Application of Detailed SUDS Modelling to Real Life Case Studies

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Synopsis

SUDs design has traditionally been relatively simplistic, using basic equations and “rules of thumb” in addition to the application of simplistic rainfall, often leading to conservative designs. This paper will explore how SUDs design on a range of real life case studies compare using the detailed modelling approach in InfoWorks against the traditional approaches. The results show the benefits of modelling from a SUDs perspective, where traditionally little modelling has been undertaken. Key issues such as infiltration loss and the modelling of permeable flows (Darcy’s Law) will be highlighted through detailed modelling of permeable pavements, swales, infiltration trenches and Geocellular Plastic Units. Comment will also be made as to how the software can be improved in the future to be more relevant to all types of SUDS applications.

Introduction

The driver for this paper is to demonstrate how the improved SUDS module within Infoworks can be used to provide a good representation of real life SUDS networks.

As SUDS are continually more widely implemented, the importance of the ability to model SUDS is becoming more apparent. There are several uses for SUDS modelling, from the initial design stage through to post project appraisal. Four possible uses are summarised below:

- Improved optimisation of small SUDS designs.
- Use as a design tool for large industrial or residential developments
- Integration of SUDS networks into larger catchment models to assess the effects SUDS networks have on the surrounding catchment;
- Use as an audit tool to assess the current and future operation and maintenance of SUDS.

Infoworks has undergone significant changes to improve how it replicates SUDS systems. Examples of some of the changes are as follows:

- Improved representation of infiltration losses;
- Introduction of the ‘pond’ node;
- Permeable flows – Darcy’s Equation;

These changes allow SUDS techniques such as Ponds, Swales, Permeable/Porous Pavements, Soakaways, Infiltration trenches and Plastic Storage Boxes to be represented more accurately. This paper uses real life SUDS examples to put these new features to the test and assess the benefits of modelling SUDS.

Three case studies are used in this investigation to demonstrate the reliability of the SUDS module within Infoworks. Case Study 1 will be used to demonstrate the representation of infiltration losses in a conduit. Case Study 2 will be used to demonstrate the pond node and the effect of infiltration rates as ponds fill and empty. Case Study 3 will be used to assess the application Darcy’s Law through permeable flows.

Case Study 1: Salford Sports Village

The aim of this case study is to demonstrate the effect of infiltration losses in a conduit, and the extent to which it is affected by contributing factors such as infiltration rate and porosity within the conduit. These two contributing factors are particularly important to assess as these can change over time due to build up of silt within the conduit.

Salford Sports Village has already been designed and constructed. This initial design brief was a storm water drainage system for amenity buildings and car park, to withstand a 1 in 100 year RP event. The conditions of the site are favourable for infiltration as the ground is made up of clayey sands and gravels with a soil permeability rate of $3x10^{-5}$m/s. The impermeable area of the site is 6000m^2. By using a traditional approach, it was estimated that 155m^3 of attenuation storage is required on site.

The SUDS structure design utilised plastic geocellular boxes below the car park permeable surface, which have low depth/high base area ratio encouraging infiltration and reducing construction costs.

Figure 1 – Example of plastic geocellular boxes as used in Case Study 1

Modelling Methodology

In this simple model a single 'infiltration trench' conduit was constructed in InfoWorks using the permeable flow solution model to provide:

- 155m^3 storage (D 0.15m x L 215m x W 4.8m)
- Infiltration rate for the site 3x10^{-5}m/s (108mm/hr)
- Porosity of 92% to represent void ratio of 'Charcon Permavoid' Plastic Boxes (as used in this project)
- Hydraulic conductivity through unit of 0.0174m/s (fast)

Modelling Results

In this case a range of constant intensity rainfall profiles with durations between 5 and 240 minutes were simulated through the conduit, for a 1 in 100yr return period. The maximum volume simulated in the conduit during all the events was 112m^3 as seen in Figure 2. This is approximately 43m^3 less than the total storage volume available. However this does not take into account any factors of safety for operational issues or time varying rainfall, which would have been included in the initial design. However it does confirm that the original design was valid and that results are replicated to a good degree, although perhaps is slightly over designed.

Further investigation of the effect of changing infiltration rates and porosity and running the model with time series rainfall allows the designer to build in a factor of safety to the design easily and efficiently. The factor of safety takes into account operation and maintenance issues that may present problems over time as the performance of the system begins to deteriorate and accounts for variability in soil permeability. Modelling the system should allow potential issues to be highlighted at the early design stage, so that appropriate measures can be incorporated into the design and where necessary added into the Operation and Maintenance Manual to avoid substandard performance.

Infoworks can be used to assess overall system performance quickly and easily, offering the tool to make rapid maintenance decisions.

