

# 1 **Coupled hydro-meteorological modelling on HPC platform for high** 2 **resolution extreme weather impact study**

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7 **Abstract:** The extreme weather impact-focused studies require coupling of accurate  
8 simulations of weather/climate systems as well as impact-measuring hydrological  
9 models that demand larger computer resources in its own right. In this paper, we  
10 present a preliminary analysis of an HPC-based hydrological modelling approach,  
11 which is aimed at utilising and maximising HPC power resource, to support the study  
12 on extreme weather impact due to climate change. Here, four case studies are  
13 presented through implementation on the HPC Wales platform of the UK mesoscale  
14 meteorological Unified Model (UM) with high-resolution simulation suite UKV,  
15 alongside a Linux-based hydrological model, HYdrological Predictions for the  
16 Environment (HYPE). The results of this study suggest that the coupled hydro-  
17 meteorological was still able to capture the major flood peaks, compared with the  
18 conventional gauge- or radar-driving forecast, but with the added-value of much  
19 extended forecast lead-time. The high-resolution rainfall estimation produced by the  
20 UKV has similar performance to that of radar rainfall products in the first 2-3 days of  
21 tested flood events, but the uncertainties particularly increased as the forecast  
22 horizon goes beyond 3 days. This study takes a step forward to identify how the online  
23 mode approach can be used, where both NWP and the hydrological model are  
24 executed, either simultaneously or on the same hardware infrastructures, so that  
25 more effective interaction and communication can be achieved and maintained  
26 between the models. But the concluding comments is that running the entire system  
27 on a reasonably powerful HPC platform does not yet allow for real-time simulations  
28 even without the most complex and demanding data simulation part.

29 **Key words:** HPC, extreme weather impact, Unified Model, UKV, HYPE, coupled hydro-  
30 meteorological modelling

## 31 **1. Introduction**

32 Extreme precipitation with great intensity and the subsequent flash flooding events  
33 arising from rivers and mountainous watersheds often lead to considerable economic  
34 damage and casualty, because water levels can react extremely quickly within rather  
35 limited warning lead-time (flash flooding). Therefore, the evaluation of potential  
36 flooding risks in extreme weather conditions, and the corresponding protection

37 measures required, demand accurate short-term flood forecasting, and more often  
38 very short lead-time forecasting – termed ‘nowcasting’ (Cloke and Pappenberger,  
39 2009).

40 Understandably, hydrological models together with hydraulic models play a key role  
41 in predicting runoff, river flow as well as possible inundations. However, the lead time,  
42 which is crucial for hazard mitigation and evacuation, is often highly limited in such a  
43 classic model chain configuration, since basically then, the lead-time is the travelling  
44 time of flood water. It is therefore, other means of providing rainfall estimates with  
45 extra lead-time (e.g., weather radar observations), have become increasingly essential  
46 in flood forecasting under extreme weather conditions (Zhu et al. 2014). However, it  
47 has also been recognised, e.g., by Golding (1998) and Smith and Austin (2000), that  
48 the performance of radar-based rainfall nowcasting deteriorates rapidly when the  
49 lead-time goes beyond 0.5hr. Then, the combination of radar nowcasting and  
50 hydrological forecasting is reduced to a normal model, or even worse. In fact, early  
51 attempts, whilst using the NIMROD radar rainfall product, already introduced a rainfall  
52 forecast from numerical weather prediction models to compensate for this  
53 shortcoming.

54 The fast development of HPC, as well as that of NWP (Numerical Weather prediction)  
55 models, has since given rise to the use of NWP, either directly or indirectly in  
56 hydrological simulations, in an effort to push hydrological forecasting beyond the limit  
57 of the rainfall-observation time-horizon. This link between two different modelling  
58 disciplines is often referred to as model coupling. The resulting coupled  
59 meteorological-hydrological models appeared from the beginning of the 21<sup>st</sup> century,  
60 being initially focused on flash flood forecasting, and later extended to handle  
61 climatic-hydrological coupling. This has facilitated many climate-change impact  
62 studies on water resources that rely heavily on the use of climate projections or  
63 simulations. Nevertheless, the linkage between the meteorological and hydrological  
64 models is scientifically challenging due to differences in model structures and issues  
65 of incompatible units (use of different scales in time and space). This is encapsulated,  
66 in particular, in the task of how best to transform and regionalise global climate  
67 scenarios, with spatial resolutions of 1,000-10,000 km<sup>2</sup>, to hydrological mesoscale  
68 catchments of (10 – 1,000 km<sup>2</sup>).

69 Simulation with meteorological–hydrological coupling in high spatial and temporal  
70 resolution is a comparatively new field of hydrological research, yet some pioneering  
71 work has recently appeared. In order to analyse the prediction of selected events  
72 characterized by peak flows, Westrick et al. (2002) proposed a hydrometeorological  
73 forecasting system for mountainous watersheds by coupling the Penn State–NCAR  
74 Mesoscale Meteorological Model (also known as MM5 for brevity; Dudhia, 1993; Grell  
75 et al., 1995) in 4\*4 km<sup>2</sup> resolution and the distributed hydrological model DHVSM

76 (Wigmosta et al., 1994). Jasper et al. (2002) compared the hydrological performance  
77 of radar and gauge measurements, with five different high-resolution numerical  
78 weather prediction (NWP) models and grid-cell sizes between 2 and 14 km. This work  
79 covered the prediction of peak-flows on the alpine Ticino-Toce watershed, using the  
80 distributed hydrological model WaSiM (Schulla and Jasper, 2000). The results suggest  
81 that, the accuracy and consistence of NWP rainfall in hydrological applications heavily  
82 depend on their process modelling at all scales of model nesting. Particularly so, as  
83 inaccuracies introduced by downscaling of precipitation from NWP models can lead  
84 to large differences in the predicted hydrological results, especially during extreme  
85 convective storm periods. Kunstmann and Stadler (2005) coupled (in 1-way manner)  
86 the mesoscale meteorological model MM5 with the distributed hydrological model  
87 WaSiM. The meteorological re-analysis data were dynamically downscaled with MM5  
88 grid cell sizes from 100 km to 2 km using four nests. Findings show that the MM5-  
89 based interpolation of precipitation yielded 21% less total yearly precipitation in the  
90 catchment area, compared to the station-based interpolation. Yarnal et al. (2000)  
91 linked a high-resolution meteorological model (MM5 at 4 km resolution) and a suite  
92 of coupled hydrological models (HMS) in the Susquehanna River Basin Experiment  
93 (SRBEX). This work points out that the coupled model has to confront several issues,  
94 such as, physics and parameterizations for a mesoscale atmospheric model to match  
95 the time-scales of climate coupled to the hydrological process models, meteorological  
96 and climatological process models with different scales; and the immense  
97 computational needs accordingly. Xuan et al (2009) also indicted that the inaccuracies  
98 and uncertainties in NWP could propagate to the downstream hydrological models,  
99 and they proposed to use an ensemble-based approach, together with effective bias  
100 correction, to mitigate this problem.

