lake Elsinore Task Force, 2007; Strayer et al., 2008). For instance, after a suitability and feasibility analysis of possible techniques compatible with the hydro-morphometric characteristics of Lake Varese (Northern Italy), Premazzi et al. (2005) recommended hypolimnentic withdrawal and oxygenation in order to accelerate the lake response. On the other hand, Brookes et al. (2008) conducted water quality and treatment study on artificial destratification using a bubble plume aerator and two surface-mounted mechanical mixers to effectively control algae and cyanobacteria in Myponga Reservoir, South Australia, using laboratory experiments and small-scale field trials. According to Lürling and Faassen (2012), combined sediment dredging and Phoslock addition are the most promising measures for controlling cyanobacterial hazards in an urban pond.

Promising studies are already underway to combine techniques in-river. To make progress in reducing eutrophication in the Forge River, Swanson et al. (2009) recommended a combination of relatively low-cost projects from the scenarios they considered; taking into account dredging the mouth of the Forge to open communication with Moriches Bay and installing a bubbler aeration system to be operated seasonally. The 1999/2000 large scale trial of oxygenation and Phoslock application as a remediation technique for the Canning River, South Australia, showed that the bioavailability of phosphorus in the water column and in sediments of the river was best reduced when both techniques were applied together.

Similar mechanisms can be considered in the Nakdong River, where the internal loading has been presumed to be important and where after the maximum practicable external P load control, only small changes in the river quality had been observed. Following the river bottom area study, applying P inactivation and oxygenation techniques for instance may play a vital role in the management of river water quality. Alternatively, since several studies already conducted on the River Nakdong agree with the influence of flow on phytoplankton communities, the flow manipulation technique is likely to have a positive impact on the recent algal bloom. However, there is a need to test the effectiveness of flow management strategies to determine which can be successfully implemented under various river conditions.
conditions and in different locations. The relevance of greater P retention efficiency in headwaters for downstream ecological response must be studied in detail so that the beneficial effects of in-stream processing can be more adequately incorporated into river basin management plans.

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