Thirlmere Reservoir Water Balance Model

Alistair Cook and Ed Henderson

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Executive Summary

This report describes the development and use of a simple water balance model for Thirlmere reservoir. The reasons for developing the model were to improve understanding of the reservoir during Storm Desmond and provide a tool for calculating the water release rate necessary to significantly reduce the risk of flooding in Keswick. The proposal is that water should be released from the reservoir to create spare capacity that can be used to store water during a storm therefore preventing or reducing discharge from the reservoir. A reduction in the rate of runoff from the reservoir during a storm could reduce the flood peak in Keswick. The model has been verified against reservoir water level data collected during November and December 2015, a period of record-breaking rainfall and extreme flooding. Using the model, it has been calculated that the release rates between 600 and 900 Ml/d (10 cumecs) proposed by the reservoir operators United Utilities (UU) would not have reduced the peak flow sufficiently in Keswick to prevent flooding during Storm Desmond. If a warning of a severe storm had been received six days prior to Storm Desmond, the six-day release rate required to prevent flooding in Keswick during Storm Desmond is calculated to be 2500 Ml/d (28.9 cumecs). This compares with peak flood flows of around 46 cumecs in the 1995 flood, 48 cumecs in the 2005 flood, 60 cumecs in the 2009 flood and 104 cumecs during Storm Desmond. If an alternative approach using target reservoir levels of 3 m below full is adopted during the usual flood season then release rates up to 1200 Ml/d (13.9 cumecs) are required to achieve these targets. It is recognised that UU do not wish to cause flooding or erosion while making pre-storm or target releases but it is proposed that the release rate required to make the scheme effective is greater than the 10 cumecs proposed by UU and much less than the damaging rates experienced in the 1995, 2005, 2009 and 2015 floods.

Introduction

Since the floods in the Derwent catchment in 2005, Keswick Flood Action Group (KFAG) has called for Thirlmere reservoir (Figure 1) to be managed to create storm water storage. If the reservoir water level could be managed to lower the level a few metres below the sill level before a storm, the storage space created could hold a substantial fraction of the catchment storm runoff in the reservoir. It has been suggested that by doing this, river water levels between Thirlmere and Keswick during a flood event would be reduced. This has the potential to substantially reduce flood risks in Keswick and reduce the impact of damaging floods between the reservoir and the town.

This potential role that Thirlmere could play in flood risk reduction in the Upper Derwent catchment was partially recognised by United Utilities (UU) and the Environment Agency (EA) in around 2010 when they adopted a number of 'trigger levels' for different months of the year in an attempt to create storage space in the reservoir by lowering the water level. Essentially, this meant that UU would release water until the 'trigger level' for the month was reached. When this trigger level was reached, these additional discharges would be stopped. However, this system failed to reduce flood risks because the valves used to release the water did not have the capability to release enough water to prevent the reservoir from quickly refilling during periods of rainfall. This failure was illustrated by major flooding in December 2015. The failure of this system is mirrored in the name used for the levels. Calling the levels ‘trigger levels’ shows that they were a trigger for stopping releases. Instead, the levels should have been ‘targets’ that the reservoir management should have strived to achieve. However, with the present valves, the targets were unachievable except when there was little rain in the Thirlmere catchment.

After the 2015 flood, which was the largest of the three most recent Derwent catchment floods (others being 2005 and 2009), UU and the EA met with KFAG to re-examine the management of Thirlmere. The EA commissioned a study that confirmed that the creation of water storage in Thirlmere could reduce flood risks between the reservoir and Keswick (AECOM, 2016). The EA has also included Thirlmere as one of its ‘initial key actions’ in the Derwent catchment to provide flood protection (Environment Agency, 2016a). It has been said by a local Professor Emeritus in Hydrology that ‘Thirlmere could be the only feature of the Derwent catchment that has the capability to make a real difference to flood risks’.

This report describes the analysis of data and the development of a spreadsheet model to calculate what reservoir water levels need to be achieved prior to a storm to reduce flood risks. The purpose of the model is to allow the necessary drawdown release rate to be identified, i.e. the rate required to lower the reservoir quickly enough to create sufficient storm water storage before a storm arrives. Data from the period covering November and December 2015 which saw a series of storm events has been used to develop and test the model.

It is recognised that KFAG does not have the resources of industry or the regulator and have had to use whatever data and information are available. Some of these data, particularly reservoir water level data and catchment rainfall data have been kindly provided by UU and the EA.

Thirlmere

Before describing the spreadsheet model, it is useful to describe how water moves through Thirlmere. Thirlmere is a reservoir which stores water using a dam that was constructed in the late 1800s. Water stored in the reservoir originates in the catchment above the reservoir. The catchment covers an area of approximately 41 km^2. When rain falls in the catchment, some is lost to evapotranspiration, some refills soil water stores, some is temporarily lost to groundwater but the rest runs off the land into the reservoir. The volumes of water running off the catchment and entering the reservoir can be calculated by multiplying a depth of 'net' rainfall by the catchment area. For example, 1000 mm of rain would generate 41 million m^3 of water and 100 mm of rain would generate 4.1 million m^3. The runoff is converted from a gross figure to a net figure using a 'runoff coefficient'. This allows some of the rainfall to be lost to evaporation, soil water and groundwater recharge.

As Thirlmere covers an area between approximately 2.5 km^2 and 4.8 km^2 depending on the depth of water, it is possible to calculate the change in water level if a certain volume of runoff is added to the reservoir. For example, if the 4.1 million m^3 of runoff generated by 100 mm net rainfall was added to the reservoir with an area of 4.2 km^2, the water level would be raised by 976 mm. This assumes that the reservoir is not full. When the reservoir is full, water discharges over a weir and into a tunnel spillway. However, the weir and tunnel spillway do not have an infinite discharge capability and therefore when there is more inflow into the reservoir than the weir tunnel/spillway can cope with, the water level increases above the height of the weir. It should also be noted that the surface area of the reservoir increases as the height of the stored water in the reservoir increases.

Storm Desmond (5th-6th December 2015) was the largest rainfall event that the reservoir has experienced at least in modern times and probably in the lifetime of the reservoir (from 1894). The depth of rainfall measured at Dalehead near Thirlmere during Storm Desmond set a new UK 48-hour record of 405 mm (actually 405 mm in 38 hours). If all this rainfall was added to Thirlmere (without losses to evaporation or groundwater recharge), it would convert to a runoff volume of approximately 16.6 million m^3 (16,600 megalitres). If a runoff factor of 0.8 is applied (i.e. 80% of rainfall becomes runoff), the volume entering the reservoir would be 13.3 million m^3 (13,300 Ml). Applying this to a reservoir area of 4.2 km^{2}equates to a depth of approximately 3.2 m. Therefore, if the reservoir water level had been slightly more than 3 m below the level of the weir at the start of Storm Desmond, the reservoir could have stored all the runoff from the Thirlmere catchment if the runoff coefficient of 0.8 is applicable. However, because the reservoir does not have vertical sides, the water level reduction required to store all the Storm Desmond runoff is more like 4.5 m.

If it had been possible to manage the reservoir in this way prior to Storm Desmond it would have made a significant difference to flood water levels in downstream communities such as Keswick. This was proved by AECOM (2016). However, prior to Storm Desmond, there had been two other large rainfall events in the catchment (Storm Abigail: 12-13 Nov and Storm Barney: 17-18 Nov) and these had filled the reservoir to overflowing by 30th November. Therefore, at the start of Storm Desmond, Thirlmere was already full and overflowing and runoff into the reservoir served to increase the water level and increase discharge into St John's Beck.

The flooding in Keswick during Storm Desmond was worse than in 2005 and 2009. The peak river flow rate for Storm Desmond at the Low Briery river gauging station has been estimated by the EA at 343 cubic metres per second (cumecs). The Thirlmere catchment is approximately 28% of the area of the catchment above Low Briery. If the rainfall was evenly distributed across the Low Briery catchment, it could be assumed that approximately 28% of the peak flow at Low Briery can be attributed to the discharge from the Thirlmere catchment. However, as the highest 38-hour precipitation total was measured at Thirlmere, it is likely that there was a concentration of rainfall in the Thirlmere catchment.

Therefore, the percentage of the flood water in Keswick that originated in the Thirlmere catchment is likely to be greater than 28%. The current estimate for the peak discharge through St John's Vale just downstream from Thirlmere is around 104 cumecs[1] or 30% of the peak flow at Low Briery. UU have reviewed the maximum flow rate through the weir/tunnel arrangement. The present suggestion from UU is that the tunnel has a maximum capacity flow rate of 110 to 116 cumecs (CRM Rainwater Drainage Consultancy Ltd, 2017). If it is assumed that the peak flow from Thirlmere and the peak flow from the rest of the Low Briery catchment arrive in Keswick at about the same time and that the EA figure of 104 cumecs is accurate, if the discharge from Thirlmere could have been stopped at the reservoir, this could have reduced the peak flow in Keswick from 343 cumecs to 239 cumecs (343 cumecs minus 104 cumecs). If the higher UU figure of 110 cumecs is adopted, the peak in Keswick is reduced to 233 cumecs. It is understood that the flood defences in Keswick can prevent flooding up to a maximum river flow around 260-270 cumecs (although a figure of 240 cumecs has been mentioned in some correspondence from the EA). This suggests that if it had been possible to store all the Storm Desmond runoff in Thirlmere, there would have been little or no flooding from the river in Keswick.

It is recognised that there is some considerable uncertainty in a simplistic representation of a complex process and therefore to clearly define how much storage is required to substantially reduce flood risks in Keswick, a more detailed analysis similar to that provided by AECOM (2016) is required. The modelling reported by AECOM (2016) was flawed in that it did not consider the actual rainfall depths in the Thirlmere catchment but used a spatially averaged value covering the whole of the Greta catchment. The AECOM study therefore needs to be repeated but using more realistic spatially variable rainfall.

In order to model how the reservoir levels vary in response to the combined actions of runoff input and discharge output, it is necessary to make three concurrent calculations, i.e. input, change in water level and output. The spreadsheet model presented here is an attempt to do that. However, this calculation is made easier by the availability firstly of rainfall data and secondly reservoir water level data. The first comes from a rain gauge at Thirlmere. The second comes from a reservoir water level gauge. Both are operated by the Environment Agency which has kindly provided the data for November and December 2015. The reservoir water level data have been supported by additional data from United Utilities for the 5th–6th December 2015. Additionally, it was possible to observe the filling of the reservoir in November 2015 and to directly compare the rainfall inputs with the known volumes as the reservoir levels rose. This assisted the identification of a relationship between reservoir levels and water volumes.

