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Scoping the risk assessment process for small reservoirs

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Scoping the risk assessment process for small reservoirs

R&D Technical Report FD2640/TR1

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Statement of use
The aim of this study was to scope the risk assessment process for reservoirs with a capacity of less than 10,000m³. The risk assessments will be used to inform decisions on whether the minimum reservoir volume to require registration under the Flood and Water Management Act should be adjusted. They may also be required as part of the Environment Agency's responsibilities under the Flood Risk Regulations 2009.

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Executive summary

The aim of this project is to scope methodologies that will allow an assessment to be made of the risk posed by raised reservoirs with a capacity of less than 10,000m^3. The methodology will be used for two different purposes.

The first is to inform decisions arising from the Flood and Water Management Act. The Act enables reservoirs of 10,000m^3 or larger to be brought within reservoir safety legislation (the Reservoirs Act 1975 currently only covers reservoirs with a capacity greater than 25,000m^3). This project has scoped risk-based methodologies to provide an evidence base for this minimum reservoir volume. This is because the Act contains powers for the 10,000 m^3 figure to be adjusted upwards or downwards according to evidence. Evidence as to whether it needs to be adjusted upwards would be derived from the registration and risk-assessment process. However, the Act provides no process by which evidence can be gathered as to whether the figure is too high. For the purpose of determining the appropriate minimum reservoir volume to be included within reservoir safety legislation only the risk to life due to an unplanned escape of water will be considered.

The second use of the outputs is to develop a methodology to satisfy the Environment Agency's obligations with regards to reservoirs under the Flood Risk Regulations 2009. This legislation requires the Environment Agency to determine in relation to each river basin district whether, in its opinion, there is a significant flood risk from the sea, main rivers and reservoirs. For those areas identified as flood risk areas, a flood hazard map and flood risk map must then be produced. For reservoirs this process has begun with the National Reservoir Inundation Mapping project (NRIM) which has carried out reservoir inundation mapping for all reservoirs registered under the Reservoirs Act 1975. However, the Environment Agency must assess the flood risk posed by all reservoirs, including those with a capacity of less than 25,000m^3.

It is a requirement of the Reservoirs Act 1975 for reservoir owners to register with the Environment Agency. During registration of these reservoirs, details of the location and other reservoir characteristics are recorded in the Reservoir Enforcement and Surveillance System (RESS) database. Furthermore, these reservoirs must be annually assessed meaning there is generally a good level of information available. This data was used during the NRIM project to carry out inundation mapping of reservoirs registered under the Reservoirs Act 1975. However, historically there has not been a requirement for reservoirs smaller than 25,000m^3 to be registered in this way and therefore the data required for this project is not readily available.

It will be necessary to locate as many small raised reservoirs as possible before they can be risk assessed. This can be carried out through use of GIS software to search OS Mastermap and the NEXTMap Britain DTM for features likely to represent waterbodies. An analysis of the surrounding ground levels as recorded in the DTM may then be undertaken in order to determine whether the waterbody is raised above ground level.

Three methodologies that will allow an assessment to be made of the risk posed by small raised reservoirs have been scoped. These have differing levels of accuracy and anticipated costs:

- High Level Screening – generalised qualitative analysis requiring little input data and producing a comparative consequence score for each reservoir location
- Intermediate – risk assessment based on detailed modelling but with assumptions made regarding reservoir details. 2D modelling carried out for each reservoir location using a set of dam breach hydrographs representing a range of potential reservoir volumes
- Detailed – risk assessment based on detailed 2D modelling and using individual reservoir details to produce a specific breach hydrograph for each location

Experience gained through case study trials has shown that individual reservoir parameters (such as dam height and storage volume) are likely to be both costly and time consuming to acquire, and may be of questionable accuracy. In contrast reservoir locations, ground topography and details of flooding receptors are relatively easy to obtain and are generally of a good quality.

It is anticipated that there will be a large number of small reservoirs requiring a risk-assessment. Therefore, in formulating the methodologies preference has been given to techniques which can be automated and which require minimal user input and judgement. The use of automated methods also improves consistency as it reduces scope for individual user judgement.

The High Level Screening method has been found to be significantly more time-consuming and subjective than anticipated. It delivers outputs that are considerably less useful than the other proposed methodologies, but may be more costly to implement. It is therefore recommended that this methodology is not developed further.

The Intermediate method uses simple inputs and produces results that can be used to provide an evidence base for the lower limit on reservoir volume for the Flood and Water Management Act. This method cannot produce individual risk assessments for each reservoir as it uses generic breach hydrographs. However, it provides a detailed assessment of the level of risk of each reservoir location, which may be used to facilitate the risk-based allocation of resources for further study.

It has been found to be difficult to collect the information necessary in order to produce reservoir-specific breach hydrographs. The information cannot be obtained with sufficient accuracy from a desk study so it would be necessary to carry out site visits, or request this information from reservoir undertakers. This too would be very costly

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1. Introduction

The overarching aim of this project is to develop a methodology that will allow an assessment to be made of the risk posed by raised reservoirs with a capacity of less than 10,000m^3. The methodology developed will initially be used for two different purposes.

The first is to inform decisions arising from the Flood and Water Management Act. The Act enables reservoirs of 10,000m^3 or larger to be brought within reservoir safety legislation (the Reservoirs Act 1975 currently only covers reservoirs with a capacity greater than 25,000m^3). This project has scoped risk-based methodologies to provide an evidence base for this minimum reservoir volume. This is because the Act contains powers for the 10,000 m^3 figure to be adjusted upwards or downwards according to evidence. Evidence as to whether it needs to be adjusted upwards would be derived from the registration and risk-assessment process. However, the Act provides no process by which evidence can be gathered as to whether the figure is too high. For the purpose of determining the appropriate minimum reservoir volume to be included within reservoir safety legislation only the risk to life due to an unplanned escape of water will be considered.

The second use of the outputs is to develop a methodology to satisfy the Environment Agency's obligations with regards to reservoirs under the Flood Risk Regulations 2009. This legislation requires the Environment Agency to determine in relation to each river basin district whether, in its opinion, there is a significant flood risk from the sea, main rivers and reservoirs. For those areas identified as flood risk areas a flood hazard map and flood risk map must then be produced. For reservoirs this process has begun with the National Reservoir Inundation Mapping project (NRIM) which has carried out reservoir inundation mapping for all reservoirs registered under the Reservoirs Act 1975. However, the Environment Agency must assess the flood risk posed by all reservoirs, including those with a capacity under 25,000m^3. The Flood Risk Regulations 2009 state that if identified as having a significant flood risk, maps must be produced to include:

- "The number of people living in the area who are likely to be affected in the event of flooding
- The type of economic activity likely to be affected in the event of flooding
- Any industrial activities in the area that may increase the risk of pollution in the event of flooding
- Any relevant protected areas that may be affected in the event of flooding
- Any areas of water subject to specified measures or protection for the purpose of maintaining the water quality that may be affected in the event of flooding, and
- Any other effect on
  - Human health
  - Economic activity
  - The environment (including cultural heritage)"

It is a requirement of the Reservoirs Act 1975 for reservoir owners to register with the Environment Agency. During registration of these reservoirs details of the location and other reservoir characteristics are recorded in the Reservoir Safety team's reservoir database. Furthermore, these reservoirs must be annually assessed meaning there is generally a good level of information available. This data was used during the NRIM project to carry out inundation mapping. However, historically there has not been a requirement for reservoirs smaller than 25,000m^3 to be registered in this way and therefore the data required for this project is not readily accessible.

The project aims have been achieved through the following objectives:

1. Identify data sources that can be used for the risk assessment and assess for completeness, quality and accessibility.

2. Identify information required to assess risk posed by small reservoirs. This includes information on receptors of impacts and information on the hazards posed.

3. Develop methodology for risk assessment appropriate to the number of reservoirs that are likely to be assessed and the resources available.

4. Undertake a number of case studies to test and validate the methodology. This will consider a range of different reservoir types and situations.

2. Reservoir data

2.1 Identify information required to assess risk

2.1.1 Introduction

In order to fully assess the risk of any small reservoir failure it is necessary to evaluate both the consequence of the dam failure and the likelihood. For instance, failure of a reservoir close to an urban area could have very large consequences but if the reservoir has been recently constructed, is regularly inspected and is in very good condition the likelihood of failure is small and therefore the overall level of risk is reduced. A calculation of risk can be given as: Consequence x Likelihood.

It is very difficult to accurately quantify the likelihood of failure of very low probability events such as reservoir failure. This is because the low failure rate means that there is a paucity of historical data available from which to extrapolate the future likelihood of failure. This is compounded by the numerous possible trigger events and failure mechanisms which must be considered in relation to reservoir failure. In such situations purely consequence-based conditional risk assessments may be undertaken. In these assessments a particular trigger event and failure mechanism may be assumed to occur, with likelihood consequently assigned a score of 1 in the risk assessment.

The following sections identify the relevance of different consequence and likelihood factors in regards to small reservoir failure. In section 2.2 the data sources that are available to measure these factors are assessed.

2.1.2 Consequence factors

Location, density and type of downstream properties – Two of the most crucial consequences of failure are the population at risk and the Likely Loss of Life (LLOL). These will be strongly dependent on the area that is at risk of flooding and the location, density and type of properties within that area. The location and density of properties will affect the number of properties inundated, while property type can give an indication of the number of people at risk and the vulnerability of those people to flooding (e.g. ability to evacuate, amount of warning necessary to evacuate).

Location of critical infrastructure – The economic cost and societal consequences of a loss of essential services are likely to be significant. For example, if reservoir failure is likely to result in a need to close a motorway/railway then alternative routes for emergency services would need to be identified.

Location of environmentally sensitive areas – Negative environmental consequences of flooding need to be identified as the impact could be significant. In addition, the Flood Risk Regulations 2009 state that relevant protected areas that might be affected by flooding must be considered. Although it is difficult to quantify environmental consequences in relation to other factors it is nonetheless necessary to identify environmentally sensitive areas that are at risk.

Location of environmental hazards – Flood damage to some types of infrastructure, for instance disabling of a sewage treatment works, could lead to negative environmental consequences. It is a requirement of the Flood Risk Regulations 2009 that any industrial activities that may increase the risk of pollution in the event of flooding be considered.

Downstream topography – The topography around a reservoir is of great significance as it affects all consequences. Flood extent, flow depth and flow velocity are all dependent on the downstream topography. A steep, narrow valley will channel the flow and lead to locally higher flood depths and velocities, while a broad, flat flood plain will lead to a greater inundated area, but much lower risk to life as flood depths and velocities will be considerably lower.

Triggering of reservoirs in cascade – The downstream impact of a reservoir failure may be made much more severe if the failure of a small raised reservoir results in flow into a larger reservoir downstream. This could trigger the failure in cascade of the larger reservoir and lead to a more significant downstream impact. It may be the case that reservoirs with a capacity of less than 10,000m^3 are unlikely to trigger cascade failures due to their small size.

Storage volume – The larger the volume of water released due to reservoir failure the larger the resulting flood extent. Since a main objective of the project is to provide an evidence base for the minimum reservoir volume to require registration, it is important that storage volume is incorporated into the risk assessment.

