A Conversion Protocol To convert PR Equation (Wallingford) Runoff Models to New UK Runoff Models

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1. Introduction

In December 2002 Southern Water Services commissioned a team of Consultants comprising Richard Allitt Associates Ltd, Earth Tech Engineering Ltd and Black & Veatch Consulting to undertake modelling studies for all the catchments within the Southern Water region which drain or spill to designated Shellfish Waters.

In total there are 34 catchments with a total population in excess of 750,000 which were included in the study. Of the 34 catchments involved the 20 largest catchments had previously been modelled using a variety of modelling programs (Wassp, Wallrus, Spida, Hydroworks and Infoworks) and these accounted for 740,000 of the total population. All of these models used the standard "Wallingford" PR Equation Runoff Model. The 14 remaining catchments required new models to be built and these have been built using the New UK Runoff Model.

A specific requirement of the UK interpretation of the Shellfish Waters Directive[1] is that simulations are carried out for a minimum of 10 years of rainfall but with a preference for 15 years of rainfall. These simulations could be undertaken either using discrete storms (probably 300 to 450 storms would be required) or by using a continuous series. The preference was to use the continuous series which could either be a Historical Storm Series (HSS) which is a tipping bucket rainfall record from a representative site within the catchment or a series from a Stochastic Rainfall Generator (SRG) such as STORMPAC. The continuous series could either be simulated as individual years or as the whole period. The larger models would need to be run for the individual years whilst the smaller models could be run for the full period. In either case it is essential that the New UK Runoff Model is used throughout the models to enable the runoff to vary with the catchment wetting and drying in response to the periods of rainfall and intervening dry periods.

Southern Water had made a significant investment over the years in their stock of models and many of the models to be used for the Shellfish Study were amongst the largest which Southern Water have. In particular there were two catchments with populations of 221,000 and 136,000 respectively. It would have been impossible within the available timescale and within the available budget to build and verify new models for the 20 catchments with existing models. It was therefore necessary to develop a protocol which all 3 Consultants could follow to convert the existing models to use of the New UK Runoff Model. A brainstorming session was held with representatives from Richard Allitt Associates, Earth Tech Engineering and Black & Veatch Consulting to develop a protocol. A first draft was developed and then trialled on a medium sized catchment. The success of the protocol was then examined and refinements made. The final version of the protocol was the fifth amendment. This protocol was then used on all 20 catchments with a success rate of just over 85%.

The purpose of this paper is to bring the protocol into the public domain so that it can be universally adopted and where necessary refined and developed further.

Before detailing the protocol it is useful to review various alternative runoff models which are available within the Wallingford Software programs*.

2. Runoff Models Available

Rainfall runoff modelling is extremely complex and has been the subject of much academic research over past decades and indeed is continuing today in many establishments around the world.

The software produced by Wallingford Software contains a variety of different runoff models which can be used. The variety of models available can be daunting and it is not surprising that many modellers do not fully understand all of the models available. The more commonly used ones are reviewed in the section below and are also summarised in Table 1 below:-

Runoff Model	Application	Comments	Suitability
Fixed Percentage Runoff	Can be applied individually to all surface types within a drainage area.	Simply insert a percentage for the runoff from each surface type.	Suitable for all catchments where a good estimate of the runoff percentages can be made.
Wallingford Procedure Runoff aka PR Equation aka Standard Runoff aka Constant PR Model	This is the DEFAULT model in all Wallingford Software products. MUST be used to represent all surfaces within a drainage area.	Needs to be used with care and observing the limitations of this model. Uses UCWI values to set initial conditions which then remain throughout storm.	Suitable for all urban catchments in the UK. Design values of UCWI are readily available.
New UK Runoff Model aka Variable PR Model	This model only applies to permeable surfaces and must be applied to all the permeable surfaces in a drainage area.	Impermeable surfaces use a fixed percentage runoff. Permeable surfaces use this model and the runoff varies with increasing or decreasing wetness. Uses API30 values for catchment wetness which are updated throughout the storm.	Suitable for all urban catchments in the UK. No definitive values of API30 yet available for design storms.
SCS Method (USA Soil Conservation Service Model)	Can be applied individually to all surface types within a drainage area or mixed with fixed percentage runoff.	Principally a rural catchment model.	Essentially only suitable for wholly or predominantly rural catchments but can also be used to model a rural catchment draining into an urban catchment.
Green-Ampt	Can be applied to individual surfaces.	An infiltration model for pervious and semi-pervious surfaces.	Suitable for rural surfaces and pervious surfaces within a catchment. Associated in the US with the SWMM runoff routing model.
Horton	Can be applied to individual surfaces.	An infiltration model for pervious and semi-pervious surfaces.	Suitable for rural surfaces and pervious surfaces within a catchment. Usually associated with the Desbordes or SWMM runoff routing models.
Constant Infiltration (ConstInf)	Can be applied to individual surfaces.	The ConstInf model allows a constant infiltration to be set from the surface into groundwater. This is effectively a loss to the system but if the storage capability is exceeded a fixed runoff occurs.	