Conceptual Model

The concept of the model is a simple water balance. This can be described as a balance of inputs, outputs and changes in the volume of water stored in the reservoir. The inputs are runoff from the catchment around the reservoir and direct rainfall onto the reservoir surface. The outputs are flow over the reservoir weir, water supply discharges to Manchester and Keswick and controlled releases into St John's Beck. The latter is known as compensation flow and is designed to keep St John's Beck flowing at an ecologically reasonable level even when the reservoir is not overflowing. The water balance can be expressed as:

Inputs = Outputs – Change in Storage

Therefore, at the start of Storm Desmond, runoff from the surrounding land will increase the water level over the crest of the weir resulting in increased discharge and increased storage (because the water level

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[1] This value has been calculated using UU water level data for Storm Desmond and a new stage-discharge relationship provided by UU (see CRM Rainwater Drainage Consultancy Ltd, 2017).

has increased). Water outputs from the reservoir do not equal water inputs because there is a change in storage. Change in storage is negative when input (runoff) is less than output (abstraction and discharge) so that the reservoir levels goes down as water is discharged for supply purposes and compensation flow. The opposite occurs when rainfall is large enough to produce runoff into the reservoir greater than the amount being abstracted and discharged.

Inputs - Rainfall and Runoff

The record of 15-minute rainfall depths at Dale Head by Thirlmere for November and December 2015 is shown in Figure 2. The volume of rainfall falling on the catchment every 15 minutes is calculated by multiplying the rainfall amount in mm by the catchment area in km^2 all multiplied by 1000 to allow for units. However, it is known that because the input from parts of the catchment (i.e. the Mill Gill, Lad Knot and other subcatchments) is controlled by UU, the catchment area varies depending on whether the runoff from these subcatchments is directed into Thirlmere or into St John's Beck. Generally, the runoff from these subcatchments is directed into Thirlmere when it requires additional water and away from it when does not, e.g. when the reservoir is full. The removal of the subcatchments from the total catchment area reduces it from 42 km^2 to 40.3 km^2. It is postulated that this occurred between 11th November and 30th November. It is believed that from 30th November to the start Storm Desmond on 5th Dec 2015 runoff from Mill Gill and Lad Knot Gill entered the reservoir. During the storm, runoff from the catchments overspilled their channels and flowed overland to St John's Vales and St John's Beck.

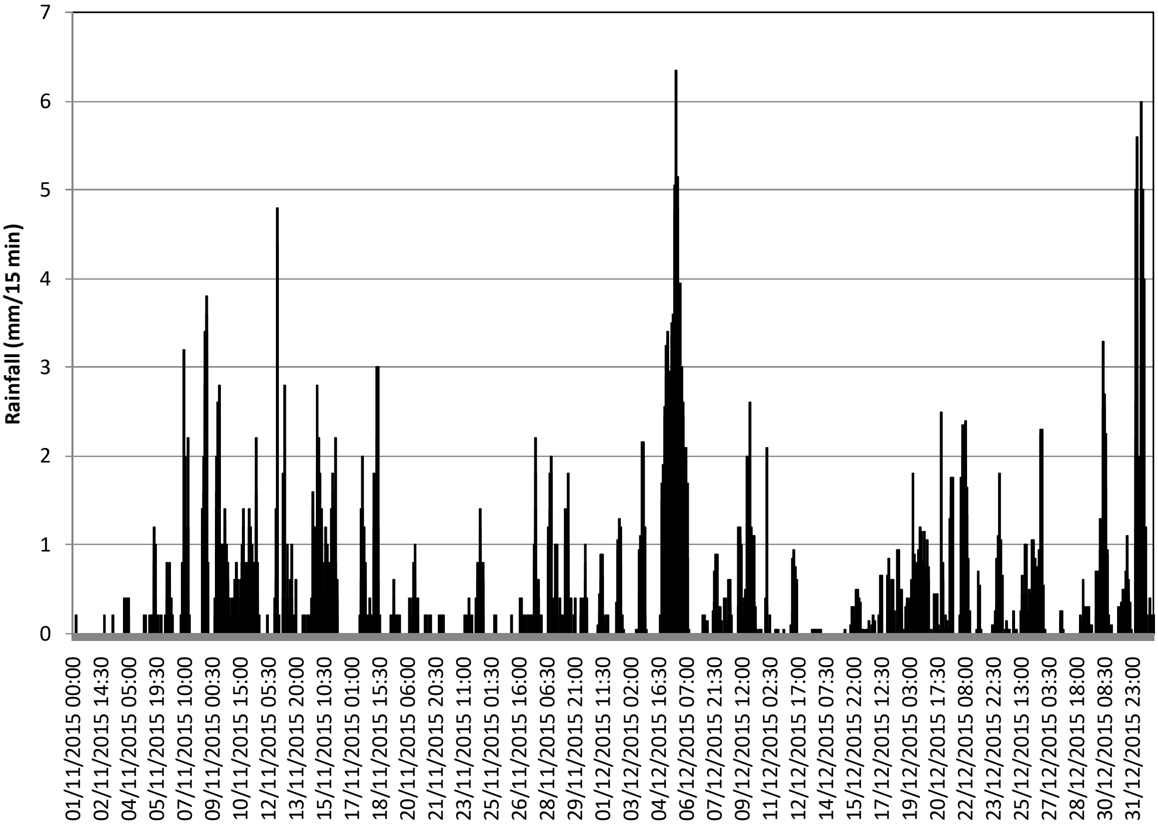

Figure 2: 15-minute rainfall recorded at Dale Head near Thirlmere November December 2015.

Discharges

There are two types of releases from Thirlmere reservoir. These are managed releases and releases over the spill weir. Releases over the spill weir occur when the reservoir level reaches the level of the weir.

These are not strictly releases as they are not controlled. They should therefore be termed 'discharges'. Managed releases are those controlled by UU and are essentially releases for the purposes of water supply, river flow maintenance and reservoir level control. Figure 3 shows the releases during November and December 2015. Trigger releases refer to releases aimed at lowering the reservoir level to what are known at 'trigger levels'. KFAG had long recognised the potential effectiveness of reservoir storm storage, calling for example for 3 m drawdown in December. However, the current trigger levels are the best that UU were able to offer when these were agreed.

The trigger levels are 3 m from August through to November, 2 m in December and 1 m in January. However, this method of flood control has not been effective because it is not possible to release enough water from the reservoir relative to the volume that enters the reservoir from rainfall, especially during winter storms. Because the current release valve can only release water at up to 140 megalitres per day (Ml/d), it takes too long to lower the reservoir to the trigger level. In comparison, a large storm can generate so much runoff that it soon refills the reservoir once it has been lowered. The trigger release rates shown in Figure 3 are 1,042 cubic metres per 15 minutes (100 Ml/d) which is equivalent to approximately 1.16 cumecs. The top 1 m of the reservoir holds approximately 3.5 million m^3, so a release rate of 1.16 cumecs (100 Ml/d) would take 35 days to lower the reservoir by 1 m. This is far too slow when the time gap between storms can be measured in a few days as seen in December 2015. By comparison, a release rate of 700 Ml/d could lower the water level by 1 m in just under five days. With the Met Office now being able to give warnings of severe storms six days before their arrival, a release rate of 700 Ml/d would allow UU to create approximately 1.3 m of storage in that time. However, it is debateable whether 1.3 m of storage would be enough to substantially reduce downstream flood risks during very large storms.

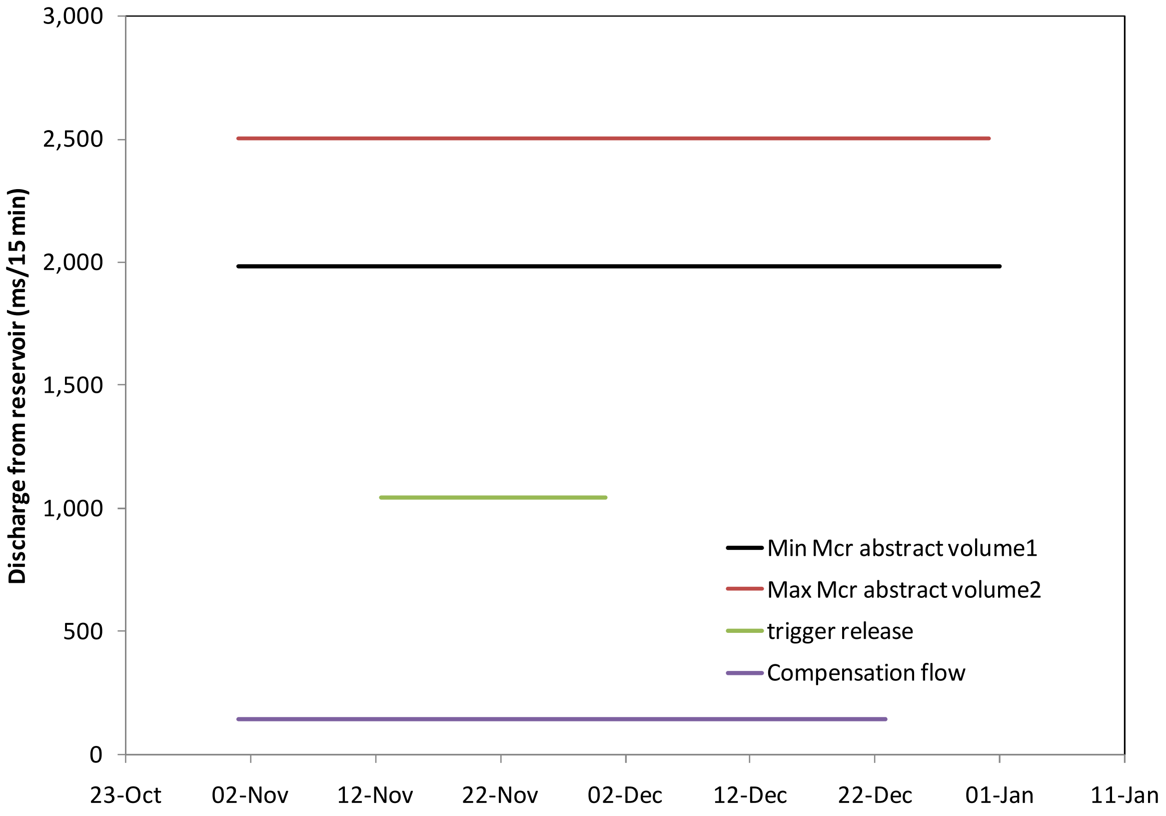

Figure 3: Managed releases from the reservoir Nov-Dec 2015.

The model has been constructed using a key source of information which is the reservoir water level data collected by UU and the EA using instruments located near the weir above the spillway. These instruments measure and record the depth of water above the instrument automatically every 15 minutes. The EA data provided cover the whole of November and December 2015 while the UU data provided cover 4th-6th December.

The UU data were provided as a height of water over the discharge weir. The highest value in this dataset was 1.56 m recorded on 5/12/15 at 18:30 hrs. These data have been converted to mAOD using a weir level of 179.27 mAOD provided by UU (CRM Rainwater Drainage Consultancy Ltd). This gives a peak reservoir water level during Storm Desmond of 180.83 mAOD and a peak rate of discharge from the reservoir of 104 cumecs using the new CRM stage-discharge relationship.

The EA data have been provided both as a water level above a local datum and as a level in terms of metres above ordnance datum (mAOD). The highest water level reading provided by the EA is 180.56 mAOD recorded on 5/12/15 at 18:00 hrs. This value is 0.27 m less than the highest value recorded by UU. However, some of the EA data have been created by the EA using a spline interpolation to infill a gap in the data when the instrument failed during the peak of the storm. The UU data have not been edited. Therefore, the UU data have been used to infill the gap in the EA data. The resulting reservoir water level time-series for December 2015 is shown in Figure 4.