Dam height – The dam height affects all consequence factors as it changes the way in which water would be released during a reservoir failure. This is because the dam height affects the cross-sectional area of the breach, and the greater the breach cross-section the greater the peak discharge. This will in turn have a significant impact on flood extent, depth of flow and velocity of flow.

Dam type – This affects the way in which the dam would be expected to fail in the event of a breach. Empirical equations exist to estimate the flood hydrograph for different dam construction types. If the ‘credible worst case’ is to be modelled, and therefore the breach is assumed to extend to the dam toe, then the dam construction type will not affect the volume of water released in a breach, but will have an impact upon the peak outflow. This is because gravity dams would generally be expected to fail in a very short space of time, while earth embankment dams would be expected to fail more slowly. It should be noted that in the NRIM study it was found that over 90% of reservoirs registered under the Reservoirs Act 1975 have earthfill dams. For the small reservoirs covered by this study it would be expected that an even greater proportion will be earthfill. It is therefore likely to be reasonable to assume that all reservoirs within the scope of this study have earthfill dams.

Trigger event – Affects all consequences as the volume stored, speed of breach development, population at risk and amount of warning will all depend on the failure trigger mechanism.

2.1.3 Likelihood factors

Trigger event – Each trigger event has a certain probability of occurrence. This must be quantified if a true risk assessment is to be carried out. For instance if the trigger event is assumed to be a severe flood causing overtopping failure, it would be necessary to estimate the Probable Maximum Flood (PMF) event and assess the effect that this has on reservoir water levels, and whether this could cause a breach.

Dam type – The likelihood that a particular trigger event will initiate a breach is dependent upon the dam construction type, amongst other factors. A qualitative measure of the likelihood of failure of particular dam types is proposed by Hughes and Wanner (2009). In this method a qualitative risk score is assigned to different dam construction types.

Condition of Dam – Dam condition has a very significant impact on the likelihood of failure. Dams that have not been kept in good condition are clearly more likely to fail. It might be expected that small reservoirs would generally be in a poorer condition than reservoirs that are covered by the Reservoirs Act 1975, because there is no obligation to implement structured maintenance or inspection.

Age of Dam – The age of a dam may provide an indication of how likely a dam is to fail. This is because the date of construction reflects the design standards and construction techniques in use at the time. Since design and construction practices have consistently improved over time, it may therefore be expected that older dams may be more likely to fail. For large reservoirs with complex design and construction this relationship may be expected to hold true; However, small earthfill embankments of the type expected for the majority of small raised reservoirs are simple structures and are less sensitive to changes in design and construction practices. For the reservoirs within the scope of this study it is therefore questionable whether this is a reliable indicator of the likelihood of failure.

Ownership – Ownership can provide an indicator of the likely condition of the reservoir. It has been seen in the NRIM study that reservoirs owned by utility companies tend to have a higher quality of data available than those owned by individuals or small organisations, possibly indicating better maintenance and monitoring processes. However, it is expected that the majority of the reservoirs covered in this study will be owned by individuals or small organisations, rather than large utility companies. It is therefore questionable how much information this factor is likely to provide.

Impounding, non-impounding or service – The Reservoirs Act 1975 gives the following definitions for non-impounding and service reservoirs:

- Non-impounding reservoirs – “A reservoir which is not designed to obstruct or impede the flow of a watercourse”
- Service reservoirs – “A non-impounding reservoir constructed of brickwork, masonry, concrete or reinforced concrete”

Impounding reservoirs are not specifically defined in the Reservoirs Act 1975 but may be taken to be reservoirs which are designed to obstruct or impede the flow of a watercourse. This type of reservoir represents the majority of reservoirs in the UK.

The reservoir type can affect the possible failure mechanisms. It is very unlikely that a non-impounding reservoir will fill such that it fails as a result of overtopping. In addition it has been identified that the assumption of the NRIM study that all reservoirs fail by overtopping can be somewhat conservative for some non-impounding reservoirs.

2.2 Identify potential data sources

2.2.1 Reservoir locations

The first step required in order to conduct a risk based assessment is to locate small raised reservoirs in England and Wales.

The proposed methodology to achieve this is explained in detail in section 3. The overall concept involves a search of the LIDAR/InSAR composite Digital Terrain Model (DTM) to identify flat areas that are likely to be waterbodies. By using OS Mastermap and the Environment Agency’s Reservoir Enforcement and Surveillance System (RESS) database (containing all reservoirs with a volume greater than 25,000m^3) as filters, waterbodies that are not small reservoirs should be screened out. This process will not be completely accurate as it is expected that some waterbodies will not be located and that some large waterbodies that are not raised reservoirs will not be filtered out.

OS MasterMap is produced by the Ordnance Survey and is a continually updated database that contains a variety of information structured into different product layers. These consist of

- Topography Layer – Includes half a billion features on landscape representing features such as buildings, fields, fences, water bodies and intangible objects such as county boundaries.
- Integrated Transport Network™ (ITN) Layer – Includes 5445,000km of Great Britain’s road network from motorways to local streets.
- Address Layer 2 – Includes over 28 million addresses with classifications, unique property identifiers such as building name aliases, geographical addresses, objects without postal addresses such as churches and multiple occupancy information for flats.
- Imagery Layer – Seamless picture of Great Britain

Between them they contain over 450 million geographic features found in the real world, from individual addresses to roads and buildings. Every feature within the OS MasterMap database has a unique common reference (a TOID®) which enables the layers to be used together.

This data can be used to locate all water bodies within Great Britain using the topography layer and these can be verified using the imagery layer.

It may be possible to use Google Earth (or similar) aerial imagery as a final, manual, stage to verify waterbodies selected through GIS queries.

The results of the case study trial of this methodology are presented in section 4.2.1

2.2.2 Reservoir details

The RESS database contains the best available data provided to the Environment Agency for all reservoirs currently covered by the Reservoirs Act 1975. This data has been updated with information provided by reservoir undertakers and was used in the NRIM project to carry out inundation mapping. Since similar data are not available for small reservoirs other potential data sources must be considered and assessed for applicability to the project. The data sources considered here were often used in the NRIM project as secondary sources to carry out verification checks of the data provided by the Environment Agency and by reservoir undertakers.

Digital Terrain Data (LIDAR/InSAR)
InSAR data are available for the whole of England and Wales, while there is approximately 65% coverage of LIDAR. A composite of these two DTMs has recently been produced to create a single layer that provides the best available DTM for all areas of England and Wales.

Dam height – A DTM is the only potential data source for identifying dam height without conducting a site visit. However, the quality of data obtained from the DTM is dependent on the quality of the DTM available. LIDAR resolution is to a 2m grid and has a vertical accuracy of 0.15m, whereas InSAR resolution is to a 5m grid and has a vertical accuracy of 0.5m to 1.0m for most data points. Vertical accuracy of these DTMs can be considerably inferior for highly vegetated areas, for dense urban areas and areas of steep topography. In this project, the dam heights of small reservoirs are expected to be in the range of 1-4m and therefore the error in measurement could be significant (especially where InSAR is used).

In order to extract dam height data from the DTM the ‘vertical mapper’ tool in MapInfo could be used to draw a cross section through the dam to identify the crest and toe. However, when dealing with a very large number of reservoirs a manual process is considered to be too time intensive, subjective and costly. An alternative automated approach could be adopted to extract an estimate of dam height by interrogating the DTM around the reservoir location. The dam face could be automatically determined and compared to the surrounding elevation. The potential accuracy of this process based on the case study findings is discussed in section 4.2.4.

Reservoir Area – As explained above, the process for locating reservoirs is based on searching the DTM for flat regions. During this process it would be possible to create a polygon around the flat area which would provide a measurement of reservoir area. However, this measurement would be based on the area that is shown in the DTM; therefore if the reservoir were drawn down when the DTM was created the area measured would not represent the normal reservoir area.

Impounding or non-impounding – A good DTM coverage of the area around a reservoir may enable the type to be identified in some cases. A small impounding reservoir would be expected to have a single dam and higher topography on all other sides, whereas a small non-impounding reservoir might be expected to have embankments on all sides.

An automated process could be developed to establish reservoir type based on the assumptions mentioned above. A buffered zone around the reservoir area could be automatically generated. If the majority of land within this buffered zone was found to be below the identified water level the reservoir can be assumed to be non-impounding, otherwise the reservoir can be assumed to be impounding. This process might fail for flood storage areas (which are normally empty) or where reservoir water levels were drawn down on the day the DTM was created. In addition if there is significant tree coverage of the reservoir this may affect the accuracy of ground levels captured in the DTM and consequently reduce the accuracy of this process.

Dam length – The DTM could also be used to measure dam length. This information is only required to derive the breach hydrograph for concrete/masonry dams. The quality concerns here would be due to potential tree coverage along the dam edge meaning that it may not be possible to clearly identify the entire length of the dam. In addition, the issues mentioned previously with regards to the DTM accuracy when measuring dam height mean that for many small raised reservoirs the embankment may not be clearly defined in the DTM.

Again, an automated process could be developed to locate and measure straight edges on the reservoir perimeter. This assumes that the only straight edge along the perimeter is the dam and that the reservoir was not drawn down on the day that the LIDAR/SAR was created.

Google Earth or similar aerial imagery

Google Earth provides coverage across England and Wales; however the image quality does vary between regions. It would be possible to use aerial images to establish some reservoir parameters but it would not be possible to incorporate this into an automated process. To make Google Earth more usable within this project a Google Earth geo-referenced layer could be created to allow each reservoir to be quickly located based on an assigned identification number.

Impounding or non-impounding – From simply looking at the reservoir and surrounding areas on an aerial image it is thought that the reservoir type could be identified. Impounding and non-impounding reservoirs have different characteristics that would allow them to be categorised. Manual interpretation would be required to classify each reservoir which would bring an element of subjectivity to the data collection process. If every reservoir had to be looked at individually this would be a very time-consuming and expensive process.

Dam type – A similar procedure could be carried out to establish dam type. It would be necessary for someone with experience of dam construction to look at each individual case. It may be relatively simple to decide between earthfill and concrete dam construction but further classification would be more challenging. Again, tree coverage of the dam or poor quality aerial images is likely to make the process difficult (or impossible) for a significant proportion of the reservoirs identified, which would affect the quality and completeness of the data obtained. However, as noted previously it may be possible to simply assume that all reservoirs located are retained by earthfill dams of some kind.

Google Earth could also be used as a verification tool to check other reservoir details such as the dam length.

OS mapping (present and historical)
It is likely that the majority of the small reservoirs of interest in this project are shown on OS maps. Using geo-referenced OS map backgrounds in GIS software packages it may be possible to obtain some of the required reservoir details. The use of 'Envirocheck' is one possible source; this website provides the 'industry standard on desk study information'.

Age – The approximate year in which each small reservoir was constructed could be identified by using historical OS maps for each location. The quality of the data obtained would be dependent on how frequently the maps are updated, how many OS maps can be obtained for each area and the quality of the cartography. For instance, if OS maps are only updated every six years the precise year of construction clearly cannot be obtained from this analysis alone. Once the location of the reservoir has been identified a GIS software package could be used with a series of geo-referenced OS map backgrounds to find the earliest map in which the reservoir features. However, the significant time taken to carry out this analysis should be weighed up against the limited value that this information would add to the risk assessment.

