PONDS VS WETLANDS – PERFORMANCE CONSIDERATIONS IN STORMWATER QUALITY MANAGEMENT

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Abstract *Ponds and wetlands are commonly used in urban design to meet a number of urban planning objectives including the management of urban stormwater for water quality improvement. Ponds and wetlands are detention systems with their differences typically being reflected in their surface area to volume ratio and water level fluctuation. These differences influence a number of hydrologic, hydraulic and botanic factors of the detention system, which affect their performance in stormwater treatment. The detention periods of stormwater inflow into these systems are often used as a measure of the performance of these facilities as pollution control systems. However, it is widely recognised that other factors such as the flow hydrodynamics within the detention system and vegetation density and layout can have a significant influence on the performance of these facilities. The appropriate selection of ponds and wetlands for stormwater treatment requires a balance of the advantages and disadvantages of these systems as stormwater quality treatment facilities. This is dependent on the type and priority of pollutants to be removed and the association of these pollutants to the particle size fractions of stormwater sediments. This paper discussed the various issues and performance considerations associated with the comparison of ponds and wetlands for stormwater pollution control.*

1. INTRODUCTION

Ponds and constructed wetlands are commonly used in urban design to meet a number of planning objectives including the improvement of stormwater quality discharged from urban catchments. In catchments that are served by separated stormwater drainage and sewerage systems, the improvement to the quality of stormwater has been identified as an essential element towards protection of aquatic ecosystem of the receiving waters. The utilisation of ponds and wetlands form part of an integrated stormwater management strategy that may include a range of other devices such as gross pollutant traps and swale drains.

Ponds are generally small artificial bodies of open water with a small range of water level fluctuation. Emergent aquatic macrophytes are normally restricted to the margins because of water depth, although submerged plants may occur in the open water. Constructed wetlands are shallow detention systems, which regularly fill and drain. Wetlands are typically extensively vegetated with emergent aquatic macrophytes. Many definitions of wetland exist in the scientific literature. Some parts of the stormwater management industry refer to the whole system of marshland, pond and urban forest as a constructed wetland. While good urban design often involves a combination of these features to achieve a range of functions, it is more accurate and less confusing, both in general communications and in technical design, if the term wetland is restricted to those environments it best describes, ie. natural or constructed marshes and swamps.

As stormwater quality treatment facilities, ponds and wetlands are essentially detention systems. Differences in their hydrologic and treatment processes are largely related, either directly or indirectly, to the relative size of the permanent pool (in relation to the total available storage volume) and the depth of inundation in the permanent pool. The former has a significant influence on the detention period of stormwater inflow to the system while the latter influences the pre-dominant water treatment mechanisms promoted within the system.

Ponds, constructed wetlands and urban forest are utilised to promote landscape amenity in urban development and recent data suggest that the presence of a wetland or pond in a residential estate can increase surrounding property values by as much as 300%. Consequently landscape aesthetics can often dominate design considerations and can sometimes lead to inappropriate design of these systems for urban stormwater treatment. The appropriate selection of ponds and wetlands in urban design requires a balance of the advantages and disadvantages of these systems against a range of stormwater management and urban design objectives. This paper discussed the various issues and performance considerations associated with the comparison of ponds against wetlands for stormwater pollution control.

2. URBAN STORMWATER POLLUTANTS CHARACTERISTICS

Urban stormwater pollutants range from gross solids to fine particulates to soluble contaminants. The appropriate selection of stormwater treatment measures is often based on the proper definition of the target pollutant. In catchments having separate stormwater and sewerage systems, a significant proportion of pollutants conveyed in stormwater are transported in particulate form with only a small fraction of pollutants in dissolved form. Urban pollutants such as metals and nutrients are associated with the finer fraction of the sediment particles transported in stormwater. For example, various field studies (eg. Pitt & Amy, 1973, NCDNRCD, 1993 and Woodward-Clyde, 1994) indicate that almost half of the heavy metals (represented by copper, lead and zinc) found on street sediments are associated with particles of 60 to 200 μm in size and 75% are associated with particles finer than 500 μm in size. Similarly, between 50% to 75% of phosphorus transported in stormwater is associated with particle size finer than 100 μm. Colloids (particle size < 2 μm) can contain as much as much as 25% of the total phosphorus load in stormwater and have significant electrical charge which can keep them in stable suspension in the water column (Lawrence and Breen, 1998).