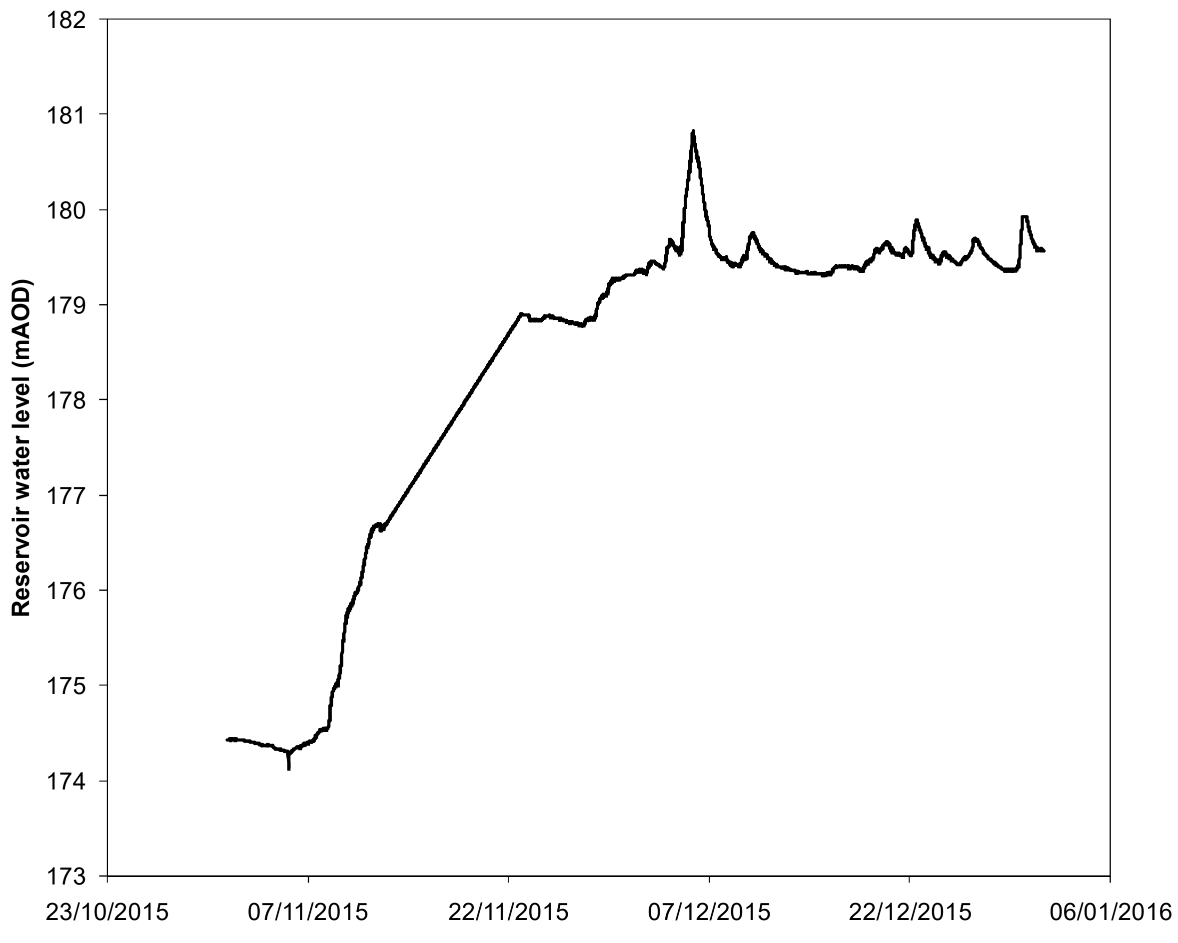

Figure 4: Thirlmere reservoir water levels between 3rd and 11th December 2015.

By subtracting the weir level (179.27 mAOD) from the data, they can be converted to depths over the weir. These are shown in Figure 5. In this figure a value of zero is where the water level is the same as the top of the weir, negative values are when the water level was below the top of the weir and positive values when it was above the top of the weir. In early November, the water level was 5 m below the weir. During November, there was a considerable volume of rain and this gradually re-filled the reservoir until it was full on 30th November. The peak depth of water over the weir was 1.56 m and occurred on 5th December at 18:30 during Storm Desmond.

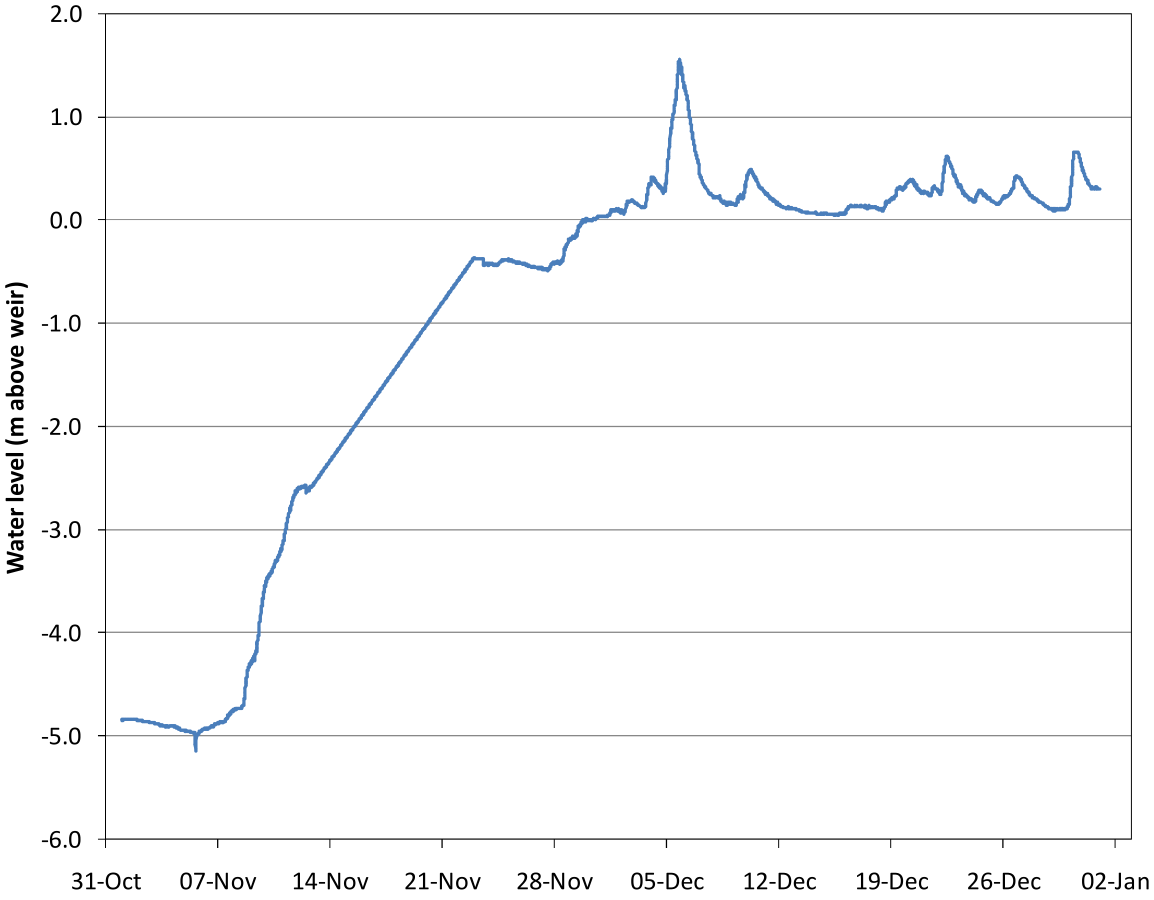

Figure 5: Measured water depths over Thirlmere weir 1st November to 31st December 2015.

CRM Rainwater Drainage Consultancy Ltd have provided a new stage-discharge relationship for the weir using a physical model and this has been used to calculate the volumes of water discharge over the weir during December 2015. This is illustrated by Figure 6 which shows the discharge from the reservoir via the overflow weir for November and December 2015. There was no overflow during almost the whole of November as the water level was below the level of the weir. Discharge commenced on 30th November at 11:45. It peaked five days later on 5th December 2015 at 18:30 during 38 hours of record rainfall. The peak discharge calculated using the new stage-discharge relationship was 104 cumecs. A peak flow of 104 cumecs is approximately 30% of the peak discharge through Low Briery during Storm Desmond (343 cumecs).

The total discharge over the weir during the Storm Desmond hydrograph (4/12/15 17:00 to 9/12/15 10:00 hrs) was around 13,150 mega litres (ML) or 13.15 billion litres (13,150,000,000 litres) or 13.15 million m^3 (13,150,000 m^3). It is interesting to compare this volume with the volume of rainfall. The total rainfall depth measured at Dale Head for a period of 38 hours was 403 mm. Applied to a catchment area of 34.13 km^2 (i.e. excluding the Mill Beck catchment) this is equivalent to a volume of 13.8 million m^3. The two figures of 13.8 million m^3 rainfall and 13.15 million m^3 runoff are very close and suggest a runoff coefficient of 0.95 although it must be recognised that measuring rainfall at only one gauge does not give a very reliable measure of rainfall across the whole catchment. There are also other uncertainties such as evapotranspiration and changes in soil water storage although given the substantial antecedent rainfall and the time of year, these are likely to be small to negligible.

