Estimating flood peaks and hydrographs for small catchments:

R8 – Accounting for vegetation and land management

FCERM Research & Development Programme

Research Report

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Executive summary

This report presents a brief review of research into the relationship between catchment vegetation, land management and flood runoff, with the aim of considering the potential for improving the estimation of design flows on small catchments by taking vegetation type and land management into account.

Although there has been a wealth of research investigating the complex effects of land use management on flooding, there are few tools readily available to practitioners that allow them to quantitatively assess the effects of catchment vegetation and land management on the flood frequency curve. Hydrologists are encouraged to apply their judgement when faced with unusual catchments.

This report was written in 2017 to inform subsequent stages of the overall project SC090031 from that time. It represents scientific consensus from that time. Further developments may have occurred since this report was written.

Important Note:

Work on Project SC090031 ‘Estimating flood peaks and hydrographs in small catchments (Phase 2)’ began in December 2013. Tasks carried out in the early stages of the project have already been documented in several project notes and reports, so it is possible that there may be inconsistencies, particularly in the various data sets and methods that have been applied at different points in time. This report provides a summary of the research carried out throughout the project, and we have detailed the data sets and methods used in each of the stages and tasks.

1. Introduction

1.1 Purpose of this report

This report briefly reviews research into the relationship between catchment vegetation, land management and flood runoff, with the aim of considering the potential for improving the estimation of design flows on small catchments by taking vegetation type and land management into account.

1.2 Accounting for vegetation in current flood estimation methods

Flood Estimation Handbook (FEH) methods do not take any direct account of vegetation type or land management apart from distinguishing between urban and rural areas. No attempt is made to account for any differences in the flood-generation potential of the various rural land use types such as pasture, arable crops, woodland or sports/amenity turf. Some users of the FEH may make allowances for such features in an informal way, for example, by influencing their judgement on the choice of a donor site.

Some flood estimation methods used overseas do account for differences in land cover. The Irish Flood Studies Update research developed catchment descriptors that measure the proportion of pasture, forestry and peatland in a catchment (Mills and others, 2014). However, none of these variables were found to be significant in the development of regression equations for estimating design flood peaks and hydrographs, apart from in the rather specialised situation of catchments where no estimate of BFI is available, where the FOREST descriptor can be used to estimate parameters that control the shape of design hydrographs.

2. Overview of research

This section gives an overview of research into the effects of land use, land management and vegetation on flood runoff and how such effects can be quantified.

2.1 Agricultural land use

Construction Industry Research and Information Association provides a valuable review of land use effects on flooding in 'Land Use Management Effects on Flood Flows and Sediments – Guidance on Prediction' (CIRIA, 2013). It cites agricultural intensification, brought about by government policy and local decisions over the last 60 to 70 years, with increasing stocking densities, ploughing, reseeding, installation of field drainage, use of heavy machinery, and removal of trees and hedgerows, as all potentially contributing to changes in the way that both runoff and floods are generated and conveyed through the rural landscape. The earlier comprehensive national research project 'Review of Impacts of Rural Land Use and Management on Flood Generation' (O'Connell and others, 2004) concluded that there is plenty of evidence that changes in land use and management practices affect runoff generation at the local scale, but the effects are complex and variable depending on catchment characteristics. They also reported that there is also only limited evidence that any local changes in runoff are transferred to the surface water network and propagated downstream. These general findings agree with several other reviews of the impact of land use, land management and land drainage on flooding that have taken place over the last 10 years, namely Environment Agency (2007), Haycock Associates (2008), Wheater and Evans (2009), Halcrow (2012) and CREW (2012).

CIRIA (2013) also cites several research studies that provide evidence that 'modern' farming techniques can greatly influence the pathways of water flow through soils that are agriculturally managed. Increased stocking rates, increased use of fine seedbeds, increased production of late harvested maize and the greater area of autumn sown cereals being grown have all been shown to increase the generation of surface runoff by degrading the condition of the surface and near surface soil layers and its ability to infiltrate and/or temporarily store incident rainfall. However, the scale of the increased runoff varies and is linked to several interrelated physical and climatic factors operating at any particular site.

O'Connell and others (2004) reviewed a range of studies that explored how agricultural underdrainage systems (pipe drains and mole drainage/subsoiling) and larger arterial land drainage schemes affect runoff generation. Again, the complexity of local conditions (including drainage network design, soil type, and antecedent wetness conditions) resulted in both increases and decreases in runoff being reported.