* The protocol was developed to convert the Wallingford Runoff (PR) Model to the New UK Runoff Model – these are the runoff models used in Wallingford Software products. Therefore the protocol is not directly applicable to other Software products.

2.1. Fixed Percentage Runoff Model

This model, as the name suggests, is simply based on each surface type having a fixed percentage runoff. For example paved surfaces might be allocated an 80% runoff and roofs might be allocated a 90% runoff. It is difficult to know what percentages should be used and there is little advice currently available. This is the simplest runoff model to use but because of the difficulties in determining suitable percentages it is rarely used.

2.2. Wallingford (PR) Runoff Model – (aka Standard Runoff Model or Constant Runoff Model)

When the Wallingford Procedure was first released in 1983 we were introduced to the "Percentage Runoff Equation" (or PR Equation):-

$$PR = (0.829 \times PIMP) + (25 \times SOIL) + (0.078 \times UCWI) - (20.7)$$

This equation was the result of regression analyses carried out on data from 510 storm events from 17 different catchments. This was based on a statistical approach and the equation explained 58% of the variation in the data with a standard error of 10.3%. In WaPUG User Note No 9[2] Ron Chapman explains the PR Equation and concludes that the PR Equation has many limitations and users must be aware of these if they wish to obtain realistic results. He goes on to state that users should make the effort to understand the significance of the parameters used. With low values of PIMP, SOIL or UCWI unreasonably low or even negative values of PR can be created. To overcome this, the software sets a lower limit of 20% and an upper limit of 100%. With typical summer UCWI values it is necessary for the PIMP value to generally be in excess of 40% for the PR value from the equation to be above the minimum 20%.

The overall runoff from a contributing area (to a single node) is quite complex with individual runoffs from the different surface types depending on the individual areas of each surface type and weighting factors with pervious areas only having 10% of the weighting of impermeable surfaces. This means that all surfaces (even permeable ones) produce runoff provided that the rainfall is in excess of the initial losses.

The essential point of the Wallingford (PR) Runoff Model is that the percentage runoff (PR) remains constant throughout the simulation period and is set from the initial conditions. In the earlier days when WASSP was still in use the PR equation was applied across the whole catchment but advances were made when WALLRUS was released which applied the PR equation to each individual contributing area. The PR equation uses the UCWI (Urban Catchment Wetness Index) which for verification storms is individually calculated using data from the Met Office and the precipitation over the previous 5 days.

In spite of the quite severe limitations of the PR equation the Wallingford (PR) Runoff Model (Constant Runoff Model) has achieved remarkable success with many hundreds of models which were satisfactorily verified. A key factor in the success of this runoff model was the advice in 1989 from the WaPUG Committee to use the "10 metre rule" (see WaPUG User Note 21[3]). The use of the 10 metre rule had the effect of keeping the minimum PIMP values above 40%. Another factor in the success of the Wallingford (PR) Runoff Model was the readily available values of UCWI for use with synthetic design storms.

Most modellers are now using Hydroworks and Infoworks and there is a lack of appreciation that the "10 metre rule" should still be applied if the Wallingford (PR) Runoff Model is used as there have been no changes to the PR equation or its validity since the days of WASSP and WALLRUS. It is unfortunate that the 10 metre rule has fallen into disuse and this will undoubtedly lead to problems in some catchments.

2.3. New UK Runoff Model – (Variable PR)

The "New UK Runoff Model" was first introduced in 1993 by Wallingford Software to overcome the problems which the Fixed PR model gave with longer duration storms. The New UK Runoff model is effectively only applied to the pervious areas and the runoff from the impermeable surfaces is a fixed percentage defined by the user. The New UK Runoff Model updates the percentage runoff at each major timestep in accordance with the increasing or decreasing wetness of the catchment.