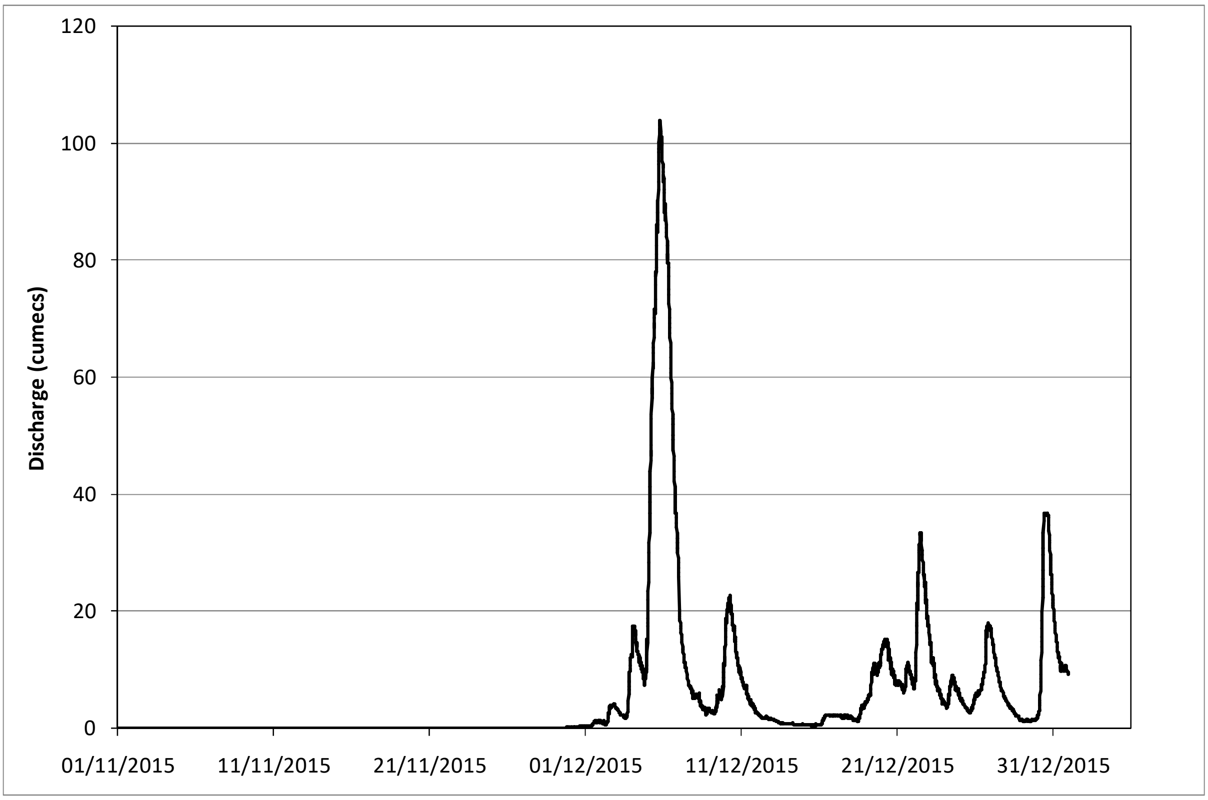

Figure 6: Discharge over the Thirlmere weir 1st November to 31st December 2015.

At a meeting in June 2017, UU stated that the tunnel (into which water discharges after passing over the weir) starts to 'choke' at 90 cumecs so that when the water is 0.9 m from the top of the wave wall, discharge is 101 cumecs and when it is 0.3 m from the top of the wall the discharge is 116.5 cumecs. UU water level data show the water level reached 0.91 m from the top of the wave wall during Storm Desmond and therefore the discharge could have been limited to around 101 cumecs. This figure of 101 cumecs compares with the current figure of 104 cumecs. If discharge is theoretically limited to 101 cumecs and the discharge was 104 cumecs, this suggests that the spillway arrangement was at or very close to its limit. This is a situation which should not occur as reservoir spillways are designed to be able to pass flows up to around the probable maximum flood (PMF) flow which is regarded as a 1 in 10,000-year event. A recent report by Jacobs for UU stated that 'For the observed peak reservoir outflow of 101.9 cumecs during Storm Desmond this yields a return period of 1 in 11,200 years' (Jacobs, 2017).

Abstraction

United Utilities takes water from the reservoir to supply its customers. It also discharges water into St John's Beck to maintain an agreed flow rate when the reservoir is not overflowing (compensation flow). These losses from the reservoir are included in the model at 240 million litres per day (Ml/d) for abstractions and 13.6 Ml/d (0.16 cumecs) for compensation flow (see Figure 3).

Reservoir Volumes

Because the model is a water balance model and includes changes in reservoir water storage, it is necessary to calculate the volume of the reservoir and to recalculate it as water enters via runoff and leaves via discharge. The volume has been calculated from:

$$V = 676.8\ (D+7.76)^2 \qquad (2)$$

Where V is the volume of water in the reservoir and D is the depth of water in the reservoir. D is the measured depth of water above the EA level gauge plus 7.76 m. This method for reservoir volume calculation was developed by comparing reservoir water level data with UU reservoir volume data for November 2015.

Model Optimisation

Because there is uncertainty in model input parameters, particularly runoff input to the reservoir, reservoir surface area at different levels and discharge from the reservoir, it is necessary to investigate the effects of different parameter values on the performance of the model. For example, it is not known exactly how much rainfall fell on the Thirlmere catchment during the modelled period (November and December 2015) and how much of this entered the reservoir. Therefore, different values of runoff coefficient have been used to see how this affects the model. Similarly, as the exact timing and scale of UU discharges is also not known, these have also been modified to see how they affect the model. However, UU discharges are known to be relatively small compared with the very large runoff input volumes and so only play a very small part in the model.

Figure 7 shows the cumulative inflows, outflows, releases and change in storage for November and December 2015. Effectively, this means that discharges to the aqueduct are discontinued in the model around the start of Storm Desmond, trigger releases started in mid' November and stopped at the end of November. The agreement between the modelled cumulative inflow and measured outflow gives confidence in the model.

Because inflows should be equal to outflows plus any change in storage, the top two lines, cumulative inflow (green) and cumulative outflow, releases and change in storage (pale blue) should match. This has been achieved by modifying the values for the runoff coefficients and releases (UU abstractions). The values of the runoff coefficient that gives the best match between inflows and combined outflows plus change in storage are:

1/11/15 to 4/12/15	75%
4/12/15 to 16/12/15	85%
16/12/15 to 31/12/15	75%

These runoff values change in response to changes in vegetation and soil water storage. That is, when the vegetation storage and soil water storage are at full capacity and no more water can be stored, any new rainfall will all become runoff, i.e. 100% runoff. The values used above can be regarded as a reasonable representation of increasing catchment wetness during November and December 2015 with the series of storms increasing catchment wetness and culminating in the highest percentage runoff during Desmond.

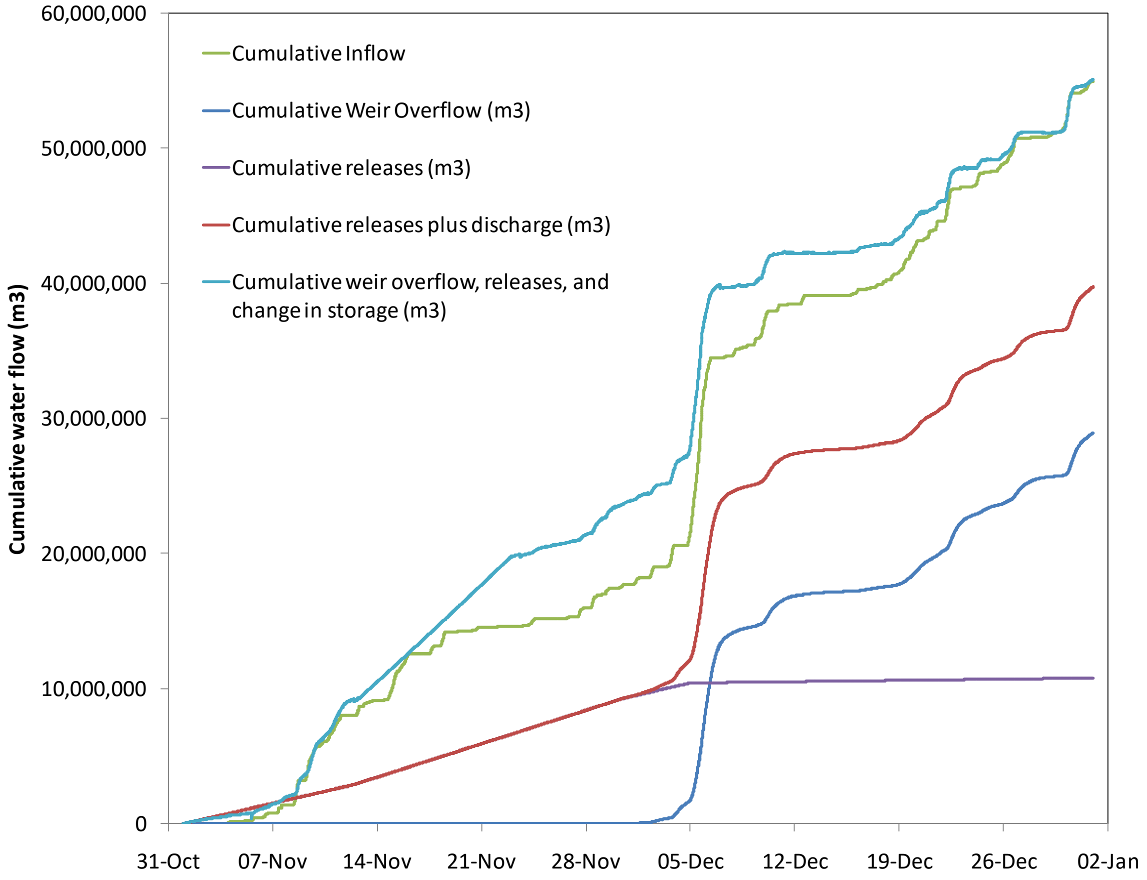

Figure 7: Reservoir cumulative inflows, outflows, releases and change in storage, November-December 2015.

The pattern of releases that gives the best fit is:

Dates	To Thirlmere Aqueduct (Ml/d)	Comments
All dates	240	Standard abstractions.

Dates	'Trigger' Releases (Ml/d)	Comments
1/11/15 to 12/11/15	0	Reservoir level below trigger level so releases not required.
13/11/15 to 30/11/15	100	Reservoir at or above trigger level so releases required.
30/11/15 to 31/12/15	0	Reservoir overflowing. Trigger releases not allowed when reservoir overflowing.

Dates	Compensation Flow (Ml/d)	Comments
All dates	13.6	Compensation flow at all times.

Once the model was established with reasonably representative parameter values giving a good balance between inflows, outflows and change in storage, it was developed so that it could be used to calculate the effects of managed releases to create storm water storage space. This was achieved using the following method:

1. Calculate change in reservoir water level based on volume of inflow from runoff and initial reservoir surface area calculated from initial measured water level.
2. Add change in water level to initial reservoir water level.
3. Convert abstraction volume to water depth using reservoir surface area. Subtract abstraction depth from reservoir level.
4. If the resulting reservoir water level is higher than the weir level then calculate discharge over weir.
5. Convert discharge volume to water depth using reservoir surface area.
6. Subtract resulting water depth from reservoir water level to give new water level.

This is repeated for each of the subsequent 15-minute timesteps for November and December with the only exception that in step 2, the change in water level from step 1 is added to the reservoir water level from step 6 rather than the initial water level.

In this process, the critical component is the reservoir surface area as this is used to convert the volumes of inflow (catchment runoff), outflow (discharge over weir), other outputs (abstractions, trigger releases and compensation flow) and changes in storage to depths. There is a complex relationship between reservoir water area and level such that as the reservoir level gets higher, the surface area increases in a complex way owing to the shape of the land around the reservoir.

Table 1 shows estimated reservoir lengths, widths and calculated areas. Lengths and widths were estimated from a map of the reservoir.

Table 1: Estimated reservoir lengths and widths and calculated surface areas.

