Modelling of Sustainable Solutions at a Rejuvenated Brownfield Site

Nicholas Anderson (Entec UK Ltd)
Mike Reeves (Wallingford Software Ltd)

1. INTRODUCTION

The use of Sustainable Drainage Systems (SuDS) is becoming increasingly widespread. There is a need for integrated modelling to design the SuDS systems and assess their impact on the surrounding catchment. This paper details the hydraulic modelling of a rejuvenated brownfield site which includes a variety of SuDS. The paper discusses the choice of the design parameters and shows the impact of changes in these parameters.

2. CATCHMENT DESCRIPTION

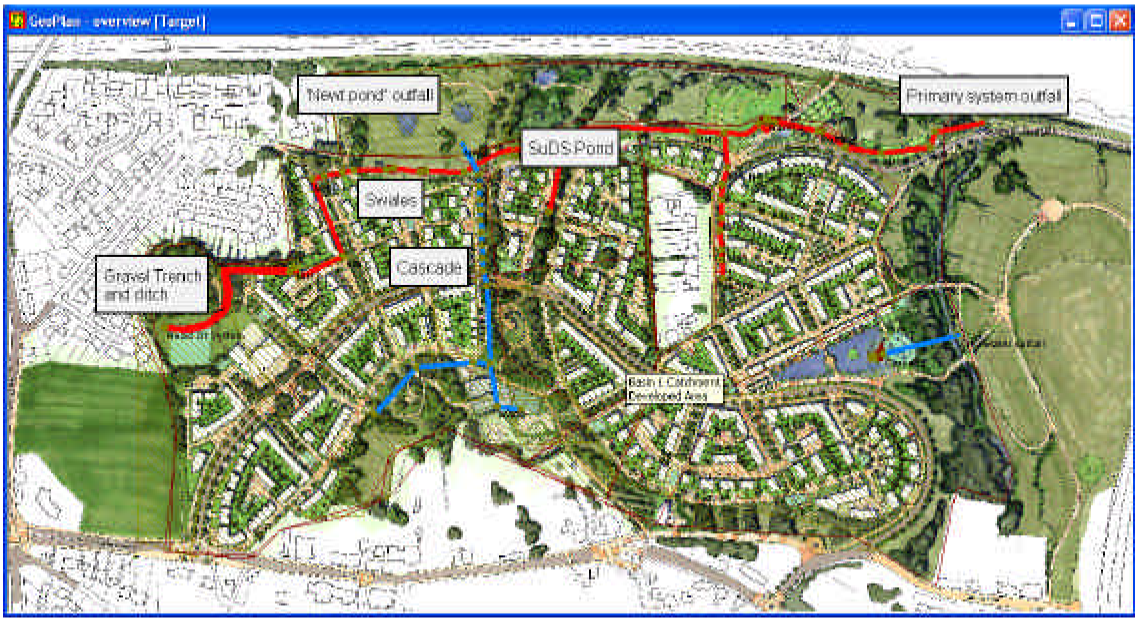
Telford Millennium Community (TMC) is one of seven Millennium Communities throughout England. TMC comprises 35 hectares of brown field land, north-west of Telford, in the heart of England. The site slopes fairly steeply from South West to North East, with a total fall across the site of about 12 m. The site currently consists of 15 Victorian terraced houses and has been left fallow for many years. There are areas within the site that have subsequently become important habitats for wildlife. A local watercourse that passes through the site also requires protection against the threat of contaminated inflows, in addition to flood risk protection from surface water runoff inundation.

The proposed TMC development comprises mainly housing, with some live/work units, a school, some small offices and retail and leisure services. The development also incorporates habitats for a variety of wildlife including a resident population of Great Crested Newts, a protected species. The TMC project seeks to promote the use of SuDS for flow conveyance, attenuation, flood risk reduction, passive treatment to improve water quality and to maintain the existing hydrological regime to protect the Great Crested Newt population.

The proposed layout of the catchment is shown in the Figure below. The catchment is served by separate storm and foul systems. For reasons which will subsequently be explained, the storm system is divided into a system to convey flow directly to the newt ponds (shown in blue) and a primary system to provide both flood protection and to control the existing hydrological regimes through the northern wildlife corridor (shown in red). The Figure also shows the SuDS features which will be incorporated into the drainage system, which are:

- Two grassed swales
- A gravel trench, sited at the bottom of a grassed ditch
- A pond

The Figure also shows a cascade, serving the newt pond system, which will be briefly discussed later.



