Aquifers, Tunnels and Trains… The Sodbury Tunnel Story

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SYNOPSIS

Closures due to flooding within the Sodbury Tunnel cost Network Rail millions each year in compensation paid out to train operators. As part of a flood alleviation scheme, Haswell Consulting Engineers developed an InfoWorks model to replicate system behaviour. As well as the usual interaction between rainfall and runoff, the unlined tunnel passes through three major aquifers which has the potential to contribute up to 2.5 m^3/s flow to the system from large surface exposures. The impact and extent of these aquifer flows were investigated and modelled, using various catchment parameters including Soil Moisture Deficit (SMD), groundwater level, cumulative and intensity rainfall data to try and determine a pattern to the high flows which were causing track closure. Some verification was undertaken within the system and the captured data included a closure in January 1999 which was one of the larger closure events in the last five years. The Groundwater Infiltration module within InfoWorks was tailored to represent the prevailing catchment conditions and used to replicate the high aquifer flows observed in the system. Following further historical verification, flood alleviation options were developed. Initially based on hard engineering (big pumps and big off-line storage), softer, more sustainable solutions were then developed in discussion with the Environment Agency to include gravity driven solutions and storm water balancing on designated 'sacrificial flood areas' in association with an impact analysis on the receiving watercourse and the surrounding area. This, in conjunction with long term monitoring and early warning systems, should help reduce closure times and delays to train services.

INTRODUCTION

The Sodbury Tunnel sits on one of the major rail routes within the UK. It is on the direct route from Bristol and South Wales to London both for freight and passenger services. It has historically been susceptible to flooding which causes severe disruption to services. It is estimated that the route is closed an average of 24 times per annum, resulting in the cancellation of 40 freight services and diversion and cancellation of 50 express passenger services. The problem has received national news coverage and has been discussed in various parliamentary sessions, so there is pressure to engineer a solution. The cost to Network Rail is not only large in terms of compensation, but also in terms of adverse press and political pressure until a solution is in place.

THE TUNNEL

The tunnel was constructed around 1900 for the South Wales and Bristol Direct Railway. It runs some 4 km from just west of Badminton Station to east of Chipping Sodbury Yard. The tunnel itself is an arched brick lined tunnel some 27' 6" across and 20' 9" high (see figure 1). The tunnel was constructed at a 1:300 gradient from Badminton, falling in a westerly direction to Chipping Sodbury. The sole drainage conduit was a central brick culvert with a capacity of around 380 - 400 l/s. This also collects all flow from track drainage conduits (cess drains) in the eastern cutting and transfers flow directly to the Kingrove Stream in Chipping Sodbury Yard. The tunnel passes through a varied geology in its 4 km, some of which has a large influence on its drainage characteristics.

Figure 1 –Sodbury Tunnel

TUNNEL FLOODING

The tunnel has been prone to flooding for many years with flows regularly exceeding the track level. In the days of steam, the excess flow was not as great a problem. Engines were heavier and could retain stability on the track under flood conditions. They had to travel slower, but could pass through standing water at quite a depth (See Figure 2). With the advent of lighter and streamlined diesel engines the excess flood waters became an issue.

Figure 2 – Modern Day Flooding and a Steam Engine Passing through Flood Waters (Both West Cutting Looking East)

To be able to develop flood alleviation solutions for the tunnel, a better understanding of the hydrology and more importantly the hydrogeology of the tunnel catchment needed to be obtained in order to replicate observed flows and levels.

CATCHMENT HYDROLOGY

The hydrology of the tunnel catchment is fairly straight forward. The cuttings to the east and west are deep and topographically isolated from the surrounding catchment. The cuttings provide some runoff from rain falling within them, but do not comprise a particularly large area and therefore generate a very small percentage of total flow within the system. Investigations undertaken in a previous study had highlighted several natural catchment areas which could physically drain into the tunnel system and these were included in the initial HydroWorks model passed to Haswells. These catchments are predominantly pervious areas based on surrounding farmland. However, in the overall water balance of the tunnel drainage system, flow from direct runoff is a small percentage of total flow.