Figure 1 - Runoff on a meadow with underdrainage, North Yorkshire

Kwaad and Mulligen (1991) monitored runoff from two high-intensity rainfall events on field plots of a loess (fine sandy/silty) soil under different maize management systems. Rainfall runoff coefficients were 42% for conventional management, 47% for direct drilled management and 15% for plots that were tilled in autumn and spring. Charman (1985) reported that direct drilling and reduced cultivation techniques could lower field runoff by 17 to 49% for a range of arable crops. Quinton and Catt (2004) explored contour ploughing and minimum tillage at a field scale over a 10-year period in the Woburn Erosion Reference Experiment. There were no significant differences between the standard and minimal tillage cultivations. Mean event runoff from the across-slope/minimal tillage treatment combination was found to be significantly less than from the up-and-downslope/minimal tillage cultivation, the up-and-downslope/standard cultivation and the across-slope/standard tillage cultivation.

Deasy and others (2014) analysed runoff data from studies of arable in-field land management options applied for reducing diffuse pollution to see if these treatments could also potentially reduce downstream flooding. The in-field management options included ploughing, minimum tillage, contour cultivations, upslope-downslope cultivations, and with/without tramlines. However, the study was unable to allow significant treatment effects to be determined and upscaling and longer-term studies of these in-field treatments were recommended. It should also be noted that there are problems with the stability of machinery working across the slope, which currently restricts the use of contour cultivations in parts of the UK where the fields have more complex slope configurations.

2.2 Forestry

Although the theory of forests acting as sponges soaking up water is popular, scientific studies have shown that the influence of forests on flooding and runoff is more complex

(UNFAO, 2005). Most of the well-known experimental hydrological studies of forestry in the UK have been on upland catchments such as Plynlimon or Coalburn, investigating plantation forestry. The effects of forestry on runoff have been complicated by the influence of drainage ditches dug before the trees were planted.

Perhaps because of the complications of the crop cycle and management practices (such as drainage), there is little evidence from regional flood studies in Britain that the area covered by forest is a significant independent variable in the regression equations used for flood estimation (Institute of Hydrology, 1991). However, this does not mean that forests have no effect on a local scale. Forests and forest soils (with their deep litter layer) are capable of storing and transpiring more water than grassland or arable crops. Therefore, in the absence of complicating factors such as drainage, one can expect a reduction in downstream flood volumes and an increase in time to peak. These effects were found in a comparison of flood events on the paired Wye (grassland) and Severn (67% forested) catchments at Plynlimon. The reduced volumes on the Severn were attributed to the generally drier antecedent condition of the soil beneath a tree cover.

More recently, Marc and Robinson (2007) analysed the long-term evaporation data sets from the Plynlimon catchments for the whole period 1972 to 2004. They identified four distinctly different periods of evaporation. In 1972 to 1976 the annual forest evaporation was 250 mm greater than the grassland as the forest trees were actively growing. During 1977 to 1982 the forest evaporation was only 140 mm greater than the grassland evaporation as the forest reached maturity. During 1983 to 1994 the forest evaporation was only 50 mm greater than the grassland catchment after trees were felled. Finally, in the period 1995 to 2004 the forest and grassland evaporation was almost identical as further felling took place. Over the whole 32-year monitoring period the mean annual flow for the grassland catchment had increased by 310 mm, while for the forested catchment it increased by 453 mm, partly as a result of observed climate change effects, but also indicating a clear hydrological consequence of the tree felling operations in the Severn catchment.

A review of several studies in the Environment Agency (2007) reported that upland conifer plantations may reduce peak flows for small to medium-sized events but have little effect on more extreme events. Deciduous trees only provide good interception loses when the leaves are fully formed.

Reductions in peak flows predicted by plot scale models and data at Pontbren in mid Wales have been interpreted as indicating the potential of small-scale land management changes for reducing hillslope runoff peaks. Wheater and Evans (2009), reporting modelling results from Pontbren, stated that for frequent events, the median effect of reverting the catchment (about 12 km^2) to a 1990s pattern of land use (intensive sheep production) would increase flood peaks by 13%. On the other hand, introducing optimally placed tree shelter belts to the current land use would reduce peak flow by nearly 30%, and introducing full woodland cover would reduce flows by 50%. For an extreme event, the corresponding median effects would be a 5% increase and a 5% and 36% reduction, respectively. In their interpretation of the results of the Pontbren modelling, Jackson and others (2008) comment that the magnitude of the effect cannot be considered as conclusive due to variation and uncertainty in the hydraulic conductivity and soil moisture measurements and incomplete knowledge of the connectivity of these soils to in-field underdrains.