Dam length – OS maps could be used to provide measurements of dam length. However, there is no guarantee that all of the smallest reservoirs will have been recorded – they may have been overlooked or considered too small to be included. Furthermore, the OS maps may not accurately portray the dam length and therefore measurement from the map is questionable.

Site visits
All the required reservoir data could be obtained during site visits to each reservoir. Dam height, type and length could be accurately recorded. Reservoir type and an estimate of the period of construction (for instance

Victorian or modern), could also be obtained. Additionally, an assessment of condition of the dam could be conducted. This would enable an analysis of the likelihood of failure to be included in the risk assessment. However, even though the reservoir locations will be known it will be necessary to contact owners in order to obtain their permission to visit each site. Establishing ownership would be a very difficult task and it is also likely that some reservoir owners will not allow access.

Land Registry

If site visits are necessary, ownership of the reservoirs will need to be identified in order to arrange visits with the reservoir owners. The Land Registry now licences polygons which give an indication of the registered extent of a property in shapefile format. These could be used in GIS software packages to identify ownership of reservoirs. Although this process may be relatively straightforward to identify individual reservoirs, it may be a very time-consuming process to apply to all the reservoirs that are located.

2.2.3 Flooding receptors

Property and infrastructure at risk can be identified using automated GIS routines to extract points representing flood receptors falling within a polygon or grid. This can be done at all levels of analysis from high level screening to detailed modelling. Information such as depth, velocity, Flood Hazard Rating and timing of inundation can also be attributed to individual receptors if inundation modelling is carried out. The Flood Hazard Rating is a means of assessing the danger to people from flood waters (Udale-Clarke et al. 2005).

A number of different data sources are required to conduct this type of assessment.

Digital Terrain Data (LIDAR/InSAR)

In section 2.2.2 the use of a DTM for obtaining reservoir details was assessed. In terms of precise ground levels the accuracy of LIDAR and InSAR is questionable but overall DTMs (especially LIDAR) provide the best possible representation of floodplain topography. DTMs are required inputs for hydraulic modelling in order to predict where the flood wave would travel; therefore they are very important in identifying flooding receptors. The use of LIDAR and InSAR for this purpose is common.

Although LIDAR does provide the most accurate representation of topography, due to its high resolution, bridges across watercourses and in floodplains must be removed before the DTM is suitable for hydraulic modelling. If this is not done these bridges form artificial dams which would significantly affect the flood extent. The LIDAR/InSAR composite layer has been edited to remove the majority of, but not all, structures.

National Property Database

The National Property Dataset (NPD) provides details on property location, use, size and value in England and Wales. It has been developed to support economic damage assessments for flood scenarios so it could easily be used within this project. The NPD is primarily based on Address Point and Valuation Office Agency (VOA) rating data (for commercial property) and Land Registry residential property values. Each property is assessed for its rateable value and coded based on its use. The rateable value is a measure that broadly represents the annual rental value that could be generated from a commercial property if it were available in the open market at a particular date.

Property damage values (using the Multi-Coloured Manual MCM code) are also included in the NPD. The property damage calculation is intrinsically related to flood depth which is an element of the Flood Hazard Rating.

The quality of data obtained from the NPD depends on the quality of the source datasets and on the quality of the matching process to combine the source datasets. Of the source datasets the OS MasterMap data are of the highest quality. The VOA data are of lower quality and lower accuracy. Accuracy of the match between VOA and OS MasterMap Address varies between 60 and 80%. This value has been estimated in work carried out by JBA in the 'Receptors Vulnerable to Flooding Project' for the Environment Agency in 2006. Where the match is incorrect, the type of the property and the value of the property are incorrect. This is important at detailed scales and when assessing individual properties.

Receptors Vulnerable to Flooding

The Receptors Vulnerable to Flooding (RVF) database can be used with ArcGIS queries to show which receptors fall in the inundated extent.

The Receptors Vulnerable to Flooding Database, based on the approach developed in the Flood Vulnerability Mapping Scoping Study produced by JBA in March 2006, brings together nine national datasets and provides full coverage of England and Wales. The Database not only provides a summary of receptors vulnerable to flooding per 100m grid cell but also GIS point, polygon and grid data show the make up of vulnerable groups, vulnerable buildings and land use in their exact location. This dataset includes locations of properties using NPD data and Master Map data and also locations of sensitive infrastructure including: IPPC (Integrated Pollution Prevention Control) National Dataset; REGIS (National Dataset of waste management sites); RAS (Radioactive Substances National Dataset); Water Company Sewage & Water Treatment Plants - subset of the WIMS (Water Information Management system) dataset

The base maps include:

- Social Vulnerability Base Map – Includes the distribution of vulnerable population and building type plus the level of social vulnerability derived from the Social Flood Vulnerability Index (SFVI) and 2001 Census data.
- Building Vulnerability Base Map – Includes the location of vulnerable buildings (without vulnerable population) (e.g. hazardous sites, emergency response centres)
- Land-Cover Vulnerability Base Map – Land cover vulnerability to flooding - based on land use e.g. arable and horticulture, grassland, semi-natural vegetation and woodland

This would provide a good analysis of potential flooding receptors and because it would be based on a standard and automated analysis the information obtained would be quantitative and comparable at a national level.

The following datasets make up each base map:

Table 2.1 – Datasets contained in the Receptors Vulnerable to Flooding database

Base Map Name	**Data Source**
Social Vulnerability Map	• Health and Safety Laboratory National Population Database • National Property Dataset 2005 (NPD)[1] • Social Flood Vulnerability Index (SFVI)[1] and 2001 Census data
Building Vulnerability Map	• NPD[1] • MasterMap • IPPC[1] - Integrated Pollution Prevention Control) National Dataset • REGIS[1] - National Dataset of waste management sites) • RAS[1] - Radioactive Substances National Dataset) • Water Company Sewage & Water Treatment Plants[1] - subset of the WIMS (Water Information Management system) dataset
Land Cover Map	• Centre for Ecology and Hydrology Land Cover Map 2000 (LCM 2000)

[1] Datasets owned by the Environment Agency

The Receptors Vulnerable to Flooding Database includes information at four spatial scales:

1. Summary information at 100m by 100m grid level
2. Point level information including building type and associated population (where available)
3. SFVI and Census information at Output Area scale (approx 125 houses)
4. Land cover raster data at 25 m resolution

National Receptor Dataset

The National Receptors Dataset is currently being developed by the Environment Agency. This will provide details of many different flood risk receptors and will include the following information:

Table 2.2 – Datasets contained in the National Receptors Database

Receptor type	Receptor
Human Health	• Flooded Economic Deprivation Index from Northern Ireland Neighbourhood Information Service (NINIS) analysis • Flooded Vulnerability Index based on Census data • Count of residential properties * 2.5 • Flooded elderly population index • Flooded key services including: o Fire stations o Police stations o Hospitals o GP surgeries o Schools o Water treatment works o Water pumping stations o Sewage pumping stations o Waste Water Treatment Works o Ground mounted electrical substations o Flooded road/rail lengths
Economic Activity	• Property damages across all categories • Agricultural damages for broad land classes • Road/rail lengths flooded
Environment	• Flooded Areas of Special Scientific Interest (ASSI). This includes all Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) etc • Flooded Wastewater Treatment Works (WwTW) and Power Stations (PS) • Flooded Industrial Pollution and Radiochemical Inspectorate (IPRI) sites
Cultural Heritage	• Flooded Sites and Monuments Record (SMR) sites/ Listed buildings / sites of archaeological interest

The above list of receptors is designed to allow the provisions of regulation 21(1) of the Flood Risk Regulations 2009 to be met when producing flood risk maps for areas determined by the Environment Agency as having significant flood risk.

This regulation states that if part of a river basin district is identified as having a significant flood risk, maps must be produced to include:

- “The number of people living in the area who are likely to be affected in the event of flooding
- The type of economic activity likely to be affected in the event of flooding
- Any industrial activities in the area that may increase the risk of pollution in the event of flooding

- Any relevant protected areas that may be affected in the event of flooding
- Any areas of water subject to specified measures or protection for the purpose of maintaining the water quality that may be affected in the event of flooding, and
- Any other effect on
  - o Human health
  - o Economic activity
  - o The environment (including cultural heritage)"

Once completed the National Receptors Dataset is therefore likely to be the most appropriate receptor dataset for use in assessing the downstream consequence of reservoir failure.

Environmental Dataset
It is possible to obtain map overlays for environmental desk study investigations. The main purpose of these environmental mapping packages is to provide the necessary information for conducting Environmental Impact Assessments. For example 'FIND – Professional Mapping Intelligence' (www.findmaps.co.uk) offer an 'Areas of Natural Importance' layer which provides a variety of information including Sites of Special Scientific Interest, Special Areas of Conservation and Areas of Outstanding Natural Beauty. As this layer can be obtained in shapefile format it could be used to identify some of the environmental risks of reservoir failure.

Local Resilience Forums (LRFs)
LRFs are very experienced in preparing plans for dealing with emergency incidents within their designated areas. LRFs have already been briefed on aspects of reservoir safety and inundation mapping during the NRIM project and contacts are also available for main emergency planning officers in each region. The local knowledge that LRFs hold would be very useful in assessing all types of flooding receptors and in general the information would be of good quality. However, as so many different LRFs would be involved, the quality and content of the information provided would vary significantly. The information is also likely to be of a qualitative nature making comparison between regions and an analysis on a national scale very difficult.

It would be difficult to obtain useful information from LRFs unless they were asked to comment directly on an inundation map. Without providing this, or something similar, the quality of data obtained would be significantly reduced. The logistics of utilising LRFs is also a concern since it would be a time-consuming, expensive process and would result in variable results.

Civil Contingencies Secretariat (CCS)
The CCS aims to improve UK resilience to emergencies by building capabilities needed to absorb, respond and recover. As part of the NRIM project CCS have been provided with an outline shapefile showing all areas at risk of flooding in the event of a reservoir failure. Using this shapefile in conjunction with a critical national infrastructure dataset, CCS is able to identify critical national infrastructure that is at risk at a national level. This process must be carried out

by CCS for security reasons. A quality issue that should be noted is that the analysis to date has been based purely on flood extent; to do a more thorough analysis on the scale of damage that would be likely, the maximum depth and velocity of the flood wave would also have to be considered.