CATCHMENT HYDROGEOLOGY

The hydrogeology of the catchment is of much greater significance to the verification and understanding of the tunnel drainage system. The tunnel passes through a succession of strata dipping gently west to east. The sequence is illustrated in figure 3.

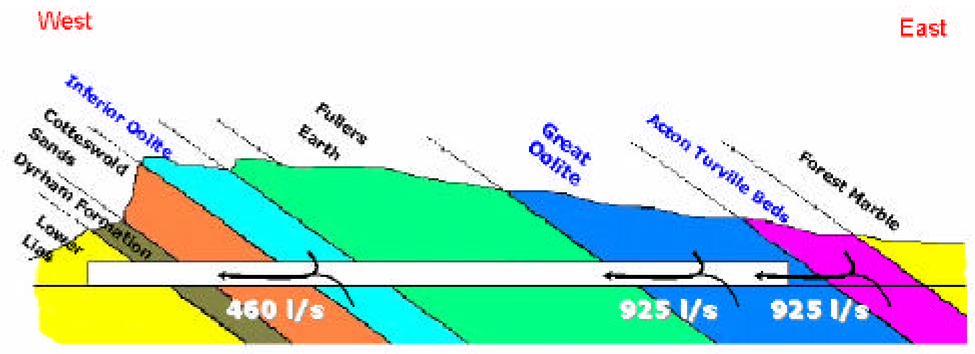

Figure 3 – Geological Succession of the Sodbury Tunnel

The succession comprises a mixture of limestone, mudstone and sandstone. An independent hydrogeological report was commissioned to asses the potential aquifer flow through the whole tunnel. This highlighted that the strata of particular significance in terms of aquifer driven inflow (highlighted in blue writing within figure 3) are the Acton Turville Beds, Great Oolite and Inferior Oolite. These three formations were identified as having characteristics that would generate significant flows after and during periods of rain. The three strata are described in more detail below along with estimations of flow based on 20mm of rain falling on a wet catchment that were identified in the hydrogeological report.

- *Acton Turville Beds* – A succession of shelly oolitic limestones with hydrogeological conditions allowing flow through fractures and fissures. Taking into account bed thickness, porosity, hydraulic conductivity and transmissivity it was estimated the flow could be generated in the order of 925 l/s.

- *Great Oolite* – This is an oolitic limestone, with groundwater flow being generated by primary porosity within the rocks as well as karst developed fractures. This lithology has similar general characteristics to the Acton Turville beds and as such the estimated flow generated from this formation following 20mm of rain on a wet catchment is approximately 925 l/s also.

- *Inferior Oolite* – This formation has the same properties as the Great Oolite, but has a significantly smaller outcrop. Potential flow generated from here is approximately 460 l/s.

This information was taken forward to be used within the verification to help identify and generate aquifer flows within the model. It was also observed that a number of minor watercourses within the area disappeared into sink holes within the area, the exit point not being found. One major spring point was identified in the tunnel and was later monitored with a 'V' notch weir.

DRAINAGE MODELLING

The original hydraulic model provided had been constructed in HydroWorks and was mainly based on survey information and Network Rail records. The model included representations of the receiving watercourse, the Kingrove Stream and two further watercourses which cross the railway on aqueducts, but do not interact significantly with the drainage system, the River Frome and the Luckington Brook. All major drainage conduits were included in the model. The east cutting cess drainage (up and down cess) is connected to the head of the tunnel culvert, which runs the length of the tunnel and outfalls to the Kingrove Stream. Once out of the tunnel additional conduits were available for drainage including further cess drains and a trapezoidal flood relief channel. All these features were included in the original model.

Invert levels of the tunnel culvert were interpolated from available data and assumed to be parallel to track levels as no survey was available in this conduit due to access restrictions. The interaction of the cess drains, the trackbed and the 3' culvert required further investigation as long sections of the original model showed inconsistencies in drainage levels and sewer interaction causing excess flooding.