The site includes redundant mine workings and colliery spoils and there is therefore potential for the inflow of contaminants. A 1.2mm Flexible Polypropylene Alloy Geomembrane is proposed to protect the storm water systems and ultimately the wildlife from pollution. The main attributes of the geomembrane is that it is strong and flexible, conforming well to sub-grade irregularities and protrusions, as well as settlement and subsidence under stress. It has environmental resilience in resisting stress cracking, aggressive chemicals attack, weathering, and UV rays. It is simple to install and repair; uses standard welding techniques to deliver high joint integrity and has a low permeability to gases. (Waterlines Solutions UK, 2004, http://www.water-lines.co.uk/.) Unfortunately this impermeable barrier limits the effectiveness of many SuDS, this will be discussed later.

3. PROJECT DESCRIPTION

The project comprised the design of the hydraulically independent storm systems serving the newt ponds and also the spine road and homezone areas. The reason that two systems are required is that runoff from highways and other hard standing areas may contain pollutants such as heavy metals (zinc, copper, cadmium) and chlorides. These pollutants are harmful to newt populations and required controlling from entering their habitat. Therefore, to reduce the effects of contamination, the newt ponds will be mainly served by undeveloped green areas, although to maintain the existing hydrological regime there will be the need to discharge some roof and hard standing areas.

The design criteria, including that of the SuDS were specified to meet the following three surface water management objectives.

- Reduce Flood Risk in accordance with PPG25[1]
- Ensure the existing sensitive ecological habitats are maintained
- Provide a cost effective drainage solution that mitigates future cost and safety

[1] PPG25 Development and flood risk. This guidance was produced by The Government and explains how flood risk should be considered at all stages of the planning and development process in order to reduce future damage to property and loss of life.

The project was completed by first predicting the existing hydrological performance of the undeveloped catchment. This was required to provide a benchmark against which development could be assessed. This assessment is presented in section 3.1.

Both storm systems were then modelled using the InfoWorks CS software package. InfoWorks CS was chosen because it has the ability to represent the hydraulic aspects of SuDS structures and to allow them to dynamically interact with more familiar hydraulic drainage structures including pipes, channels and manholes. The model is used to compare the developed catchment against the predicted existing performance to determine whether the design objectives have been met. Representation of the Newt pond system is presented in section 3.2 and representation of the primary system, including the SuDS is presented in section 3.3.

3.1 Existing Hydrological Assessment

The rainfall runoff method for estimating design floods, calibrated with site specific parameters was used to predict existing hydrological performance and provide a benchmark against which development could be assessed. The rainfall runoff method relies on rainfall frequency estimates to provide inputs into a model which converts rainfall to runoff. Rainfall frequency estimates were taken from the Flood Estimation Handbook (FEH) CD-ROM.

The steps in implementing the rainfall-runoff method were:

- Establish the parameters of the unit hydrograph, from flood event data and from catchment descriptors;
- Determine a percentage runoff to convert to total rainfall to effective rainfall;
- Construct the design storm by determining its duration, depth and profile;
- Combine the effective rainfall profile with the unit hydrograph by convolution to give the flood hydrograph
- Add base flow to the flood hydrograph.

Catchment descriptors summarise properties of river catchments, including urbanisation and rainfall characteristics. They are required for flood estimation at sites where there is no gauged record and for comparison of hydrological similarity.

Current hydrological practice considers the FEH approach to be only suitable at sites greater than 50ha. Since the proposed development site is only 38ha; a calibrating method was employed to reduce the level of inaccuracy. The rural Mean Annual Flood value QBAR was recreated for the TMC catchment from the following equation.

$QBAR_{RURAL} = 0.00108 \times AREA^{0.89} \times SAAR^{1.17} \times SOIL^{2.17}$ (Equation 1)

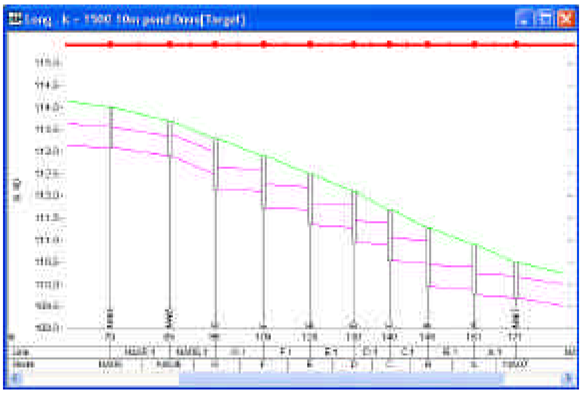
Marshall (1994)

The rural growth factors were subsequently read from tables 3.1, 3.2 and 3.3 in CIRIA Book 14, (Hall M.J, et al), with the extracted values used to calibrate the peak flow estimates from FEH generated hydrographs. The hydrograph distributions were retained with the values calibrated pro-rata.