Length (m)	Width (m)	Area (m^2)
5330	500	2,665,000
5366	513	2,752,758
5402	526	2,841,452
5438	539	2,931,082
5474	552	3,021,648
5510	565	3,113,150
5546	578	3,205,588
5582	591	3,298,962
5618	604	3,393,272
5654	617	3,488,518
5690	630	3,584,700
5726	643	3,681,818
5762	656	3,779,872
5798	669	3,878,862
5834	682	3,978,788

5870	695	4,079,650
5880	700	4,116,000
6010	775	4,657,750
6140	850	5,219,000
6270	925	5,799,750
6400	1000	6,400,000

Figure 8 shows the relationship between reservoir water level and surface area. A line has been fitted to these data and the equation for the line has been used to calculate the reservoir surface area for any given depth. In the model, this equation is used to convert water inflows and outflows to increments in water depth. This is done for each 15-minute timestep.

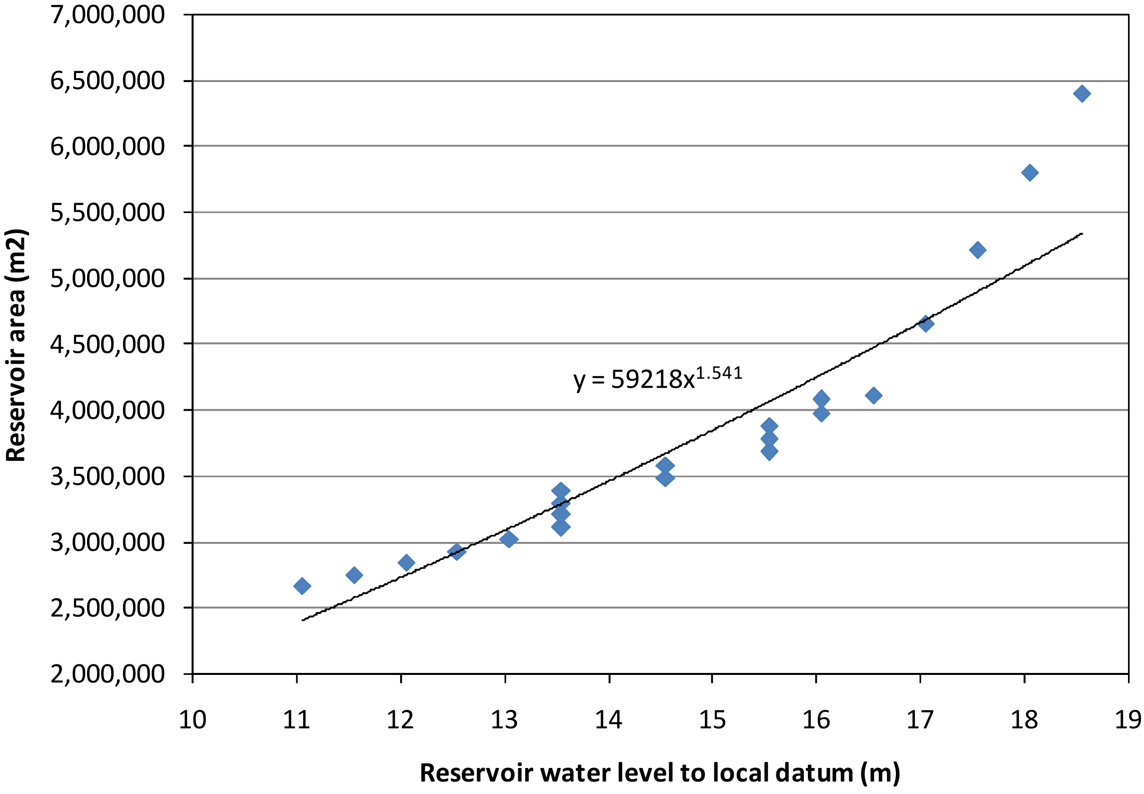

Figure 8: Relationship between reservoir water level and surface area.

The resulting model is shown in Figure 9 and Figure 10. Figure 9 shows the measured and calculated reservoir water levels for November and December 2015. This shows a reasonable agreement between the measured and calculated water levels which suggests that the model is a good simulation of the actual water balance. Figure 10 shows the measured and modelled discharge from the reservoir for November and December 2015. Note that discharge did not start until early December. The fit between the measured and modelled values is not perfect and this is thought to be due to the approximate relationship between reservoir water level and surface area. This is regarded as sufficient for the purposes of this model.

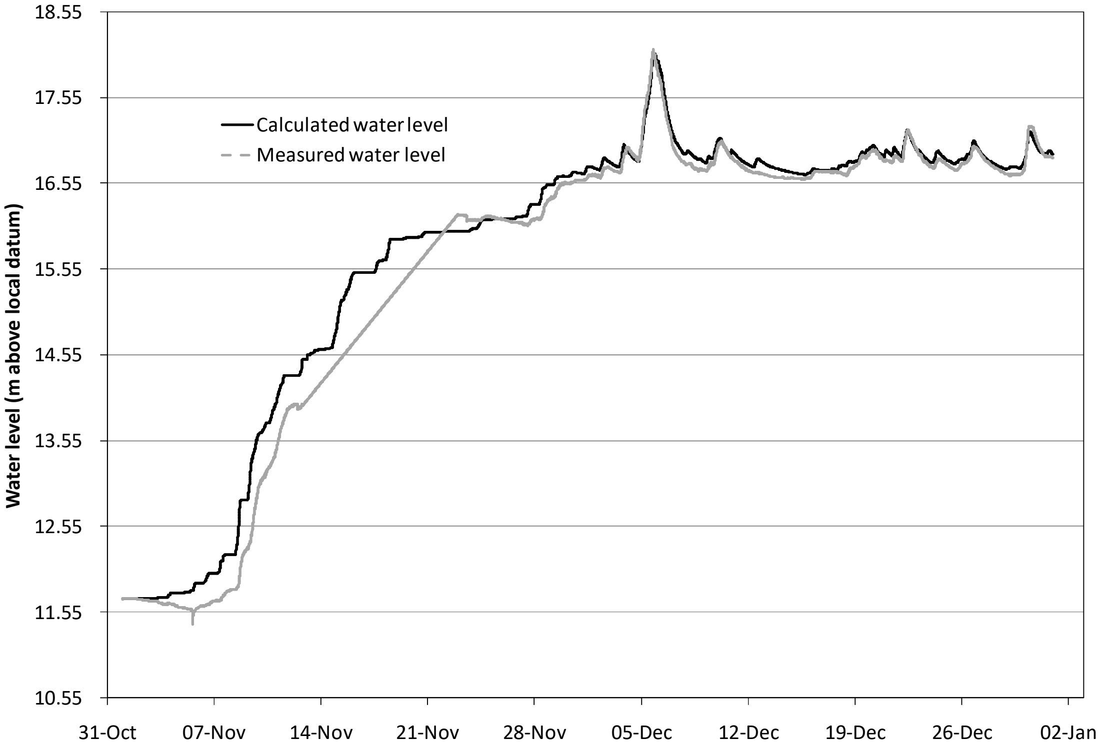

Figure 9: Measured and calculated reservoir water levels in November and December 2015.

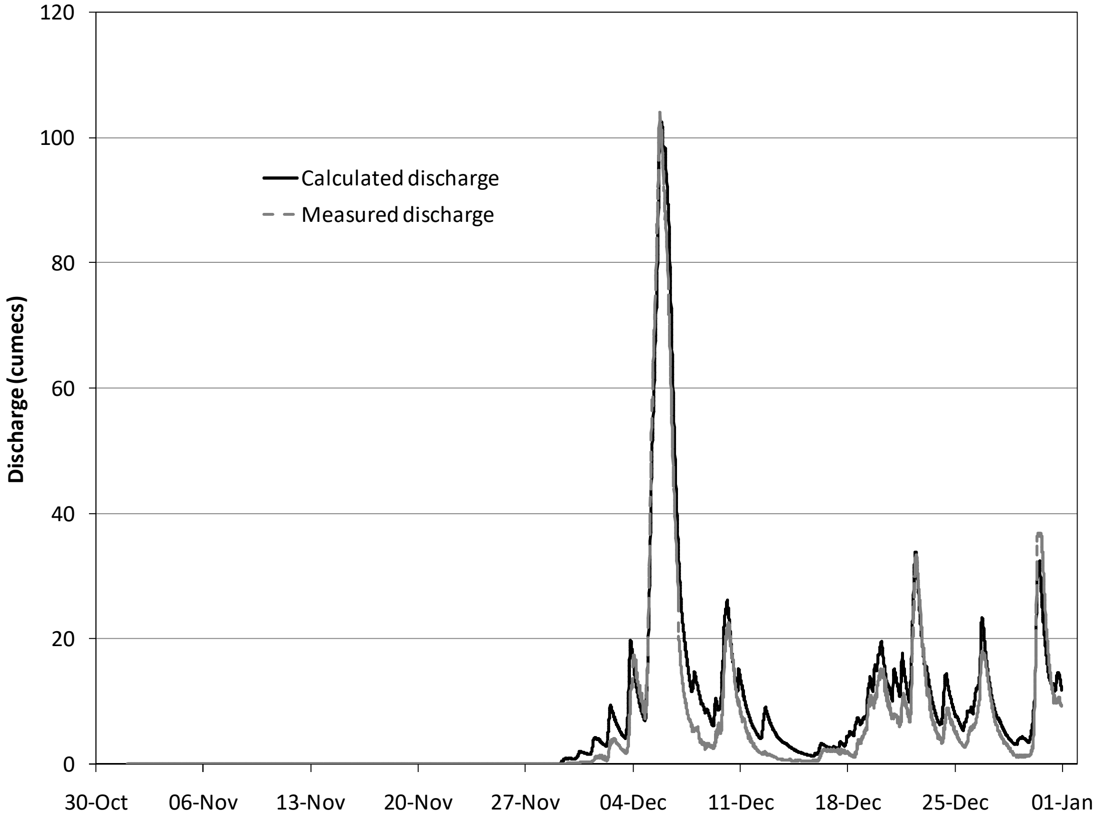

Figure 10: Measured and calculated reservoir discharges for November and December 2015.

Figure 11 shows the measured and calculated water levels for December 2015. This shows that there is a reasonable agreement between measured and modelled reservoir discharge for December 2015. The model is particularly good at matching measured peak rates of discharge.

Figure 12 shows the measured and calculated discharges for December 2015. The agreement between the model-calculated values and the measured values is regarded as reasonable and particularly good for peak reservoir water levels.