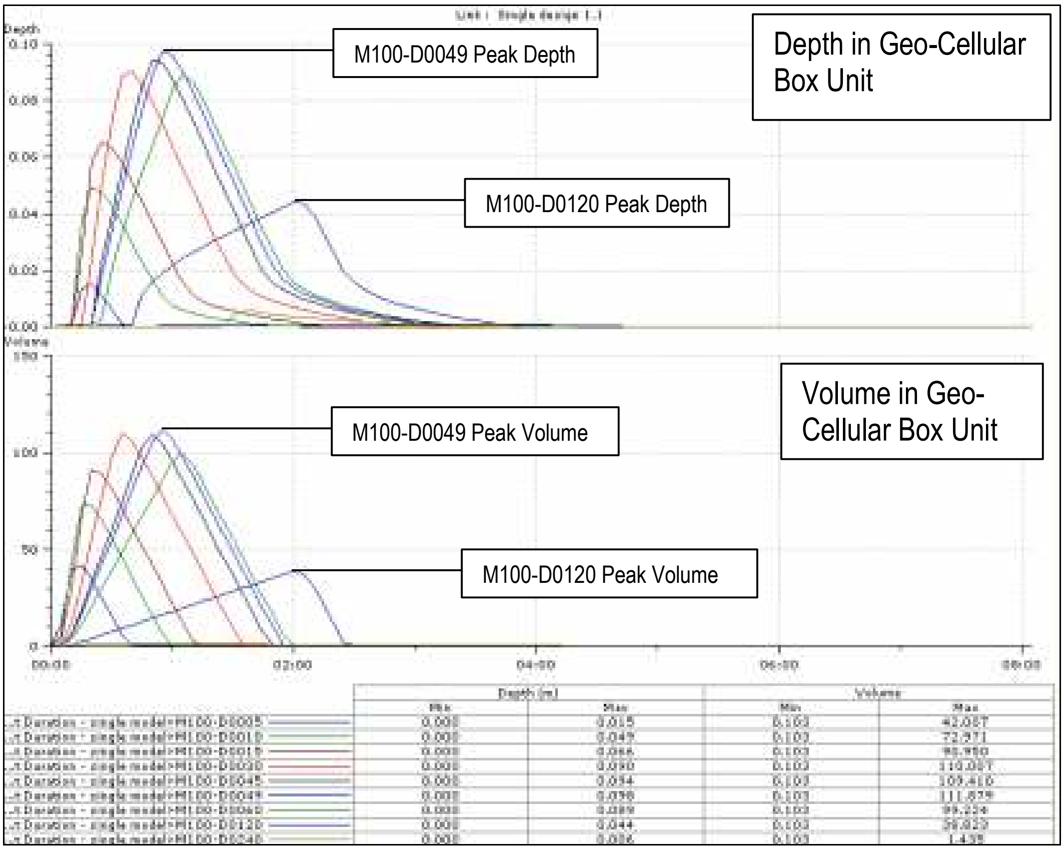

Figure 2 – Depth and volume in permavoid unit during a constant rainfall event.

<u>Effect of Infiltration Rate on System Performance</u>

Figure 2 demonstrates that the critical duration event for this particular conduit is M100-D0049. Therefore this event was used in the next stage of analysis, which was to test the effect that changing the infiltration rate has on the depth of water within the conduit. A range of infiltration rates between 30 and 180mm/hr were tested to assess the effect on the water level within the conduit.

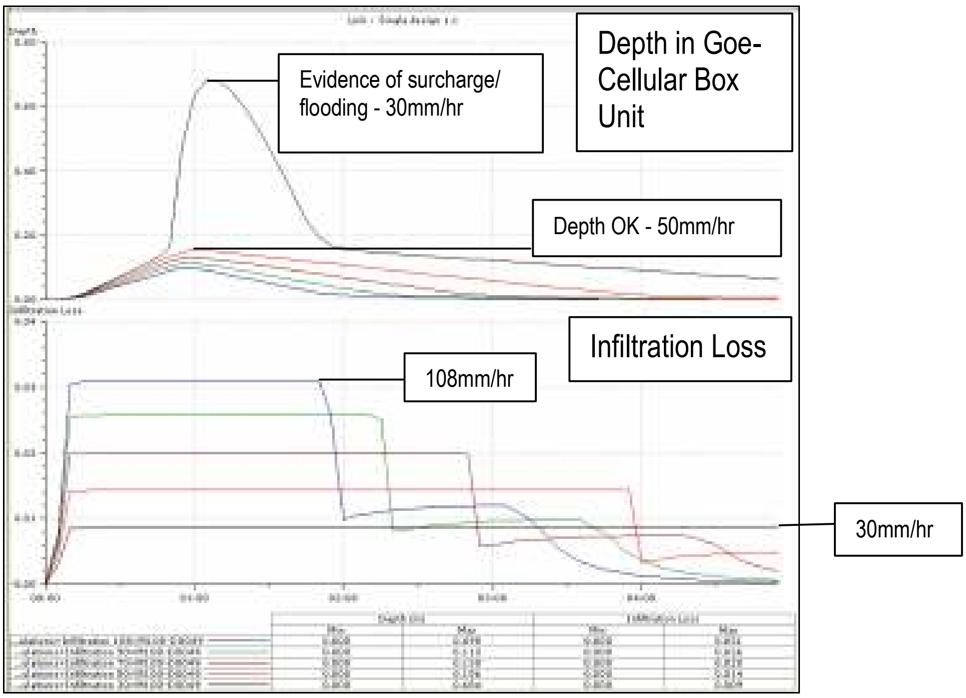

Figure 3 – Change in depth as infiltration rate changes.

As would be expected, Figure 3 demonstrates that as the infiltration rate is reduced the depth of water in the conduit rises, until it reaches a point where there is no longer enough capacity in the system and it shows signs of flooding/ surcharging. This can be seen by the large peak on Figure 3. In this case the critical infiltration rate is somewhere between 30mm/hr and 50mm/hr. This gives enough information for the designer to decide if they require a larger or smaller factor of safety incorporated into the design of the system. In this case, the model simulations suggest that the factor of safety is in the order of 5. Although engineering judgement is still necessary to determine what factor of safety is required, the model is very useful to determine how the overall performance will change based on alteration of contributing factors.