Ponds and wetlands are commonly employed to remove sediment and sediment-bound pollutants such as nutrients and metals. These systems are also expected to remove soluble pollutants through biochemical mechanisms. Their effective utilisation often requires gross pollutants to be removed prior to stormwater inflow to ponds or wetlands. An approach to the appropriate sizing of these detention systems can involve an analysis of the physico-chemical characteristics of the target pollutant and its association with particle size fractions. The settling characteristics of the target particle size fraction can then be used to determine the required detention period for their removal.

3. SYSTEM HYDROLOGY AND HYDRAULICS

3.1 Detention Period

The hydrology of a stormwater detention system defines the treatment processes promoted within the system. As discussed in the previous section, the detention period of the inflow is often an indicator of the expected performance of the system in removal of stormwater pollutants entering the system. The hydrology of the stormwater detention system is dependent on the hydrologic characteristics of the inflow and the hydraulic characteristics of the basin outlet structure. In the past, practitioners have assumed that the detention period of runoff entering wetlands is a constant, which is only strictly true under steady and ideal plug flow conditions. Plug flow conditions never occur in natural systems. Furthermore, urban stormwater runoff is generated from intermittent episodes of storm events of varying intensity and duration and stormwater wetlands and ponds very seldom operate under steady flow conditions. In recognition of this, some practitioners have sought to determine the mean detention period of an inflow to a pond or wetland, as equivalent to the time difference between the centroids of inflow and outflow hydrographs. As pointed out by Fabian and Wong (1997), this measure of the mean detention period is strictly only applicable to systems without a permanent storage.

For detention systems with a permanent pool, the water quality of the initial stages of the outflow hydrograph represents the ambient water quality of this permanent pool and is unrelated to the water quality of the inflow. Under ideal flow conditions, the water entering the detention system will only exit the system when the entire permanent pool volume has been displaced by the inflow hydrograph. The detention period of the inflow is thus dependent on a number of factors including the ratio of the volume of the inflow hydrograph to the storage volume of the permanent pool and, in many cases, the dry weather period preceding the next storm event.

The varying rates of runoff into stormwater detention systems and variations in basin hydrodynamic behaviour (eg. antecedent storage condition, unsteady flow conditions, etc) result in constantly changing detention times of inflows. Detention periods in stormwater detention systems should therefore be considered as a distribution to describe the range of detention times that can occur within the system. This distribution, which reflects the influence of the stochastic nature of inflow and antecedent storage conditions, is referred to by Somes and Wong (1998) as the 'probabilistic residence time distribution' (PRTD).

Figure 1 shows the PRTD curves derived for a hypothetical detention system using 100 years of historical rainfall data for Melbourne. The detention systems simulated are controlled by a riser outlet with varying size of the permanent pool and the curves clearly show that the effect of the permanent pool is to extend the detention period of the inflow, consistent with the discussion presented earlier. This shift is largely due to the increased dominance of the inter-event dry period in defining the detention period. This occurs, as the size of the permanent pool becomes a significant proportion of the total available detention storage. Ponds, with the majority of its detention storage being in the form of a permanent pool, are thus expected to promote longer detention period compared with constructed wetlands.