Table 2.3 provides a summary of the review of data requirements, availability and quality. (Objectives 1 and 2) To ensure consistency with other flood risk assessments, the data quality score (DQS) in the final column is based on the following data quality system, proposed in the Surface Water Management Plan Technical Guidance, Living Draft V1:

1. Best of breed – No better available; not possible to improve in near future
2. Data with known deficiencies – Best replaced when new data are available
3. Gross assumptions – Not invented but based on experience/judgement
4. Heroic assumptions – An educated guess

Table 2.3 – Summary of the review of data requirements, availability and quality

Data Required	Data Source	Summary	DQS
Location, density and type of downstream properties	National Property Database	Up to date information on property (includes information on property type). Used in RIM project to obtain LLOL data. Automated approach if used in conjunction with inundation mapping. Can be used to carry out standardised downstream assessment for all modelled reservoirs.	2
	OS Mapping	Provides the location of downstream properties. Deficiency due to need to carry out manual assessment (count up of properties and estimate of those most at risk)	3
	RVF (and NRD when complete)	This dataset includes locations of properties using NPD data and Master Map data. This dataset is only as accurate as the datasets used to compile it. Errors found in the data include missing data, mismatches between different sources of data and errors in input of source data. This data provides a snap shot in time of flood vulnerability.	1
Location of sensitive infrastructure	CCS	Location of critical infrastructure available as a GIS layer held by CCS. Due to security reasons only CCS can carry out this analysis. Possibly also useful to identify potential environmental hazards	1
	LRFs	Have local detailed knowledge on their designated areas. Data provided would be qualitative and of varying quality therefore difficult to use to make qualitative assessment and comparisons between different areas.	3
	RVF (and NRD when complete)	This dataset includes locations of sensitive infrastructure (as detailed in the text above). This dataset is only as accurate as the datasets used to compile it. Errors found in the data include missing data, mismatches between different sources of data and errors in input of source data. This data provides a snap shot in time of flood vulnerability.	1
Location of environmentally sensitive areas	Environment Dataset	Assuming the GIS layer holds all the environmental data that is required to make the required assessment on impact on environmentally sensitive areas data this is useful. Potential deficiencies where not all data are held in the GIS layer. Could also be costly to obtain data for all of England and Wales.	2
Downstream topography	LIDAR	Best available representation of topography. Widely used in hydraulic modelling. This would not require much processing prior to use but does not provide complete coverage of England and Wales.	1
	InSAR	Although of lower quality than LIDAR this has been used in the RIM project and shown to be acceptable for inundation modelling.	3
	LIDAR/ InSAR Composite	This DTM provides complete coverage of England and Wales using higher quality LIDAR data where available and InSAR data where it is not.	2
Triggering of reservoirs in cascade	LIDAR/ InSAR	Where downstream reservoirs are affected by the release of water from an upstream reservoir failure they will be 'filled' in the DTM during inundation modelling. Deficiency due to fact that DTM might record a reservoir water level that is drawn down. Requires judgement to decide if cascade is triggered.	3
Storage volume	LIDAR/ InSAR	From dam height and reservoir area (both likely to have to be obtained from DTM) estimate of storage volume is based on an empirical relationship. Educated guess due to inaccuracies in measurements and empirical relationship.	4
Dam height	LIDAR	Only possible method of finding dam height without conducting site visit. Judgement required to decide where crest and toe should be measured. Vertical accuracy 0.15m	3
	InSAR	Due to the poor vertical accuracy (0.5-1.0m) likely to be significant errors when measuring dams that are only between 1m and 4m high.	4
Dam type	Google Earth	Possible in most cases to determine between earthfill and concrete dams. Further classification not possible from aerial image alone. Manual approach therefore judgement required. Some images will be of poor quality therefore cannot be used to establish dam type leading to gaps in the data.	3
Condition	Site Visit	True assessment of condition only possible via a site visit. Educated guess could be made based on other factors (age/ownership/dam type). However, these factors are also difficult to accurately obtain. Require ownership details to get permission for site visit, time consuming and expensive process.	3
Age (indicator of condition)	OS Mapping	Quality of data obtained linked to the number of OS maps that can be obtained and the frequency of which OS maps are updated. Gaps are likely where OS maps cannot be obtained. Inaccurate data obtained where maps miss small reservoirs. Manual process required – time consuming and expensive.	4
Ownership (indicator of condition)	Land Registry	Unlikely to contain ownership details of all reservoirs. May be a suitable method if access to Land Registry database can be provided. The best available method to obtain this data.	3
Impounding or non-impounding	Google Earth	Manual assessment to determine the reservoir type based on certain characteristics of impounding and non-impounding reservoirs. Time consuming, expensive process and judgement required. Some images will be of poor quality meaning assessment will not be reliable.	3
	LIDAR/ InSAR	Possibility for an automated process to be developed based on assumptions regarding surrounding topography. Would require set of assumptions and rules to be set.	3

2.3 Conclusions

It is believed that the location of inland waterbodies can be obtained with a reasonable degree of confidence. The method is described in detail in section 3.1 and the case study analysis is discussed in section 4.2.1.

It is also possible to filter out those waterbodies that are not raised above ground level with a reasonable degree of confidence. The process will involve a number of assumptions and errors and will therefore not provide a definitive list of raised reservoirs. Through the process of locating waterbodies it will also be possible to find the surface area of each identified reservoir. However, all other reservoir information is likely to be either very expensive to obtain or be of a low quality (in terms of both accuracy and completeness).

High quality topography data in the form of an InSAR/LIDAR composite DTM is available for all of England and Wales. Whilst LIDAR data are much more accurate than SAR, the NRIM project has shown that DTMs derived from InSAR data are satisfactory for inundation modelling.

Detailed information on the type and location of reservoir flooding receptors is available from a number of sources, principally the Environment Agency's National Property Dataset and Receptors Vulnerable to Flooding dataset (although once completed it is anticipated that the National Receptors Dataset will replace these). Therefore, it is thought that if inundation modelling is carried out the consequences of reservoir failure can be assessed.

Using the available receptor datasets it is possible to assess the consequences of reservoir failure with regards to a number of different receptor types (as required in the Flood Risk Regulations 2009). However, it should be noted that the consequences of failure upon each receptor type should remain discrete. It is not possible to quantify the consequences of failure of different receptors to produce a combined consequence rating. To do so would require a judgement to be made of the value of a human life in relation to, for instance, damage to an environmentally protected area or economic damage.

The low quality and completeness of reservoir information means that it is not feasible to carry out a full risk assessment for every reservoir. For small reservoirs, condition is considered to be the key factor in terms of likelihood of failure and this is not easily quantified without carrying a site visit. In the NRIM project, age and ownership were used as indicators of condition in order to assess likelihood of failure. However, both age and ownership are difficult to accurately extract from the data sources available for small reservoirs, and may have less relevance in determining the likelihood of failure than for large reservoirs.

If likelihood of failure does need to be included in the analysis, site visits would be required to assess condition. Extrapolating results for condition from a small sample of site visits may give an overall depiction of the general likelihood of failure of small raised reservoirs; but in order to produce individual risk assessments every site would have to be visited. It is concluded therefore that it would be more appropriate to carry out a purely consequence-based assessment.

3. Proposed methodologies

As detailed in the previous section, individual reservoir parameters (dam height, storage volume etc) are hard to acquire, while reservoir locations and details of receptors are relatively easy to obtain and are of a good quality. This makes any assessment of likelihood of failure very difficult, but the scope of this study means that a purely consequence-based assessment of either 'likely loss of life' (for the Flood and Water Management Act) or environmental, economic and societal impacts (for the Flood Risk Regulations 2009) is adequate.

For inundation mapping, there is sufficient data available to identify the breach location that will result in the worst-case consequences of failure and to model any generic breach hydrograph at this location to find the impacts. It is much harder to make an assessment of the most likely breach location and to derive the corresponding specific breach hydrograph for that location, as the information required is likely to be hard to obtain and of poor quality.

It is anticipated that there will be a large number of small reservoirs requiring a risk-assessment. Therefore, in formulating the following methodologies preference has been given to techniques which can be automated and which require minimal user input and judgement. From experience gained during the NRIM project, the manual collection of reservoir data was a labour-intensive exercise and had a high cost associated with it. The use of automated methods also improves consistency as it reduces scope for individual user judgement.

Three methodologies with differing levels of accuracy and anticipated costs have been produced. These are:

- High Level Screening – generalised qualitative analysis requiring little input data and producing a comparative consequence score for each reservoir location
- Intermediate – risk assessment based on detailed modelling but with assumptions made regarding reservoir details
- Detailed – risk assessment based on detailed modelling and using specific reservoir details derived from a desk study

3.1 Identification of small raised reservoirs

Currently no data are held by the Environment Agency on the locations of small reservoirs (defined as reservoirs with a capacity of less than 10,000m^3 stored above ground level). A key part of this project is therefore to scope methodologies for locating all raised small reservoirs within England and Wales. The process of locating reservoirs using the techniques outlined below would be done in two stages. The first stage involves identification of waterbodies within England and Wales and the second to identify those which fall within the scope of this project.

Two methods have been identified for carrying out Stage 1 of this analysis. These could work as stand alone methods or could be used in combination.

Stage 1: Slope analysis/Master Map
The first method that has been investigated involves an analysis of topographic slopes. The processes of LIDAR and InSAR, used to create DTMs, are not able to accurately obtain the surface level of waterbodies. Areas of water are consequently manually added to the DTM; therefore they are guaranteed to be perfectly flat. Consequently, by searching for features with a slope of between 0 and 0.001 (thus excluding all areas which are not completely flat) it should be possible to identify all waterbodies. Using ArcGIS tools to identify flat areas within the NEXTMap Britain DTM a dataset can therefore be created which contains waterbodies.

The second method is to use OS Master Map data to identify features that are attributed with the theme ‘water’.

The resulting polygons from the two above methods could then be run through an intersect query creating a master dataset with a more comprehensive coverage. However, it is expected that this will require filtering as it will contain some areas which are not waterbodies, as well as waterbodies which are not reservoirs.

The above analysis will not differentiate between waterbodies and sections of rivers / canals which are also perfectly flat. It will therefore be necessary to filter out rivers and canals. This can be done through a geometric filter, as all river and canal sections identified will be long and comparatively narrow, making it possible to simply exclude all polygons identified which have a high length to width ratio. In addition, the OS Master Map ‘water’ theme includes waterbodies but does not include rivers and canals, so by intersecting the two identification methods described above it is possible to include a further filter.

In order to reduce this dataset by excluding those reservoirs which are above 25,000m^3 a further intersect query would be required. The Environment Agency’s RESS database would be used to identify these reservoirs. Where the polygons extracted from the slope/MasterMap analysis intersect with locations in the RESS database it can be assumed that the waterbody that has been identified is a large reservoir. These waterbodies can then be removed.

The above methodology will not identify service reservoirs (as they are often buried) and flood storage areas (as they are often empty). However, data on these assets are held by water utility companies and by the Environment Agency and it is anticipated that this information could be obtained for this study.

Stage 2: Identifying whether the waterbody is raised above ground level
Once a list of waterbodies has been produced it will be necessary to filter out those which are not raised reservoirs. The data required to carry out this part of the analysis includes the reservoir polygons derived in Stage 1 and the NEXTMap Britain DTM.

In order to establish the height of the reservoir itself the centroid of the waterbody must be located with a single point. A simple interrogation of the

DTM at this point would provide the elevation of the water surface. Alternatively the area of DTM within the reservoir polygon could be interrogated to provide the average elevation within the waterbody as a whole.

The next step is to establish the height of the topography surrounding the waterbody. For a raised reservoir the surrounding topography must be lower than the water surface along at least part of the reservoir perimeter. A buffer created around the reservoir area polygon would be created and used to draw a comparison of the elevation of the water surface with the surrounding topography. A number of points (for example 50) would then be created around the edge of the buffered zone and these would be interrogated to extract the height of the DTM at each. Analysis could then be carried out to calculate the number of points around the buffer which are at a higher elevation than the water surface. If any points are found to be lower than the reservoir surface it may conservatively be assumed that the waterbody is raised.

To further reduce this list down to those reservoirs of interest in this study (i.e. those with a capacity of less than 10,000m^3) a manual desk top inspection of the polygons remaining could be carried out. This would be done with reference to OS Master Map, OS 10K Raster Maps and Google Earth Imagery. Assumptions relating the volume of the reservoir to its surface area and dam height would need to be made in order to do this.