Dixon and others (2016) used a spatially distributed flood model to explore the effects of different woodland and wood-based restoration scenarios on flood hydrology in the 98 km^2 Lymington River catchment in the New Forest. Riparian forest restoration at the sub-catchment scale, representing 20 to 40% of the total catchment area, was shown to generate up to 19% peak flow reductions through desynchronization of the timings of sub-catchment flood waves. Similarly, flood plain forest restoration covering 10 to 15% of total catchment area generated a 6% peak flow reduction after 25 years' post-restoration.

Towards the end of this project, the Centre of Ecology & Hydrology (CEH) completed a systematic literature review of the effect of trees on fluvial flooding (Stratford and others, 2017). The question posed by the review was 'Do trees in UK-relevant river catchments influence fluvial flood peaks?' There was no unequivocal answer. Overall, there was broad support in the 72 papers that were reviewed for the conclusion that tree cover influences flood peaks. However, if a distinction is made between studies based on observations and those based on models the conclusion is less clear. Most statements supporting both the relationship between tree cover and peak flows are based on model outputs. If the observation-based statements are considered in isolation, the results are more mixed. Most statements from observed case studies report that the peak flows of large floods are not influenced by tree cover.

2.3 Generalisation of site-specific results

It should be noted that all the monitoring results reported above are site specific, therefore generalising these results to other sites or catchments with their own particular set of conditions is extremely problematic.

Following a review of a wide range of both monitoring and modelling studies, CIRIA (2013) provided a useful qualitative guide to the typical effect of land use practices on flood generation, in terms of the direction of change for the resulting flood peak, as shown in Table 1.

Table 1 - Effect on flood peaks of common land use practices (modified from CIRIA, 2013)

Land use	Changed from	Direction of change of the flood peak
Trees (coniferous plantations)	Ungrazed moorland	Reduction
Trees (deciduous plantations)	Ungrazed moorland	Reduction
Trees (deciduous strips)	Improved grassland	Reduction
Grassland (heavy grazing)	Ungrazed moorland	Increase
Grassland (light grazing)	Ungrazed moorland	Increase
Peatland (drained)	Intact moorland	Increase
Peatland (blocked drains)	Drained moorland	Uncertain

The type, characteristics, condition and management of the land cover in a catchment, together with the inherent characteristics and condition of the underlying soil and its drainage (both naturally and artificially induced), will greatly influence both the pathways and rate of water movement over the soil surface, into the soil profile (infiltration, shallow interflow, deeper percolation), through subsoil drainage systems (if present) and subsequently into the main arterial drainage network. In catchments containing agricultural systems this is further complicated due to the spatial and temporal variability in the condition of the vegetation on the soil surface and the condition of the soil surface and the underlying topsoil, which take place during cropping seasons (for example, cultivations, tillage, crop growth, livestock grazing, crop harvesting). In cultivated fields there is also a link between the steepness of the ground surface, direction of ploughing/tillage and the potential for runoff generation. Best practice agricultural advice would be to always plough across the slope, but the general variability of the slope across many undulating British fields, together with hazards associated with driving machinery directly across these variable slopes, means that this is not always possible and/or practical.

As the catchment scale increases, the interactions of other catchment physical and climatic factors begin to complicate the situation, together with related temporal effects (Pattison and Lane, 2012 and Lane, 2017). It is also expected that relative effects of land use management interventions will decrease with increasing magnitude of event (Jackson and others, 2008 and Lane, 2017). This view would be consistent with more theoretical studies of process controls on the probability distributions of flood flows, which have suggested that, in the most extreme events, the rainfall frequency distribution controls the magnitude-frequency relationship for flows, but that the processes associated with catchment soil moisture storage modify this distribution in the lower magnitude events (Beven, 1986; Sivapalan and others, 1990).