Effect of Porosity on System Performance

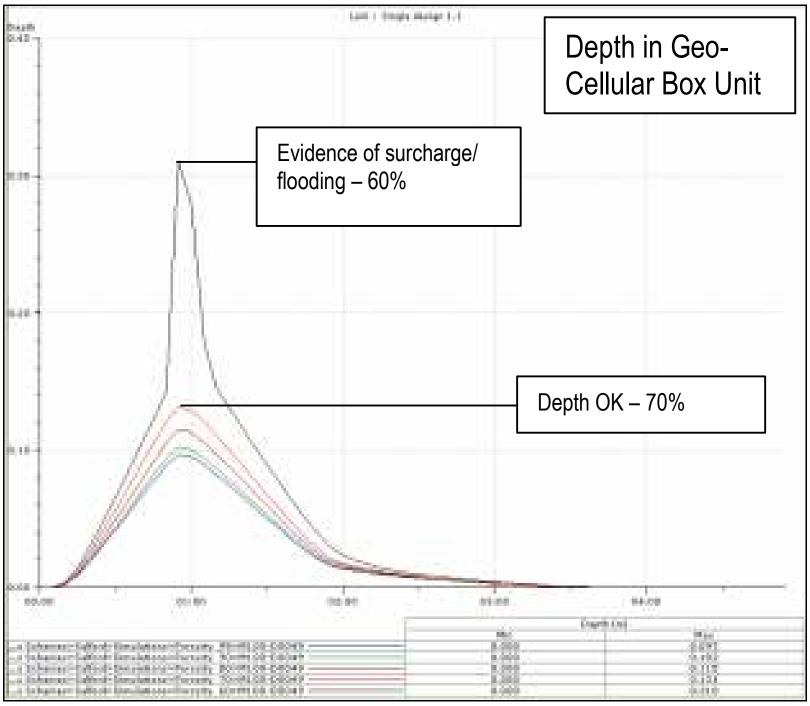

Figure 4 – Change in depth as porosity reduces.

The final section of the performance analysis of Case Study 1 assesses the effect of changing the porosity on the depth of water within the conduit. The range of porosity values used to assess the performance of the system are between 60% and 95%.

As would be expected Figure 4 demonstrates that as the porosity is reduced, the depth of water within the conduit increased. This graph shows a similar pattern to the infiltration rate analysis, and identifies the critical porosity value as between 60% and 70%. Therefore in reality if silt fills up more than 35% of the open volume of the geo-cellular boxes the system is likely cause flooding. However knowledge of this early on means it can be incorporated into the design of the system and any necessary adjustments can be made to the system. Optimisation of the design comes from a good working partnership and good communication between the modeller and the designer.

During this analysis, a limiting factor of modelling infiltration using Infoworks was identified. While modelling infiltration from a conduit, infiltration continues out the base of the conduit once the total volume of flow into the conduit has already infiltrated. This does not affect the peak results, however it does affect the total volume of infiltration and therefore the total volume figure cannot be used. Therefore it is recommended that this is rectified.

Whole Network Performance Analysis

The initial analysis was undertaken on just one conduit to test the performance of Infoworks in a simple manner. However Infoworks comes into its element when the network is larger or contains a series of components (as Case Study 3 demonstrates), as the effect of making simultaneous changes to the design can be assessed just a easily as making one change. A network of further pipes and nodes were added to this model to replicate the individual tanks of geo-cellular box units throughout the site, rather than representing them all as one large tank, which is how it has been modelled up to this point. The overall network can be seen on Figure 5.

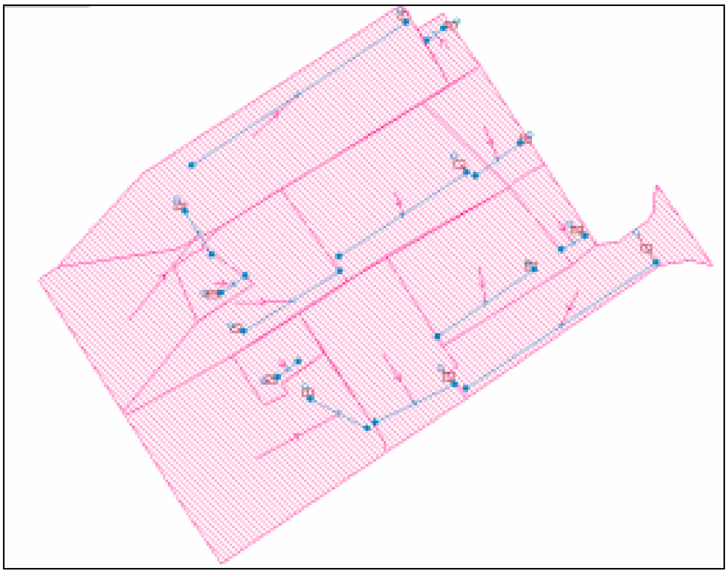

Figure 5 – Larger network of pipes at Salford Sports Village to replicate whole system

The infiltration rate was set to 72mm/hr to allow for a factor of safety in the design and each of the tanks were individually sized. All the conduits were set to the same porosity, infiltration rate, conductivity etc. The only difference between the tanks was the size of the geo-cellular boxes. Table 1 shows the effect of the relationship between the size of the tank and the size of the subcatchment. From this model the tanks that are likely to surcharge or flood (highlighted in pink) are quickly identified and can be resized accordingly. The benefit of using Infoworks for SUDS designs becomes more apparent when trying to design more complex systems.