3.2 High Level Screening method

A 'rolling-ball' flow path analysis of the available DTM is proposed for the High Level Screening method to provide an initial understanding of the potential consequence of a hypothetical reservoir failure. 'Rolling-ball' methods are extensively used in urban drainage analysis as an efficient means of understanding above-ground flood response. The 'rolling-ball' algorithm calculates a down slope flow angle for relevant pixels in the DTM and it can therefore be used to track the likely flow path down the steepest gradient. In some cases multiple breach scenarios may be required to investigate all possible routes for water to escape. This process, using toolkits within ArcGIS, such as ArcHydro, creates a likely flow path from the breach location, therefore giving an initial indication of communities and areas that are potentially at risk. Flow paths will continue to the extent of the DTM; therefore termination criteria based upon simple rules will be required. These could include the presence of a downstream urban area above a certain size, crossing a set number of impounding structures or a set maximum length of flow pathway. These criteria would be set through testing to derive realistic values. This approach is intended to require the lowest possible computing time and cost and could be used as a screening tool to filter out reservoirs which can readily be shown to present no risk at all and to rank reservoir locations based on the potential consequence of failure.

Once the flow path has been created further interrogation of the DTM using available query techniques in ArcGIS can be used to identify the shape of the valley at different locations along the flow path. Where the valley is steep and narrow, flood water would not be able to spread out but would travel with a greater velocity. In contrast, when the valley is wide and flat there is a higher chance that the flood extent would be larger, albeit with a reduced velocity and depth.

Using available datasets representing population and infrastructure the flow path could be used to give an indication of the likely consequence of the flooding. Consequence analysis requires a region based analysis and as such flood inundation areas need to be assumed. In order to create these regions the flow pathway could be buffered either simply using a set distance or using a more complex procedure involving hill climb/local contouring methods. Alternatively the flow pathway could be intersected with other polygon datasets such as urban areas, delineated from data such as the National Property Dataset, National Receptors Database, or with the Environment Agency Flood Zone or Surface Water Flood Maps. Different land uses within the run out zone could also be accounted for via path distance analysis.

it should be noted that this method does not take storage volume into account and therefore cannot be used on its own as an evidence base for the minimum reservoir volume to require registration. However, it may be used as a screening tool to identify those reservoirs likely to have a significant consequence of failure.

3.3 Intermediate method

Since a main objective of the project is to provide an evidence base for the minimum reservoir volume requiring registration, it is important that escapable volume is incorporated into the risk assessment. In the Intermediate method, rather than attempting to estimate, measure or otherwise obtain an accurate escapable volume, it is proposed that a range of different breach hydrographs for a variety of different volumes, for example from 2,500m^3 to 15,000m^3, are derived. Using each of these breach hydrographs and 2D hydraulic modelling techniques a series of inundation maps could be produced to show the downstream impact for a range of reservoir volumes. Independent of the actual volume and other details of the identified reservoirs the analysis would provide different levels of consequence for the various assumed volumes. Once an ‘acceptable level of risk’ has been identified it would be possible to find out what the reservoir volume would have to be in order to pose an unacceptable level of risk.

This methodology allows an assessment to be made of the overall risk posed by both existing reservoirs and of any that may be constructed in the future as it uses existing reservoir locations to provide a representative sample of present and future reservoirs. The individual parameters of the reservoir at each location are not taken into account in order to produce a generalised assessment of the likely level of risk posed by different reservoir storage volumes.

A 2D modelling approach using modelling software such as JFLOW-GPU, Infoworks RS or TuFLOW would be used for the purposes of this exercise. One option would be to use the hydrodynamic model JFLOW-GPU to model the spreading of a breach hydrograph over the selected DTM. This modelling technique was used in Phase 1 of the NRIM Project for the Environment Agency. JFLOW-GPU is a rapid 2D raster based model, which requires very little setting up, but which constitutes a diffusion wave approximation to the 2D depth averaged shallow water equations (Hunter et al., 2008). Although this cannot model the inertial effects of the flows associated with dam failure, the development and attenuation of the flood wave in terms of height and time of arrival has been compared in detail with fully hydrodynamic models (Infoworks RS and TuFLOW) and gave similar values. This testing was carried out as part of the Pilot Study for the Rapid Reservoir Inundation Mapping Project for the Environment Agency in 2008. The outputs from this process include; flood extent, depth, velocity, Flood Hazard Rating, time of initial inundation and time of maximum inundation, derived from post-processing of intermediate grids written out of the model at specified intervals (for example every five minutes).

This methodology allows the modelling of multiple breaches, which is important where different breach locations are likely to result in significantly different flood extents.

Owing to the fact that a suit of hydrographs will be modelled for each reservoir; most potential cascade failures are likely to be taken into account implicitly by the hydrographs generated for greater volumes. The small reservoir volumes considered in this study means that they are unlikely to trigger the failure of Large Raised Reservoirs (registered under the Reservoirs Act 1975) or of reservoirs which lie a significant distance downstream. It is therefore considered reasonable to model the cascade failure of a number of small, closely spaced reservoirs with a single breach hydrograph.

In principle it is possible to explicitly take account of reservoirs failing in cascade through this method. Rules can be applied such that, for instance, if the dam of a downstream reservoir is overtopped by a certain depth then it is assumed to fail and an additional breach hydrograph is modelled at this location. However, the modelling of cascades to this level of detail is not considered appropriate due to the lack of reservoir-specific information available. Since the initial breach hydrograph is already simply one of a generic set, it would be difficult to derive a means for calculating the subsequent cascade failure hydrographs.

The NRIM trial study investigated various methodologies for estimating the breach outflow hydrograph for a hypothetical reservoir failure. The adopted methodology makes use of several empirical equations.

As discussed in Section 2.1.2, over 90% of the reservoirs that are currently within the Reservoirs Act (volume greater than 25,000m^3) have earthfill embankment dams. This percentage is likely to be even greater for the smaller reservoirs of interest in this study. Small dams retaining a shallow depth of water have smaller loads imposed on them and so are more likely to be of simple earthfill construction. In the assessment of small reservoirs an assumption could therefore be made that all reservoirs found have earthfill embankment dams. By making this assumption the empirical method proposed by Froehlich, D. C, (1995) can be used to estimate peak breach outflow hydrographs for all reservoirs in the project. This empirical method requires dam height and escapable volume to be known parameters. The Intermediate method looks at a range of possible escapable volumes; therefore the only reservoir parameter that needs to be identified is dam height. Analysis of the Froehlich method has shown that for each escapable volume there is a critical dam height that gives the maximum peak discharge, see Figure 3.1 below. This is due to the need to modify the initial estimate of peak breach flow to ensure that the volume under the hydrograph is correct. For the purpose of inundation mapping to ensure a worst case inundation scenario, it would be necessary to assume this critical dam height. Use of the Froehlich method would ensure consistency with the NRIM project as this method was used to produce dam breach hydrographs for all embankment structures as well as for composite embankment/gravity dams.

For the particular range of escapable volumes and critical dam heights used in this method, the Froehlich empirical equation for embankment dams gives a more severe hydrograph, with a greater peak discharge, than the method proposed in CIRIA C542 (Hughes et al, 2000) for gravity dams. Therefore it is both reasonable and conservative to adopt the Froehlich equation and assume that all small reservoirs have embankment dams

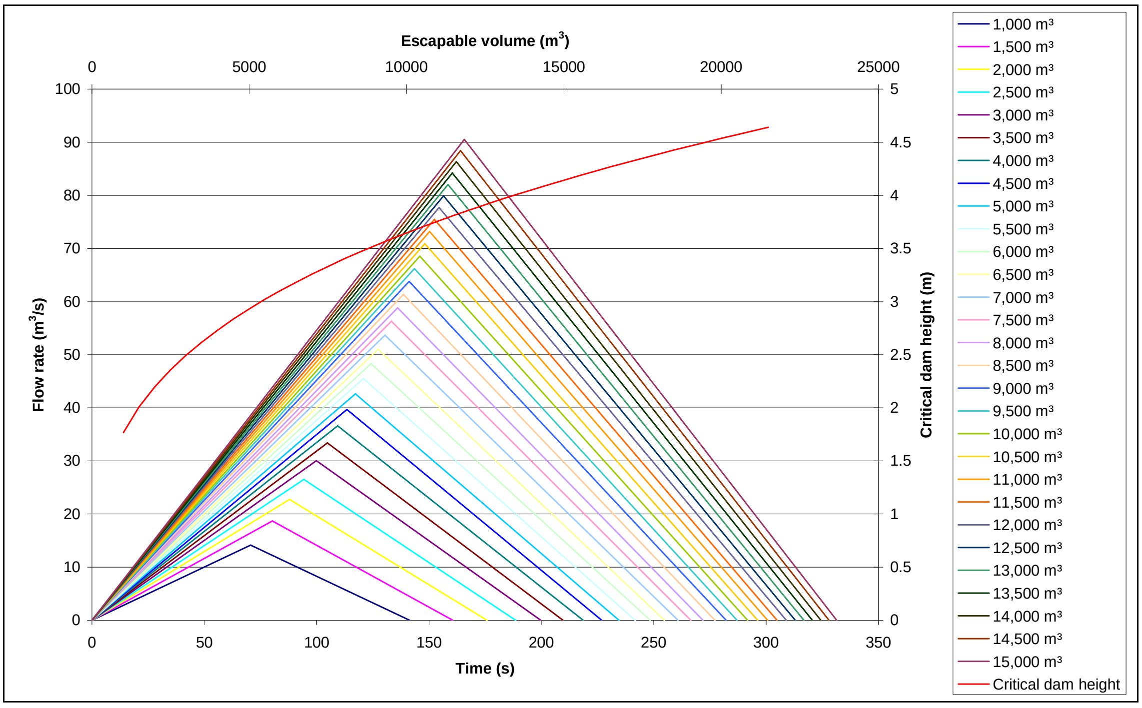


Figure 3.1 – Worst-case hydrographs generated for different reservoir volumes also showing critical dam heights for each reservoir volume

Flood inundation modelling in the Intermediate method could be carried out for all small raised reservoirs identified or for a carefully chosen representative sample. This is dependant upon whether it is necessary under the Flood Risk Regulations 2009 to produce individual risk assessments for every reservoir or whether it is acceptable to carry out an analysis of a representative sample. The modelling would produce a prediction of the arrival time, depth, velocity and extent of flooding resulting from the dam breach flood wave. A downstream assessment using the various available datasets and standard GIS query techniques would identify the number of properties at risk, the population at risk and the likely loss of life. This assessment could also assess other potential consequences of the hypothetical dam failures, for example environmental impacts and critical national infrastructure at risk through use of the datasets contained within the RVF or NRD databases.

The downstream assessment would enable an analysis to be made of how consequence varies with reservoir volume. Figure 3.2 below shows an example of how plotting volume against consequence could be used to identify the minimum volume that would require registration. Once an acceptable level of consequence has been agreed, this can be used to find the corresponding reservoir escapable volume.

