Using Continuous Simulation to Assess the Impacts of Inundation on Emergent Vegetation in Stormwater Wetlands

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Keywords: *Stormwater wetlands; emergent vegetation; hydrological modelling; continuous simulation*

EXTENDED ABSTRACT

Urban stormwater wetlands have been widely embraced by the community as a beneficial part of the stormwater infrastructure. This is in part due to their perceived benefits in terms of improving general ecosystem health, as well as the improvement in public amenity due to the presence of a semi-natural water body. The vegetation that is a dominant feature of these shallow ephemeral and perennial wetland systems plays an important role in the treatment of the stormwater within the system. Typically, artificial wetlands include a variety of vegetation types including those that are emergent, floating leaved attached, free floating and submerged. Some of the most important functions of the vegetation within the wetland are the result of physical processes such as the filtration of particles, reduction in turbulence, stabilisation of sediments, and provision of increased surface area for biofilm growth on stems, leaves, roots and rhizomes.

The dynamic nature of urban hydrology means that the vegetation in stormwater wetland systems is affected by a regime of wetting and drying cycles. The duration, frequency and depth of inundation has a significant impact on the survival of vegetation and is an essential component in the selection of appropriate vegetation species for different parts of the wetland. These problems are especially important during the during the initial plant establishment phase of the wetland construction, when the vegetation is highly sensitive to these inundation events.

This paper describes a study in which a continuous simulation hydrologic model is used to predict the rainfall and runoff from an urban catchment into newly constructed stormwater treatment wetland in Brisbane.

The model was tested against the water level information collected at the site during the water sampling period. Comparison of the observed and simulated water levels indicate that the draining of the wetland following a storm event is being reasonably well predicted. This indicates that the theoretical outlet hydraulic characteristics provide a good prediction of the wetland outflow. However, there are some periods where there is a rise in observed water level, but a much smaller rise in simulated water level. Short duration, localised thunderstorms dominate the hydrology of small urban catchments such as this, so that it is common for rainfall to be recorded at the rain-gauge, but only limited runoff occurring at the catchment site. The opposite effect also often occurs.

The model has been used with observed rainfall covering a two-year period in which detailed observations were made of vegetation establishment. An analysis of the frequency and duration of inundation from the results of the model simulation provide an explanation of the fate of vegetation establishment in different parts of the wetland.

The model has also been applied to a long-term simulation of the catchment and wetland hydrology, to demonstrate the benefit of using statistical information on the frequency and duration of inundation in the selection of suitable vegetation species for different parts of a stormwater treatment wetland.

The model results indicate that the survival of vegetation within a constructed wetland is due no only to the frequency of inundation within the wetland, but also to the duration of the subsequent inundation events. The continuous simulation model also provides a means to undertake long-term simulation of the hydrologic processes within the catchment and wetland. This long term simulation allows a statistical assessment of vegetation survival that is not easily undertaken from a short term set of water level observations.

1. INTRODUCTION

Urban stormwater wetlands have been widely embraced by the community as a beneficial part of the stormwater infrastructure. This is in part due to their perceived benefits in terms of improving general ecosystem health, as well as the improvement in public amenity due to the presence of a semi-natural water body. The vegetation that is a dominant feature of these shallow ephemeral and perennial wetland systems plays an important role in the treatment of the stormwater within the system. Typically, artificial wetlands include a variety of vegetation types including those that are emergent, floating leaved attached, free floating and submerged. Some of the most important functions of the vegetation within the wetland are the result of physical processes such as the filtration of particles, reduction in turbulence, stabilisation of sediments, and provision of increased surface area for biofilm growth on stems, leaves, roots and rhizomes.

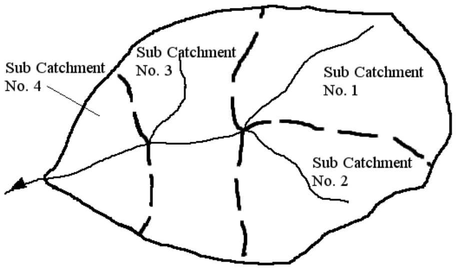
The dynamic nature of urban hydrology means that the vegetation in stormwater wetland systems is affected by a regime of flooding and drying cycles. The duration, frequency and depth of inundation has a significant impact on the survival of vegetation and is an essential component in the selection of appropriate vegetation species for different parts of the wetland. These problems are especially important during the during the initial plant establishment phase of the wetland construction, when the vegetation is highly sensitive to these inundation events.