US Node ID	Max DS Depth (m)	Max US Depth (m)	Depth of Surcharge	Height of Box (mm)
Tank10a	0.312	0.334	0.162	150
Tank11a	0.28	0.332	0.13	150
Tank12a	0.137	0.142	-0.013	150
Tank13a	0.153	0.16	0.003	150
Tank1a	0.128	0.133	-0.022	150
Tank2a	0.069	0.08	-0.081	150
Tank3a	0.268	0.271	0.118	300
Tank4a	0.107	0.116	-0.043	150
Tank5a	0.433	0.46	0.283	150
Tank6a	0.13	0.135	-0.02	150
Tank7a	0.099	0.105	-0.051	150
Tank8a	0.379	0.386	0.229	150
Tank9a	0.521	0.54	0.371	300

Table 1 – Individual geo-cellular tanks assessed for depth of water in the tank.

Case Study 2: Site X

The aim of Case Study 2 is to assess the performance of the pond node which allows infiltration from both the side of the pond and the base of the pond, taking into account vegetation and a liner in the base of a pond.

Site X is a new housing development of approx 5ha, which has been built but cannot be identified due to client confidentiality. The model built for Site X was part of an audit of the surface water system post-construction. The model does show some flooding issues, which tie in with real flooding issues that have been recorded on site.

Therefore if modelling has been used as part of the design process, it may be that some of the problems may have been avoided.

The system is mainly large conventional pipes to provide attenuation, and flow is controlled using orifices. The system has a limited outfall and therefore any flows, greater than the orifice control, are initially attenuated and then overflow into an infiltration basin, which has an emergency overflow into the local water course.

<u>Infiltration Basin Modelling – Pond Node Parameters</u>

<u>Modelling Methodology</u>

The infiltration basin was modelled using a pond node, and a range of infiltration rates were used to assess the performance of the pond.

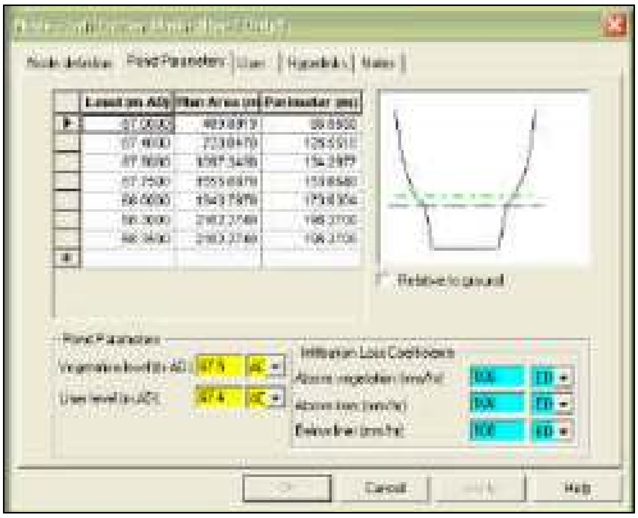

Figure 6 – Pond Parameters

Infiltration loss coefficients can be specified for three different parts of the pond which are above the vegetation level, between the vegetation and liner levels and below the liner level. This allows different infiltration rates to be applied to the base and the sides of the basin.

If the pond is contained within a single subcatchment, any rainfall that falls on the dry part of the catchment will be subject to normal runoff conditions, however any direct rainfall into the wet area of the pond will be assumed to have no losses associated with it and 100% runoff.

When simulating using the pond node, evaporation is also taken into account based on the surface water area and the evaporation rate which is specified in the rainfall data.

<u>Modelling Results</u>

In this case study the effect of changing the infiltration loss coefficients on the pond performance is assessed against pond water level and infiltration loss from the pond. The infiltration rates used lie in the range 10mm/hr to 200mm/hr. These were used to assess the different drain down times for the basin.

Figure 7 demonstrates how the drain down times for the basin increase as the infiltration rate is reduced. At an infiltration rate of 100mm/hr the pond takes approximately 18hrs to drain down. If the infiltration rate is much lower than 100mm/hr the basin takes longer than a day to drain down. The sensitivity testing demonstrates the importance of variations in soil permeability and drain down times. The generally accepted 'rule of thumb' is that ponds or tanks should be able to half-empty within 24hrs to reduce the risk of overtopping due to successive storms. In systems like this one, it is sensible to assess Time Series Rainfall to test how critical this lengthy drain down time is against real rainfall data.