101 The majority of the studies cited above have been relying on the use of the so-called  
102 downscaling of large-scale NWP results using regional meteorological model such as  
103 MM5. These studies are often conducted in an off-line manner where hydrological  
104 modellers have hardly any control of NWP except the meso-scale one used for  
105 downscaling. However, the work presented in this paper, not only focuses on the  
106 performance of coupled high-resolution meteorological–hydrological simulations for  
107 extreme storm events on a HPC platform, it is also aimed at exploring the potential of  
108 building and running fully-coupled NWP-hydrological forecasts on a single computer  
109 platform; and therefore is able to obtain first-hand knowledge on fully integrated  
110 hydro-meteorological modelling. As such, we did not apply the meteorological model  
111 in forecasting mode, but used hindcasting mode instead, to test the model  
112 performance and benchmarking over several selected historical events.

113 One of the main challenges faced in coupled NWP-hydrological model simulation, or  
114 operational forecasting, is their reliance on computationally implementing NWP. In  
115 turn, this necessities the use of HPC, a procedure which can be performed in two

116 different fashions. Firstly, through an *offline approach*, where the hydrological model  
117 receives data that is generated from NWP beforehand, as for example, the data  
118 disseminated from various national meteorological centres. Alternatively through an  
119 *online mode*, where both NWP and the hydrological model are executed, either  
120 simultaneously or on the same hardware infrastructures, so that more effective  
121 interaction and communication can be achieved and maintained between the models.  
122 Most existing studies have adopted the former approach to ease technical demands  
123 on HPC as well as on NWP.

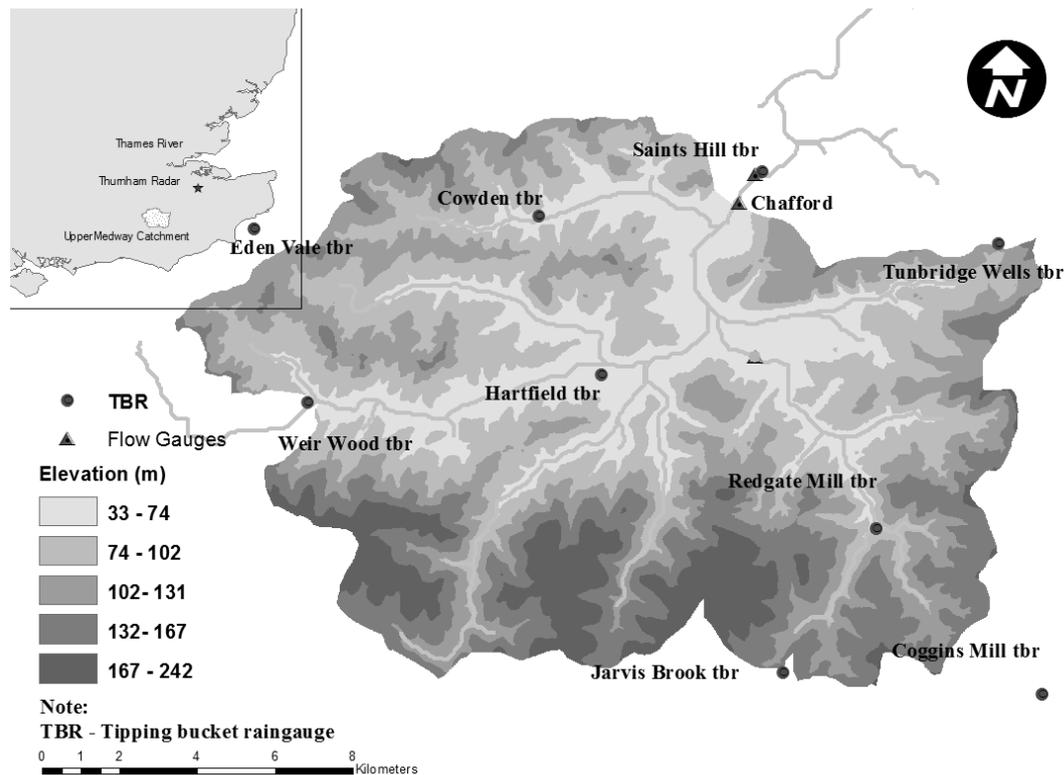
124 In contrast, this study takes a step forward to identify how the latter approach can be  
125 used, once HPC installation has been resolved. Moreover, it is worth noting that this  
126 experiment of a fully-coupled NWP-hydrological forecast is preliminarily designed to  
127 be a one-way coupling system in this study, which will form the basis for extension  
128 into a two-way coupling system, which will be developed further in the future.

## 129 **2. Materials and Methods**

130 In this study, the principal goal of the experiment has been to simulate the river basin  
131 response to extreme storm events, by linking a semi-distributed hydrological HYPE  
132 model to the UK Met Office Unified Model (UM) at a much finer spatial scale (1.5km).  
133 The combined high-resolution one-way driven model experiments generate runoff  
134 hydrographs for three extreme flood events, which occurred in the Upper Medway  
135 catchment (220 km<sup>2</sup>) located to south of London in the UK (see Figure 1).

136 The catchment elevation varies between 30 m and 220 m above mean sea-level and  
137 the majority of slope ranges from 2 degrees to 8 degrees, which makes up around 70%  
138 of the whole catchment. This suggests that the main scenery of the Upper Medway  
139 Catchment is small hills surrounding the flat, little relief low-lying area without much  
140 variation of elevation. The land use in the catchment can be simplified and described  
141 as permanent grass (over 95%). the major soil types in the Upper Medway Catchment  
142 can be categorised as silty loam and clayey silt, according to the National Soil  
143 Resources Institute (NSRI) data. The geology of catchment is a mixture of permeable  
144 (chalk) and impermeable (clay) and the dominant aquifers consist of the Ashdown  
145 Formation and the Tunbridge Wells Formation of the Hastings Group. The saturation-  
146 excess mechanism is the major runoff generation process in the catchment.

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148

149 Figure 1. Map of raingauges and flow gauge locations on the UpperMedway  
 150 Catchment (Source: Zhu and Cluckie (2012))

151 In such model experiments, two different sets of meteorological input data were used:  
 152 (1) surface observation data from station measurements and from weather radar  
 153 estimation, and (2) forecast rainfall data from high-resolution UM simulation suite,  
 154 UKV with grid-cell sizes 1.5 km. The experiments were designed as: (1) selecting  
 155 representative storms and hydrographs for simulation; (2) simulating these storms  
 156 using the high-resolution UKV simulation model, and (3) modelling the river-basin  
 157 response to the simulated storm events using the HYPE hydrological model.

158 One notes that Met Office has used the operational high-resolution UK 1.5 km model  
 159 (UKV) under the New Dynamics algorithm specification. This introduces nested  
 160 operations, through parallel suites PS30 and the time periods of interest. As such, this  
 161 consists of a Global 25km simulation, followed by a North Atlantic European 12 km  
 162 simulation, and finally, a UKV 1.5 km simulation. Each such simulation stage provides  
 163 the necessary lateral (spatial-temporal) boundary conditions for the regionally-refined  
 164 subsequent stage.