The adoption of a continuous hydrologic rainfall-runoff catchment model with a wetland hydrologic model provides the designer with useful information when designing the vegetation layout within a wetland. Using a long-term rainfall record, the designer can make a statistically-based assessment of the inundation frequency and duration for different water levels in the wetland. By combining the continuous simulated record of water levels with a topographic map of the wetland the areas that are suitable for different plant species can be determined. The survival of previously planted areas can also be easily assessed where historical rainfall information is available, even when no water level observations have been made.

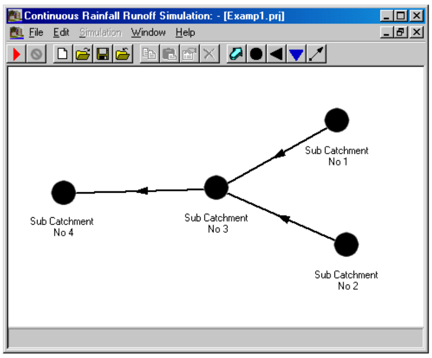
This paper describes a study in which a continuous simulation hydrologic model is used to predict the rainfall and runoff from an urban catchment into newly constructed stormwater treatment wetland in Brisbane. The model has been used with observed rainfall covering a two-year period in which detailed observations were made of vegetation establishment. An analysis of the frequency and duration of inundation from the results of the model simulation provide an explanation of the fate of vegetation establishment in different parts of the wetland. The model has also been applied to a long-term simulation of the catchment and wetland hydrology, to demonstrate the benefit of using statistical information on the frequency and duration of inundation in the selection of suitable vegetation species for different parts of a stormwater treatment wetland.

2. THE URBSIM HYDROLOGIC MODEL

UrbSim is a program that has been designed to simulate the rainfall and runoff processes from an urban catchment. The catchment area is subdivided into a number of sub-catchments, with the boundaries of each lying along the watershed boundaries that drain to the sub-catchment outlet. The arrangement of the sub-catchments within the catchment will form a network. The outflow from one sub-catchment will drain directly into the upstream end of the sub-catchment arranged downstream from it in the network. Figure 1 shows a diagrammatic representation of a catchment with sub-catchment subdivision, plus the equivalent UrbSim model structure.



a) Catchment Subdivision



b) Catchment Model Structure in UrbSim

Figure 1. The Catchment Subdivision with the Equivalent Urbsim Model Structure

UrbSim models the rainfall and runoff processes in an urban catchment using two separate steps. The first step is the generation of daily rainfall excess, based on the daily rainfall and potential evapotranspiration (PET) applied to the sub-catchment area. The second step is the conversion of this rainfall excess into runoff and the routing of this runoff to the sub-catchment outlet. The conversion of the rainfall excess to runoff is undertaken at the time step defined by the user, which will generally be smaller than 24 hours. This runoff is then added to the upstream runoff that has been translated through the sub-catchment to the outlet.

2.1. Daily Rainfall Excess Model

The daily rainfall excess model is based on the GURUH model by Newton et al. (in review), which uses a hybrid metric-conceptual approach to represent rainfall runoff processes (Wheater et al. 1993). The 16 model catchment parameters are linked to the conceptual components of urban catchment response described by Boyd et al. (1993). Newton et al. (in review) show that the model is able to predict the impacts of urbanisation by a comparison of simulated pre and post-urbanisation peak flow ratios against values published by Hollis (1975) and Codner et al. (1988). GURUH adopts a similar daily rainfall excess modeling approach as the CRCCH model by Chiew and McMahon (1999) and to AWBM for non-urban catchments, Boughton (1993).