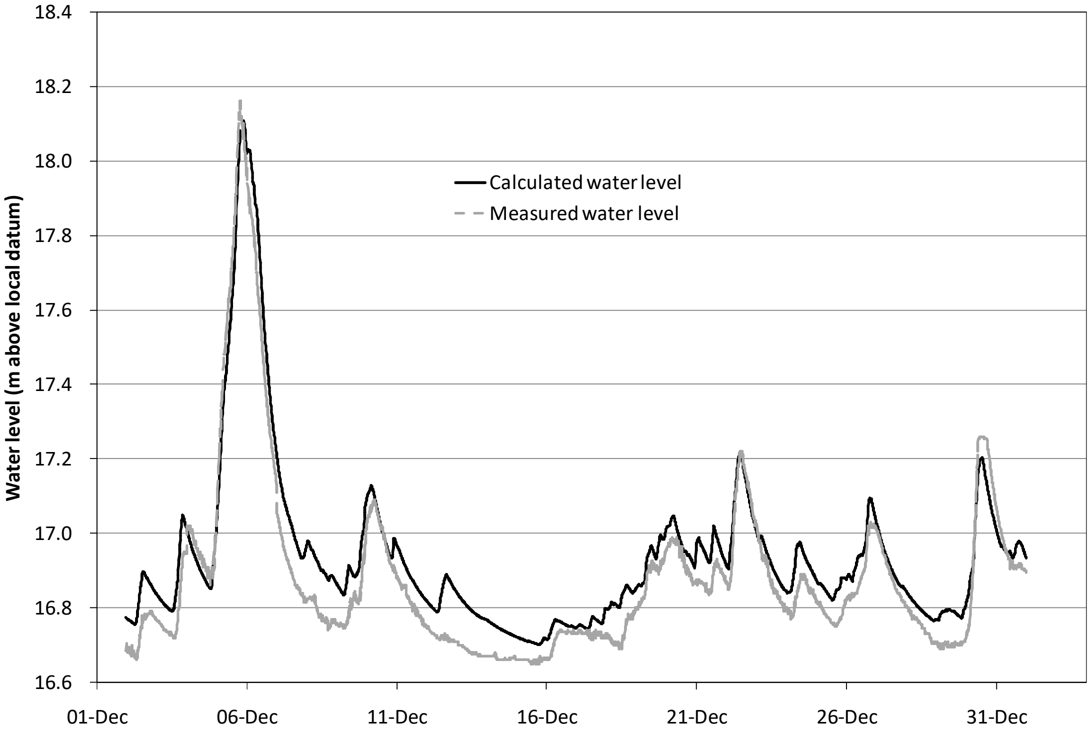

Figure 11: Measured and calculated reservoir water levels for December 2015.

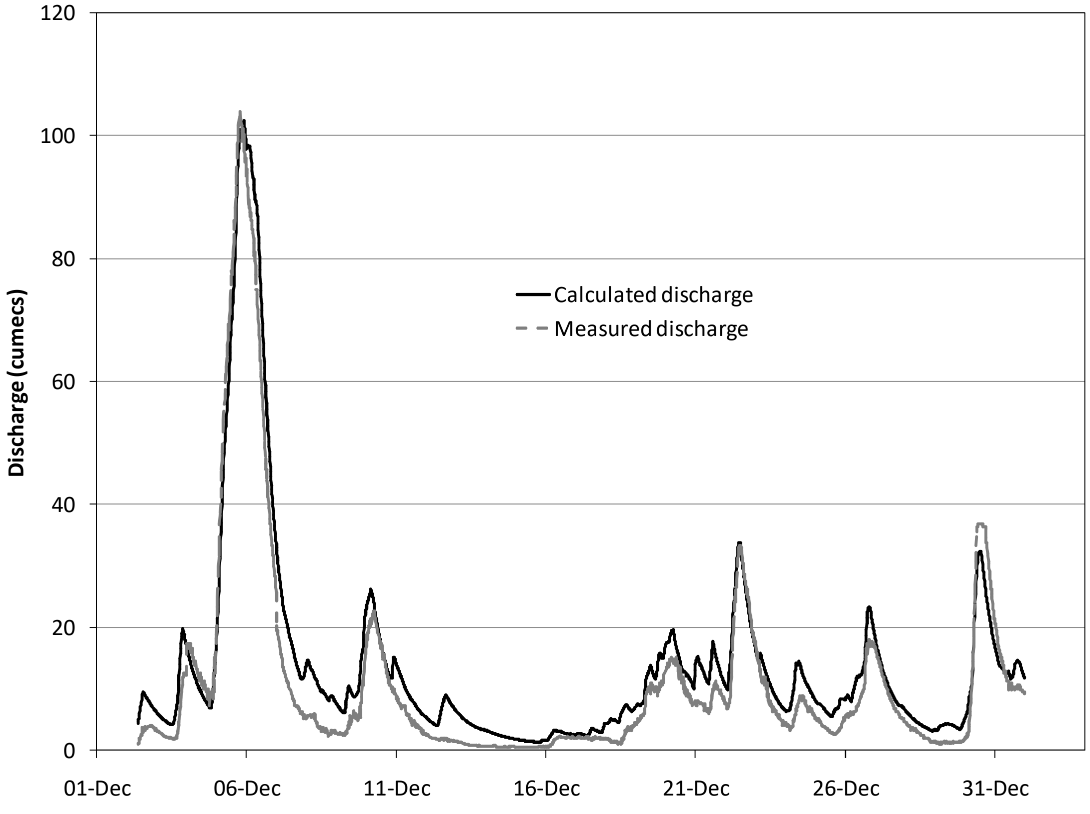

Figure 12: Measured and calculated reservoir discharges for December 2015.

Results

The main reason for developing the model is to use it as a tool to identify the pre-storm reservoir release rates required to create enough storm water storage space to make a significant difference to flood risks downstream to Keswick. The model has been used to predict what would happen to the outflow from the reservoir if different release rates were used to create storm water storage space. Using the model in this way allows the optimum release rate to be identified.

In recent discussions with the EA and UU, their currently preferred release rate is 900 Ml/d. This is going to require an existing reservoir valve or valves to be upgraded and it has been proposed to do this as part of the ongoing construction of a new pipeline linking Thirlmere with West Cumbria.

Figure 13 shows the 15-minute rainfall measured at Dale Head between 29th November and 7th December 2015. This shows that in the period 29th November 00:00 hrs to 4th December 18:45 hrs (inclusive) prior to Storm Desmond, there was a relatively small amount of rain at Dale Head (108.4 mm). It is envisaged that water could have been released from the reservoir during this period to prevent the reservoir from filling prior to Storm Desmond on 5th / 6th December and maintain some storage capacity ahead of the storm.

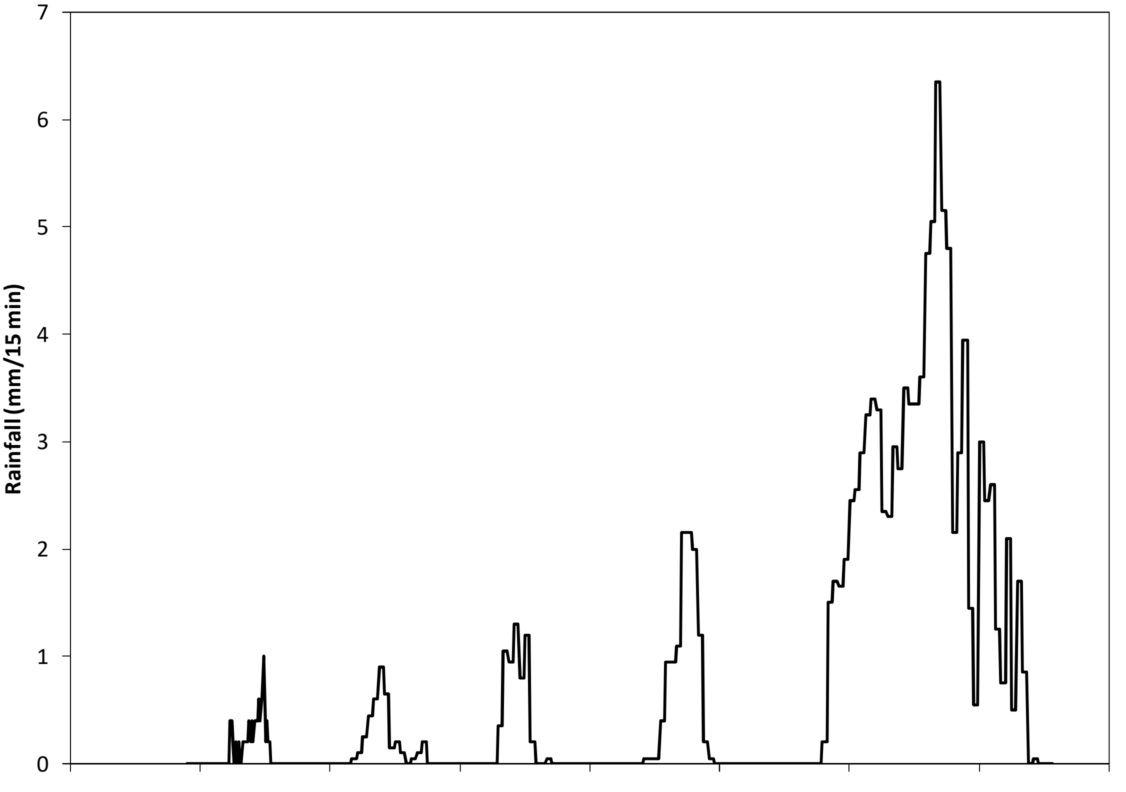

Figure 13: 15-minute rainfall measured at Dale Head between 29th November and 7th December 2015.

It has been recognised that there is a limit to how much water can be released into St John's Beck so that flooding and environmental damage is not caused. Figure 14 shows the discharge from Thirlmere during Storm Desmond between 29th November and 10th December 2015 using UU reservoir level data and the reservoir stage-discharge outflow relationship identified by CRM Rainwater Drainage Consultancy Ltd [2017]). The new stage-discharge relationship provided by CRM Rainwater Discharge Consultancy Ltd is regarded as more accurate at high flows that the EA gauge on St John's Beck. Most river flow gauges are highly inaccurate during flood events. Therefore the calculated discharge from the reservoir during November and December 2015 is used as a record of flow in St John's Beck rather than the data from the EA gauging station.

The flow in St John's Beck during the period prior to Storm Desmond (i.e. before 5th December) was around 2-18 cumecs. There were no reports of flooding in St John's Vale during this period. This illustrates how there can be periods prior to large storms or between storms when river flow is relatively normal providing an opportunity for pre-storm reservoir discharges to reduce levels and create storm water storage in the reservoir.

National River Flow Archive (NRFA) information shows that a flow of 20 cumecs has been equalled or exceeded in 22 years of the 41-year record. There have been eight years in the record when a flow of 30 cumecs was equalled or exceeded and four years when 40 cumecs was equalled or exceeded in the 41-year record (Jan' 1995, Jan' 2005, Nov' 2009 and Dec' 2015). This demonstrates how St John's Vale is familiar with high river flows and their damaging effects although it is recognised that UU do not wish to cause such effects in any actions to re-naturalise the river flow regime or to maintain target reservoir levels.