2.4 Tools and techniques for quantifying effects on flood flows

Various models and tools have been developed to explore how land use management change could affect flood peaks and flood hydrographs. Baseline models are calibrated and validated to measured data sets, and statistical techniques, together with expert knowledge, have been applied to modify particular model parameters representing land use management change factors (Environment Agency, 2016).

O'Connell and others (2004) and Packman and others (2004) describe how changes to the FEH/ReFH model, in terms of modifying the parameters, namely time of peak and percentage runoff relating to the soil condition (using analogue HOST classes to represent a degree of soil degradation), could be used to explore strategic land use management changes within the context of developing catchment flood management plans (CFMP).

The Environment Agency (2010) reports the development of a spreadsheet based CFMP tool by Cranfield University and JBA in which the SCS curve number method, together with the WaSim soil moisture model, have been linked with several national data sets on soils, land cover and agroclimatic conditions to predict percentage changes in daily runoff depth as a result of the land use and/or land management modification. These percentage changes in runoff depth can then be applied directly to a ReFH rainfall-runoff model of the policy unit to generate the resulting total flow event hydrograph. The main strengths of the CFMP tool are (i) computational efficiency and ease of use; and (ii) the large number of land use scenarios (improved grassland, cereals, horticulture/non-cereal, semi-natural vegetation, and woodland) covering a range of return periods that can be explored for any catchment in England and Wales. The CFMP tool does not require any input data as the runoff frequency curves for all possible scenarios are stored within the tool's internal spreadsheet database.

CIRIA (2013) lists the main assumptions and limitations of the CFMP tool:

- the combination of climate, land management and soil type under investigation can be adequately represented by the 68 agro-climatic areas defined by Smith (1976)
- WaSim can be parameterised using physical properties representative for each HOST-type soil, thereby avoiding the need for calibration
- the impacts of the spatial distribution of responses within the catchment are negligible (this assumption is required to facilitate the spatially lumped model)

- the SCS CN method, originating from data from the mid-west USA, can adequately represent conditions in England and Wales (see Holman and others, 2011, Bulygina and others, 2011)
- continuous hydrological predictions are unavailable, the current tool does not consider how changes in rural land use or land management might explicitly alter the timing of the flood event hydrograph
- the results given are for T-year daily maxima

Halcrow (2012) put forward the recommendation that to properly model the potential hydrological benefits of land use changes in a catchment the approach would need to:

- be distributed
- be capable of running continuous simulation
- be partly or wholly physically based so that landscape, soil and vegetation can be represented
- contain detailed modelling of surface flow so that effects can be tracked downstream

However, no existing models meet these specific requirements apart from research-level, wholly physically based hydrological models, which typically require a lot of detailed site or catchment-specific data requirements. Halcrow (2012) proposed that a semi-physical distributed approach should be adopted (Figure 2). An additional requirement would be for the model to be capable of accounting for runoff at a range of event scales, including the effects of antecedent conditions. No examples of this approach being applied to any case study catchment have been reported at the time of writing (2017).