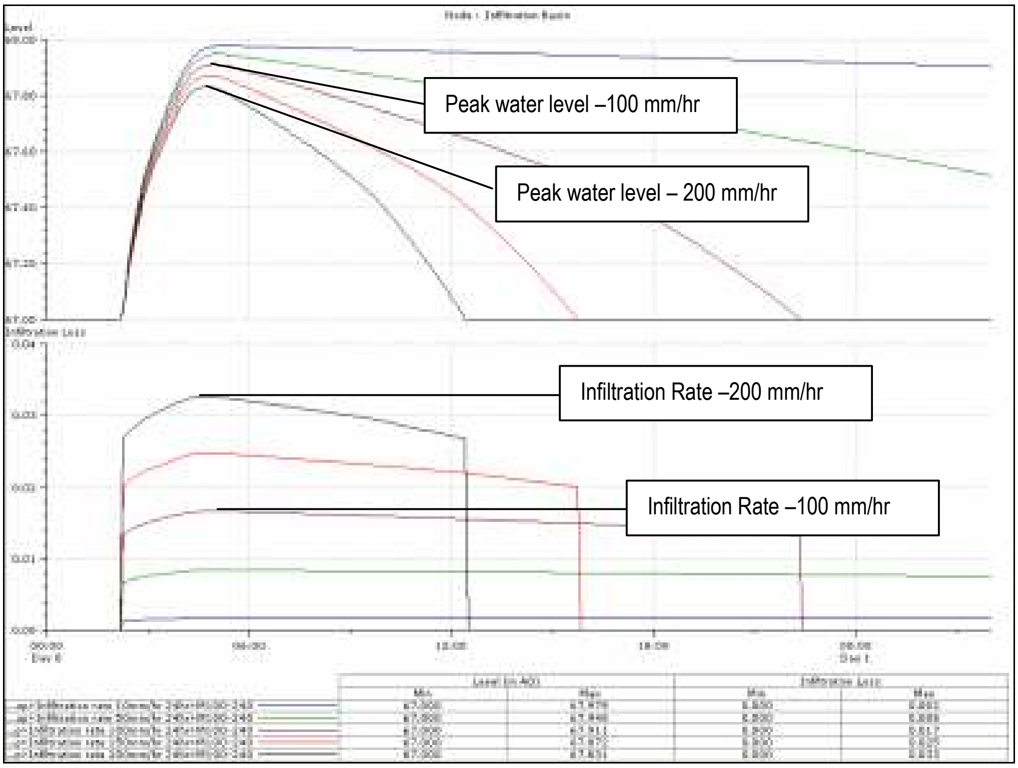

Figure 7 – Effect of infiltration rate on pond level

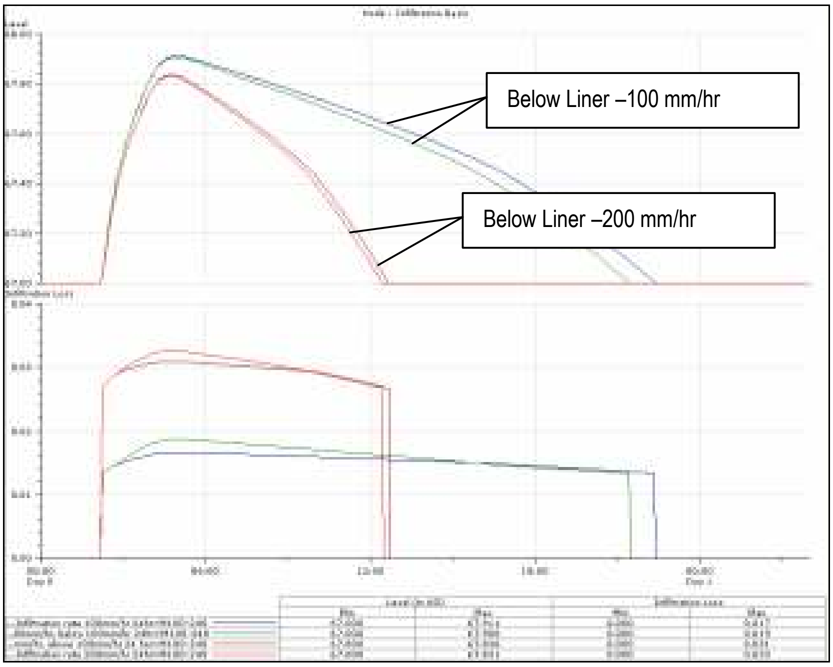

Figure 8 – Effect of changing infiltration rate below and above the liner

Figure 8 demonstrates the effect of changing the infiltration rate below the level of the liner and above the level of the liner based on the pond parameters given in Figure 6. The graph indicates that changing the infiltration rate below the level of the liner has a much greater effect than changing the infiltration rate above the liner. This is due to the fact that the base area is below the level of the liner and is the largest surface area through which infiltration occurs.

However this does clarify that the pond node is simulating infiltration as expected, however further investigation should be undertaken to assess the impact of runoff variability and evaporation at a pond node.

Case Study 3: Leicester Park & Ride Model Build

Case Study 3 demonstrates the use of Darcy's Law as a solution flow model. This is a significant development in the software. As with the infiltration components, before using the Darcy's Law on real design it was considered vital that a number of sensibility tests be undertaken to establish that the model was implemented correctly in the software, and also to test how sensitive it is to key parameters. The following demonstrate the results of these trials and help summarise the fundamentals of the physics of flow through permeable media using Darcy's Law.

Leicester Park and Ride is currently at initial design stage and is still subject to planning permission. It is located in an area where the ground conditions are not suitable for infiltration therefore this is ideal to assess the effects of Darcy's Law without further parameters affecting the results. In this system all flow has to be stored within the site as the outfall is limited to 20.4l/s.

The main component of this case study is to assess the sensibility of Darcy's Law, however this case study will also be used to show how a larger model with a series of treatment stages can be used to replicate flow patterns and relationships throughout the whole system.

The outline of this design is a park and ride scheme in Leicester. The size of the site is approx 4ha, which is split into 11 separate parking areas. Each of the parking areas has permeable block paving with a sub base storage layer below, some of which fall down to the road and are picked up by conventional pipes, the rest drain directly into a swale running along side of the site. The roads drain straight into a gravel filter trench running along the roadside.

The main storage on the site is provided in the sub base underneath the car park areas, in the gravel trenches and at the lower end of the swale. The sub base below the parking areas will be used to complete the sensibility tests on the permeable flow.

Application of Darcy's Law – Permeable Flow Through a Pipe

The sub base below the car park areas can be used to assess the effects of changing the parameters affecting permeable flow within a conduit.