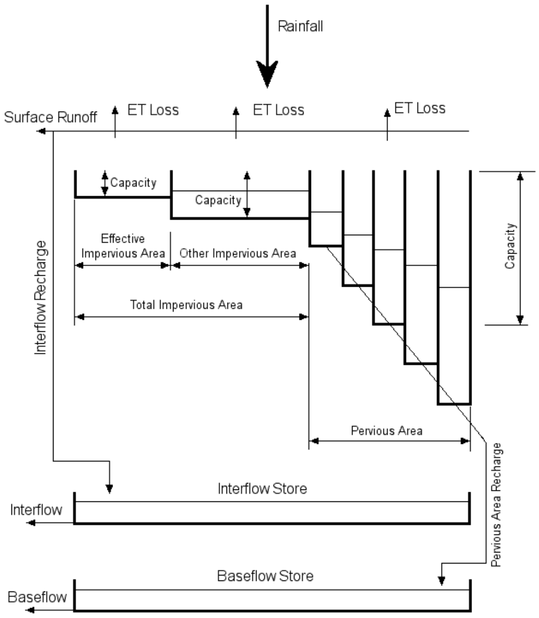


Figure 2. Daily water balance model conceptual storages.

In UrbSim, the sub-catchment area is divided into three separate surface storages as shown in Figure 2. These include:

- The Effective Impervious Area: This includes only that part of the Total Impervious Area that is effective in directly producing runoff from the sub-catchment, and is similar to the directly connected impervious area.
- The Other Impervious Area: The remaining part of the Total Impervious Area that is not effective in directly producing runoff from the sub-catchment.
- The Pervious Area: The sub-catchment area that is not covered by paved surfaces.

The rainfall is aggregated for each day of the simulation period, and added to each of the conceptual storages. Surface runoff is produced if the volume in the conceptual storage exceeds its capacity. A proportion of surface runoff recharges the sub-surface interflow store. The baseflow store is recharged from the pervious store. The daily rainfall excess is calculated as the sum of the Surface Runoff, the Baseflow and the Interflow.

2.2. Sub Daily Rainfall Runoff.

The runoff from overland flow at the sub-catchment outlet is calculated for each time step during the day. The sub daily runoff from the Effective Impervious Area is first calculated, followed by the sub daily runoff from the remainder of the sub-catchment. For each case, the runoff is calculated by solving the conservation of mass equation, applied to lumped conceptual storages. The daily rainfall excess is disaggregated to the sub daily time step, based on the sub daily rainfall pattern.

The flow routing model uses the continuity of mass equation for flow through conceptual storages within the sub-catchment node. UrbSim models the overland flow on the impervious and pervious parts of the sub-catchment separately, using an area weighted routing algorithm. This algorithm uses a model that is similar to that adopted in the WBNM rainfall runoff routing model, described by Boyd et al. (1995) and Boyd et al (1987).

The channel flow model routes runoff from upstream sub catchments through the channel system within the sub catchment, using either an area weighted routing, or a Muskingum method routing algorithm. The Muskingum method routing algorithm adopted is similar to that described by Raudkivi (1979) and Bedient and Huber (1992). The Muskingum routing parameters remain constant within a reach throughout the simulation. UrbSim automatically subdivides the reach into a number of sub-reaches so that the lag in each sub-reach is set equal to the time step adopted in the simulation.

2.3. The Wetland Hydrologic Model.

The UrbSim model also allows for the inclusion of basins or water bodies such as wetlands, in which the surface area and outlet discharge versus elevation characteristics are known. The model uses a level-pool routing algorithm to solve the continuity of mass equation for the basin. The algorithm uses a three-point Lagrange interpolation algorithm to determine the water level, volume in storage and outflow from the wetland or basin at each sub-daily time step.

The hydrologic model only models the inflow, outflow and storage volume characteristics within a basin. The model has not been designed to model the transport of pollutants through a basin. Therefore the model is not designed to predict the treatment processes within a wetland.

The UrbSim model has been adopted in this study as it has been demonstrated by Newton et al. (in review) that it is able to accurately predict the impacts of urbanisation in an urban catchment. When combined with the wetland hydrologic model, UrbSim is able to predict the sequences of wetting and drying within a wetland with complex topography. This is vitally important in terms of the survival of vegetation within the wetland.

3. BRIDGEWATER CREEK WETLAND

The Bridgewater Creek Wetland is a constructed stormwater treatment surface-flow wetland, which was installed by the Brisbane City Council between May and October 2001. It is situated in the “Bowies Flat” parkland in Brisbane, Australia. The subtropical climate has an average annual rainfall of 1028 mm. Two thirds of the annual rain falls between December and March. Although rain does fall during the winter months, it is generally considered as the dry season.