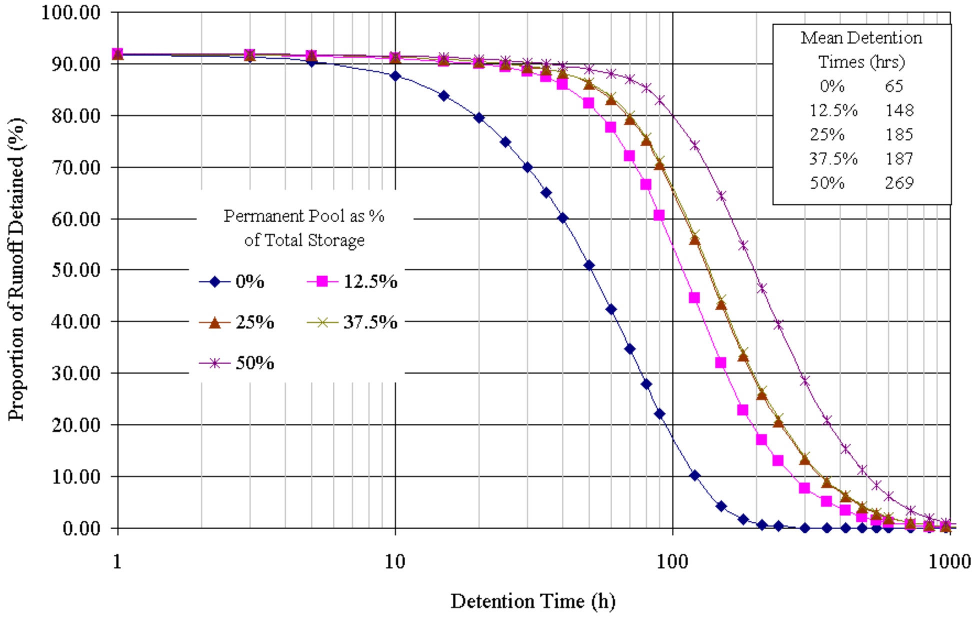

Figure 1 Effect of increasing permanent Pool Volume on PRTD – Riser Outlet (Somes & Wong, 1998)

3.2 System Hydraulics

The computed PRTD curves are based on the assumption of ideal hydrodynamic flow conditions, and were derived to gain an insight into the influence of the intermittent nature of stormwater inflow on the long-term distribution of detention times in a wetland system. Ideal flow conditions are associated with flow patterns that resemble plug flow, and when the entire volume of the pond or wetland is being utilised. As indicated earlier, ideal flow conditions never occur in stormwater ponds and wetland systems and both systems can be subjected to inefficiencies associated with preferential flow paths (short-circuits) and ineffective utilisation of the available detention storage (ie. stagnation and stratified zones).

A key factor that differentiates the hydrodynamic behaviour of wetlands and ponds is the much higher degree of water level fluctuation in constructed wetlands. The filling and draining cycles of constructed wetlands have the tendency to promote a more effective utilisation of the available storage compared with the flow pattern through a permanent waterbody. Flow conditions in the latter case is more susceptible to hydraulic inefficiencies within the pond due to zones of re-circulation and stagnation reduce the engaged basin volume. This was demonstrated by Walker (1995) as shown in Figures 2 and 3. The two figures show the flow pattern in a wetland during its filling stage and when operating at full water level. The wetland outlet hydraulics is controlled by a weir structure such that at the filling stage, the flow pattern the inflow is highly two-dimensional as water is distributed to all areas within the wetland. When full, a dominant flow path exists (as shown in Figure 3) leading to significantly reduced detention period.

Vertical stratification in ponds can also result in ineffective utilisation of available storage, all of which can reduce the significant advantage of longer detention period in ponds compared to wetlands.

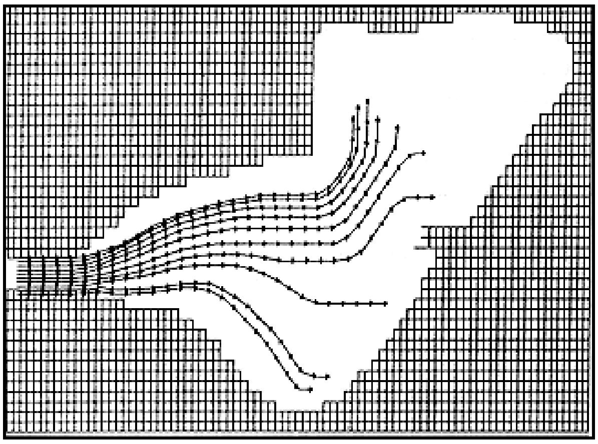

Figure 2 Flow pattern in a constructed wetland when filling (Walker, 1995)

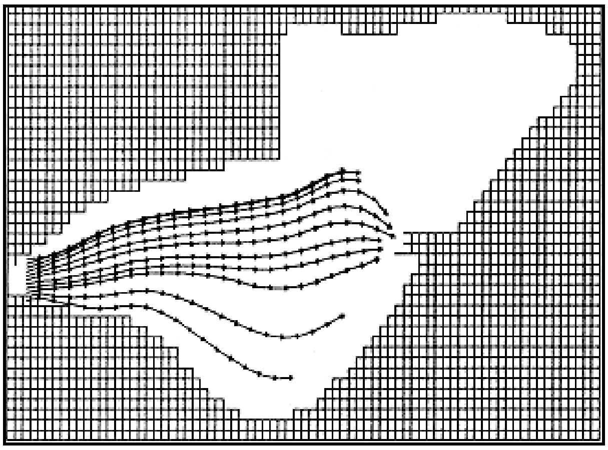

Figure 3 Flow pattern in a constructed wetland under full storage conditions (Walker, 1995)