The New UK Runoff Model is explained by Martin Osborne in WaPUG User Note 28[4] and it can be seen from this that a key factor is the precipitation over the previous 30 days as defined with the API (Antecedent Precipitation Index). The API value is updated throughout the simulation event. The formula for API_{30} is:-

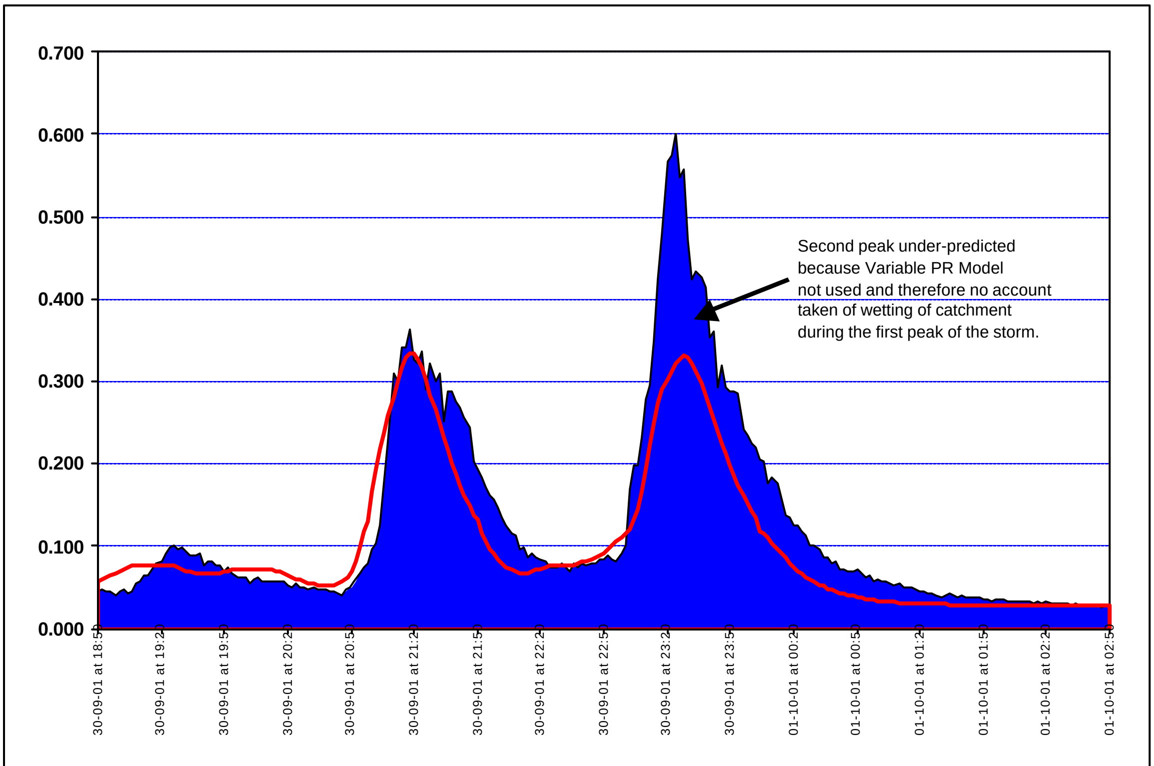
$$API_{30} = \sum_{n=1}^{n=30} \left(P_{-n} \; C_p^{\,n-0.5} \right)$$

where
P-n is the effective rainfall (after allowances for evaporation) and
Cp is a decay constant based on soil class (0.1 for soil class 1 up to 0.99 for soil class 5)

As with other runoff models the user includes areas in the model representing the 3 surface types♣ (road, roof and pervious). The user also decides what proportion of the impermeable surfaces (roads and roofs) contribute runoff to the sewers; this is termed the 'effective impervious area factor' (IF) which can range typically from 0.45 for poor surfaces to 0.75 for good surfaces. This means that after initial losses are allowed for a fixed percentage of the rainfall (45% to 75% in the examples above) is turned into runoff. The remaining proportion of the impermeable surfaces (55% to 25%) is assumed within the model to drain to the pervious surfaces which have the New UK Runoff Model applied.

Since the New UK Runoff Model was introduced it has been used to infill the recession part of the hydrograph which is strictly rainfall induced infiltration rather than runoff. The main reason the New UK Runoff Model was used in this way was because there was no alternative method available. There is now an alternative method available (the infiltration module in Infoworks) and perhaps the time is now right for the New UK Runoff Model to be used as it was originally intended which is to model the runoff from permeable surfaces.

The hydrograph illustrated overleaf shows a verification plot in a Trunk Sewer where the New UK Runoff Model has not been applied. It can clearly be seen that the second peak is significantly under-predicted because the simulated runoff flows have not responded to the wetness of the catchment which increased after the first period of rainfall. This clearly demonstrates the need to apply the New UK Runoff Model.