Modelling Methodology

The car park areas were modelled as subcatchments draining to a conduit with a high runoff coefficient of 0.9 to represent the runoff from the new car park. The conduit contains a permeable media so the runoff flows through the conduit are much slower than in a standard pipe. This is represented in Infoworks by setting the solution model to Permeable Flow, which enables Infoworks to calculate the flow using Darcy's Law for horizontal flow through a permeable media.

$$Q = k_f A_c S \qquad \text{(Eq. 1)}$$

where:

Q	=	flow (m^3/day)
K_f	=	hydraulic conductivity (m/day)
A_c	=	cross sectional area (m^2)
S	=	hydraulic gradient (m/m) from inlet to outlet

Therefore the effect on the flow is expected to be as follows:

- The greater the hydraulic gradient across the pipe, the greater the flow should be. This is dependent on the water level at the top of the pipe, the water level at the bottom of the pipe and the length of the pipe.
- The larger the cross sectional area the greater the flow should be
- The higher the hydraulic conductivity the greater the flow should be

The following results summarise the effects of changes to each of the three above parameters.

Modelling Results

The following sensibility tests are undertaken on one conduit, which represents one section of car park. The graphs for three 100yr design storms are shown on Figure 9. Unstable depths can be seen at the start of each event during low flows, however the peak results and the drain down time from the conduit are as expected.

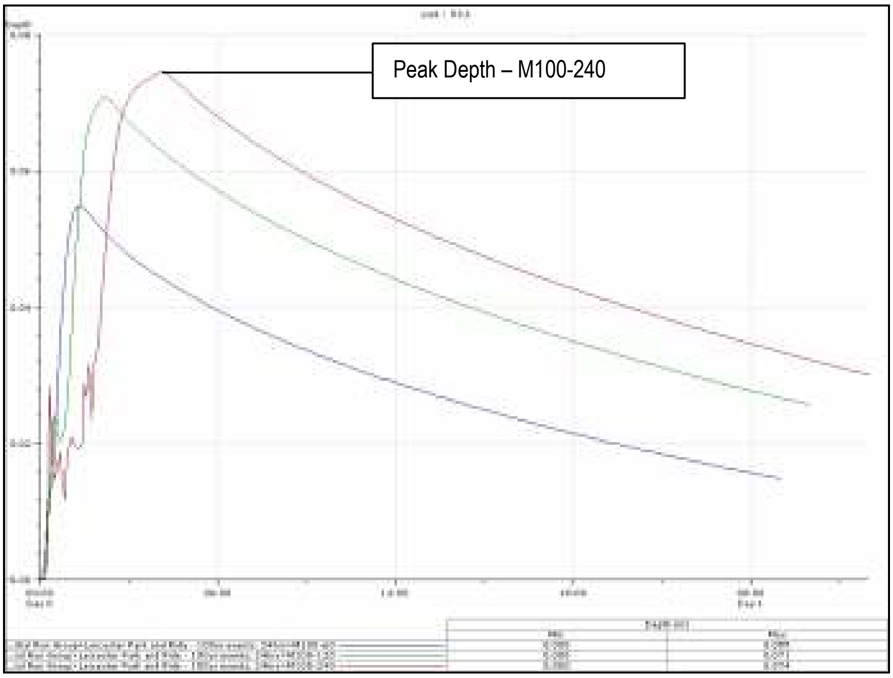

Figure 9 – Depth at upstream end of pipe

Design rainfall has been simulated using the United Kingdom Rainfall Model and the critical storm duration has been identified in most parts of the model as a M100-240 event. For the following assessments the use of one event is sufficient to simplify the process, therefore all the examples used in this case study have been investigated using a M100-240 storm.

Effect of Hydraulic Head Along Pipe on Downstream Flow Rate

The effects of making change to each contributing element of Darcy's Law are shown below. Table 2 shows the effect that a change in hydraulic head along the pipe has on the downstream flow rate in the conduit. With the exception of the first couple of hours where an instability has already been recognised, the flow rate increases as the hydraulic head across the pipe increases.

Time From Start of Sim	Downstream Water Depth	Upstream Water Depth	Hydraulic Head Along Pipe	Downstream Flow Rate (m^3/s)
0hr	0.0001	0.00014	0.00004	0
1hr	0.00775	0.01687	0.00912	0.00042
2hrs	0.00768	0.03241	0.02473	0.00037
3hrs	0.01069	0.05682	0.04613	0.00061
4hrs	0.00917	0.06021	0.05104	0.00049
5hrs	0.00768	0.05872	0.05104	0.00037
6hrs	0.00691	0.05654	0.04963	0.00032
7hrs	0.00646	0.05462	0.04816	0.00029

Table 2 – The effects of the difference in upstream and downstream water levels on flow rate.

Effect of Conductivity Rate on Downstream Flow Rate

Figure 8 shows the effect of decreasing the conductivity through the pipe. It should be noted that when the conductivity is higher and the inflows into the pipe are smaller, the model is less stable. Therefore permeable flow is more suitable for less conductive materials such as clays, sands and soils, rather than gravels and plastic geocellular boxes. These may therefore be better represented using the full solution model[1]. Figure 8 also confirms that as the conductivity increases in the pipe, so does the depth and flow through the downstream end of the pipe. The conductivity rates tested were 0.006m/s, 0.012m/s and 0.018m/s.