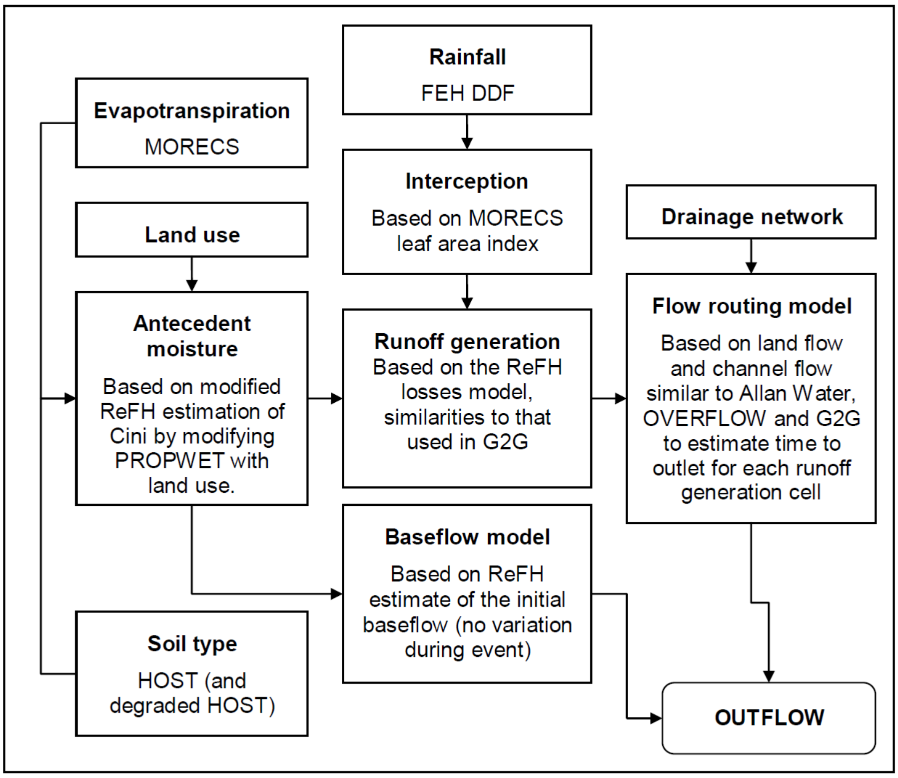

Figure 2 - Hydrological assessment tool schematic (Extract from Halcrow, 2012)

There is merit in exploring the use of a distributed modelling approach further, and Lancaster University and Newcastle University have carried out work in this area. A Lancaster Environment Centre PhD project sponsored by the JBA Trust is now exploring the use of dynamic TOPMODEL (more parametrically and computationally efficient than Grid-to-Grid, G2G, etc.) to provide this type of distributed modelling at catchment scale (Metcalfe and others, 2017).

2.5 Amenity turf for sport venues

Modern sports venues (for example, for football, cricket, rugby, hockey, athletics, golf, horse racing) have intensive drainage systems installed (either for natural grass turf or artificial turf). These are managed to maximise infiltration into the underlying soil and substrate layers (whether natural or artificially created) in order to retain the playability or use of the venue for a long as possible during the year. This makes the inherent drainage, flow pathways and runoff characteristics of these surfaces fundamentally different to that of, say, a typical agriculturally improved grassland.

Flood risk assessments are often required in support of planning applications to create new sports pitches or to build on old ones. Existing methods of flood estimation for these very small catchments, often situated in the urban/peri-urban landscape, are unable to account for the clear differences between agricultural grassland and sports turf, leading to considerable difficulty in comparing pre- and post-development estimates of runoff, and therefore the design of any flow attenuation features.

During the early stages of this project, correspondence with the sports turf consultancy and research organisation Sports Turf Research Institute (STRI) identified the following points with respect to sports field drainage and runoff:

- for very small catchments or parts of a catchment (such as a sports field) more detailed information is required on local soil and infiltration/runoff characteristics - slope is often found to be a critical factor in the design of drainage systems when using the MicroDrainage software, the results of which are sensitive to small changes in gradient for very flat areas
- HOST classifications derived from the original 1:250,000 scale national soil maps do not provide enough detail for many sports venue catchments - this requires more detailed knowledge of each particular site to be acquired - one of the difficulties is that the information must be readily available as the scale of smaller projects often does not warrant costly investigations
- for sports fields it is essential to consider the type of artificial drainage, that is, the pipes/pipes and slit drains/drainage layer and soil/root zone material used as this will have a major bearing on infiltration/runoff and potential attenuation of peak drain flows
- the type and condition of the turf can influence runoff - a strong and dense grass cover is more effective in controlling runoff than a weak grass sward and bare ground
- the design and management of the grassland areas surrounding sports pitches, which can form part of a facility, with longer areas of higher/coarser/denser amenity grass could act to control runoff
- applying a simple percentage increase factor to reflect the potential increase in drainage discharge with enough accuracy for small catchments (for example, dominated by sports fields) would be too generalised
- STRI is always trying to refine its design procedures to reflect the situation on small sites. This appears to provide a reasonable estimate of typical drain flows, but the methods are relatively crude
- it would be good to have a model that permits the input of different relevant factors that influence the soil infiltration rates/drain flow rates and potential attenuation, thereby allowing different scenarios to be evaluated
- Murray Simpson completed a PhD at Loughborough University in 2016 on runoff rates from sports pitches (Sustainable Drainage of Sports Pitches) - this was mainly for artificial surfaces, but he compiled some data for natural grass turf pitches as well - the monitoring is still operational at some sites - it may be possible, under appropriate licence agreements, to obtain these data sets to use in other research - the research is summarised by Fleming and others (2016)
- laboratory studies on micro-scale representation of sports pitches and their drainage characterisation, together with the supporting monitoring data from the field sites, have been used to develop a numerical model which predicts outflow rates and quantifies the system storage and losses - the model has been developed for artificial turf pitches but there is potential to transfer the underlying methodology and calculations to more natural grass systems