The wetland’s catchment is approximately 180 ha in area and is dominated by residential land use. The wetland is about 0.8 ha in area and treats the stormwater delivered by Bridgewater Creek and the runoff from a stormwater drain, which collects road runoff from an adjacent residential area. Outflow from the freshwater wetland flows into Norman Creek, a tributary of the Brisbane River, which itself drains into Moreton Bay.

The stormwater treatment train at the wetland consists of trash racks at the inlet from the drainage system, followed by a sediment pond and a macrophyte zone. During high intensity storm events, the stormwater can pass the macrophyte zone via an overflow bypass, leaving the sediment pond and flowing around the macrophyte zone. The macrophyte zone, which is dominated by shallow water bodies with fringing vegetation, consists of five ponds as shown in Figure 3. Open water zones dominate the first two ponds, whereas the last two ponds are more densely vegetated. The stormwater enters the macrophyte zone in pond 2, through two circular culverts, which are water level controlled. The outlet structure is situated in pond 6 and regulates the outflow from the wetland with an orifice-plate.

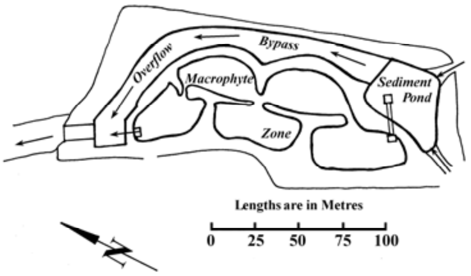


Figure 3. The Bridgewater Creek wetland.

3.1. Model Calibration

A long-term monitoring program has been undertaken at the Bridgewater Creek wetland as part of a monitoring strategy for urban stormwater treatment systems. This forms part of the research component of the CRC for Catchment Hydrology - Urban Stormwater Quality Program. Water quality samples, vegetation surveys and water level observations were taken throughout the inlet pond and macrophyte zone of the wetland.

During the sampling program between August 2002 to February 2004, a daily sampling frequency was adopted for water levels within the wetland. In some cases the sampling frequency was less often than daily, and it was not always possible to sample during storm events. Water levels were recorded at both the inlet and outlet structures from the macrophyte zone. In all cases, there was negligible difference between water surface levels recorded at the two sampling points.

The UrbSim hydrologic model was used to model rainfall and runoff from the urban catchment draining to the Bridgewater Creek wetland. At the time of undertaking this study, no flow data from the site was available to calibrate the model. The catchment hydrologic parameters adopted in the model were those determined from a calibration of the UrbSim model to another urban catchment located in Brisbane (Jenkins and Newton 2005). A topographic survey of the wetland was undertaken to determine the surface area versus elevation data. The outlet hydraulic characteristics were determined from a theoretical analysis, based on the as-constructed details of the outlet structure.

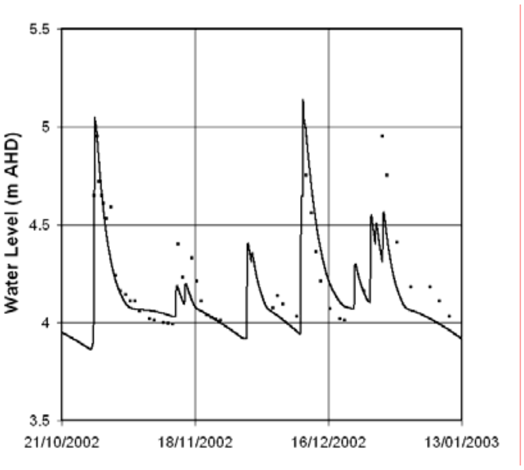


Figure 4. Comparison between the observed and simulated water levels within the wetland.

The model was then tested against the water level information collected at the site during the water sampling period. An example of the simulated versus observed water levels is shown in Figure 4. These results indicate that the uncalibrated model catchment response produces water level changes in the wetland that are similar to those observed. Draining of the wetland following a storm event is being reasonably well predicted. The theoretical outlet hydraulic characteristics also appear to provide a good prediction of the wetland outflow.

During some periods there is a rise in observed water level, but a much smaller rise in simulated water level. It is noted that short duration, localised thunderstorms tend to dominate the hydrology of small urban catchments. Rainfall is often recorded at a rain-gauge, with limited runoff occurring at the catchment site. The opposite effect also often occurs. Although spatial variation of the catchment rainfall will overcome some of this problem, more research is required on appropriate rainfall distributions for calibration and design where limited rainfall data is available.