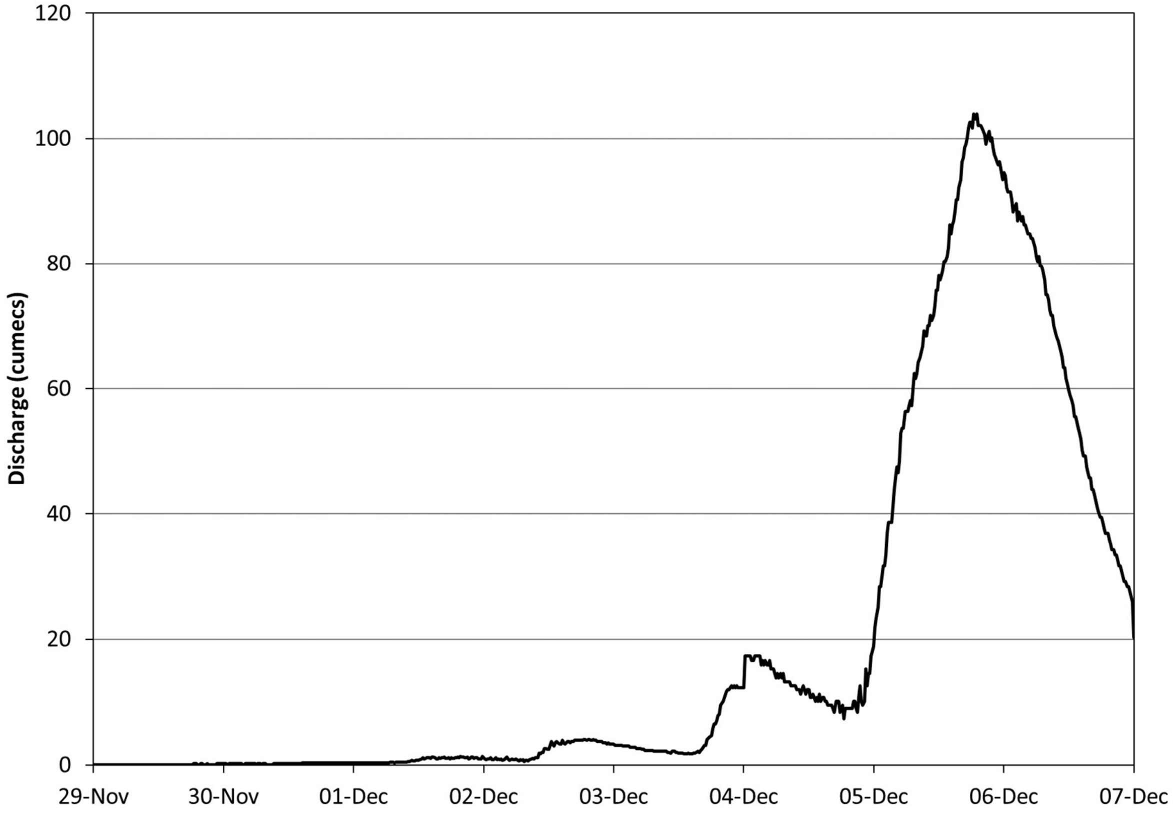

Figure 14: Discharge to St John's Beck from Thirlmere between 29th November and 7th December 2015.

Figure 15 shows a comparison of measured discharge in December 2015 with predicted discharge if there had been six days of water release at 900 Ml/d before Storm Desmond. The six-day period starts on 28th November at 09:00 hrs and ends on 4th December at 09:00 hrs. The model predicts that the peak discharge would be reduced from 104 cumecs to 90 cumecs, a reduction of 14 cumecs. As the peak discharge in Keswick during Storm Desmond was around 342 cumecs and the existing defences can withstand a peak around 240-260 cumecs, it is necessary to reduce the peak by approximately 82-102 cumecs. Therefore, a reduction of 14 cumecs is not sufficient.

It is difficult to predict the effect of flow reductions at Thirlmere on the flows in Keswick. During Storm Desmond, the peak flow at Low Briery was around 343 cumecs (value calculated by EA using hydraulic modelling). If the peak discharge from Thirlmere was 104 cumecs, the runoff generated by the rest of the catchment, particularly the Glendermackin and Glenderaterra catchments, must be responsible for the remaining 239 cumecs. There is only one river flow gauge in this 'remaining catchment' and that is at Threlkeld and only measures runoff from the Glendermackin sub-catchment.

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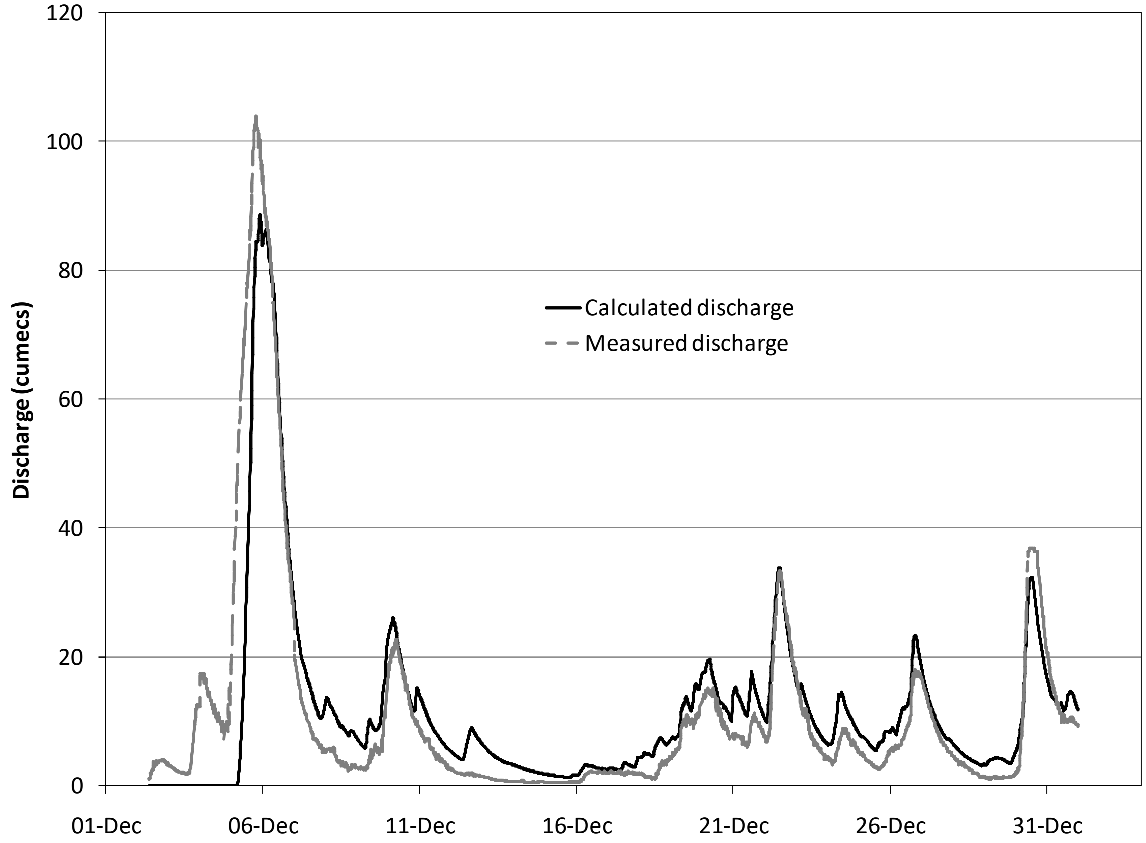

Figure 15: Comparison of measured discharge in December 2015 with predicted discharge if there had been six days of water release at 900 Ml/d before Storm Desmond.

Modelling carried out by Aecom for the EA (Aecom, 2017) has identified a figure of 145 cumecs for the 0.1% AEP flow (this can be adopted as the best available estimate for the peak flow through the Thirlmere gauge during Storm Desmond). If this is combined with a figure of 104 cumecs from Thirlmere, this gives a total peak of 249 cumecs from Thirlmere and the Glenderamackin which is 72% of the peak at Low Briery. The combined area of the Thirlmere and Glenderamackin catchments is 73% of the area of the catchment to Low Briery. The close agreement of these two percentages gives some confidence in the 145 cumecs figure for Threlkeld. However, as the rainfall totals were higher in the Thirlmere catchment than in the Threlkeld catchment, it would be expected that the contribution from the former would be greater than that from the letter. Therefore, it is still possible that either the Threlkeld peak was less than 145 cumecs or the Thirlmere peak was greater than 104 cumecs, or both.

Aecom (2017) also mentions a peak discharge of 200 cumecs for Threlkeld based on the revitalised flood hydrograph method (ReFH2). However, this would be 58.3% of the peak at Low Briery which is unrealistic when the Glenderamackin catchment to Threlkeld is 44.3% of the Low Briery catchment. For the Glenderamackin catchment to deliver a percentage of the peak flow greater than that percentage area, the rainfall would have to have been proportionally greater in the Glenderamackin catchment than in the Thirlmere catchment and rainfall data show this was not the case.

In terms of the effectiveness of stopping storm discharge from Thirlmere, it is simpler and more effective to remember that preventing the 104 cumecs discharge from Thirlmere would reduce the peak flow at Low Briery to 239 cumecs (343-104) which the defences in Keswick can just about cope with. The peak flow figures from UU for Thirlmere (104 cumecs), from the EA for Threlkeld (145 cumecs) and from the EA for Low Briery (343 cumecs) show that preventing all discharge from Thirlmere during Storm Desmond could have prevented flooding in Keswick during Storm Desmond.

If the flood in Keswick (~343 cumecs) was made up of 30% from Thirlmere (104 cumecs) and 70% from the rest of the Greta catchment (Glenderaterra, Glenderamackin, etc.) (239 cumecs), the peak flow at Thirlmere would have to have be at or very close to zero cumecs to prevent the Storm Desmond flood. Figure 15 shows that the discharge of 900 Ml/d for 6 days prior to Storm Desmond would have reduced the peak discharge to 90 cumecs giving a total flow through Keswick of around 323 cumecs which is much higher than the defendable flow of around 240 cumecs. Therefore, a discharge of 900 Ml/d for 6 days prior to Storm Desmond would not have prevented flooding in Keswick. A release rate of 900 Ml/d over a period of six days can only lower the reservoir by approximately 1.6 m assuming no inflow during this six-day period.

By varying the 6-day, pre-storm discharge rate in the model, it is possible to identify the release rate required to achieve a peak Thirlmere discharge of zero cumecs. Figure 16 shows the calculated discharge resulting from a pre-storm release rate of 2500 Ml/d (28.9 cumecs). This is the release rate identified using the model which would have been required to prevent flooding in Keswick during Storm Desmond. This 6-day release rate results in a reservoir water level 3.64 m below the weir level at the start of Storm Desmond (4th December 2015 at 19:00 hrs). This is substantially greater than the 1.6 m provided by a release rate of 900 Ml/d.