3.2 The Newt Pond Drainage System

One aspect of the newt pond drainage system worth mentioning is the cascade used to dissipate energy in a steep area of the catchment. The dissipation of kinetic energy is essential in preventing scouring in the downstream channels.

Cascades usually consist of open channels with a series of drops at invert levels. The TMC cascades are no exception, with the steps to be constructed from gabions and backfilled with earth to create a step length. Step heights and lengths were designed in accordance with CIRIA Report 33. Design calculations were completed to ensure that sub critical flow conditions were present in the exiting flows. The type of cascade used at TMC was a pooled step type.



The cascade was modelled as a series of short open channels, as shown in the adjacent figure. It was found that changing hydraulic roughness and even the geometry of the model had little effect on hydraulic performance within the cascade itself. The model results, whilst not being able to replicate the exact flow categories along the length of the cascade gave realistic results in terms of outflow depths and velocities.

Therefore the number of steps, step lengths and gradient of the cascade could only be confidently designed by hand calculation. When modelling a cascade, the important issue is that there should be at least one manhole representing a drop.

3.3 The Primary Drainage System

The primary drainage system flows west to east across the catchment. At the head of this system there is an area of about 1.3 hectares comprising a school playing field. This is represented in InfoWorks CS using the groundwater infiltration module. The system then receives flow from the homezone areas, which are represented using a fixed percentage runoff contribution.

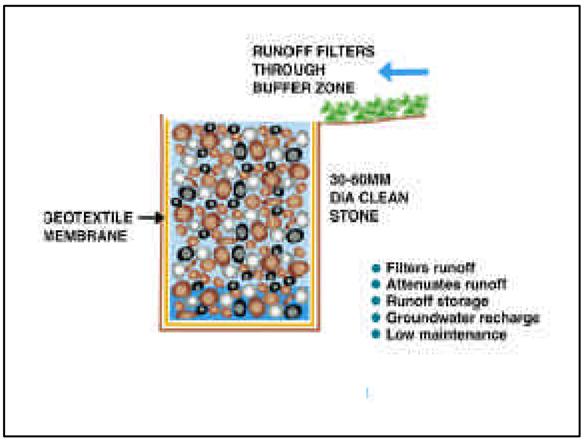
The underlying principle in the design of this system was that the existing hydrological conditions in the undeveloped site should not be altered. A gravel trench, two swales and a pond used to provide the necessary attenuation and storage of flow. These are discussed in the sections below.

3.3.1 Gravel Trench

A trench filled with gravel was required to attenuate the flows leaving the school playing field. This SuDS was chosen is preference to other forms of flow storage and attenuation as it was not considered desirable to have an open body of water within school grounds.

The longevity of such a trench is enhanced through the incorporation of a filter strip, gully or sump to remove excessive solids at the inflow. These reduce the likelihood of blockages of the interstices. These structures facilitate the storage and filtering of water on route from the source to the discharge point. Many similar structures include the ability to loose flows to the surrounding soil through infiltration. However this was not possible in this catchment due to the contaminated land.

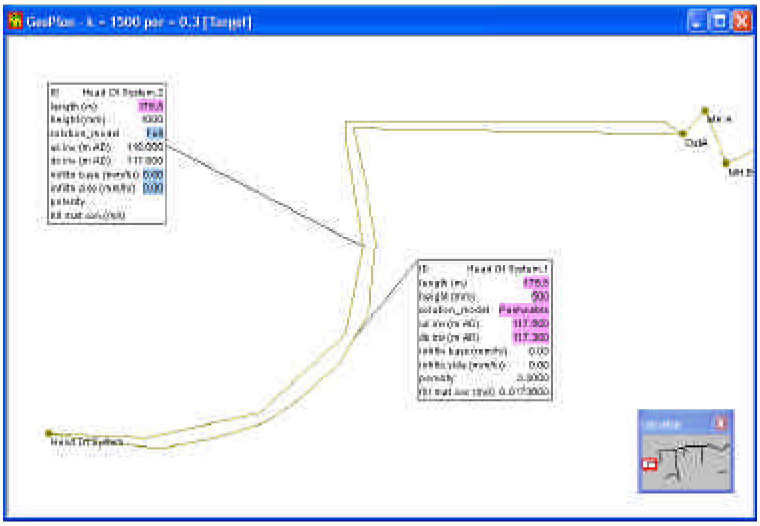
The gravel trench used in this project is 500 mm deep and 176 m long, with a gradient of 0.00114. It differs from the adjacent figure in that it sits at the bottom of a drainage ditch. When the capacity of the gravel is exceeded, the flow can pass over the gravel whilst being contained within the ditch. The ditch has a side slope of 1:4 which is required for safety and so that the grass can be easily cut