The New UK Runoff Model has gained little use (other than to provide a delayed response) principally because of the difficulties in using this runoff model in a design situation as there is currently no widely

♣ more than 3 surface types can now be modelled if necessary accepted methodology available for determining suitable design values for the Antecedent Precipitation Index (API).

3. Protocol to convert Wallingford (PR) Runoff to New UK Runoff

The conversion protocol set out below is a 14 step process which concludes with re-verification of the model with an up to date flow survey. The protocol was never intended to enable models to be converted without some form of verification / calibration with current flow survey data.

The protocol is set out under 3 headings depending on the status of the original model and the availability of flow survey data from the time the model was built and verified. The 3 headings are:-

3.1. Model without Contributing Areas Defined

These models are those where the geographical coverage and extent of each contributing area is not known. Dummy contributing areas can readily be created for these models within the Infoworks program. These dummy catchments are circular, are centred on the appropriate node and have an area which matches the area stated for the contributing area.

3.2. Model with Adequate Contributing Areas Defined

These models will probably have been produced in Infoworks or where the contributing areas have been defined in an external program such as MapInfo. Where these areas are not already included they can be readily imported into the Infoworks model.

3.3. Model with Same Network and with Original Flow Survey Data

These models could strictly speaking also be either of the above types but rather than have a complex matrix of model types those with original flow survey data have been treated as the third type. Modellers will need to use Engineering Judgement to decide which of the steps for the other two model types are appropriate.

Where a particular cell is empty for a step there is no work needed at that stage and the Modeller can move on to the next step.

<table>
<tr><th></th><th>MODEL WITH ADEQUATE CONTRIBUTING AREAS DEFINED</th><th>MODEL WITHOUT CONTRIBUTING AREAS DEFINED</th><th>MODEL WITH SAME NETWORK AND WITH ORIGINAL FLOW SURVEY DATA</th></tr>
<tr><td>Step 1</td><td colspan="2">Check that the “Original” model is the verified model or is a derivative which has a full audit trail.

If the model is not already in Infoworks format convert it to Infoworks taking care to include all relevant LUD, RPF files etc.</td><td>Check that the “Original” model is the original verified model and that no schemes have been implemented or added to the model since the flow survey.

If the model is not already in Infoworks format convert it to Infoworks taking care to include all relevant LUD, RPF files etc.</td></tr>
<tr><td>Step 2</td><td colspan="3">Create a new version of the model (branch from the “Original” model) referred to as the “Translated” model. No alterations are to be made to the “Original” model and all further work will be done on the “Translated” model.</td></tr>
<tr><td>Step 3</td><td colspan="3">Assess whether any additional nodes need to be added at Flow Monitor locations and manholes upstream & downstream of Flow Monitors.

Where sections of the model contain modelling procedures used in the original modelling (eg single equivalent pipes etc) these should be corrected at this stage. Also where additional nodes are considered necessary these can be added at this stage.</td></tr>
<tr><td>Step 4</td><td colspan="3">Convert impermeable areas to ‘absolute’ values.</td></tr>
<tr><td>Step 5</td><td></td><td colspan="2">Visit the catchment or otherwise identify the contributing areas to each modelled node. Create the contributing areas, ideally following property boundaries.</td></tr>
<tr><td>Step 6</td><td></td><td colspan="2">Undertake new ‘Area Take Off’ retaining the existing impermeable areas (Surfaces 1 & 2) in the model but updating Surface Type 3 so that Surface 3 is the remainder of the contributing area up to a maximum of 5 times the paved surfaces (Surface 1). The 3 Surface areas added together will in most cases not add up to 100% of the contributing area.</td></tr>
<tr><td>Step 7</td><td>Check that the model uses “Fixed” runoff for impermeable areas and New UK Runoff for permeable areas.</td><td colspan="2">Change the ‘Land Uses’ to give 65% fixed runoff from Surface 1 (paved) and 80% for Surface 2 (roof). Area 3 should use the New UK Runoff (using default values).</td></tr>
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<tr><th></th><th>MODEL WITH ADEQUATE CONTRIBUTING AREAS DEFINED</th><th>MODEL WITHOUT CONTRIBUTING AREAS DEFINED</th><th>MODEL WITH SAME NETWORK AND WITH ORIGINAL FLOW SURVEY DATA</th></tr>
<tr><td>Step 8</td><td colspan="3">Determine API30 values for use with design storms (summer and winter), for the selected multi-peak storm selected from the south-east Annual Time Series and also for any flow survey storms used to re-verify the model.