This comparison can be done nationally to produce evidence for the lower limit in the Flood and Water Management Act, or can be done by reservoir to produce a ranked list of reservoir locations that are inherently high risk. Further information may then be sought on reservoirs in these high-risk locations. If this analysis were carried out on all reservoir locations identified this would enable the Environment Agency to make an initial assessment of which areas are potentially at significant risk of flooding from reservoirs, as required in the Flood Risk Regulations 2009. No further action would be necessary for those areas identified as not being at significant risk, while the ranked list of high-risk locations could be used to prioritise the production of flood hazard maps and flood risk maps.

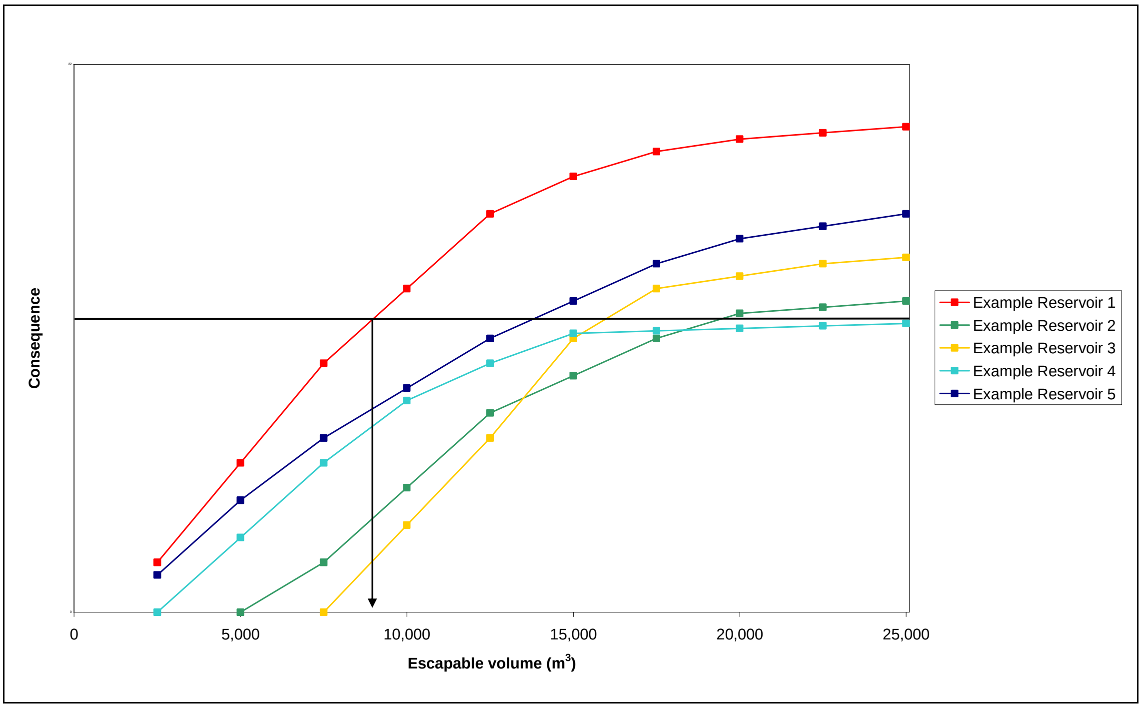


Figure 3.2 – Example of Intermediate method analysis to identify minimum reservoir volume

The results could also be analysed at a regional level to determine whether the minimum volume should be varied based on other factors. Using standard GIS queries it would be possible to evaluate whether the minimum volume should be linked to such factors as the distance between the reservoir and nearby urban areas.

The analysis of the relationship between volume and consequence could be used to produce a ranked list of reservoir locations that are inherently high risk due solely to their location. For example, in conjunction with Defra research study FD2641 “Scoping the process for determining acceptable levels of risk in reservoir design” a consequence level below which the reservoir does not need to be considered further can be established. If at some volumes, the analysis predicts that the consequence of failure is above this level, then further analysis would be required to establish the actual volume and dam height. In this way the Intermediate method provides a starting point and screening tool for the risk-based prioritisation of reservoirs for further study.

This Intermediate method is not strictly a full risk-assessment of current reservoirs, but because it looks at a range of different volumes it can highlight reservoirs that are likely to have a high consequence and the findings would also be applicable to reservoirs that will be constructed in the future.

In the Flood and Water Management Act, it is the duty of the reservoir owner to inform the Environment Agency that they own a reservoir above the minimum capacity. The Environment Agency will send a questionnaire to owners to obtain all the parameters required to conduct a more detailed risk assessment. Hence it is not a significant problem that a full assessment for the reservoirs is not carried out as part of this project.

Having said this, the Flood Risk Regulations 2009 requires a risk assessment of all reservoirs (even those below the limit adopted in the Flood and Water Management Act) This method will therefore not fully satisfy these requirements, although it will identify those that pose no risk and should also provide a starting point (i.e. a ranked list) for further study.

In order to relate the generic hydrographs used in this method to actual reservoir capacities, it is necessary to consider the reservoir water level at the time of failure, as this will have a significant impact on the volume of water released. For these consequence assessments it is recommended that the worst credible case be modelled, and therefore that the reservoir water level is assumed to be as high as might reasonably be possible. In the NRIM project this was taken to be:

- 0.5m above dam crest level for impounding reservoirs
- 0.1m above crest level for non-impounding reservoirs
- At crest level for service reservoirs

However, it was found that this assumption led to overestimates of reservoir storage capacity in some cases, particularly for reservoirs with a low dam where the volume assumed to be stored above crest level was a significant proportion of the total volume. In addition the fact that reservoirs below 25,000m^3 have not historically been subjected to statutory inspection means that they are likely to have small spillways and are therefore perhaps more likely to fail before crest level is reached. If the worst credible case is to be modelled it is considered that the reservoir must be full to crest level, as it is perfectly reasonable for this to occur through blockage of the spillway. However, it may not be appropriate to assume any further water level rise above the crest.

3.4 Detailed method

The Detailed method would involve the same modelling techniques as outlined in the Intermediate method but would aim to base the inundation modelling on bespoke hydrographs. This would require a desk study or site visits to collect relevant data for each reservoir. Details of the data sources that can be used to collect this information are discussed in section 2.

A measurement of dam height from the available DTM could be used with the reservoir area, obtained during the search for reservoirs, to estimate the escapable volume. The worst case scenario in terms of potential inundation would be attained if the volume was calculated by multiplying dam height by reservoir area. However, this is considered to be unrealistic for most reservoirs (with the exception of service reservoirs) as this assumes that the reservoir must have vertical sides and a perfectly flat bed. Another potential estimate of escapable volume is to use a multiplication factor such as 1/3 dam height multiplied by area. From analysis of the data collected in the NRIM project this value of 1/3 was judged to be approximately the average ratio between dam height and volume. However, if this were used it would have to be accepted that since this is only the average relationship, in some cases it could underestimate or overestimate the stored volume. There would be significant uncertainty in any volume estimated in this way, due to the deficiencies in the quality of dam height data and the assumptions that must be made in deriving a relationship between dam height, surface area and volume.

Equipped with a dam height, an estimated escapable volume, dam type and reservoir type a custom-made hydrograph can be derived for each reservoir based on the same specification used in the NRIM study.

This methodology can provide information relating to multiple breaches and can also incorporate cascade scenarios. When the failure of downstream reservoirs would result from the release of water into them (from the subject reservoir) the volumes of the downstream reservoirs are added to the volume of water from the subject reservoir. Fully automated procedures would be used to identify potential cascade reservoirs using the same specification as that for Phase 1 of the NRIM Study. Where these reservoirs are greater than 25,000m^3, it may be assumed that these would not be breached by the smaller upstream reservoir.

Once completed, the inundation modelling would allow a consequence assessment for current reservoirs to be carried out. This would involve similar techniques to those described in the Intermediate method. The consequence assessments for all reservoirs can then be used to produce evidence for whether the minimum reservoir volume to be covered by reservoir safety legislation should be changed.

Where site visits are required it would be sensible to also obtain information about the condition of the reservoir and dam in order to carry out a high-level likelihood of failure assessment based on condition and dam type.

3.5 Comparison of methodologies

Figure 3.1 shows a flow chart of each of the proposed methodologies. This clearly defines the major steps and processes involved in each method to allow a direct comparison of the methodologies to be made.

Table 3.1 is provided to show a comparison of the proposed methodologies.

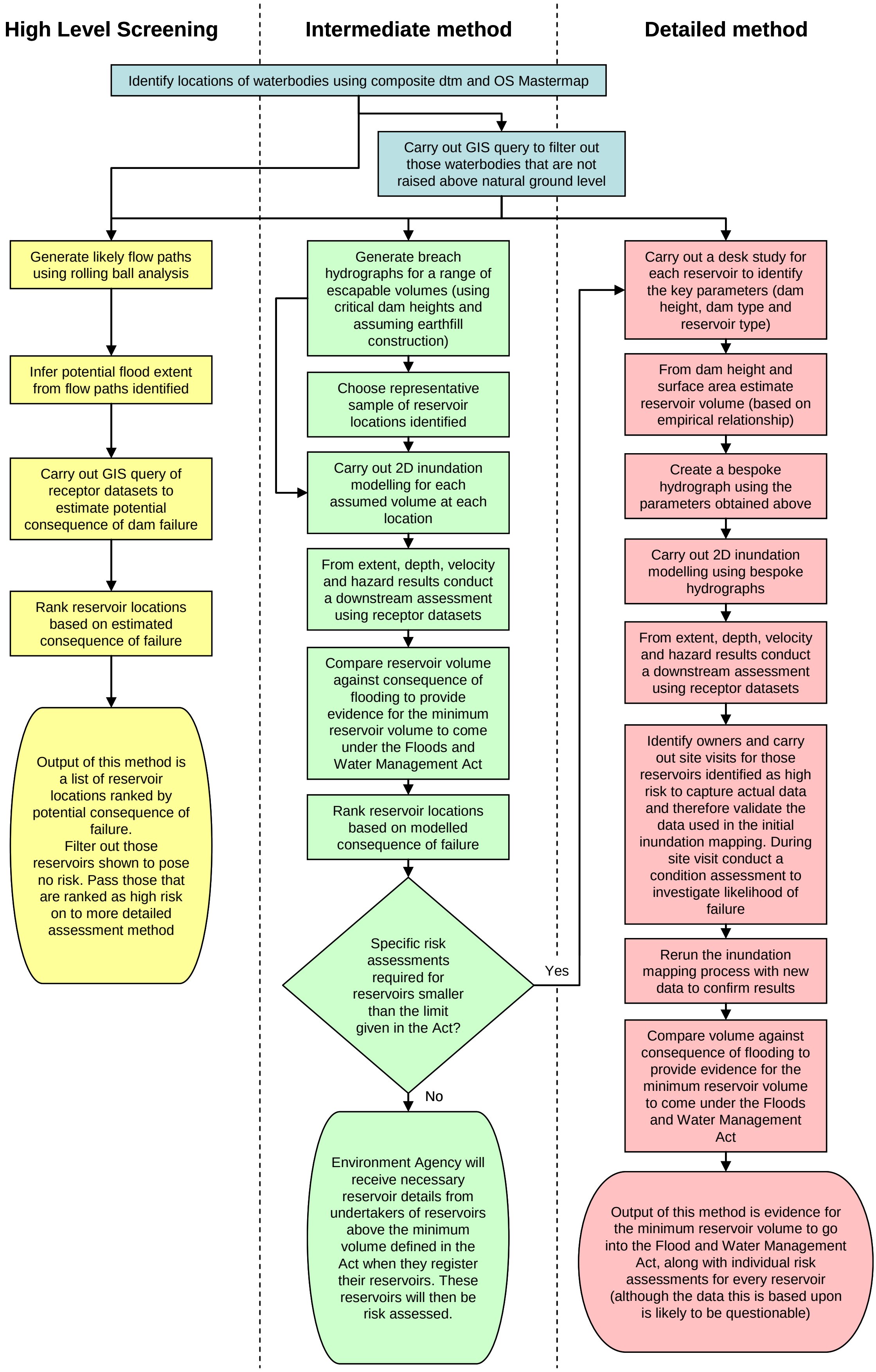


Figure 3.3 - Flow chart of risk assessment methodologies

Table 3.1– Summary of the usefulness of outputs from each of the proposed methodologies