4. FREQUENCY AND DURATION OF INNUNDATION

4.1. Vegetation Establishment Period

The Bridgewater Creek Wetland has been designed to contain different vegetation zones based on the frequency of inundation that will be expected. These zones are often referred to as the Ephemeral, shallow marsh, marsh and deep marsh, due to both the frequency and depth of inundation. Figure 5 shows the location of each of these zones. The monitoring of the wetland vegetation during the initial establishment phase indicated that vegetation in some parts of the wetland thrived. In other parts, the vegetation either did not grow as well or in some cases did not even survive.

The infrequent water level recording within the wetland meant that it was difficult to draw firm conclusions about the influence of the water level fluctuations on the vegetation survival. Therefore, the water level record produced by the UrbSim model was used to investigate the inundation characteristics during the establishment phase.

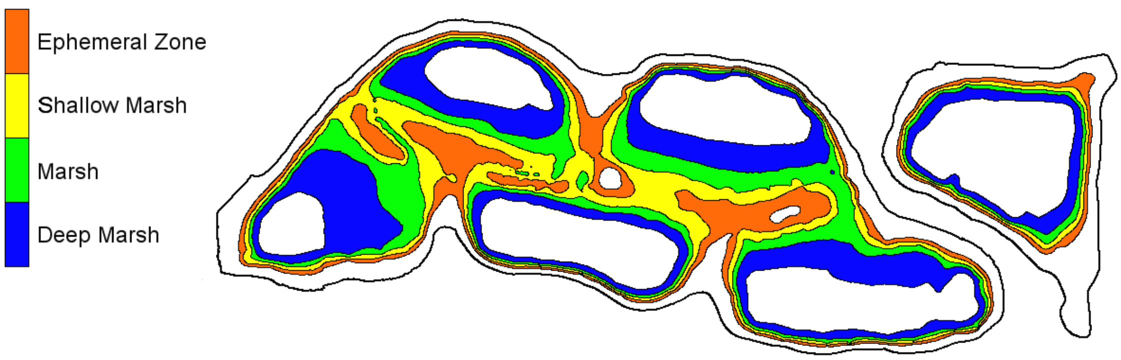


Figure 5. Location of vegetation zones within the wetland.

Figure 6 shows the frequency of inundation of the ephemeral zone from the simulated water levels. This indicates that the ephemeral zone is completely inundated 22% of the time, whilst the shallow marsh was completely inundated 78% of the time. However, a critical factor in the survival of wetland vegetation is the duration of individual inundation events. The longer an inundation event lasts, the more damage that is done to ephemeral vegetation.

Therefore, the simulation results from the UrbSim model were interrogated to determine the individual inundation durations for the establishment phase. Figure 7 shows that the duration of these inundation events varied from 7.2 hours to 28.9 days, with a median value of approximately 4.2 days.

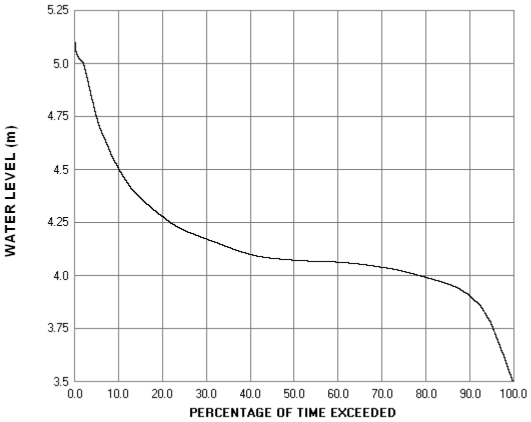


Figure 6. Frequency of inundation of the ephemeral zone in the establishment phase.

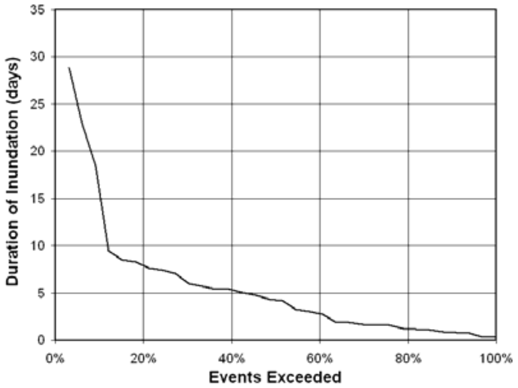


Figure 7. Duration of the ephemeral zone inundation events in the establishment phase.