165 Rainfall observations from weather radars were also introduced in this study to check  
 166 the UKV output, since rain-gauges are point-based and the radar rainfall can provide  
 167 well represented rainfall distribution. Moreover, the comparison with UKV input  
 168 through a hydrological model can be drawn, in terms of streamflow differences.

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170 The raingauge measurements are collected from nine real-time, tipping-bucket  
171 raingauges (TBRs) operated by the Environment Agency (EA). Fig. 1 shows the  
172 locations of the raingauges (circles) and the flow gauges (triangles) on the catchment.  
173 And all the flow comparisons in this study were carried out at the Chafford flow gauge  
174 close to the catchment outlet.

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176 The radar rainfall estimates used in this study is extracted from the UK NIMROD  
177 composite dataset. This has been provided and quality controlled by the UK Met Office  
178 using the lowest available scan. It has been adjusted against available rain-gauge  
179 measurement and undergone extensive processing to correct for various sources of  
180 radar error. Such radar error would include noise, clutter, anomalous propagation,  
181 attenuation, occultation, “bright band” and orographic enhancement. Therefore,  
182 these high-resolution radar composite rainfall estimates incorporate the latest UK Met  
183 Office processing algorithms to account for the different sources of errors in the  
184 estimation of precipitation using weather radars (Harrison et al., 2000). This implies  
185 that this data-set is the best possible estimate of rainfall available at the ground-level  
186 in the UK (most error-free).

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188 More details in regards to the properties of this catchment and data description used  
189 in this study , such as topography, vegetation and soil types, as well as the availability  
190 of a hydrological data set, have been detailed in Zhu and Cluckie (2012) and Zhu et al.  
191 (2014).

## 192 **2.1 UKV model configuration and implementation**

193 The unified model (UM) is an atmospheric predictive numerical modelling software,  
194 offered by the UK Met Office and written in FORTRAN. Here, its output is coupled with  
195 a hydrological model for the purpose of accurate flood and extreme storm prediction.  
196 The UM was built on Archer hardware, with specification as a Cray XC30 MPP  
197 supercomputer, with up to 4920 compute nodes, each having a two 12-core Intel Ivy  
198 Bridge series processor, providing a total of 118,080 processing cores. Each node has  
199 64GB memory, with a subset of large memory nodes possessing 128 GB.

200 Further to the successful build and implementation of the UM, output from the  
201 various implementations has been validated against results derived from other HPC  
202 architectures. The UM features a New Dynamics algorithm, which is based on a semi-  
203 implicit, semi-Lagrangian formulation, that uses a common finite-difference scheme  
204 for the fully-compressible, non-hydrostatic Euler equations, discretized on a latitude-  
205 longitude grid. The algorithm is designed around a matrix-bound approach that is used  
206 to solve the semi-implicit aspects of the scheme.

207 The high-resolution simulation was achieved using the UKV suite which is a regional  
208 configuration of the UM, derived from operations through Parallel Suites (PS30),  
209 which consist of three nested domain simulations: Global 25 km simulation, North  
210 Atlantic European (NAE) 12km simulation, and UKV 1.5 km simulation. The Global  
211 N512L70 problem suite is discretized into approximately 25 km mid-latitudes, upon a  
212 1024x769 grid. There are 70 model levels vertically and a time-step of 10 mins is used.  
213 The regional NAE problem suite has a resolution of 12km, across a 600x360 grid. The  
214 NAE suit also has 70 vertical levels but the time-step choice is 5mins. Finally, the  
215 regional UKV is set at 1.5 km resolution over a 622x810 grid with a time-step of 50sec.

216 UKV model implementation requires a few events for model run. This includes an  
217 initialisation date and a number of subsequent time-duration periods i.e. 3 days, 6  
218 Days, 8 Days and 12 days. A selection of 8 Days start dumps was used in this study,  
219 requested from ECMWF or the Met. Office. The Met. Office holds start dumps to a  
220 back-date of up to five years only; prior to that, start dumps would need to be  
221 obtained from other sources.

222 The steps of UKV process in the overall procedure are to run: first, the Global  
223 reconfiguration and forecast; second, the European reconfiguration and forecast; and  
224 finally, the UKV reconfiguration and forecast. These independent simulation steps are  
225 all dynamically-linked through lateral boundary conditions (LBCs), and regionalisation  
226 of a start dump. With the start dump reconfigured for an UM input file format (Global  
227 region), this is then utilised to initialise the Global, European and UKV reconfiguration  
228 and to obtain an additional start dump for the forecasting stage. In turn, the Global  
229 forecast is run to obtain lateral boundary conditions for the European stage, whilst the  
230 European forecast provides lateral boundary conditions for the UKV.

231 The UKV model outputs were also on a rotated lon-lat grid, whose resolution is not  
232 constant, with small deviation from 1.5 km depending on the locations. The data was  
233 further projected onto the National Grid Reference Grid to become comparable with  
234 other sources of data, such as the weather radar rainfall observation from the  
235 NIMROD system. A nearest-neighbour interpolation was used to produce the evenly  
236 distributed grid data after projecting.

## 237 **2.2 The configuration and calibration of hydrological model - HYPE**

238 Whilst many hydrological models could have been selected, e.g., see Zhu et al (2014),  
239 an open source model – HYPE (HYdrological Predictions for the Environment) has been  
240 selected in this study to avoid reliance on commercial modelling packages. HYPE is  
241 developed at Swedish Meteorological and Hydrological Institute (SMHI) with a focus  
242 on integrating water and water quality throughout the model compartments,  
243 predictions in ungauged catchments with large model set-ups, e.g. across Europe. It is  
244 a dynamical model forced with time series of precipitation and air temperature,

245 typically on a daily time-step. Forcing in the form of nutrient loads is not dynamical.  
246 Examples of HYPE applications include atmospheric deposition, fertilizers and waste  
247 water.

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249 The HYPE model is able to predict water and nutrient concentrations in the landscape  
250 at the catchment scale. Its spatial division is related to sub-catchments and  
251 corresponding characteristics, including land use, vegetation, soil type and elevation.  
252 Within a particular catchment, the model will simulate water content in different  
253 compartments, including soil moisture, shallow groundwater, rivers and lakes.

254 The default time-step in HYPE is daily, but it can be reduced to hourly, which is  
255 normally specified in the input dataset, such as precipitation. Since there is no 2-D  
256 surface runoff algorithm built in the HYPE model, it is in principle a lumped model.  
257 However, spatial variations can be accounted for by portioning the catchment into  
258 smaller sub-catchments. In this respect, the simulated precipitation was processed as  
259 the catchment average rainfall before being fed to the HYPE model.

260 The winter flood event started from 06/12/2003 to 28/02/2004 was used for model  
261 calibration, carried out using 1-hour time step rain-gauge measurements and  
262 parameterised with the streamflow observation at the catchment outlet. In order to  
263 achieve the best fit between observed and modelled flow, the model parameters were  
264 calibrated in simulation mode using a mixture of manual and automatic parameter  
265 adjustment, according to their functionalities in the model.