There are two key aspects of InfoWorks CS which allow the representation of such a structure. The first is that flows through the gravel trench will have different characteristics to the flows in the ditch, once the gravel is surcharged. InfoWorks CS allows different numerical solutions to be specified to represent these different flow regimes. Flows in the gravel are represented using Darcy flows (Shaw 1994) whereas flows in the open ditch use the standard full solution of the St Vennant equations (Yen 1973.) The choice of which solution model to use is simply made in InfoWorks CS from the conduit definition tab in the conduit properties.

The second aspect is that in traditional sewage system all flows will enter at the top (of the pipe.) However in a gravel trench, the flows will enter from the sides and therefore increase uniformerly along the length of the trench. In InfoWorks CS, subcatchments can now be specified as draining to a link, using a tick box in the sub-catchment properties. If this is specified then the runoff contribution is equally divided between the computational nodes which are equally spaced along all conduits.

The representation of the trench and overflow ditch is shown in the adjacent figure. It can be seen that there are two links, one to represent the trench and one to represent the ditch.



One of the main limitations in this representation is that the trench and the ditch are only connected at the top and bottom, whereas in reality there would be continuous cross connection between them. Once the trench becomes surcharged, at the upstream end, and flow enters the ditch, there is no way for it to get back into the trench. For this reason, when representing structures like this, it is very important that the sub-catchment is defined as draining to the link (using the 'drains to link' tick box in the sub-catchment properties) rather than draining to the upstream node.

Flow through a gravel trench is represented using the 4-point Preissmann finite difference scheme, where the two governing equations are:

1. Conservation of mass the same as for full (St Vennant) flow, but accounting for the porosity of the flow medium.

2. Darcy equation for flow rate, as recommended by, amongst others, Wilson (2004)

Darcy's Law (Shaw 1994) is as follows.

$$Q = kAi \qquad \text{(Equation 2)}$$

k = Hydraulic conductivity (m/day)
A = Cross sectional area of flow (m^2)
i = Hydraulic gradient (h/L)
h = Head differential (m)
L = Length (of filter trench) (m)

The two parameters to be assessed for any filter trench are the Darcy coefficient k and the porosity of the fill material.

It should be highlighted that coefficient k is not the velocity of flow through the gravel. It is a scalar that expresses the ease with which a fluid is transported through the void space in a porous bed. It is thus a coefficient that depends on both matrix and fluid properties (Bear and Verruijt, 1987).

The table below presents values of these two parameters taken from a number of sources. Most references provide values for a range of grain sizes from fine clays up to coarse gravels. Values only for the grain size most applicable to this study are quoted here.

Description	Grain size (mm)	Porosity	Darcy coefficient k (m/day)	Reference
Gravel, medium	8 – 16		270	Shaw E.M pg 138(1)
Course Gravel	16 – 32	0.28	270	Todd
Gavelly course sand			10 – 50	Ritzema H.P
Gravel			27 – 27,000	EAD
Uniform gravel / gravel		0.3 – 0.4	0.41 – 41(2)	Bettess R
Course Gravel		0.18 – 0.25	1000 – 100,000	Hamil L
Gravel			0.72 – 7.2	Ellis B
Sand or gravel		0.3 – 0.45		Kadlec R.H
Fine gravel	16	0.38	800	Nuttall et al
Medium gravel	32	0.40	1200	Nuttall et al
Coarse rock	128	0.45	1500	Nuttall et al

- Page 135 states 'k has high values for coarse sands and gravels (e.g. 10 to 10^3 m/day)'.
- The values quoted here relate to infiltration into the surrounding soil and should not be confused with hydraulic conductivity, the rate of flow through the trench or aquifer.

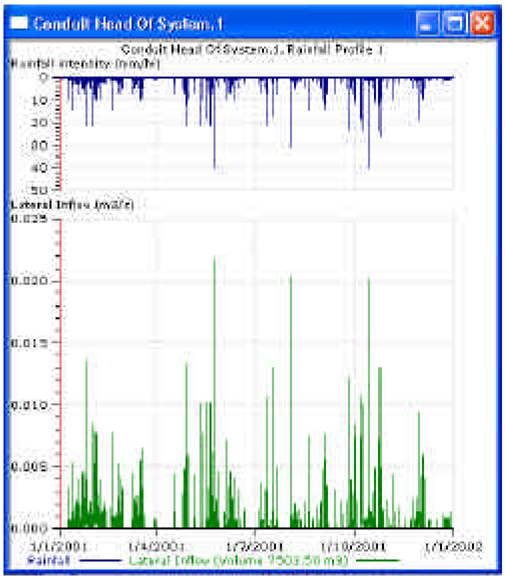
From the Table above it can be seen that there is a huge range for the quoted values of k. This study investigated the effect of changing the value of k between 270 and 1500.