The vegetation surveys undertaken between August 2002 to May 2004 indicated that much of the vegetation planted in the wetland did not survive. Although vegetation was planted throughout the marsh, shallow marsh and ephemeral zones, vegetation only survived within the shallow marsh and ephemeral zones. There was also some resorting of species from one zone to another, and the survival of this vegetation was linked to the frequency of inundation, as well as the duration of individual inundation events.

4.2. Statistical Assessment of Ephemeral Zone Vegetation

The establishment phase of the wetland indicated that certain vegetation species preferred specific locations in the wetland. Long-term hydrologic assessment of the catchment and wetland hydrology can provide more of this information. The UrbSim catchment and wetland model was then run to simulate runoff from the wetland over a period of 50 years of rainfall from the Brisbane Airport rain gauge. The simulated period included the recorded rainfall from 31/5/1949 to 16/2/2000. The inundation frequency and duration analysis was then undertaken from the water levels produced from the 50 year simulation.

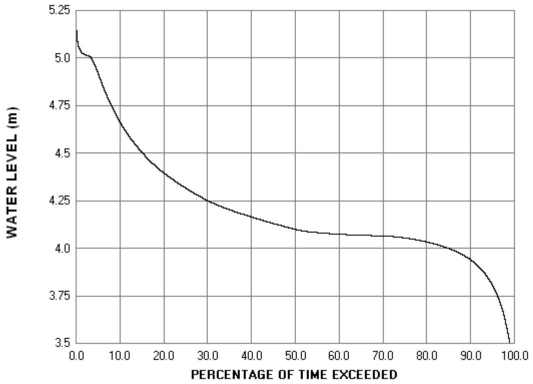


Figure 8. Frequency of inundation of the ephemeral zone, based on 50 year simulation.

Figures 8 and 9 show some similarity between the results produced from the 50 year simulation and the vegetation establishment period (Figures 6 and 7). However, during an average year the ephemeral zone will be completely inundated for a longer period of time than has occurred during the establishment period; 30% of the time compared to 22% of the time during the establishment period. Figure 9 indicates that the duration of each inundation event during an average year will be slightly shorter than occurred during the establishment period; with a median value of 3.4 days compared to 4.2 days for the establishment phase. Table 1 shows the duration of inundation statistics determined from both the establishment phase and the 50 year simulation results.

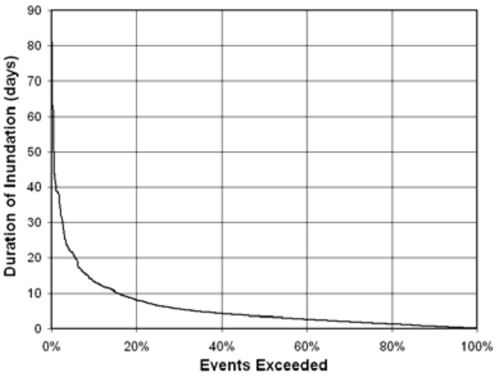


Figure 9. Duration of the ephemeral zone inundation events, based on 50 year simulation.

Table 1. Duration of inundation statistics for the ephemeral zone.

	Establishment Phase	50 year Simulation
10 percentile	9.2 days	13.3 days
Median	4.2 days	3.4 days
90 percentile	18.9 hours	16 hours
Average	5.6 days	5.9 days

5. CONCLUSIONS

Continuous simulation models of the rainfall-runoff processes overcome many of the problems of event based models by modelling both the storm events and the inter-event periods. A continuous simulation urban hydrology model is described which predicts the inundation characteristics of a constructed stormwater wetland. Comparison of the model simulation with vegetation monitoring data allows an assessment of the hydrologic factors affecting the survival of vegetation within a constructed wetland. The continuous simulation model also provides long-term simulation of the hydrologic processes within the catchment and wetland. This allows statistical assessment of vegetation survival that is not easily undertaken from a short term set of water level observations.

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