266

267 First, all the parameters went through an initial manual sensitivity analysis, to decide  
268 those worthy of further automatic parameterisation. In this study, the maximum  
269 amount of percolation (mperc1, mperc2) in soil layers needs to be calibrated for  
270 percolation to occur. In addition, the soil type related parameters, like the available  
271 storage of water in the soil, the runoff coefficient of the top-soil layer (rrcs1) is  
272 sensitive in the model. And the peak velocity of flow in rivers (rivvel) determines the  
273 peak flow delay in the model, which is also need to be calibrated. After the sensitive  
274 parameters are selected, the progressive Monte Carlo simulation was employed to  
275 reduce the parameter space in stages and finally determine the calibrated parameters  
276 for later rainfall-runoff comparisons.

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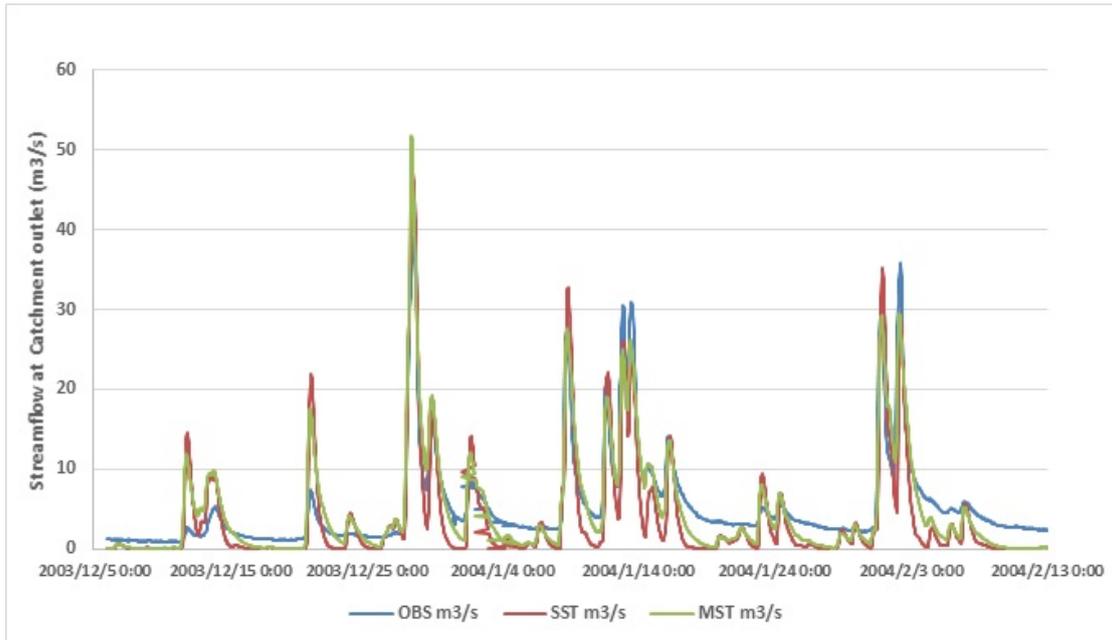


Figure 2. The comparison of model calibration with different soil settings

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The soil properties setting is critical in HYPE model. Figure 2 shows the model calibration performance with single soil type (SST) and multiple soil type (MST) settings. The soil types and the corresponding properties for the Upper Medway catchment are derived from the Hydrology of Soil Types (HOST, see Table 1), provided by the National Soil Resources Institute (NSRI) in the UK.

Table 1. Soil properties for corresponding HOST number

HOST	Water content at saturated condition	Field capacity	Wilting point	Infiltration rate (m/s)
9	0.501	0.418	0.244	3.4E-06
18	0.474	0.367	0.162	1.04E-06
16	0.46	0.378	0.219	1.9E-06
33	0.472	0.35	0.144	1.04E-06
3	0.441	0.295	0.117	3.6E-05
25	0.473	0.408	0.255	6.9E-08

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This data clearly indicates that the recessions period with SST setting was much faster than the observation, possibly due to the less resilience from a single soil type setting and the shallow depth of soil layer in the model. Consequently, multiple soil types and the increment depth of the soil layer were introduced to the model while the recession of flood was improved. Additionally, the most critical performance criteria for the model, the Nash-Sutcliffe Efficiency (NSE), increases from 0.68(SST) to 0.82(MST).

297 **2.3 The settings of a coupled UKV-HYPE case study**

298 The UKV model is set to make 36-hr forecast with a high resolution inner domain (1.5  
299 km grid boxes) over the area of forecast interest, separated from a coarser grid (4 km)  
300 near the boundaries by a variable resolution transition zone. This variable resolution  
301 approach allows the boundaries to be moved further away from the region of interest,  
302 reducing unwanted boundary effects on the forecasts.

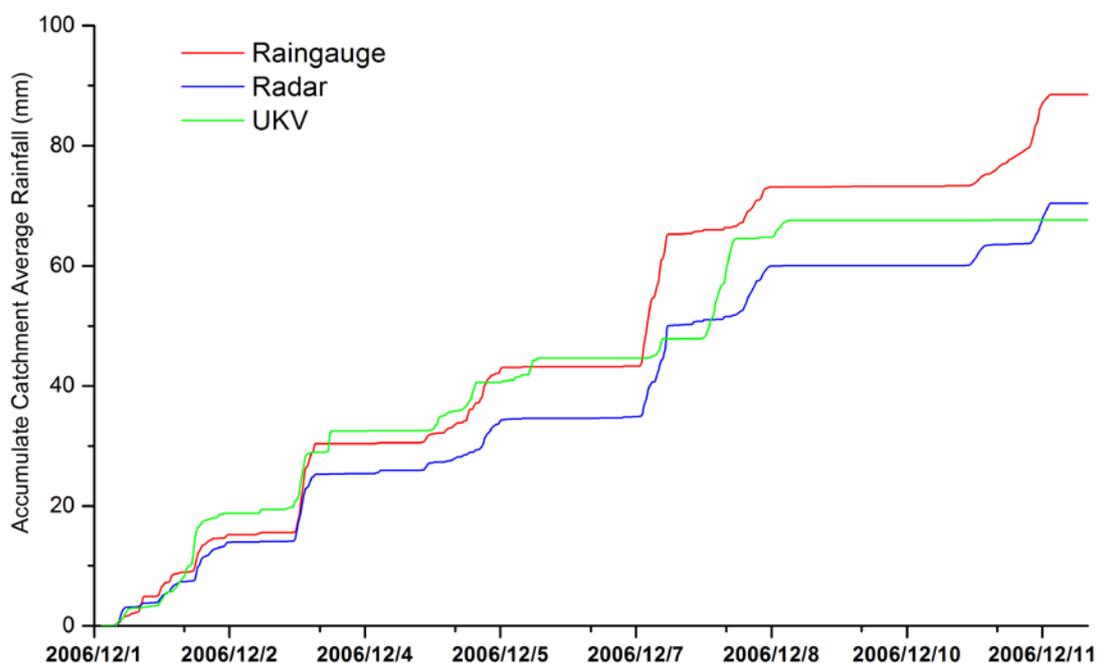
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304 Part of the motivation of using such resolution is to improve forecasts of convective  
305 rainfall. The variable resolution model with 1.5 km grid length over the UK, but  
306 increasing to 4km at the edges of the domain, enables the boundaries of the model to  
307 be pushed further away from the area of interest at lower cost, and also to reduce the  
308 resolution mismatch with the driving (12 km) model. The UKV rainfall estimation  
309 produced by the Unified Model is used as the input for the HYPE model, which  
310 provides the cornerstone to the coupled UKV-HYPE model.