Darcy's Law was originally conceived for use in clean water situations, and the flow is assumed to be laminar and uniform (Nuttall et al, 1997.) Kadlec and Knight (1996) state that the turbulence contribution is negligible when the Reynolds number is less than 1.0, and may be ignored with a small error for Reynolds numbers up to 10. Assessment of the results from this study showed that a trench with a slope of about 1:100 and a value of k of 1500, a Reynolds number of over 10 could be produced during a typical time series. Therefore it is likely that many gravel trenches are likely to be operating at or above the values of Reynolds numbers for which the Darcy equation was originally conceived. Further work, including monitoring of SUDS is required to confirm whether the Darcy equation provides a good representation of the flows in these structures.

There are three key elements of design with which the numerical modelling can assist.

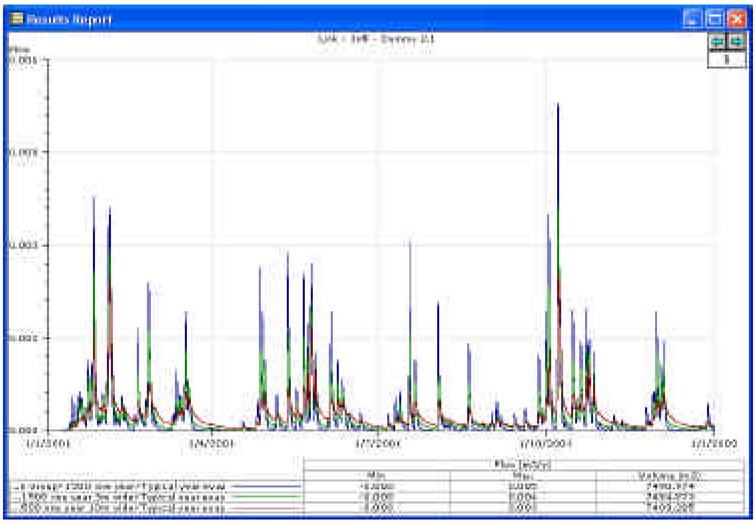
- How big the trench should be
- What Darcy value should be specified
- What is the impact of the structure downstream

The EU WFD (2000) has as much emphasis on normal operation as performance during severe rainfall events. Also antecedent conditions and an understanding of the continual wetting and drying processes are considered important in assessing SUDS. The model was therefore simulated with a typical years worth of data. The inflow at the top of the trench is shown in the adjacent Figure.



The first question to consider, is how wide the trench should be. With a wider trench, more of the flow is being held within the trench and hence the greater the attenuation provided. The adjacent Figure shows the flows in the pipe immediately downstream of the trench. The blue line represents a 0.5m wide trench, the green line 3m and the red line 10m.