The problems shown up in the longitudinal sections of drains in the cutting and in the tunnel were addressed, ensuring the drainage system was then at the correct elevations and behaving more like the observed system. This was addressed by generally amending the model to the form illustrated in figure 4.

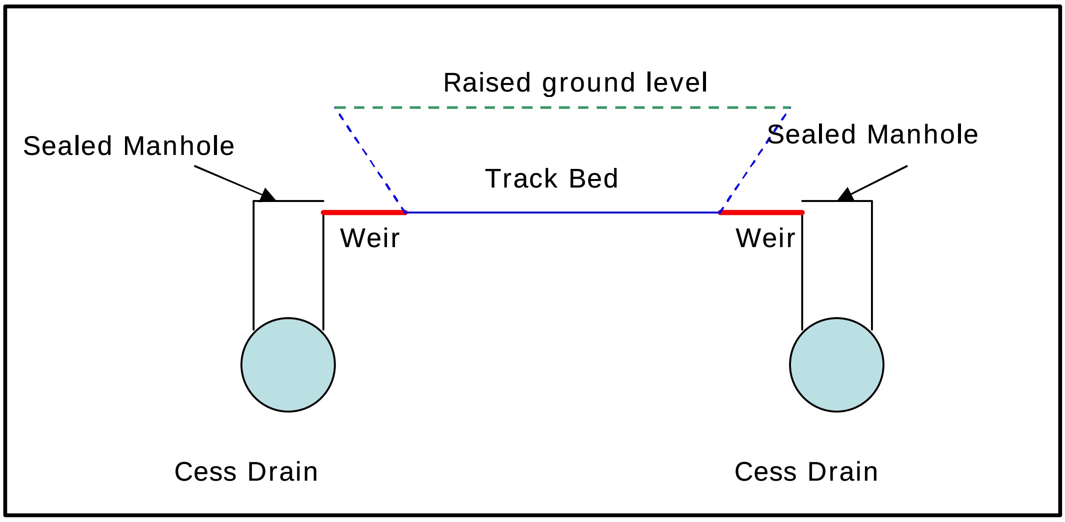

Figure 4 – Modelled Representation of Cess Drains and Track Bed Interaction

These amendments enabled the cess drains to fill and surcharge but not flood. When the cover is reached, the sealed manholes force the water to be transferred over the hypothetical weir and flow onto the track bed. With the majority of the tunnel and track being in a cutting, the track bed conduit was able to be coarsely modelled as a large, hydraulically rough, trapezoidal channel. This removed the major flooding which occurred on mathematical initialisation of the earlier model runs. Other details of the drainage in the tunnel itself were corrected, ensuring the correct transfer of flows through the system.

VERIFYING THE MODEL AND CLOSURE DETAILS

Verification was firstly based on the flow survey undertaken in 1998/1999. This had recorded 70.6 mm of rain over a 10 day period from 15th January 1999 which showed good responses on flow monitors in the cutting at Badminton station and at the Western and Eastern Portals. This coincided with a major track closure which enabled the verification of not only incoming flow, but also closure times (denoted by flow above certain levels present on the trackbed). These were the major identifiers that, once replicated in the model, identified the flow components entering the system from the aquifers.

Initially natural catchment responses were investigated within the east cutting and an acceptable verification was obtained from purely hydrological responses. However the monitors at either end of the tunnel showed vast underprediction of flow volumes and peak flow representation due to the lack of modelled flow response from the aquifers.

In order to obtain an adequate verification of the aquifer inflows and tunnel flow in general, it was decided to utilise the Infiltration Module within InfoWorks. This enabled the flow mechanism of the aquifers to be represented.

The infiltration module works on a simple process, which is illustrated in figure 5. Rain that falls on a particular catchment will generate an amount of runoff. What percentage does not go to runoff is usually lost from the system. When using the infiltration module this lost water enters the ‘soil store’ where it beings to fill. At a certain trigger point within the store Rainfall Induced Infiltration is generated. There is also flow passed to the ground store, but this function was not used within this study.