311

312 **3. Results and Discussions**

313 Four flood events were selected to evaluate the performance of UKV rainfall products  
314 through HYPE hydrological model, by comparing the simulated streamflow driven by  
315 raingauge measurements, NIMROD radar rainfall estimates and UKV rainfall data. For  
316 the first flood event, there was around 100mm depth of precipitation over the Upper  
317 Medway Catchment during 01/12/2006 to 13/12/2006, according to the raingauge  
318 rainfall record.

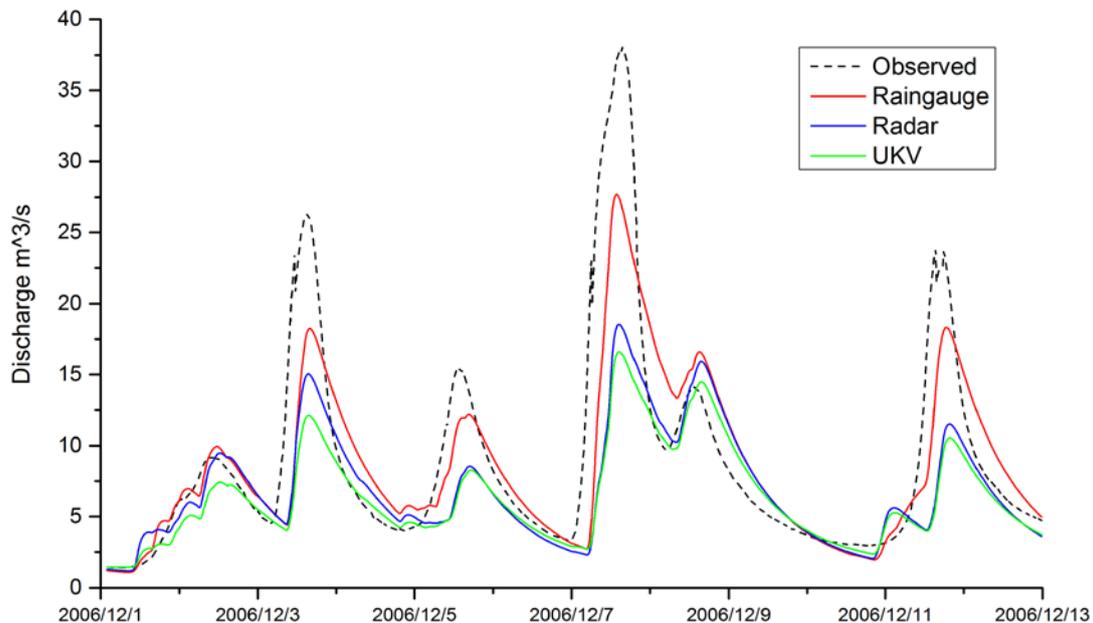


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320 Figure 3. The comparison of accumulative catchment average rainfall (Event  
321 December 2006)

322 Figure 3 shows the rainfall comparison on the accumulation of catchment average  
323 rainfall over the flood period. The UKV rainfall products has quite a good agreement

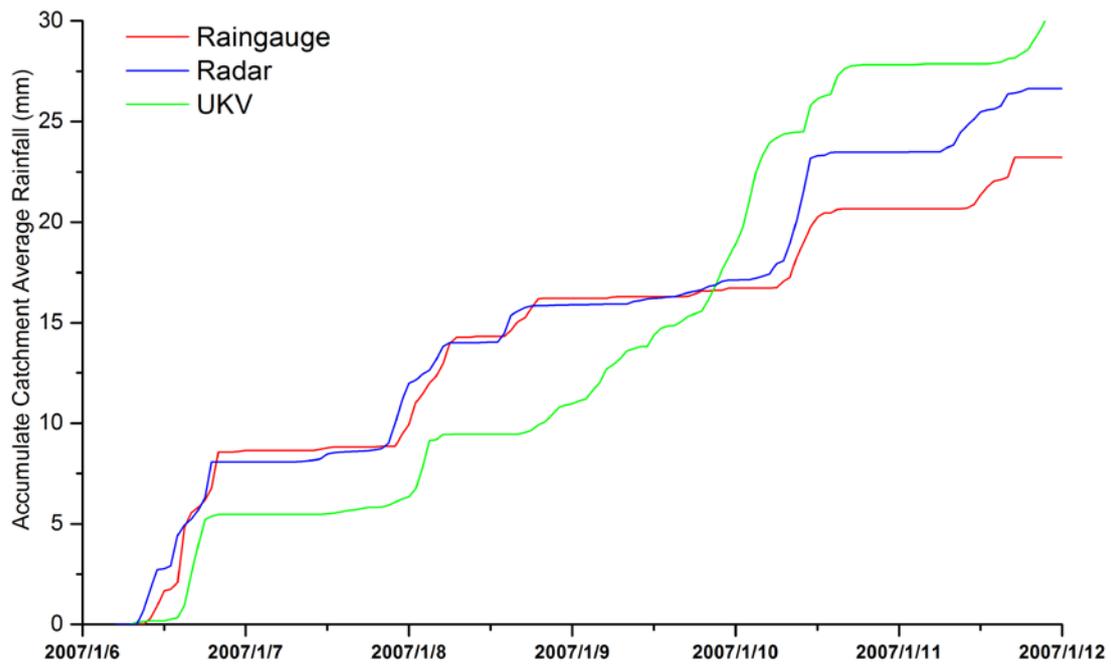
324 with raingauge measurements before the high peak flow occurred on 7/12/2006, in  
325 terms of the accumulative catchment average rainfall. However, the hydrological  
326 simulations illustrated in Figure 4 indicates that the raingauge measurements  
327 outperform the UKV rainfall product, especially on peak flow simulations.



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329 Figure 4. The comparison of flow simulation in HYPE (Event December 2006)

330 Figure 4 shows the comparison of the hydrological model performances driven by  
331 three different rainfall products in the entire event. The NIMROD radar rainfall  
332 estimates and UKV rainfall products were underpredicted on all the peak flows,  
333 especially on the highest peak flow that occurred around 8/12/2006, compared with  
334 the raingauge measurements. However, the UKV rainfall products have very similar  
335 performance with radar rainfall estimates, on the peak flow volume and the time to  
336 peak, which implies that the high resolution NWP rainfall product are as good as the  
337 radar rainfall estimates in this flood event.