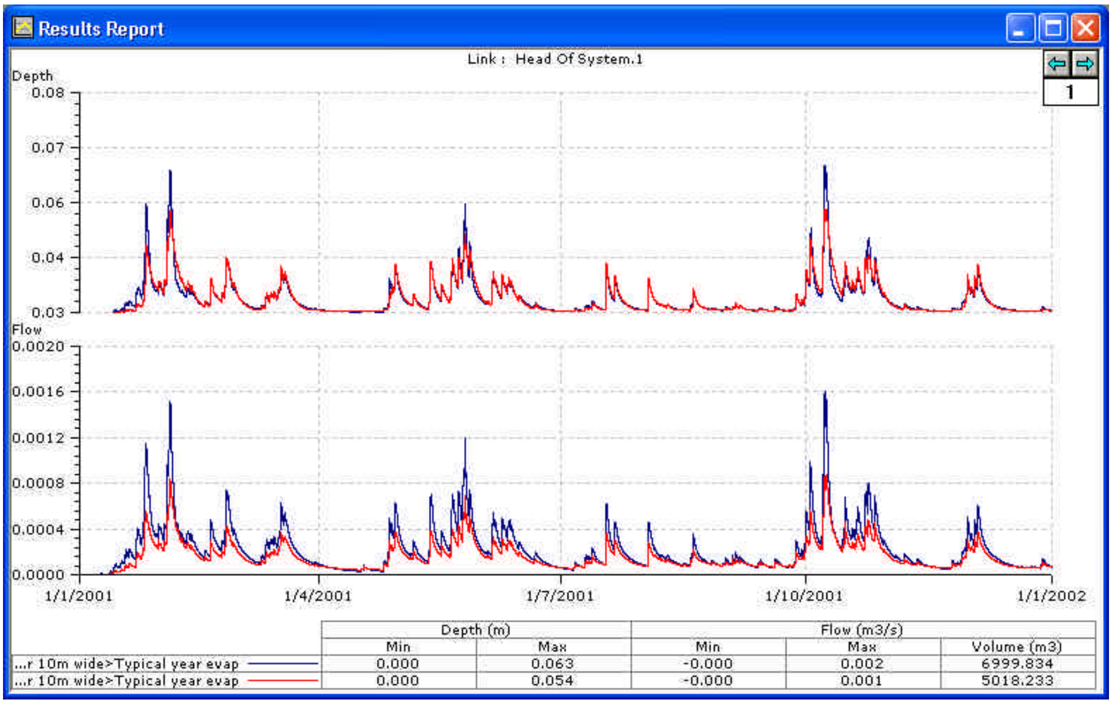
The table below shows the subsequent reduction in operation of the overflow ditch. This reduction is due in large part to the fact that a wider trench provides greater storage.



Trench Width (m)	Peak flow (l/s)	Volume (m^3)	Duration (days)
0.5	2.6	3286	170.5
3.0	1.7	2102	101.1
10.0	1.1	411	15.2

One aspect that is not addressed in this study, is what is an acceptable limit (in terms of frequency or peak flows) or the surcharging of the trench.

Sensitivity testing was conducted to help determine which Darcy value should be specified. The figure below shows two graphs representing flow and depth in the trench. In both graphs the red line represents a Darcy k value of 270 m/day and the blue line is a value 1500 m/day.



From the graphs it can be seen that differing k values have a greater impact during large events. As expected, reducing the Darcy k value, reduces the conductivity of the trench and therefore causes the overflow ditch to operate more frequently, as presented in the table below.

Darcy coefficient (m/day)	Peak flow (l/s)	Volume (m^3)	Duration (days)
270	0.8	2187	176.5
1500	1.1	411	15.2

The performance of the trench could be improved if there was the ability to loose flow via infiltration into the surrounding soil.

The graph above shows that if the Darcy k value is in the range 270 – 1500, then even during long periods of dry weather, there is still flow from the gravel trench. This has a positive impact on the ponds downstream as will be shown later.

3.3.2 Swales

A swale is an open grassed ditch used to convey flow. In this project two main swales are used. Each swale has a side slope of 1:4, which was chosen for issues of safety and to allow the easier maintenance. Each has a 'check dam' and orifice immediately downstream of it to attenuate flows. The swales are therefore effectively acting as on-line storage. The size of the dams and orifices were designed so that there would be no overtopping during a 1:100 year event and the existing peak pass forward flows from the undeveloped site would not be exceeded.

The velocity of the flows in swales will in the case of TMC allow the swale to act as a treatment facility by permitting the deposition of suspended materials; however siltation is considered a major issue in the main swales due to the treatment the flows previously received when passing through the gravel trenches, cascades and ponds..

A swale is another example of where the contribution of a sub-catchment to a link, rather than a node is useful. This can be used in a variety of situations, but is particularly useful in representing a road, car park or any other hard standing area which has a swale or gravel trench running the length of it. As water runs off the area, it will cause the flows in the swale to uniformly increase.

The critical factor when designing swales was to ensure that flows within the channel remain sub critical at all times. Sub critical flows reduce the effects of scour on the channel and allow hydraulic controls to be applied at the location such as check dams. InfoWorks CS could be used to check flow conditions for a variety of storms.

Maintaining sub critical flows alone will not prevent scour in all locations along the SuDS. Scour will remain a hydraulic problem at locations where flows are concentrated such as the inlet and outlets to check dams, basins, cascades and trenches, and where abrupt changes in flow direction occur. (May et al). These would likely be at outfalls from the pipe drainage system into swales and basins. At these locations pitching stone will be placed to reduce scour by dissipating energy and prevent damage to the hydraulic structure.