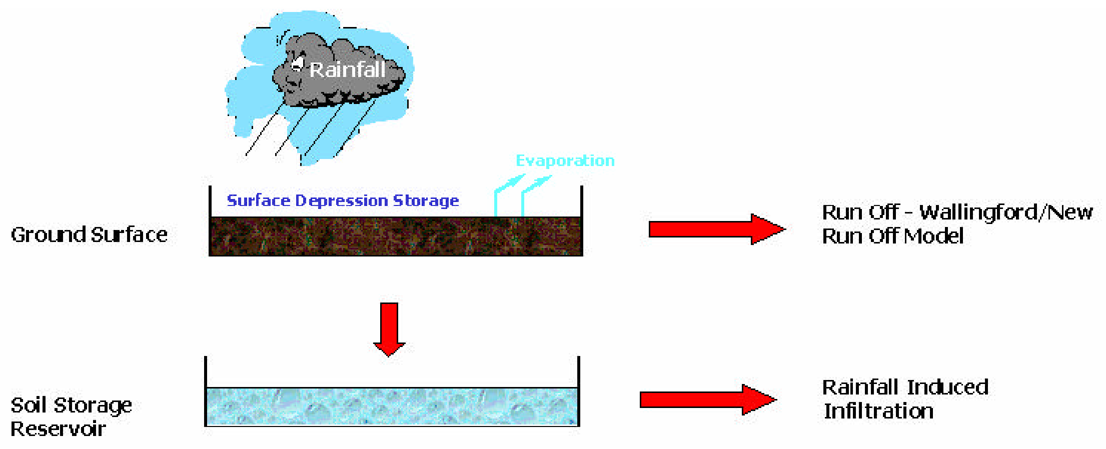

Figure 5 – Rainfall Induced Infiltration Methodology

The particular calibration of the soil store was based on initial conditions at the time of the verification event. High groundwater conditions and low SMD indicated that a quick response was probable. This enabled the prevailing aquifer conditions to be replicated and allow aquifer type inflow to take place. The aquifers were represented by a series of subcatchments within the model (see figure 6). These were given contributing areas calculated based on the extents of surface exposures of these formations as identified within the hydrogeological report, making allowances for some losses.

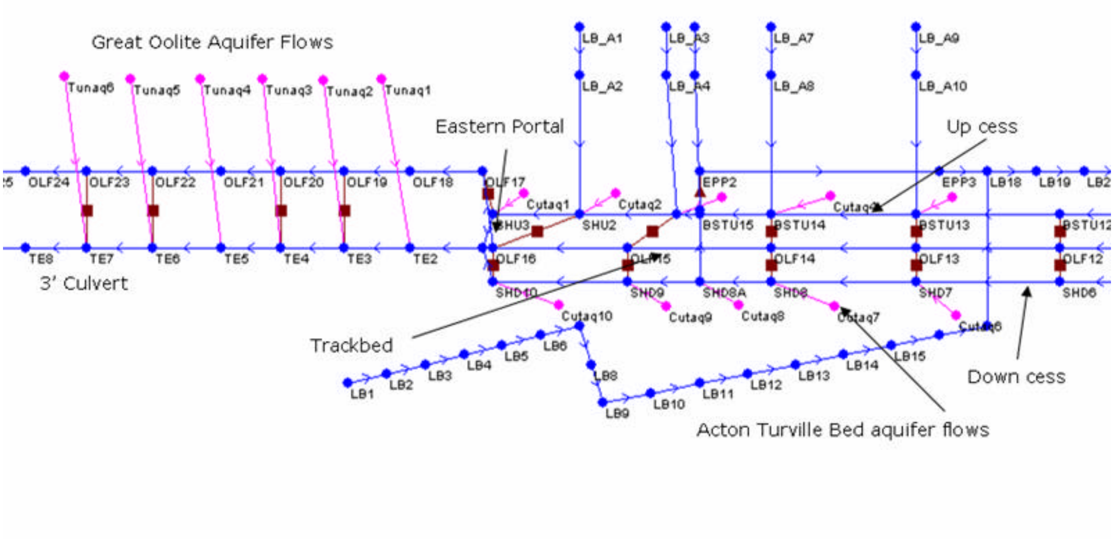

Figure 6- Aquifer Contributions Around the Eastern Portal in the Infoworks Model

These additional catchments were modelled with lower surface runoff, which allowed more flows to enter the soil store and be generated within the system as Rainfall Induced Infiltration from the soil store. Threshold levels were calibrated for this particular event allowing aquifer flow to occur as a best representation of actual conditions.