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339 For the second flood event, the comparison of accumulative catchment rainfall was  
340 shown in Figure 5. The trends on the rainfall data are reasonably good across all three  
341 data sets. The UKV rainfall data does however pick up some exaggerated noisy peaks  
342 over the period between days 09/01/2007 to 10/01/2007 (see below to cumulative  
343 rainfall data).



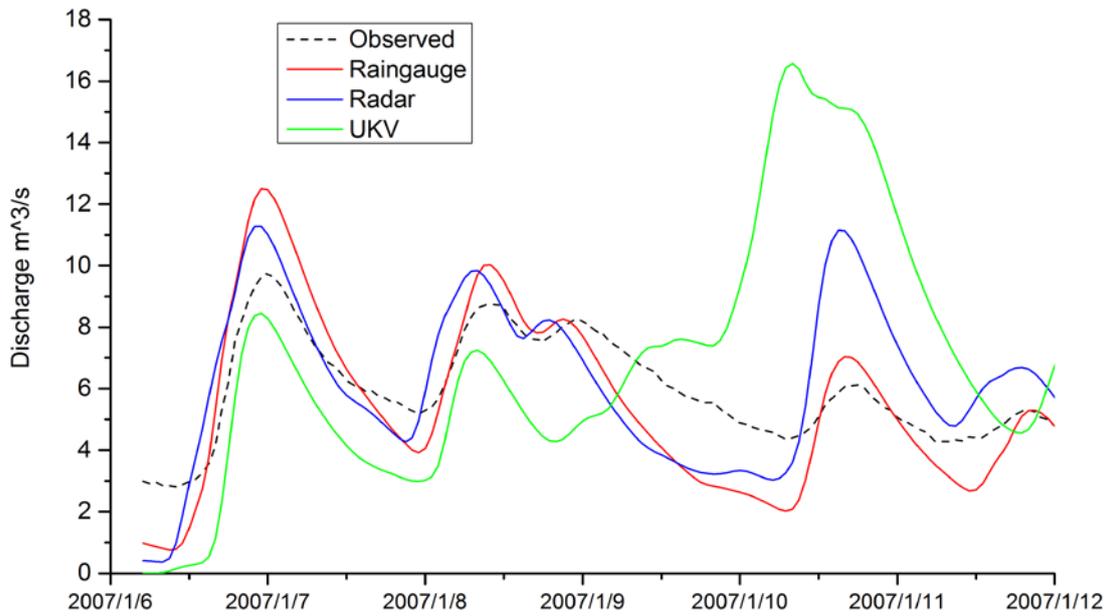
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345 Figure 5. The comparison of accumulative catchment average rainfall (Event January  
346 2007)

347 Figure 5 also shows that the NIMROD radar data produced more rainfall depth over  
348 the catchment than rain-gauge measurements, but less than the UKV rainfall. In  
349 addition, it shows similar rising cumulative rainfall for this event between all three  
350 data sets, and particularly between rain-gauge measurements and radar rainfall  
351 estimation up to 10 Jan. In contrast, one notes that the UKV rainfall underestimates  
352 rain-gauge and radar data-sets before 10 Jan, but with a similar rising trend. Departure  
353 arises subsequently between all three data sets, with UKV rainfall providing the  
354 extreme outcome.

355 The performance of UKV rainfall in HYPE model simulation for this January 2007 flood  
356 event of Figure 6 shows that the peaks and troughs are reasonably well represented  
357 against the observed data up to 10 Jan, after which the fourth peak is overestimated,  
358 and thus so is the final peak. The radar data suffers likewise, over the final two peaks,  
359 which are better captured by the rain-gauge data. The rain-gauge data does however  
360 underestimate the observed data output over this period.

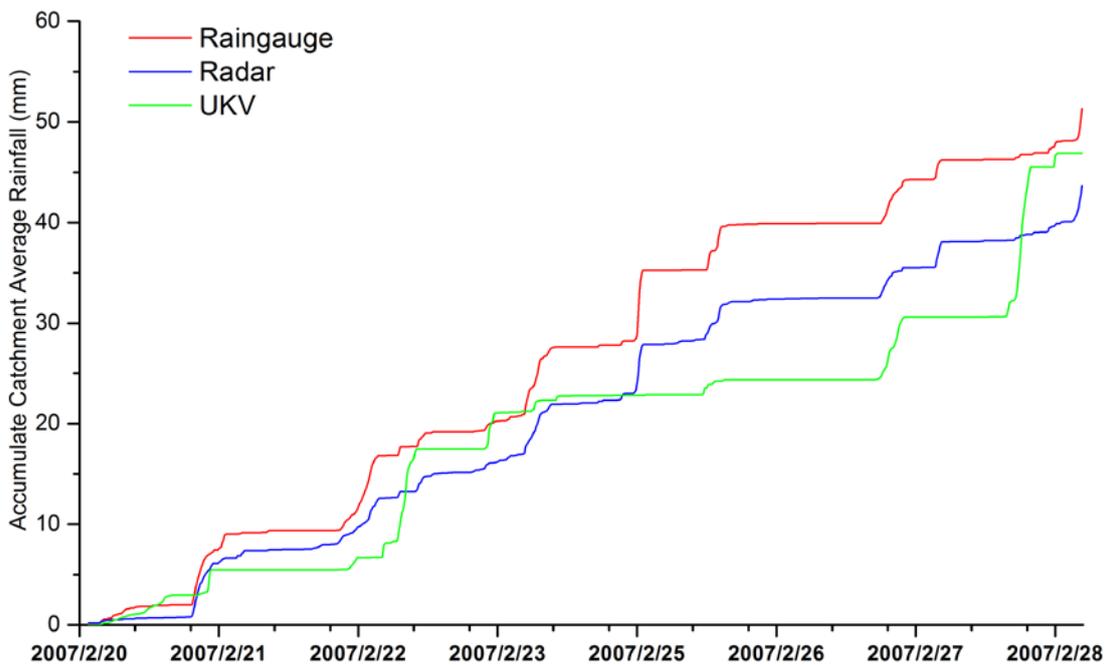
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363 Figure 6. The comparison of flow simulation in HYPE (Event January 2007)