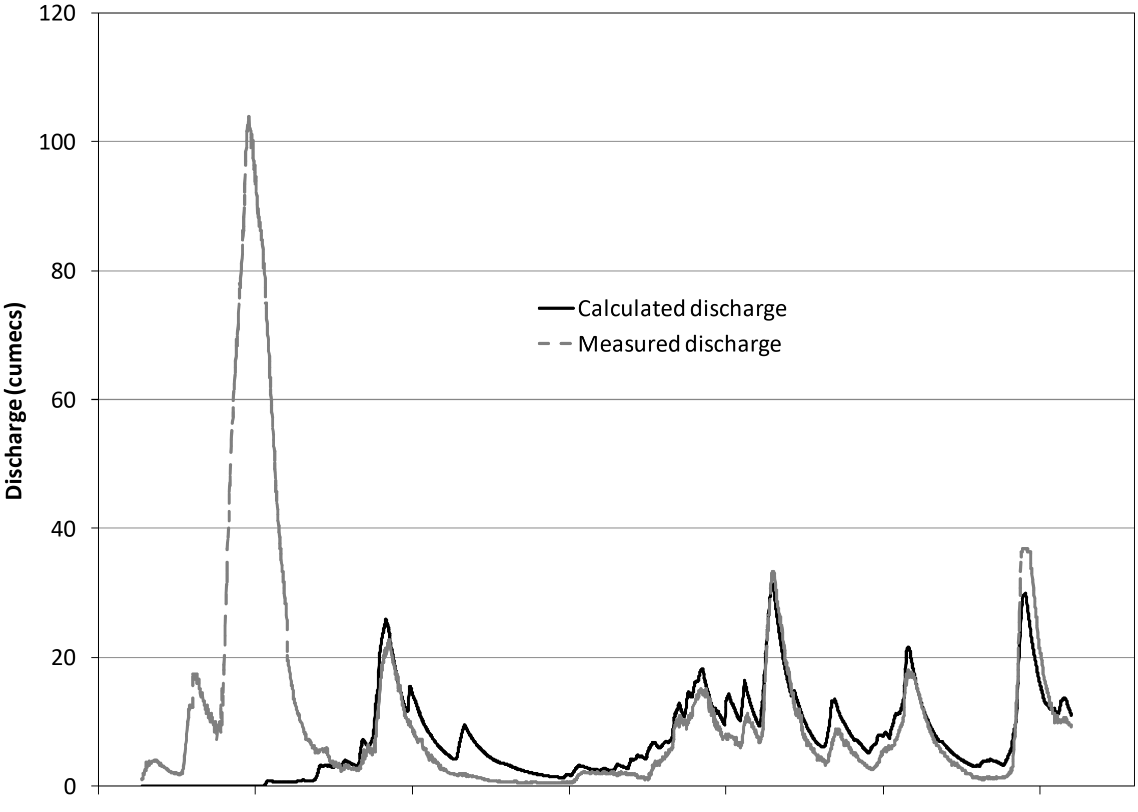

Figure 16: Comparison of measured discharge in December 2015 with predicted discharge if there had been six days of water release at 2500 Ml/d before Storm Desmond.

In achieving this substantial reduction in the peak flow between Thirlmere and Keswick, flooding would also have been reduced along St John's Beck, at New Bridge and along the River Greta between New Bridge and Keswick. It is highly likely that bridges along the railway footpath would not have been lost. Because of the lower flow rates, the erosive power of the river would have been reduced and therefore damage to the footpath would have been substantially less. The problematic mobilisation and deposition of boulders would also have been much reduced. It is also possible that the river bank erosion near Low Briery would have been less and it is therefore probable that the Low Briery landslip would not have been reactivated or the toe of the slope below the A66 removed. It is worth remembering that if the peak flow at Low Briery had been reduced to 239 cumecs during Storm Desmond, it would have been less than that in the next worst flood (the 2005 event) when the peak was 242 cumecs (National River Flow Archive, 2018). The railway path and its bridges were not damaged by that event.

A pre-storm release rate of 2500 Ml/d is equivalent to a constant discharge into St John's Beck of 28.9 cumecs which is above the reasonably common annual maximum figure of 20 cumecs (equalled or exceeded in 21 years of the 41-year record). River flow modelling by APEM (2017) showed that a total river flow of 605 Ml/d (7 cumecs) would not flood land adjacent to St John's Beck. APEM (2017) also concluded that a flow of 864 Ml/d to 950 Ml/d (10 or 11 cumecs) might be appropriate but would lead to small amounts of localised inundation. APEM (2017) identified that a flow of around 1900 Ml/d (22 cumecs) would cause 'extensive inundation of riparian land'. This is lower than the required release rate of 2500 Ml/d (28.9 cumecs) identified here. However, flows of 22 cumecs identified by APEM (2017) or 28.9 cumecs identified here are much less than the peak flows which occurred during the floods of 1995 (46 cumecs), 2005 (54 cumecs[2]), 2009 (68 cumecs[2]) and 2015 (104 cumecs). It is possible that while peak flows of 20-30 cumecs may cause some inundation of farmland, they would not cause the damaging erosion and deposition caused by flows of 46-104 cumecs.

It has been suggested that the idea of releasing water from the reservoir in reaction to a 6-day storm forecast could be regarded as a gamble based on the reliability of storm forecasting. An alternative approach could be to maintain the current 'trigger level' approach but with the use of improved valves to make it more likely that these trigger levels can be maintained particularly during periods of excessive rainfall. This approach has been explored in the model by partitioning the period between 1st November 2015 and 5th December 2015 (start of Storm Desmond) into five week-long periods where the release rate can be specified for each period.

Figure 17 shows the model-calculated reservoir discharge and water level based on a discharge of 100-1200 Ml/d (1.2-13.9 cumecs) for November and the first week of December. The details of reservoir releases required to maintain levels 3 m below full prior to Storm Desmond are shown below:

- 31st October – 7th November: 400 Ml/d (4.6 cumecs)
- 7th November – 14th November: 400 Ml/d (4.6 cumecs)
- 14th November – 21st November: 500 Ml/d (5.8 cumecs)
- 21st November – 28th November: 100 Ml/d (1.2 cumecs)
- 28th November – 5th December: 1200 Ml/d (13.9 cumecs)

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[2] Calculated using reservoir level data and CRM stage-discharge relationship.

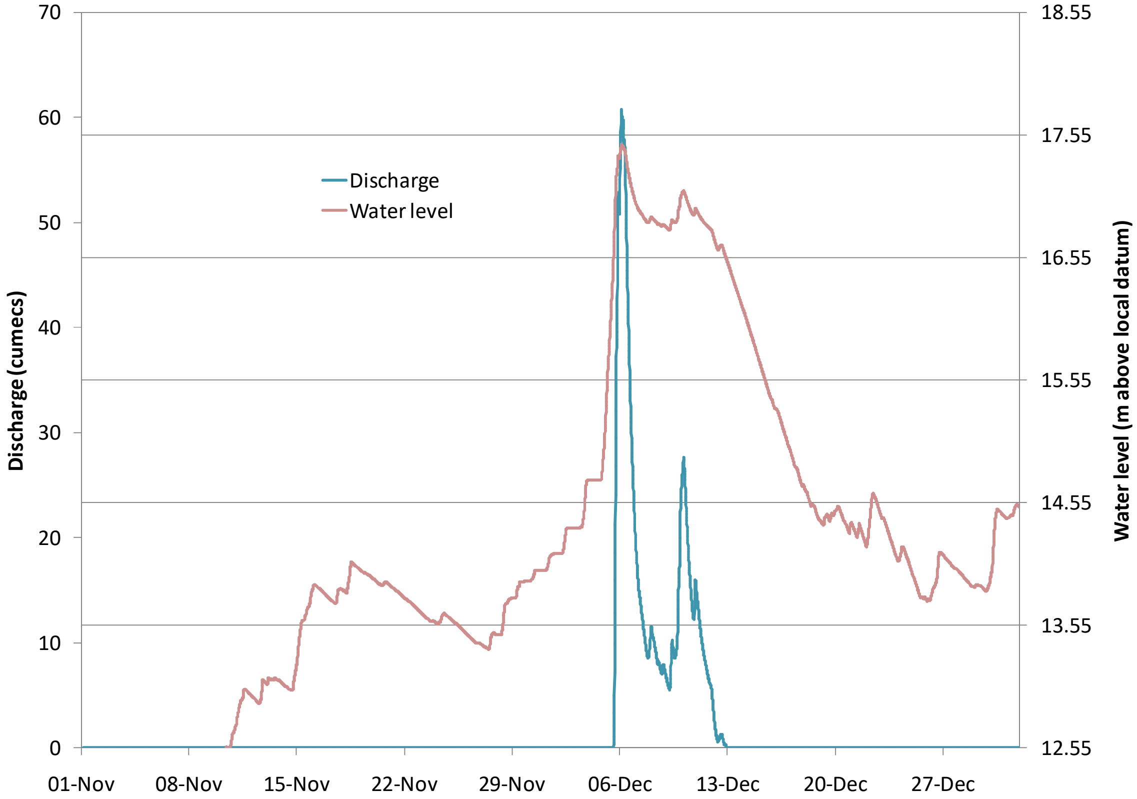

Figure 17: Model calculated reservoir discharge and water level based on a discharge of 400 Ml/d (4.6 cumecs) for the first four weeks of November.

This shows that by taking the approach maintaining effective target levels through the winter period, the target Storm Desmond discharge of 0 cumecs could have been achieved. This would have prevented flooding downstream in Keswick and greatly reduced erosion and deposition to non-damaging levels. The identified release rates of 1.2-13.9 cumecs are also less than or close to the rate of 10-11 cumecs identified by APEM (2017) as ‘appropriate’.

Conclusions

The water balance of Thirlmere reservoir can be simulated using data for rainfall and reservoir water levels as inputs to the model. By using 15-minute rainfall and water level data for November and December 2015, it has been possible to develop a simple water balance model. This model has been calibrated and tested by comparing results against measurements of water level and discharge. The tested model has been used to calculate the rate of water release from Thirlmere required to create enough storage prior to Storm Desmond in order to prevent fluvial flooding downstream to Keswick.

It is recognised that there is already a scheme in place at the reservoir to create space for storm water. This scheme has identified ‘trigger levels’ which are levels which when reached by releasing water, releases can be stopped. However, this scheme has been found to be ineffective because the rates of release are so low that it can take far too long to create any storage. The reason the current release rate capability is too low is that the existing valves do not have the capacity to release water at a fast-enough rate. The current inadequate release rate is 100 to 140 Ml/d. The main aim of the modelling work reported here is to identify what rate is required to make the scheme effective.

By using the model to predict the outflow from the reservoir during Storm Desmond if the reservoir had been lowered over a period of six days before the storm, it is concluded that the six-day, pre-storm release rate necessary to prevent flooding in Keswick during the storm is 2500 Ml/d. This release rate is equivalent to a river flow rate of 28.9 cumecs.

If a six-day storm forecast is not relied on but instead release rates are controlled to maintain a target level of 3 m below full during the flood season, the release rates could be reduced to between 100 Ml/d and 1200 Ml/d (1.2-13.9 cumecs). Application of these release rates to the five-week period prior to Storm Desmond has shown that this would have been able to prevent the Storm Desmond flooding in Keswick. This has emphasised that, at times, it will be necessary to use release rates greater than the 600-900 Ml/d identified by APEM (2017). Without this capability, it will take too long to regain control of the reservoir after substantial rainfall events.

It is also worth noting that on 29th November 2015 at 09:00 (theoretical start of water releases prior to Storm Desmond) the reservoir level measured at that time was 16.15 m. This means that the reservoir already had 0.4 m of storage capacity. If at the start of the 6-day period of water releases the reservoir was already full to the weir or greater, then a release rate greater than 1200 Ml/d would be required. This release rate could also be challenged by rainfall occurring during the six days before the forecast flooding event. Therefore, to be prudent, consideration should be given to the installation of release valves capable of 2000-2500 Ml/d.

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