4. TREATMENT PROCESSES

Water quality improvement in ponds and wetlands is promoted by a complex array of physical, chemical and biological actions. Table 1 presents a broad summary of their respective functions.

Table 1 Stormwater Treatment Operations of Ponds and Wetlands (adapted from Victorian Stormwater Committee, 1998)

Pond Operations	Wetland Operations
Physical – Sedimentation	***Physical - Sedimentation***
▪ Traps 'readily settlable solids' – settling of solids down to coarse and medium-size silt fractions. ▪ Traps adsorbed pollutants – silt particles trapped in the pond system may also retain adsorbed pollutants. ▪ Promotes flocculation of smaller particles.	▪ Traps suspended solids – vegetation in the wetland facilitates enhanced sedimentation of particles down to the fine fractions ▪ Traps adsorbed pollutants – traps a higher proportion of adsorbed pollutants through higher capture of fine particles
Biological and Chemical Uptake	***Biological and Chemical Uptake***
▪ Biological uptake of soluble pollutants predominantly by phytoplankton which remains in the water column and is susceptible to washoff during the next storm event. ▪ Chemical adsorption of pollutant to fine suspended sediment which remains in the water column for extended period and susceptible to washoff during the next storm event. ▪ UV disinfection of waterbody by sunlight	▪ Traps dissolved pollutants – vegetation provides surfaces for epiphytic biofilms which take up dissolved pollutants ▪ Chemical adsorption of pollutants to fine suspended particles which are trapped through enhance sedimentation and surface filtration facilitated by macrophytes and biofilms ▪ Promotes rapid biodegradation of organic material
Pollutant Transformation	***Pollutant Transformation***
▪ Pollutants adsorbed to deposited sediment are susceptible to release under conditions of low redox potential caused by high organic loading and pond stratification	▪ the regular wetting and drying cycle progressively leads to less reversible sediment fixation of contaminants in the substratum

4.1 Sedimentation

The main physical mechanism of pollutant removal in ponds and wetlands is that of sedimentation. Ponds, by virtual of their longer detention period, are very effective sedimentation system and provides high capture of coarse to medium silt-size solids conveyed in stormwater. While the process of particle flocculation within a pond can result in the clustering of larger particles, their removal in ponds is largely marginal. Ponds are generally less effective in removing fine-sized particles owing to: the long settling time required for the sedimentation of these particle, and the propensity for non-uniform flow (vertical or horizontal) conditions to result preferential flow paths and reduced storage utilisation. Even in well-mixed conditions turbulence and re-entrainment of particles from the sediments limit sedimentation of small particles.

As outline by Wong et al. (1998), one of the roles of wetland vegetation is the promotion of enhance sedimentation processes. These processes involve the facilitation of uniform flow conditions within the wetland and provision of a medium for small-particle adhesion. The pre-dominantly two-dimensional flow pattern through dense vegetation during the filling and draining cycle of the system further enhanced sedimentation processes promoted by the presence of vegetation in the system.

4.2 Biological and Chemical Pollutant Uptake

Soluble pollutants are intercepted through biological uptake by algae and chemical adsorption to the suspended particles in ponds and wetlands. In ponds, the predominant algal biomass tends to be phytoplankton, with the majority of phytoplankton cells remaining in the water column. Similarly, soluble pollutants may be intercepted in ponds by adsorption onto suspended particles. Owing to their low settling velocity and susceptibility to re-suspension by wind-induced turbulence, only a low percentage of these adsorbed pollutants settle in the pond. The overall result of this is that both the biologically and chemically adsorbed pollutants are susceptible to washout during the next event. In this sense, these processes cannot be considered effective pollutant interception processes as they merely transform the pollutant within the water column.