Level of Analysis	Typical decisions supported	Assumptions made	Supporting methods and tools	Supporting data	Risk metrics provided
High Level Screening	Identify reservoir locations which may be high risk (due to high consequence of failure) and therefore require further study	No consideration of reservoir details, reservoir is assumed to fail and flood wave is assumed to travel a fixed distance downstream All waterbodies located assumed to be raised reservoirs	Rolling ball analysis to find flow paths from reservoir location, overlaid with receptor details to find locations potentially at risk	DTM (InSAR/LIDAR composite) OS Mastermap "Water" theme	Ranked list of waterbody locations by potential consequence of failure (independent of reservoir details)
Intermediate	Determination of appropriate minimum volume for reservoirs in the Flood and Water Management Act Identify reservoir locations which may be high risk and therefore require further study	All waterbodies located assumed to be raised reservoirs No consideration of reservoir details – 'worst case' hydrographs for different reservoir volumes are modelled at each location Assumes that location of current reservoirs is indicative of location of future reservoirs	NRIM-style inundation mapping using 2D modelling software. Results interrogated against EA receptor datasets to find consequence metrics	DTM (InSAR/LIDAR composite) OS Mastermap "Water" theme	Consequence of failure on different receptors at different assumed capacities, either by location or aggregated over a region, or nationally
Detailed	Individual risk assessment for each reservoir Determination of appropriate minimum volume for reservoirs in the Flood and Water Management Act	Embankment is assumed to be captured accurately in the DTM when assessing dam height Volume determined using assumed relationship between surface area and volume Dam type either assumed to be earthfill or determined as best as possible through aerial photos See table on available data sources for more details – it will be necessary to make assumptions for all reservoir data collected	As above, but reservoir data collected from various sources, including Google Earth, site visits, DTM	DTM (InSAR/LIDAR composite) OS Mastermap "Water" theme Google Earth Site visits	Consequence of failure based on best available reservoir details Likelihood of failure based on best available reservoir details NOTE – reservoir information is likely to be poor quality if derived from a desk study

4. Case studies

4.1 Introduction

4.1.1 Reservoir selection

A number of case studies have been carried out to test the validity of the three proposed methodologies. In selecting the case study reservoirs every effort has been made to ensure adequate representation of the full range of conditions that are anticipated within the national reservoir stock.

Ten case study reservoirs have been selected that each demonstrates one or more of the following attributes:

1. Located in a defined valley
2. Located in a wide, open ill-defined valley
3. Located close to a densely populated urban area
4. Located in a sparsely populated rural area
5. Multiple breach locations with significantly different flow paths
6. Multiple breach locations with flow paths that can quickly merge
7. Potential to trigger other reservoirs in cascade
8. Potential to be triggered by other reservoirs in cascade

Service reservoirs and flood storage areas were not selected for the case study trial as the modelling of these reservoirs is no different to that of the other reservoir types identified. The key difference comes in the availability of detailed information for these reservoir types. For these reservoirs it is very hard to obtain data from a desk study (as service reservoirs are often buried, and flood storage areas are often empty), but the necessary data are expected to be held by water utility companies and by the Environment Agency.

The intention was for the case study reservoirs to be selected such that the key reservoir details were known or could be accurately obtained. This would allow an assessment to be made of the quality and reliability of the available desk study data sources. However, the fact that the reservoirs covered by this study are below 25,000m³ in capacity means that they have not historically been covered by reservoir safety legislation, and consequently little is known about them. It has therefore been necessary to locate most of the case study reservoirs by examining aerial photographs. Experience gained in the NRIM project has also been used to identify reservoirs as, during this project, a number of reservoirs were identified which are not registered under the Reservoirs Act 1975.

The selection of case study reservoirs in this way means that accurate information is only available for one of the case study reservoirs (U5010_NW). For all other reservoirs it is only possible to compare the results from the desk study against each other. In addition, except in two cases, it has not been possible to identify the owners of the reservoirs selected for use in the case studies. For this reason, the case study reservoirs are not identified in this report, but are given a unique reference number instead.

Table 4.1 – Matrix of attributes of case study reservoirs

Reservoir number	Region	Located in defined valley	Located in wide, ill-defined valley	Located close to densely populated urban area	Located in sparsely populated rural area	Multiple breach locations with significantly different flow paths	Multiple breach locations with flow paths that quickly merge	Potential to trigger other reservoirs in cascade	Potential to be triggered in cascade	Service reservoir	Flood Storage Area
U5001_NW	North-West	✓		✓				✓	✓		
U5002_NW	North-West	✓			✓				✓		
U5003_NW	North-West	✓		✓							
U5004_NW	North-West		✓		✓		✓		✓		
U5005_SO	South	✓			✓			✓			
U5006_TH	Thames		✓	✓					✓		
U5007_AN	East Anglia		✓		✓	✓					
U5008_NW	North-West	✓		✓							
U5009_NW	North-West	✓		✓				✓	✓		
U5010_NW	North-West	✓		✓		✓					

4.1.2 Reservoir analysis

The ten case study reservoirs have been analysed using all three methodologies to allow a comparison to be made of the results and likely costs. In addition, a sample area of the DTM has been analysed to test the methodology for locating reservoirs.

Inundation modelling has not been carried out for the Detailed method as the modelling technique is the same as that used in the Intermediate method, albeit with a bespoke hydrograph. For the Detailed method, a desk study has been carried out to find the necessary data (e.g. dam height, storage volume) from the available data sources. For a selected sample, several individuals have also been asked to use the various data sources in order to assess the potential for user subjectivity to affect the results.

4.2 Results

4.2.1 Identification of small raised reservoirs

To establish a method for identifying small raised reservoirs a variety of techniques have been tested. These have all been carried out using ArcGIS tools. The initial stage involves conducting a slope analysis to locate flat areas which are likely to represent waterbodies within the DTM. This process was tested on an area of DTM in the North West of England.

The slope analysis method is outlined in Section 3.1 and locates all flat areas within the DTM, and must therefore be filtered to remove features that are not waterbodies. During this analysis it was discovered that some reservoirs are not represented as completely flat areas within the DTM. An interesting comparison between DTMs at this stage has shown that waterbodies are represented as flat areas within the NEXTMap Britain DTM whereas in the LIDAR Composite DTM they are often not represented as perfectly flat areas. This appears to be because waterbodies have been manually enforced in the NEXTMap Britain DTM, but have not been enforced in the LIDAR Composite DTM. On this basis it is proposed that the NEXTMap DTM be used for the purpose of the slope analysis.

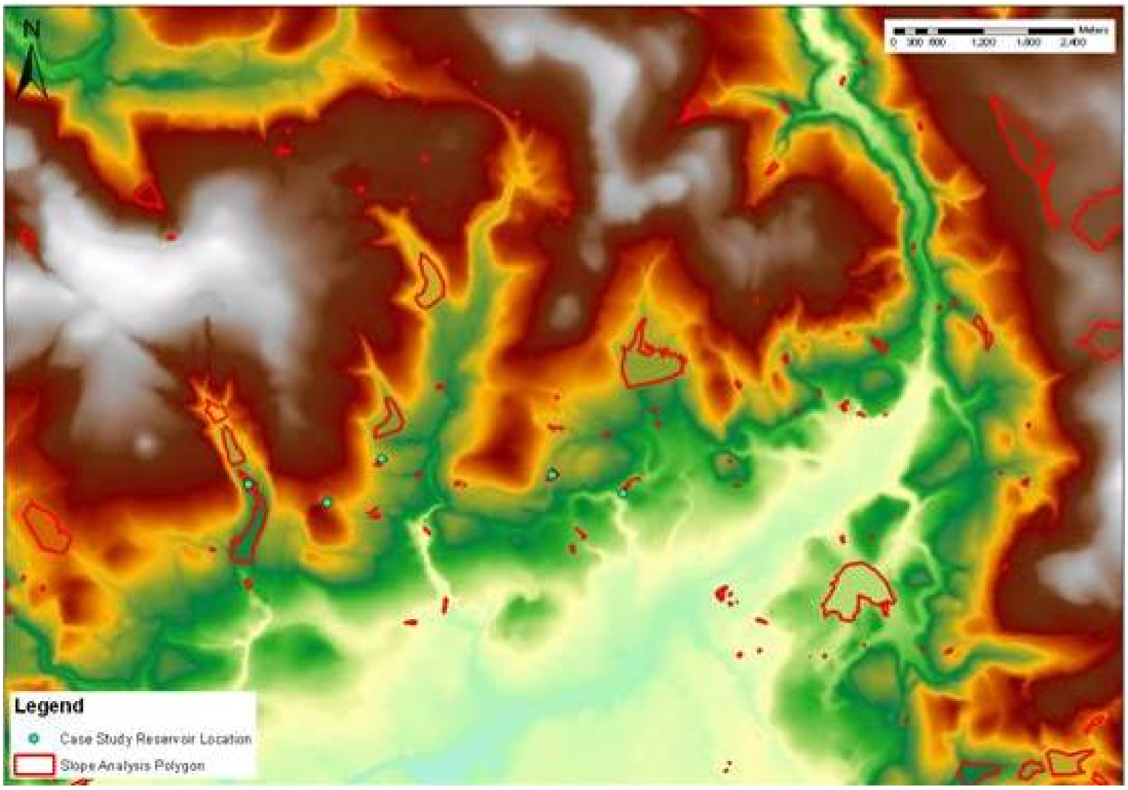


Figure 4.1 - Initial results from slope analysis

Figure 4.1 shows a sample area and the polygons extracted using this technique. It can be seen that some polygons are waterbodies whilst some (particularly those that are very small) are not and would need to be filtered out using the filtering techniques outlined in section 3.1. All of these techniques would be required in order to obtain as accurately as possible a geo-referenced list containing only small raised reservoirs.

At this stage the refined dataset could be filtered manually by viewing each waterbody individually by reference to OS 1:10,000 scale mapping, NEXTMap DTM and Google Earth Imagery. An assessment of whether it appears to represent a raised reservoir with a capacity of less than 25000m^3 can then be conducted. It would be difficult to refine the search at this stage using automated techniques.

Ultimately using this technique it is inevitable that some small reservoirs will be missed. However following the case study process it is thought that 90% of small reservoirs could be located successfully. This estimate is based upon previous work carried out and the case study testing on small sample areas. In addition, some of the waterbodies finally selected may, in fact, be natural lakes which do not fall within the remit of this study. It is considered that this is acceptable as it is likely that where water bodies are flagged as high risk these will be investigated further and any water bodies not within the remit of this study will be identified at this stage.