3. Discussion and recommendations

Of all catchment types, the smallest are the most likely to benefit from considering the influence of features such as land cover and vegetation. For one thing, flood estimation on small catchments is more uncertain and so there is more potential for improvement in the estimates. There is often no obvious or credible donor catchment. Another reason is that small catchments are more likely than large ones to be dominated by a particular type of land cover. For example, a small catchment could be entirely forested, or it could be managed by a single farming business with a particular style of land management, or it could be dominated by a golf course with closely-cropped turf. Finally, from a practitioner's point of view, getting to know the physical reality of a small catchment is often workable. In cases where full access cannot be gained, a good deal can be learned from mapping and aerial photography.

There has been a wealth of research investigating the complex effects of land use management on flooding, but there is still a fundamental need to continue with long-term multi-scale catchment monitoring studies into this topic, together with associated modelling initiatives. Current initiatives are focused in particular on the potential benefits of natural flood management measures to reduce and delay flood flows. Several developments in recent years could potentially improve the estimation of design flows for small catchments.

The spreadsheet-based CFMP tool (Environment Agency, 2010) was designed to account for the influences of changes in land use and land management on design flows at a CFMP policy unit scale. However, it can also be applied to estimating present-day design flows, accounting for crop types and field conditions. Some work would be needed to apply the tool at a local scale. The underlying databases were set up to work on the pre-defined CFMP policy unit boundaries. Application for individual catchments would require a new routine to extract the relevant catchment data from the national HOST, Land Cover Map and agroclimatic data sets.

In addition, the tool does have some limitations, in particular the fact that it considers only impacts on the depth of runoff and not on the time to peak (which affects the peak flow as well as the shape of the flood hydrograph). It is recommended that further work is carried out to address this limitation, to explore whether the tool can be applied at the scale of small catchments and to compare the results of the tool for present day conditions against those of FEH methods.

The semi-physical distributed modelling approach, as used for some investigations into natural flood management, may also have potential as a way of incorporating information on land management in estimating design flows. However, it is a complex technique which has not yet been implemented and may be too difficult to apply in many studies that require flood estimation in small catchments.

A recent Environment Agency research project, 'Making better use of local and historic data, and estimating uncertainty in FEH design flood estimation (FEH Local)', reviewed and developed techniques for incorporating local data in flood estimation. It uncovered examples of site-specific hydrological reasoning being applied to allow for the influence of unusual catchment properties (Environment Agency, 2017).

Merz and Blöschl (2008) provide some examples of how field visits or examination of topographic maps can yield clues about the flood frequency behaviour of catchments, such as the degree of incision of valleys, the presence of indicator plants, or the characteristics of the river channel. The authors state that “It would not be possible to predict the differences in catchment response between the two catchments on the basis of the quantitative catchment attributes and formal methods alone. In contrast, soft information obtained through a visual examination of the catchments during site visits may help tremendously. Clearly, site visits are instrumental in a hydrological assessment.”

One recommendation of the FEH ‘Local project’ was that a change in culture is needed to get hydrologists out from their computer models and into the field more often. Site visits are not always budgeted for in some UK hydrology practice. This is understandable when studies of large geographical areas are commissioned. However, small catchments do not take as long to explore. There is much that can be inferred about the characteristics of a small catchment by closely inspecting detailed maps and aerial photographs. Both are valuable for identifying unusual features, including vegetation types and land management practices that might be missed in a digital summary of catchment properties. However, some types of information can only be gained by site inspection and survey.

Another suggestion would be to test whether descriptors of vegetation or land management can be used to explain any of the residuals from the current FEH methods when applied to the small catchment monitoring database.

Even without any models or software tools that allow practitioners to account for information on land use when estimating design flows, hydrologists should be capable of applying their judgement when faced with unusual catchments. This requires both a grounding in catchment science and a sound understanding of the assumptions and principles of modelling techniques. This does raise educational and training implications that could potentially increase costs – or trend towards an overly-prescriptive use of analytical tools.

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