The final verification showed a much improved volumetric match at both ends of the tunnel, but more importantly, the depth and flow on the trackbed itself gave a good representation of track flooding for this particular event, and a good match on the overall closure time recorded by Network Rail for this incident. This gave much more confidence in the behaviour of the model under an extreme set of environmental conditions.

Following this verification, against good observed data, the model was further verified against a second extreme flood event and track closure data from a December 2002/January 2003 line closure. This showed similar overall catchment characteristics (SMD, groundwater level, preceding rainfall) so it was assumed that the aquifers would behave in a similar way as the original calibration for the January 1999 verification event. Again a good match on closure flow/flood level and time was obtained.

It should be noted that this limited verification (by conventional sewer modelling standards) is not sufficient to give total confidence in the model and in the predicted behaviour of the system, but it can now be used certainly as a benchmark model against the environmental conditions prevailing in January 1999.

HISTORICAL ANALYSIS – PERFORMANCE STANDARDS

With only one verification data set being available (January 1999) and a further check set in 2002/3, additional historical verification was required to increase the confidence in model predictions in assessing the performance standard of any solution. Due to the interlinking of the response of the various catchment parameters in providing suitable conditions for aquifer driven flow within the tunnel, it was practically impossible to work to a standard return period type level of service i.e. 1 in 20 year. To give some idea of what the performance of any scheme may provide, historical catchment information was collected and interrogated to try and provide some historical links between the various catchment characteristic responses and closure.

Figure 7 shows a selection of the parameters investigated and the relationship between the data and closure times.