The major difference in wetlands is that soluble pollutants are taken up by epiphytic biofilms rather than phytoplankton. The biofilms are a fixed component of the system and are supported by macrophytes. Consequently this pathway represents a true interception process. It is only under high water velocities that biofilms will be disrupted and washed out of the system and careful design of constructed wetland systems can avoid this (Wong et al., 1998). Similarly high macrophyte and biofilm surface area is also effective in promoting enhanced sedimentation and surface adhesion of suspended particles and a field study by Lloyd (1997) has provided evidence of the effectiveness of wetland macrophytes in trapping fine suspended solids in wetlands.

4.3 Pollutant Transformation

Pollutant transformation processes during the inter-event period are important in determining the long-term performance of stormwater treatment systems. In ponds, one of the most significant transformation processes occurs in the sediments. Pollutants adsorbed to the settled particles can be released under certain conditions. If sediments become reducing, pollutants such as phosphorus and some trace and heavy metals can be released into the overlying waters. Conditions that result in the development of reducing sediments include the buildup of organic material in the sediments, high loads of bio-available carbon to the system, and the development of a stratified water column which limits the supply of oxygen to the sediments. All these conditions readily occur in ponds, largely because of their low surface area to volume ratio and presence of a deep permanent pool.

Wetlands tend to have high surface area to volume ratios, which limits stratification. The wetting and drying cycles in wetlands also optimise the breakdown of organic material by facilitating both aerobic and anaerobic pathways leading to the processing of carbon being rapid and complete. Wetlands with regular wetting and drying cycles tend to have mineral sediments with little accumulated organic material. The organic material that does buildup in wetland sediments tends to be the fibrous recalcitrant fractions of plant litter, which results in the development of peat-like sediments. The development of peat-like sediments is more of a storage process than a transformation process. This would normally only occur in areas of a wetland that do not dry out.

Both ponds and wetlands support a range of nitrogen transformation. Nitrogen undergoes a sequence of microbial transformations from mineralisation to form ammonium, oxidation to form nitrate and reduction to form nitrogen gas. The mineralisation, nitrification and denitrification processes require both aerobic and anaerobic stages. Sediment nitrogen transformations tend to proceed most rapidly where oxic/anoxic micro-site heterogeneity is greatest. This is exactly the condition created in the rhizosphere of wetland plants. As a result wetlands typically have greater transformation and nitrogen gas loss rates than ponds.

4.4 Pollutant Storage

The importance of pollutant storage in stormwater treatment systems depends very much on the biogeochemical pathways of the particular pollutant. For example nitrogen and readily bio-available tend to be rapidly processed through microbial pathway and converted to gases end products (eg. nitrogen gas, carbon dioxide, methane). However more conservative pollutants in the stormwater system like sediments and phosphorus require long-term management.

The storage of sediments in stormwater treatment systems is relatively straightforward. Sufficient volume is required to store the trapped sediments for the designed maintenance period.

The storage of pollutants (eg. phosphorus) adsorbed to sediments can be a complicated process. As outlined in the previous section, pollutants adsorbed to sediments can be released if the sediments become reducing. In ponds, storage of pollutants in the sediments is only viable on a longer-term basis if organic loading to the pond can be controlled and stratification of the water column is avoided. The storage of pollutants like phosphorus in wetland sediments seems to be a more viable option. Most pollutants associated with particles are actually adsorbed to the particle's iron oxide coatings. Release of the pollutants occurs when the iron oxide coatings are reduced. However iron oxides occur in a number forms some of which are more easily reduced than others. Under conditions of repeated wetting and drying the forms of iron oxide become progressively more difficult to reduce and the associated pollutants, like phosphorus, become progressively less available.

5. APPROPRIATE SELECTION OF TREATMENT SYSTEM

Appropriate selection of treatment devices for the integrated management of stormwater requires the consideration of a range of factors over varying spatial and temporal scales. The early identification of multiply use priorities is critical for the design processes to adequately address all the necessary issues and clearly identify any compromises. Issues range from catchment scale factors such as, runoff hydrology and water quality, to local scale factors like treatment site topography, surrounding landuse and aesthetic considerations. Temporal issues include short-term interception versus long-term treatment performance.