For the design storms the API30 values are to be derived from an assessment of historical rainfall at nearby raingauges. For the storm from the ATSR an API30 value also based on the assessment of historical rainfall should be used.

For any flow survey storms the API30 value should be calculated from the rainfall in the preceding 30 days.</td></tr>
<tr><td>Step 9</td><td colspan="2">Run the “Original” model (using UCWI rainfall) and the “Translated” model (using API30 rainfall) for a series of design storms including a single peak winter synthetic design storm of 1 year and 5 year return periods and 60 minutes and 240 minutes duration. Also run both models for a multipeak storm from the south-east time series.

At a number of selected key locations in the model (say about 2% of the nodes in the model) produce depth, flow & velocity hydrographs. Plot the hydrographs and compare the results. If the graphs do not match adequately it will be necessary to make some adjustments. The first variable to be adjusted is the percentage runoff for the impermeable surfaces.</td><td>Run the “Original” model (using UCWI rainfall) and the “Translated” model (using API30 rainfall) for the flow survey storms.

At the flow monitor locations plot the two sets of predicted hydrographs and the flow survey hydrographs. If satisfactory verification is not achieved and the ‘translated’ model results do not match those for the ‘original’ model it will be necessary to make some adjustments. The first variables to be adjusted are the percentage runoffs for the impermeable surfaces (Surfaces 1 & 2).</td></tr>
<tr><td>Step 10</td><td colspan="3">Now that the “Translated” model has been proven to match the “Original” verified model in terms of the storm response the next steps are intended to make sure that the dry weather flows, the population figures, the trade flows infiltration flows etc are all correct. The “Translated” model should be frozen and a new version of the model should be created (checked out from the Translated model) which will be called the “2003[†]” model.

At this stage any errors found in the sewer data for the model (eg backfalls, steps etc) should be corrected. Where the sewer system is actually looped but is modelled as dendritic the bifurcations can be added. Also where there are any new developments which are not included in the model these can be added at this stage.

Any alterations or additions to the sewer network must be added at this stage. It is also worthwhile checking at this stage that all ancillaries (CSO’s pumping stations etc) are modelled with the latest data.</td></tr>
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[†] The model can have a different name appropriate to the current year

	MODEL WITH ADEQUATE CONTRIBUTING AREAS DEFINED	MODEL WITHOUT CONTRIBUTING AREAS DEFINED	MODEL WITH SAME NETWORK AND WITH ORIGINAL FLOW SURVEY DATA
Step 11	Remove all population figures, additional foul flows, base flows and trade flows. Carry out a new Address Point Take-off to include new population figures (check with the population source data for population densities). Add Trade flows. From current flow surveys assess any constant infiltration base flows and add them to the model (at this stage do not add any 'Infiltration Module' data or any slow response areas).		
Step 12	Add Wastewater Treatment Works and storm tanks to the model.		
Step 13	Carefully study the current flow survey data and carry out trial verifications to ascertain whether or not there is any slow response runoff and/or any Rainfall Induced Infiltration. Based on this assessment the next stages to 'calibrate' the model to match the current flow survey results will be determined. The aim will generally be to obtain a satisfactory match for flows, velocities and depths for the first peak with a number of storm events. The recession tail will be filled in by use of either the New UK Runoff Model (for slow runoff) or the Infiltration Module. It may at this stage be necessary to change the percentage runoffs from the initial estimate of 85%. Changes to the actual impermeable areas should be avoided. If the first peak is not matched satisfactorily it will be necessary to evaluate the reasons in the same manner as when verifying a model.		
Step 14	Once the first peak has been matched for individual storms and any necessary changes to add slow runoff or rainfall infiltration have been made the model should be run for the whole period (probably 20 weeks) of the current flow surveys. Verification hydrographs should be plotted and the model should then be adjusted (calibrated) to achieve a satisfactory verification over the whole period.		

[1] "Water Quality Consenting Standard Consenting Discharges to achieve the Requirements of the Shellfish Waters Directive (Microbial Quality)" *Environment Agency* 2001

[2] WaPUG User Note No 9: The Percentage Runoff Equation *R. E. Chapman* 1996

[3] WaPUG User Note No 21: Runoff Equations and Catchment Data, *WaPUG Committee*, 1996

[4] WaPUG User Note No 28; A New Runoff Volume Model, *M P Osborne*, 1993