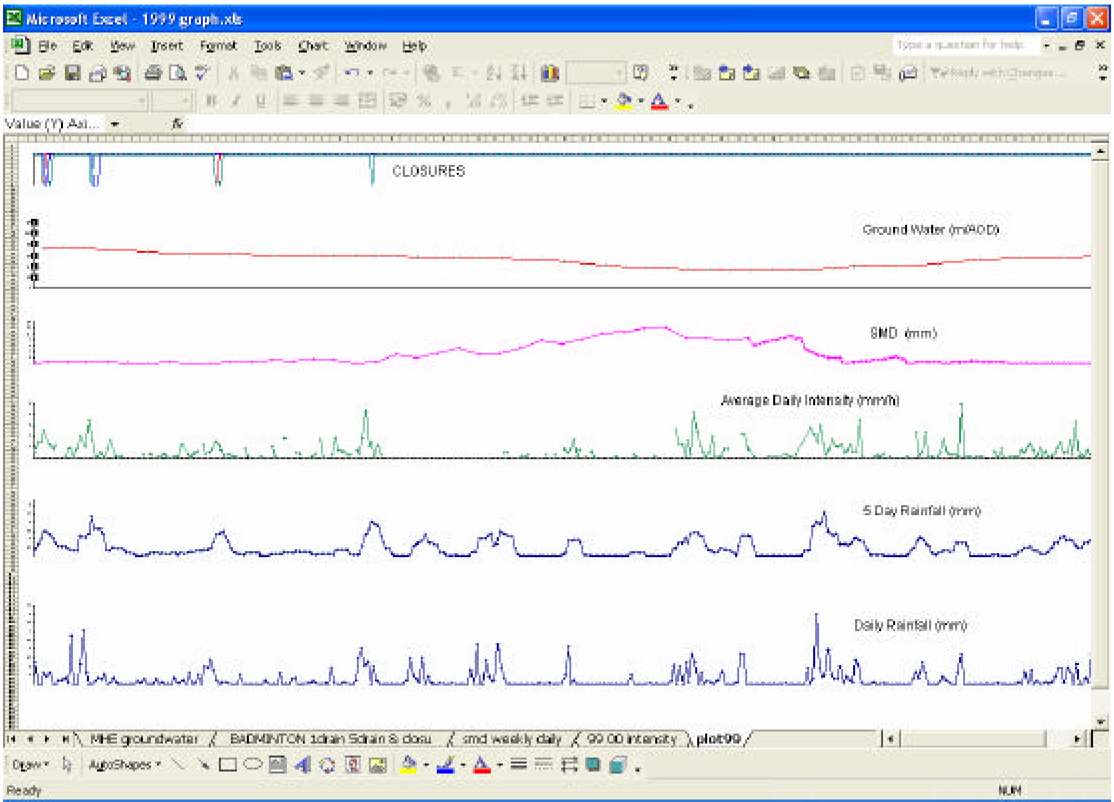

Figure 7 – Historical Data from early 1999

This figure shows four closures with the early months of 1999. In this instance the obvious relationship between groundwater level and closure is confirmed, with closures only occurring during periods of time where groundwater level is high. The relationship between SMD and closure is also easy to see from this sample, with low (0) SMD giving rise to an increased likelihood of aquifer driven flow being generated. In addition to this, rainfall intensity, daily total and 5 day totals were investigated and all generally showed what might be expected, i.e. both high totals and peaky rainfall were linked to closure events, but only when groundwater levels were high and SMD was low.

There were exceptions to this rule, with summer closures in 2002 occurring during periods of low groundwater and high SMD. However this closure event was caused by 80mm of rain falling over two days with a period of high intensity within.

Taking into consideration all of these factors, a set of closure indicating criteria was established and compared with the 1999 verification closure. These criteria were then used to assess all historic closures to give an idea of the level of performance that the proposed flood alleviation might achieve against historic closures. This figure was 20 of 25 closures over the last 5 years would be covered by a solution derived from the 1999 event.

SOLUTIONS DEVELOPMENT

Solution development commenced prior to model verification (The hazards of non-interdepartmental working!!) and was initially based on results from the existing model. These initial solutions involved hard engineering, (big pumps and big storage) and were considered unsustainable. Following verification of additional aquifer driven flow, these big engineering solutions got even bigger (storage went from 17,000 to 250,000 m^3 and pumps to 2.6 m^3/s) and were discounted due to the major environmental impact and cost of any solution. At this point a more sustainable option was proposed, based on a gravity driven solution supported by long term monitoring and an ‘early warning system’.

The main flooding points within the system had been identified at the major input points from the aquifers at the eastern portal and this was the area in which flooding was first identified and where it stayed for longest. In order to attempt to alleviate this, two high level transfer pipes were suggested, to help transfer water from the area through the tunnel, providing alleviation to the top end of the system.

During the ‘optioneering’ phase, the budget for the scheme was formalised and it became apparent that only one of the transfer pipes would be viable. In conjunction with this the existing sidings and yard area at Chipping Sodbury was formalised into a storage basin to provide the maximum attainable volume of attenuation storage within the site. This enabled a balancing of the flooding throughout the tunnel, enabling at least consistent closure time at both the east and west portals to be obtained. As well as this, additional works were added to transfer more flow to a small existing pumping station at the western portal. The solution was tailored to feed as much water to this point as possible allowing a greater volume to be pumped away.

In discussions with the Environment Agency, the discharges to the watercourse needed to be maintained much at existing levels. This was done by restricting flow at control points allowing the storage to fill up. Formalised overtopping routes were also included to allow any flow in excess of the design performance level to fill the storage and then discharge in a controlled manner to the watercourse. As part of the impact assessment on the receiving watercourse, it was confirmed that the small additional flow would have no adverse impact.

It was clear that this new affordable and sustainable solution would, however, not provide total flood alleviation and the importance of some form of ‘early warning system’ became more evident.