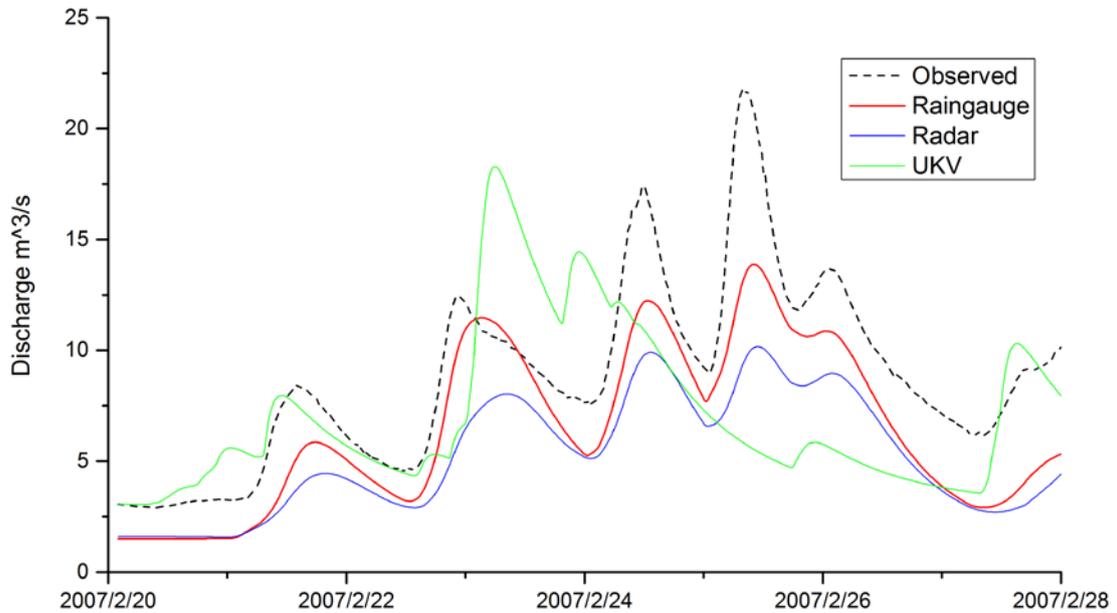
364 During the third flood event, there was a 50mm rainfall depth in total over the  
 365 catchment, recorded by the raingauges, which triggered the highest discharge at the  
 366 catchment outlet of about 25m³/s during the flood period. In terms of the cumulative  
 367 catchment rainfall, the raingauge measurement produced more precipitation than the  
 368 UKV rainfall, followed by the radar rainfall estimation.



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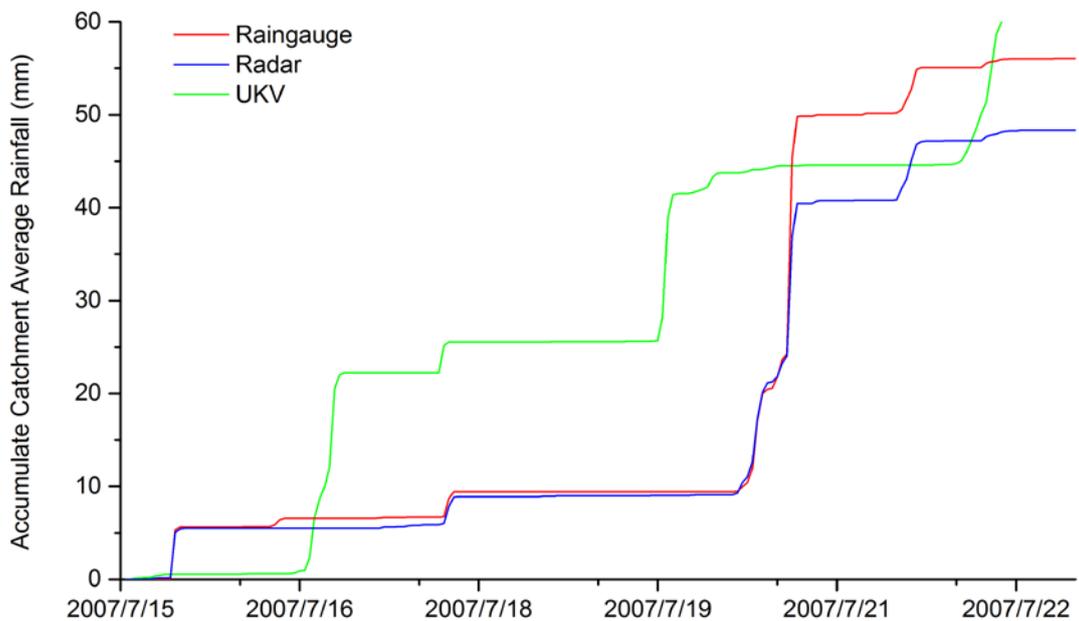
370 Figure 7. The comparison of accumulative catchment average rainfall (Event  
 371 February 2007)

372 However, Figure 7 shows that the UKV rainfall product did not capture the trend of  
 373 accumulative rainfall over the catchment, therefore totally miss the two flow peaks  
 374 after 24/2/2007, which is illustrated in Figure 8, compared with the raingauge  
 375 measurement and radar rainfall estimates. The raingauge data outperform the radar  
 376 data in this whole event, of which all the peak flows are better captured. However,  
 377 the raingauge data does underestimate the observed data output over this period.



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379 Figure 8. The comparison of flow simulation in HYPE (Event February 2007)

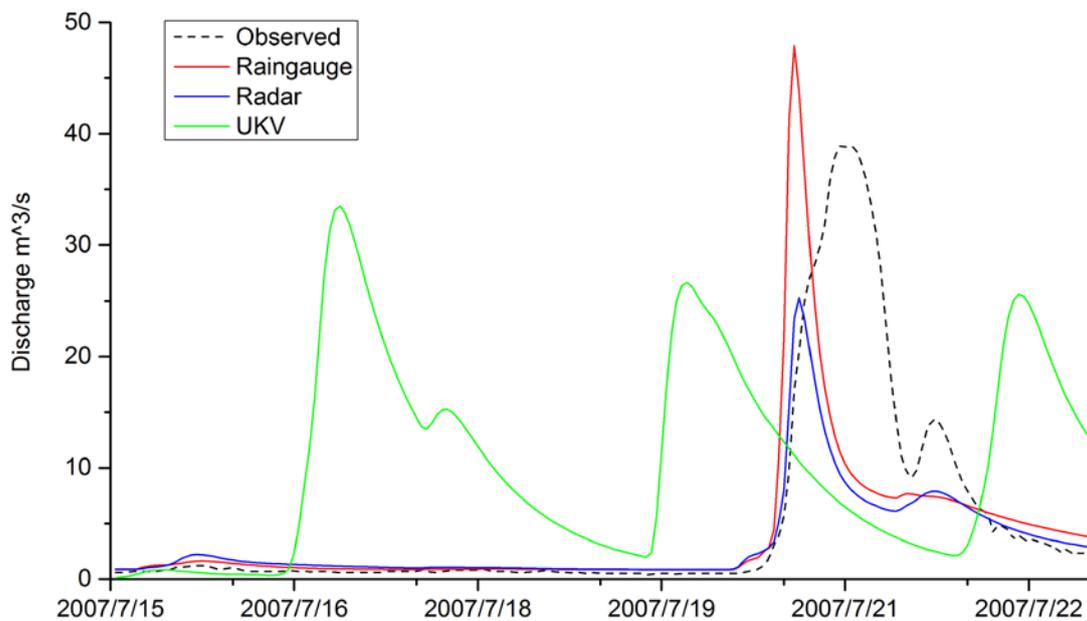


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381 Figure 9. The comparison of accumulative catchment average rainfall (Event July  
 382 2007)