It is clear that ponds and wetlands have different attributes as stormwater pollution control systems and their appropriate utilisation should be based on exploiting their strengths while managing or avoiding their weaknesses. In strict stormwater quality terms, there are clearly more positive attributes for a constructed wetland system. As outlined by Wong et al. (1998), a constructed wetland typically comprises two cells or zones, an open water inlet zone and a macrophyte zone. The function of the inlet zone is to maximise detention storage for the settling of coarse to medium-sized fractions of suspended solids, and to control inflow to the macrophyte zone. This is an important function of the inlet zone as it reduces the maintenance requirements of the macrophyte zone and provides a means of bypassing large floods around the macrophyte zone to "protect" the vegetation and epiphytes. The inlet zone may be landscaped to form an ornamental lake although it is stressed that the zone should not be excessively larger than what is required to settle coarse to medium size sediment to avoid excessive organic loading. A significant proportion of the organic load should be conveyed to the macrophyte zone where it can be processed efficiently, aided by the wetting and drying cycle of this zone.

With a smaller surface area to volume ratio, ponds do offer significant cost advantage and are perhaps most appropriate in regions of steep terrain with catchment geology predominantly yielding coarse to medium-sized silt particles.

As noted in Section 1, ponds and wetland are also use in urban design to provide landscape amenities. Community perceptions of the relative aesthetic values of ponds compared with wetlands are varied although the recent trend in residential land development has favoured a pond or lake environment as a focus. This means that a component of the drainage system initially introduced to treat stormwater and protect downstream ecosystems has to itself have good water quality and always look aesthetically pleasing. In such circumstances, it will be necessary to address the three potential water quality problems associated with a pond system, ie. (i) the potential release of phosphorus and metals from the settled particles due to low sediment redox-potential; (ii) the reduced effectiveness in the removal of the finer fractions of suspended particles which generally contains the higher fraction of sediment-associated pollutants such as phosphorus and metals; (iii) the risk of poor in-pond water quality. In practice these issues are often related, for instances decisions that compromise treatment performance will often result in water quality problems in the treatment system.

Preventive measures to reduce the risk of phosphorus and metal desorption from deposited sediment lies in limiting organic loading of the pond. This can be achieved by the installation of traps at the entrance to the pond. An alternative is to ensure that the pond is sufficient large to accommodate the organic loading from the catchment. Lawrence and Breen (1998) provided guidelines on sizing ponds to limit phosphorus release from sediments caused by organic loading. However in situations where the removal of fine particulate material is an important objective the selection of a pond treatment system is likely to result in some compromises in performance.

6. CONCLUSION

Ponds and wetlands promote different water quality treatment processes by virtue of fundamental differences in surface area to volume ratio and water level fluctuation. The detention period of stormwater wetlands and ponds are highly variable owing to the intermittent and unsteady nature of stormwater inflow. Evaluation of the probabilistic distribution of detention periods in systems of varying degree of permanent pool volume have demonstrated the tendency for the mean pollutant detention period to increase with increasing percentage of permanent pool volume in a stormwater detention system. This implies that ponds generally provide a higher level of stormwater detention compared to wetlands and are thus expected to be more effective in promoting sedimentation as a mechanism for stormwater pollutant interception.

However, systems with a high degree of permanent pool volume also have a higher propensity for poor flow patterns as characterised by the presence of short-circuit flow paths and zones of stagnation. The lack of emergent vegetation, owing to a significantly deeper depth of inundation, can also influence its effectiveness in the removal of fine suspended particles and soluble pollutants. Systems with a high degree of permanent pool volume can also lead to poor dissolved oxygen and redox potential conditions that may lead to remobilisation of contaminants in the sediment.

Each of the above factors are overcome in constructed wetlands, with their characteristics cycles of filling in draining promoting: -

- two dimensional flow pattern during the filling phase of the wetland thus ensuring effective utilisation of the available storage;

- a diversity of aquatic macrophytes within the detention system which promote uniform flow conditions;

- the presence of aquatic macrophytes facilitate effective removal of fine particulates and soluble pollutants;

- a more rapid rate of degradation of deposited organic material;

- a progressively less reversible sediment fixation of contaminants in the substratum.

The use of wetlands may not be possible in certain circumstances, eg. steep terrain or particular aesthetic preferences. However where ponds are used as the sole stormwater treatment device, some water quality and ecosystem protection compromises may occur. The most efficient systems are going to be represented by treatment trains containing both ponds and wetlands.

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