3.3.3 The Pond

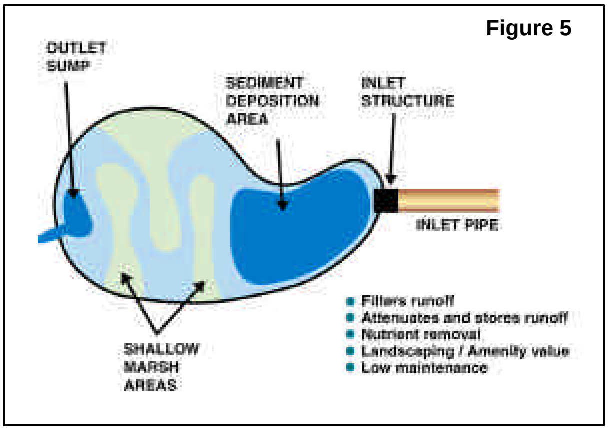


Figure 5

Although storage can be designed as wet or dry ponds (basins), or wetlands, they are most likely to contribute to visual amenity and biodiversity where they include a permanent open water body. In addition, the Great Crested Newt population requires a continuous submerged area. Ponds or wetlands can be designed to accommodate considerable variations in water level during storms, thereby enhancing flood storage capacity. By allowing adequate detention time, the level of pollutant removal can be significant. The flora and fauna of wetlands can provide a particularly good level of filtering and nutrient removal as well as having the potential to recycle grey water. Ponds and wetlands can be fed by swales, filter drains or piped systems, and the use of inlet / outlet sumps will help reduce sedimentation within the zones of vegetation.

The pond had a base level of 107.5 mAD, a normal outfall level of 108.45 mAD and an emergency overflow level of 108.95 mAD.

There are three aspects of a pond which are not seen in most traditional sewerage schemes, but do require numerical representation.

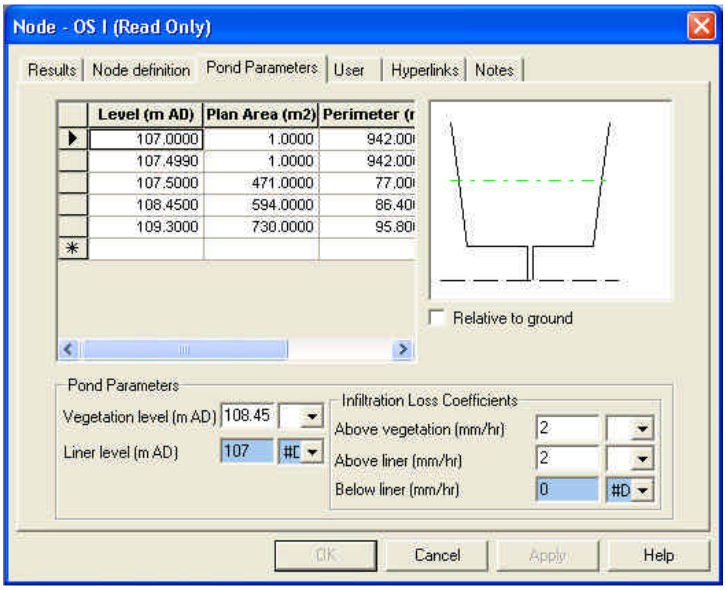
- The runoff characteristics will vary depending on the water level. When the pond level is low, much of the surrounding area is likely to be vegetated, effectively permeable area with a low proportion of runoff. As the pond fills this area becomes submerged. The surface of the pond will act as a highly impermeable area, with 100% runoff and no attenuation through routing. This means that the contribution to the pond will change due to antecedent conditions.
- There is the potential for the pond to be emptied due to evaporation (included in the rainfall event characteristics.)
- The pond can also be emptied due to an infiltration loss to the surrounding soil.

Evaporation is not thought to significant at TMC. Even during the height of the summer evaporation in the UK is only approximately 3mm/day. It would therefore have insignificant impact on the 950 mm freeboard.

The model showed how the SuDS schemes worked well together. The high attenuation provided by the gravel trench meant that the pond received a relatively constant inflow, meaning that it would not run dry, even during long periods of dry weather.