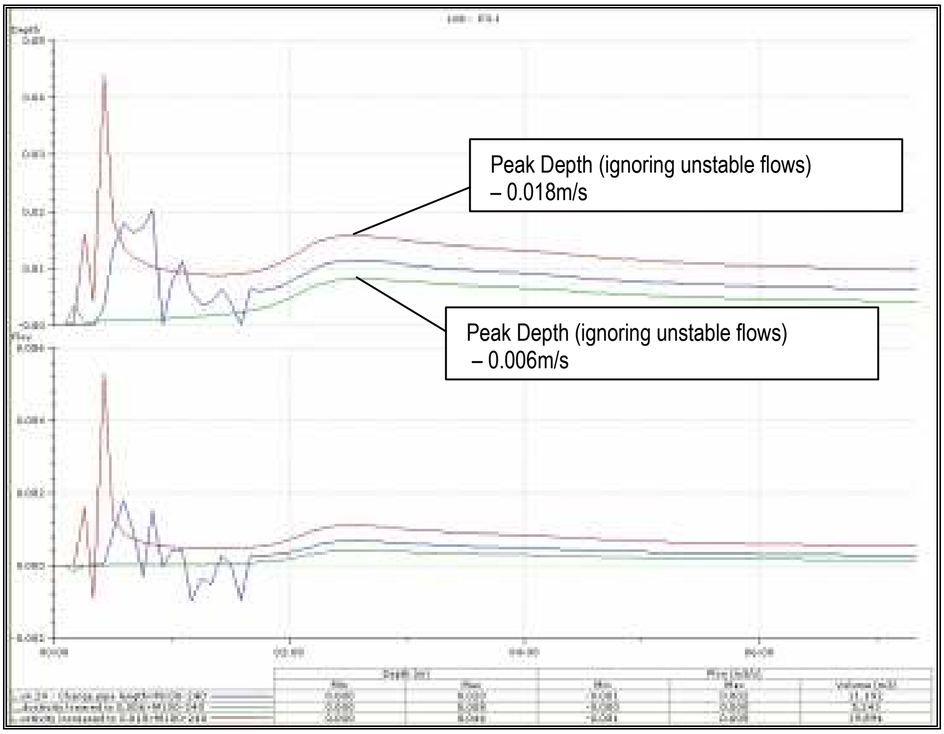

Figure 8 - Effect of conductivity rate on depth and flow.

Figure 9 shows the effect of different conduit sizes on the flow rate through the pipe. Each of the three labelled pipes has the same parameters except for gradient, width and length. As the length increases the flow rate should decrease and as the cross sectional area or gradient increases the flow rate should increase. This relationship is demonstrated by values given in Figure 9 for the three labelled conduits.

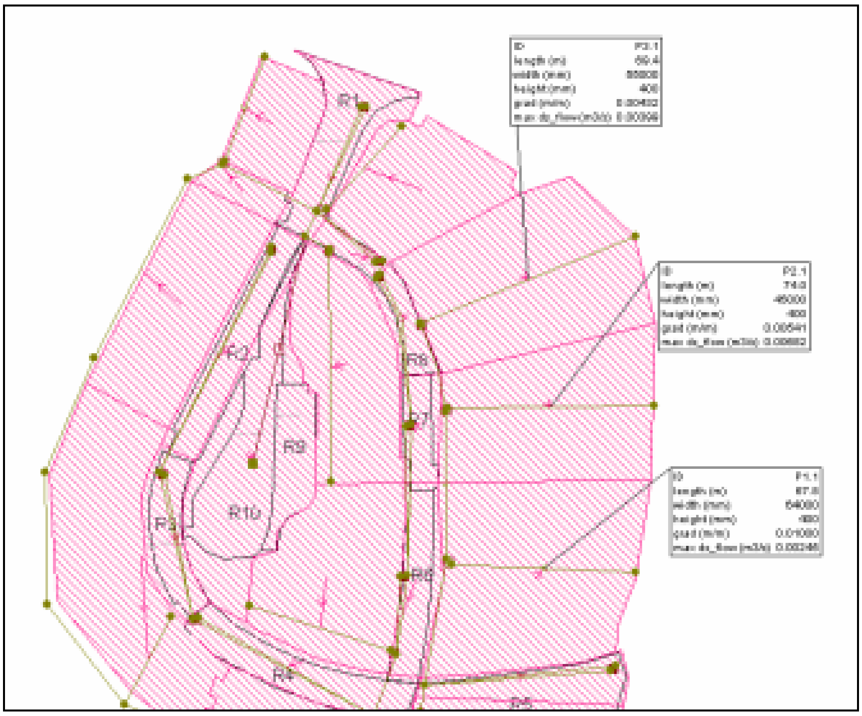

Figure 9 – Effect of conduit size of conduit on downstream flow rate.

Modelling the whole system allows each individual conduit to be optimised in terms of size, gradient, based on the permeable flow model.

As with Case Study 1, it is possible to assess the build up of silt by reducing the porosity and conductivity and using this to apply a factor of safety to the design. This is a significant advancement, as the dynamics of clogging and blocking of SUDS media in channels and trenches can now be simply replicated and assessed.

<u>Other Elements of the Park and Ride Model</u>

The Park and Ride contains a series of different treatment stages and as part of this investigation the whole model was built. Although detailed sensitivity testing was not performed on all elements of the model, there was one particular limitation that was highlighted through modelling two of the other elements:

- Gravel Filled Trench with Perforated Pipe
- Swale with Under-Drain

Both of these require flow between two conduits along the length of the conduit.

The gravel filled trench runs alongside the roads and collects the runoff from the road surfaces. The perforated pipe is located along the bottom of the trench and should fill as the water level and thus water pressure increases. The gravel filled trench was represented using a open rectangular shape using the permeable flow solution model, and the perforated pipe was modelled using a weir in the upstream manhole, so that once the gravel filled trench reached a certain level it would overflow into the pipe. This obviously doesn't take into account the pressure flow relationship for the flow entering the perforated pipe, but was the best possible solution with the current available model options.

The swale is a long channel with a drain along the bottom which collects flow as it infiltrates through the base of the swale. This was not possible to replicate exactly, so the swale was modelled without the under-drain.