383 The final event of July 2007, in terms of the flood magnitude, there was around 80mm  
384 precipitation recorded by the raingauges during 4 days which caused over 40m<sup>3</sup>/s  
385 discharge at the catchment outlet. It can be regarded as a similar case to the first flood  
386 event on December 2006, where the recorded streamflow was also around 40m<sup>3</sup>/s  
387 triggered by around 100mm of precipitation over the catchment during 12 days.  
388 However, there were no other peaks before the highest flow appeared in this event  
389 and the peak only lasted 1 day, which implied that this was a flash flood (sudden high  
390 peak flow and short period). It can also be identified from Figure 9, which clearly  
391 showed that there was a significant increase (over 40mm difference) on the July 20th  
392 for the accumulative catchment precipitation calculated from all rainfall  
393 measurements and rainfall estimation products, especially during the period from  
394 20/07/2007 08:00 to 20/07/2007 11:00, when over 30mm precipitation fell on the  
395 catchment in three hours, detected from the raingauge network.

396 Considering the differences between the raingauge measurements and radar rainfall  
397 estimates, the precipitation estimated from radar reflectivity could be heavily  
398 attenuated. After being converted to Cartesian format, the details of the signal were  
399 further smoothed by the averaging process, which could explain the reason that the  
400 radar rainfall estimates underestimated a lot more than raingauge measurements.  
401 Additionally, because the model rainfall input for HYPE is the catchment average  
402 precipitation, the rainfall distribution and heterogeneities are not simulated, so that  
403 all the modelled flow was not comparable with the observation in this extreme rainfall  
404 flood event.



405

406

Figure 10. The comparison of flow simulation in HYPE (Event July 2007)

407 The flow simulation shown in Figure 10, would appear to pick up an exaggerated peak  
408 in the UKV rainfall through HYPE model simulation after the first day (16/07/2007),  
409 which is not reflected in the other data-sets. This early disturbance influences the early  
410 undershoot of the observed-data first-peak (at 21/07/2007), and the overshoot of the  
411 observed-data second-peak (before 22/07/2007). Notably, rain-gauge data output  
412 overshoots the observed-data first-peak, whilst NIMROD radar data output provides  
413 an undershoot; both undershoot the observed-data second-peak. This is rather a  
414 testing event with only one single main flood event to sharply capture. Clearly, one  
415 would need to investigate further in this event instance as to why the early  
416 disturbance has arisen for UKV output in this case, and provide more data evidence to  
417 prove or refute this particular finding. Further case study events would help clarify this  
418 issue, as the Jan 2007 event did not show this up.

#### 419 **4. Conclusions**

420 This paper describes a recent effort of integrating both the driver NWP models and  
421 the impact analyser – hydrological model on a single HPC platform to support better  
422 and refined studies on extreme weather impacts. What distinguishes this study from  
423 others is it is first time that modellers are able to simulate the entire system, ranging  
424 from the global circulation down to a target catchment for impact study. This study  
425 also explores the feasibility of building weather/climate services together with the  
426 impact oriented analysis on a single platform; and what can be done if otherwise, for  
427 example, how computing resources can be re-arranged for that matter.

428  
429 The initial idea of this study was in fact to include a whole system model including the  
430 UKV + data processing + Hydrological models on an HPC platform. This differs from  
431 the usual approach of getting the IC/BC from a weather centre and then run a Limited  
432 Area Model (LAM) like WRF and then some hydrological simulations. It aimed further  
433 to fully integrated a hydrological model component into the UKV, which is not  
434 revealed by this paper yet, but it will form the basis for extension into a two-way  
435 coupling system, which will be developed further in the future. Therefore, this study  
436 aimed at constructing and running both NWP and the hydrological model, either  
437 simultaneously or on the same hardware infrastructures, to achieve more effective  
438 interaction and communication, so that the potential of fully-coupled NWP-  
439 hydrological forecasts on a single computer platform is explored, and the first-hand  
440 knowledge on fully integrated hydro-meteorological modelling can be obtained.

441 The study finds that when running the entire system on a reasonably powerful HPC  
442 platform, the overall time frame does not yet allow for a real-time simulation even  
443 without the most complex and demanding data simulation part. It is therefore  
444 suggested that the components responsible for large scale simulation, such as global  
445 and the European area should remain at national weather service centre where  
446 dedicated HPC resources can well deal with the demand as they already have been

447 doing. However, it is still possible to have a high resolution version with less  
448 geographical coverage running on a general purpose HPC platform together with the  
449 impact analysing model such as a hydrological model and further inundation models.  
450 This configuration also allows for finer control and/or tune the models to fit various  
451 purposes.

452

453 The other main purpose of this study is to gain the sight of how a common hydrological  
454 model can utilise the high resolution precipitation (among others) forecast and  
455 simulation in an impact study of extreme weather events. It is encouraging to find that  
456 event without fine-tuning, such as using various parameterisation schemes, the  
457 coupled hydro-meteorological was still able to capture the major flood peaks with  
458 much longer lead time compared with the conventional gauge- or radar-driving  
459 forecast (2-3 days vs 2-3 hours). The high resolution UKV rainfall shows some  
460 promising agreement with rain-gauge measurements and radar estimation in the first  
461 2-3 days in this flood event, both in the catchment average rainfall amount and  
462 hydrological simulation in HYPE.

463

464 The study also identified uncertainties associated with precipitation forecast,  
465 particularly will increase as the forecast horizon goes beyond 3 days. For example, the  
466 latter part of the flood event was not represented well by the HYPE model simulation  
467 using the UKV rainfall, compared with those using other sources of rainfall, e.g., radar  
468 and raingauges. This is, however, understandable and consistent with our previous  
469 studies using other model, see, e.g., Seyoum et al (2013). Apparently, other more  
470 complicated uncertainty-aware technique needs to be applied in this model coupling  
471 configuration, which, in fact, is the key research topic for further studies.

472

473 Overall, the value of this study is make sure that the high-res UKV can be used to drive  
474 hydrological models like HYPE; and second, the study demonstrates that it is possible  
475 that with a moderate resources requirement, a fully integrated system can be  
476 established to benefit from independent data assimilation/NWP coupled with  
477 hydrological models. Although there are many deficiencies (such as uncertainty) still  
478 exist in such system as they are in many WRF related studies, however, with the ability  
479 to simulate from source (atmospheric observations) to end (flow simulation), these  
480 issues will be addressed more efficiently in the future.

481

482 Consequently, the following recommendations for future work are made:

483 1. The study needs to be repeated and extended, as more data-sets become available  
484 from UKV.

485 2. The impact of the high resolution new radar data needs to be explored in the  
486 context of distributed hydrological modelling.

487 3. The UKV rainfall needs to be fully assessed by various lead-times and ensemble  
488 simulations, that encapsulate uncertainty generation and propagation through  
489 complex ‘cloud to catchment’ or ‘Whole Systems Modelling’ concepts.

490

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506

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