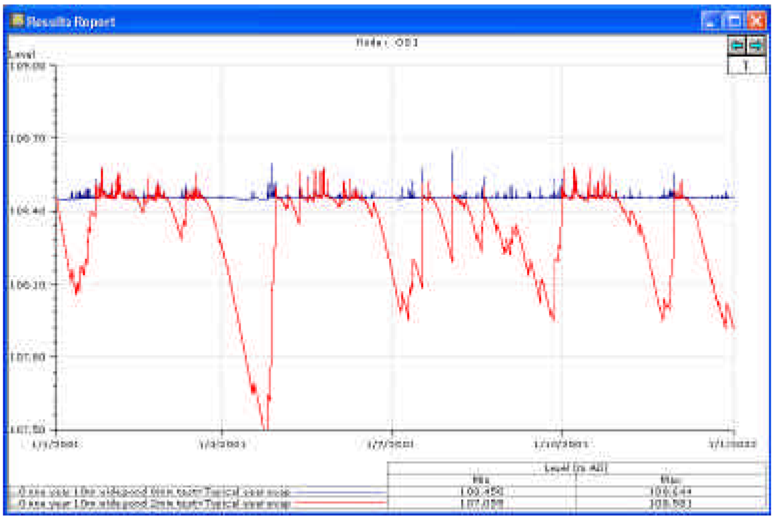
Although in this site, there could be no infiltration loss, because of the contaminated land, a short investigation was conducted into what level of infiltration loss through the sides and base of the pond would lead to the pond running dry during the typical year rainfall.

Figure below shows the representation of the pond.



The small plan area and large perimeter are used to represent the loss through the flat base of the pond.

Figure below gives a comparison of a loss rate of 0 and 2mm /hr. It can be seen that a loss rate of over 1.8mm/hr will cause the pond to run dry during the year. Table 4.4 of Bettess (1996) provides infiltration coefficients based on soil texture. Chalk and sand are quoted as having coefficients of up to 100 mm/hr and a loamy sand of up to 1 mm/hr.



4. CONCLUSIONS

Hydraulic modelling of sewerage systems and surface water management projects is not new, it is a tried and trusted way of dynamically solving often complex engineering problems, however, with the ever increasing development of SuDS, modelling is keeping pace so that the same levels of confidence and understanding can be applied to new and innovate drainage systems.

Modelling of the brownfield redevelopment at TMC has allowed the flexibility of SuDS to be demonstrated to prove that if the design criterion considers the annual performance to be as important as the 100 year performance both can be equally analysed and understood.

There are currently proposal for the post construction phase of the project to include some level of performance monitoring, hopefully this monitoring will provide data for future projects and the associated hydraulic modelling.

5. REFERENCES

Bear, J., and Verruijit, A., (1987), Modelling groundwater flow and pollution, D Reidel Publishing Company, Holland.

Bettes R. Ciria Report 156, (1996) Infiltration Drainage, Manual of Good Practice

CIRIA C522, SUDS Design manual for England and Wales.

CIRIA Report 33, The Hydraulic Design of Stepped Spillways

Ellis B. Middlesex University. Anecdotal evidence provided to the Urban Drainage discussion forum.

Environmental Assessment Division, Argonne National Laboratory. http://web.ead.anl.gov/resrad/datacoll/conuct.htm

EU Water Framework Directive (2000) http://europa.eu.int/comm/environment/water/water-framework/index_en.html

Hall M.J, Hockin D.L, Ellis J.B, (1993) CIRIA Book 14 Design of Flood Storage Reservoirs

Hamil L. (2001) Understanding Hydraulics 2nd Edition pg 530.

Kadlec R. H, and Knight, R. L., (1996) Treatment Wetlands, CRC Press.

Marshall D.C.W and Bayliss A.C. Institute of Hydrology Report No. 124. Flood Estimation for Small Catchments. June 1994.

May R.W.P, Ackers J.C, Kirby A.M, (2002) CIRIA C551, Manual for scour at bridges and other hydraulic structures

Nuttall, P. M., Boon, A. G., and Rowell, M. R., (1997) Review of the design and management of constructed wetlands, CIRIA Report 180, CIRIA.

ODPM, Planning Policy Guidance Note 25, Development and flood risk

Reed D. (1999) Flood Estimation Handbook, Institute of Hydrology (1999)

Ritzema H.P. (Ed.), chapter 12 Drainage Principles and Applications, ILRI Publication 16, second revised edition, 1994, Wageningen, The Netherlands http://www.waterlog.info/cont12.htm

Shaw E.M. Hydrology in Practice. 3rd Edition 1994.

Todd K.T Groundwater Hydrology 2nd Edition 1980.

Wilson E.M. (1990) Engineering Hydrology 4th Edition

Wilson S, Bray R, Cooper P. (2004) Ciria C609. p223 Sustainable drainage systems. Hydraulic, structural and water quality advice.

Yen B.C. Open Channel Flow Equations Revisited. J. Eng. Mech. Div. ASCE, Vol 99, No EM5.

6. ACKNOWLEDGEMENTS

The authors would like thank the following:

English Partnerships and Taylor Woodrow Developments Limited for their permission to publish information relating to TMC.

Jamie Margetts of Clear Environmental Consultants and Mike Wood and Tim Smith of Hyder Consulting Limited for their assistance in producing this paper.