It is recommended that flow between conduit along the length of conduits is incorporated into Infoworks to provide a better representation of certain SUDS techniques including those identified here.

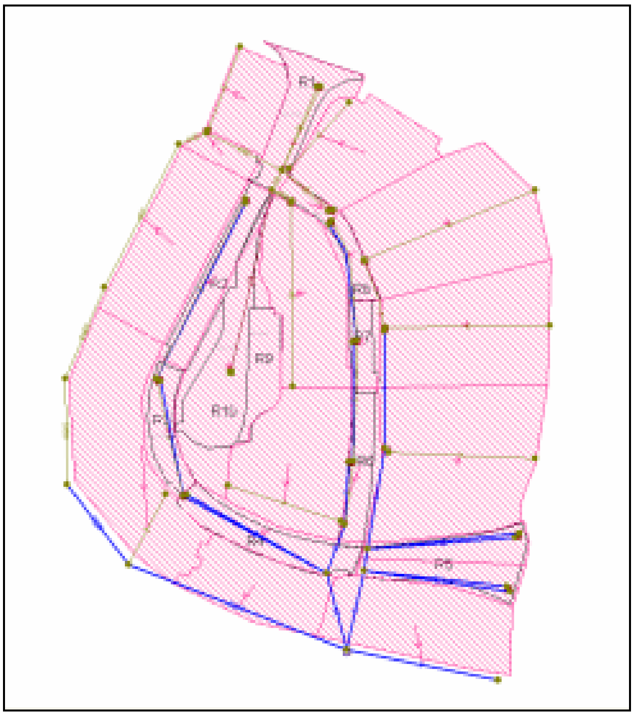

Figure 10 – M100-240 design event peak flows across whole model

Figure 10 shows the whole model which has been iteratively improved from the original design to stop any flooding occurring. This model can either be used on its own to continue to optimise the design requirements, to assess the required factor of safety to account for deterioration over time or it could also be incorporated into a larger storm model of Leicester to assess the effect this would have on the rest of the catchment and possibly even on local watercourses rivers as integrated catchment modelling progresses further.

Time series rainfall could also be applied to the whole model to assess the effect that real rainfall data has on the model, and understand how it would deal with multiple peak storms or continuous rainfall rather than just the design events used in this investigation. Due to the large amount of storage within SUDS system and the slow flows through the system, different types of events may have a more significant effect than they would have in traditional pipes where flow tends to be much quicker.

Conclusion

This paper has highlighted there are many benefits of using Infoworks to model SUDS systems, however a significant amount of engineering judgement and a good knowledge of SUDS components is still required to ensure that any changes made to the design would be appropriate on site to suit the client requirements and the site conditions.

The main benefits of modelling SUDS that have been identified in this paper are summarised below:

- Optimisation of a SUDS design
- Assessment of operation and maintenance issues at the design stage
- Assessment of the effect of a SUDS network on a larger catchment
- Sensitivity testing
- Design check against a range of rainfall types and profiles including time series rainfall.
- Ability to represent permeable flows
- Allows failure modes to be assessed.

These are all summarised under the following headings:

Optimisation of a SUDS design

Modelling SUDS provides a tool to effectively improve the design of the drainage system by making changes to all parts of the network and quickly and easily assessing the effects of the changes. The effect of changing different parameters such as size of conduits, porosity, conductivity, ground levels and invert levels can all be efficiently assessed to optimise the design for a selection of design and events. Further SUDS element can be added to the system rapidly and easily to quickly enhance the most efficient use of the space and site condition available.

The response of the model to time series rainfall can also be investigated during the design phase which allows the system to be tested under saturated condition to check the response and to understand if further safety factors should be incorporated into the design. Modelling of SUDS allows operation and maintenance issues to be addressed at an early stage.

Assessment of Operation and Maintenance Issues at the Design Stage

An assessment of the deterioration over time for example build up of silt within the system, a reduction in porous area or reduction in conductivity can be investigated at the initial design stage or once the system has been implemented to identify either a factor of safety within the design or operation maintenance requirements.

Assessment of the Effect of a SUDS Network on a Larger Catchment

The other major use for SUDS modelling is in larger catchment models where there are a number of components that interact and the impact of time of travel and time of concentration influence on the system performance. This is particularly important if the SUDS system has an emergency overflow mechanism allowing more flows through into the main sewer network or into a watercourse if part of the SUDS system fails.

Recommendations

During the investigations that have been undertaken, there have been two potential issues with Infoworks modelling process that have been identified:

1. When modelling infiltration from a conduit, infiltration continues out the base of the conduit once the total volume of flow into the conduit has already infiltrated. This does not affect the peak results, however it does affect the total volume of infiltration and therefore the total volume figure cannot be used.
2. Where the conductivity in a conduit with permeable flow is high, the flow rate and depths during low flows tend to be slightly unstable, and therefore if the conductivity is high it may be better to use the full solution model.

During the investigation there have also be two SUDS elements that have still been difficult to replicate and improvements could be made to the model to allow these to be represented more accurately. These are as follows:

- Under-drained swale – Requires a conduit that can infiltrate into another conduit below it
- Gravel Filled Trench with Perforated Pipe – Requires a very similar mechanism to transfer flow from the trench into the perforated pipe, by a pressure – flow relationship as the flow passes along the pipe.

References:

1. Reeves M; Representation of Sustainable Urban Development Structures (SUDS) or Best Management Practice (BMP) in Infoworks CS; June 2005.
2. Bettess R; Ciria Report 156 Infiltration Drainage – Manual of Good Practice; 1996