The initial proposal highlighted the need to monitor groundwater levels in the main aquifers as well as incorporating some form of SMD probes, flow monitors and raingauges to monitor catchment and system behaviour. Using the initially highlighted relationship between these characteristics a series of early warning thresholds were identified and through the telemetric links to Network Rail control centres, alerts will be automatically activated allowing the preventative measure of early diversions to be put into place before trains get trapped in operating sections. An initial proposal for telemetry monitoring can be seen in figure 8.

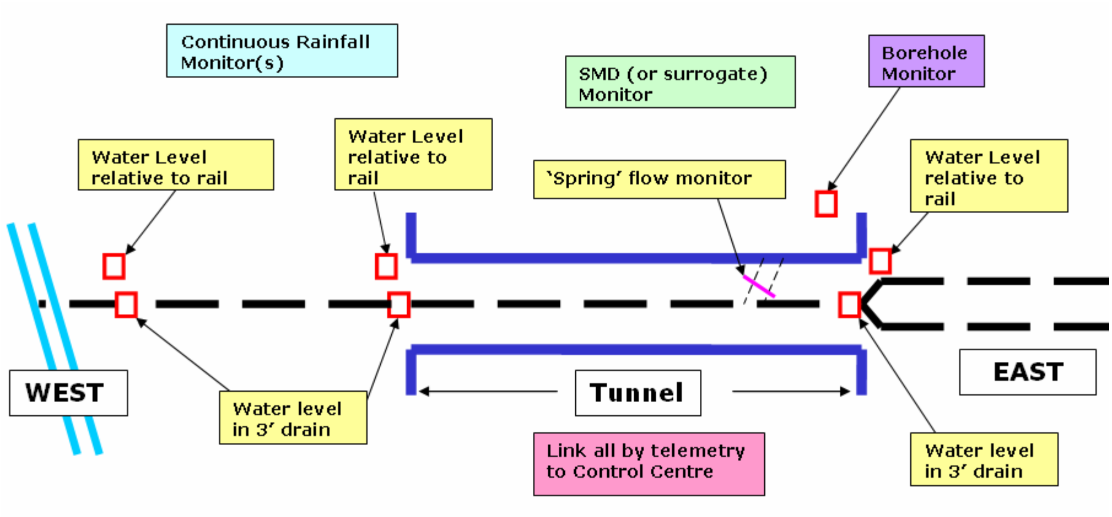

Figure 8 – Initial 'Early Warning System' Catchment Monitoring

In addition to this, wider analysis of surrounding land use, crop types, farming practises etc. was proposed to identify other factors that may influence aquifer recharge.

The final solution, although not providing 100% flood alleviation, will reduce the frequency and length of any future closures. In conjunction with an 'early warning system', Network Rail should be able to minimise the impact on train services, by the pro-active implementation of early diversions, thus preventing trains getting 'caught' in the flooded section, but also by knowing when the track is clear to send services back along the route.

CONCLUSIONS

From the start of this study it was appreciated that the amount and quality of flow survey data would not be considered sufficient for a typical sewerage scheme and as a result verification had to be made based primarily on one event followed by a lesser event and an historic comparison of recorded catchment data.

The catchment hydrogeology provided complex inflow conditions which were calibrated using an independent hydrogeological study and the use of the Infiltration Module within InfoWorks. This calibration was based on catchment conditions at the time of the verification event and was then checked against a further event with actual rainfall.

Following this the characteristics of all historic closures were identified and compared with the 1999 verification event. In doing this a set of criteria were developed to identify whether a solution based on the 1999 event would provide flood alleviation on any of the other events and a performance 'standard' was based upon it.

Following initial optioneering and a budget evaluation, initial hard engineering solutions were discounted in favour of a softer more sustainable gravity driven solution with a storage basin, providing an amount of flood attenuation, but not total removal, which was acceptable in terms of environmental impact and sustainability. This solution in conjunction with an early warning system will hopefully enable Network Rail to minimise the impact the flooding has on train services and result in reductions in delays, cancellations and compensation payouts.