It should be noted that this method will identify reservoirs of all sizes, including those already registered under the Reservoirs Act 1975, and those between 10,000m^3 and 25,000m^3 in capacity that are required to be registered under the Flood and Water Management Act. The use of the RESS to filter out those reservoirs registered under the Reservoirs Act 1975 will remove those with a capacity of greater than 25,000m^3. The filtered list will therefore contain all reservoirs with a capacity of less than 25,000m^3. The fact that it is not possible to accurately determine reservoir volume from a desk study alone means that it is difficult to filter this list further to identify only those reservoirs that are smaller than 10,000m^3. However, for the purposes of determining the minimum reservoir volume for inclusion in the Flood and Water Management Act this is not a problem, as typical reservoir locations are not anticipated to vary significantly with volume. Furthermore, if reservoirs above 10,000m^3 in capacity are identified and their consequence of failure subsequently assessed, this will provide a useful starting point for further study once these reservoirs are registered with the Enforcement Authority.

4.2.2 High Level Screening method

Input data for this method includes the following:

- DTM
- Reservoir location
- Breach location

The DTM used for the purposes of this study was the LIDAR InSAR Composite DTM processed to a 5m resolution. This was selected as it provides the most up to date information available.

The breach locations for each of the case study reservoirs have been manually selected with reference to the DTM, Ordnance Survey (OS) 1:10,000 Scale Mapping, and Google Earth Imagery. These datasets were used to identify the toe of the dam or other suitable low point to position the breach line. Two out of the ten case study reservoirs required multiple breach locations to be investigated.

Using the tools within ArcGIS (ArcHydro) a likely reservoir flood inundation flow path was identified. The tools pick out the low points in the DTM running from the selected breach location, therefore representing the drainage path. This line is generated from the breach location to the edge of the DTM. A comparison between the ArcHydro drainage path generated using the selected LIDAR InSAR Composite DTM and that from NEXTMap data was conducted. This showed significant differences in the route of the drainage line produced for some of the case studies. An example of this is illustrated in Figure 4.2 which shows two drainage paths for the same breach location. The blue line represents that generated using the NEXTMAP DTM. This follows the expected route from looking at the OS 10K Map and Google Earth Imagery. The red line generated using the LIDAR InSAR Composite DTM clearly takes a different route which is not expected. Several attempts were made to force the ArcHydro line produced using the LIDAR Composite DTM to follow the expected route by selecting different starting points for the drainage line within the DTM in this area, but this was unsuccessful. However, when using the same LIDAR InSAR Composite DTM to carry out the intermediate method 2D modelling (described in section 4.2.3) the flow followed the expected drainage route as defined using the NEXTMap DTM.

Despite this anomaly it is considered that the LIDAR InSAR Composite DTM represents the most up to date and accurate information available so would be used in preference to the NEXTMap DTM for this task. This problem emphasises the subjective nature and variability of this technique.

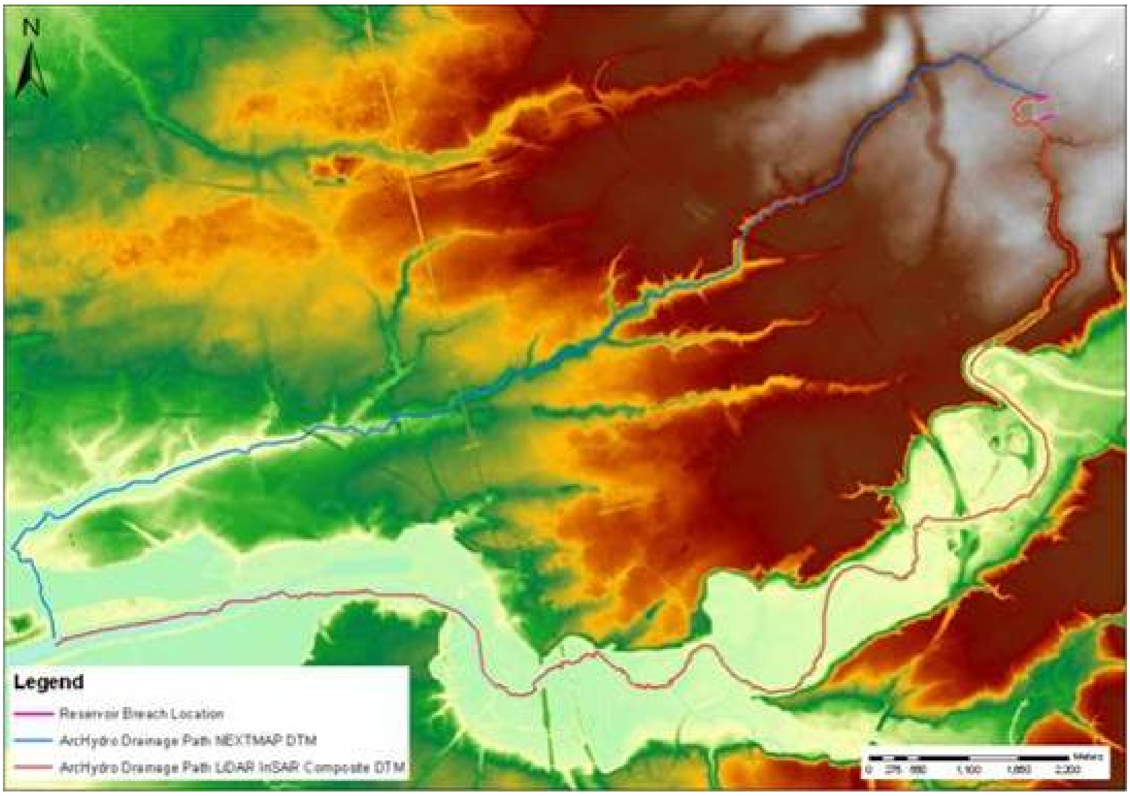


Figure 4.2 - ArcHydro centreline discrepancy

Once the flow paths had been created they were cut down to the length considered to represent the potential flood inundation area for each reservoir breach location. This procedure used the following rules as guidance:

Cut off the ArcHydro drainage line:
- At the downstream extent of any major urban area
- At any major confluence
- At any major bridge/weir/culvert.

Buffers were then created for the shortened drainage lines. It was hoped that this buffer process would allow an approximate flood inundation area to be created. Three different techniques were investigated for this purpose. These are illustrated in the figures presented in Appendix A of this report.

The first, and most simplified, technique investigated was based on delineating urban areas along the flow path. This was carried out with reference to OS 1:50,000 Scale Mapping together with data points from the Ordnance Survey's Address Layer 2 dataset. Polygons were manually drawn in ArcGIS to represent urban areas (this process could not be automated). Where the likely area of inundation was very urbanised, the urban area was broken down by using major roads or other significant infrastructure. The idea behind this technique was to use the urban area as a buffer and to calculate a percentage of each urban area likely to be inundated. This technique was not advanced further owing to problems encountered in delineating the appropriate limits of urban areas. This is illustrated in Figure 4.3, where arbitrary cut-offs were used to avoid extending the urban area to unmanageable and unrealistic proportions:

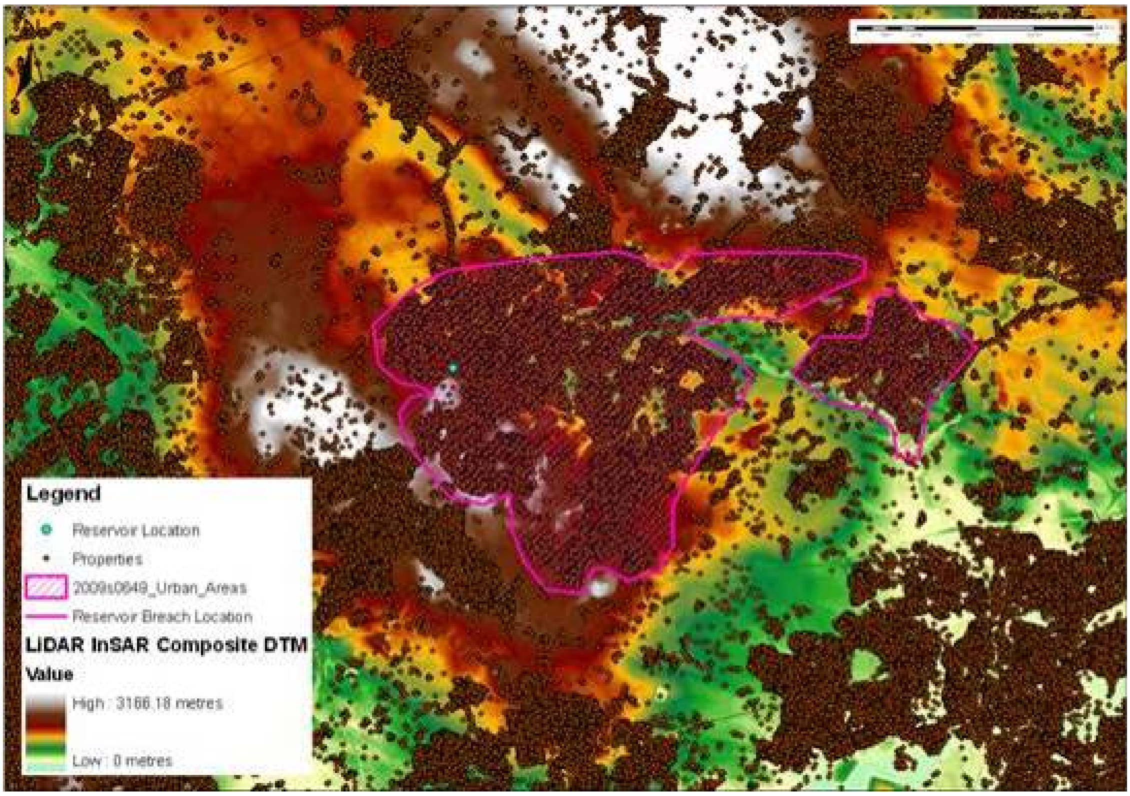


Figure 4.3 - High Level Screening method urban area delineation

The second technique to approximate flood inundation areas involved the use of existing flood datasets. For the purposes of this exercise the Environment Agency's Flood Zone 2 data representing the 1 in 1000 year return period flood event was selected. This dataset was chosen as it was considered to be the most similar to reservoir breach scenarios. In order to pick out the areas of the flood zone applicable to each breach location it was necessary to trim the flood zone dataset to match the length of the drainage path line, excluding any tributaries which would not be inundated by the flood water from the reservoir. This was done manually using informed judgement and is a process that could not be automated. This is illustrated in Figure 4.4.

The third technique that was investigated involved hill contouring. This technique was more complex, involving striking out cross sections along the drainage path at selected intervals to a defined height in the DTM. The height selected after testing was set at 6 metres above the breach level. This value was chosen as it seemed to provide the best representation of the floodplain. Several cross section spacing intervals were tested including 50m, 100m and 200m. In order to create the buffer to represent the flood inundation outline the end points of the cross sections were joined to create a polygon. This was done manually owing to the small number of case study reservoirs; however, this process could be automated. This was all carried out using ArcGIS tools and is illustrated in Figure 4.5.

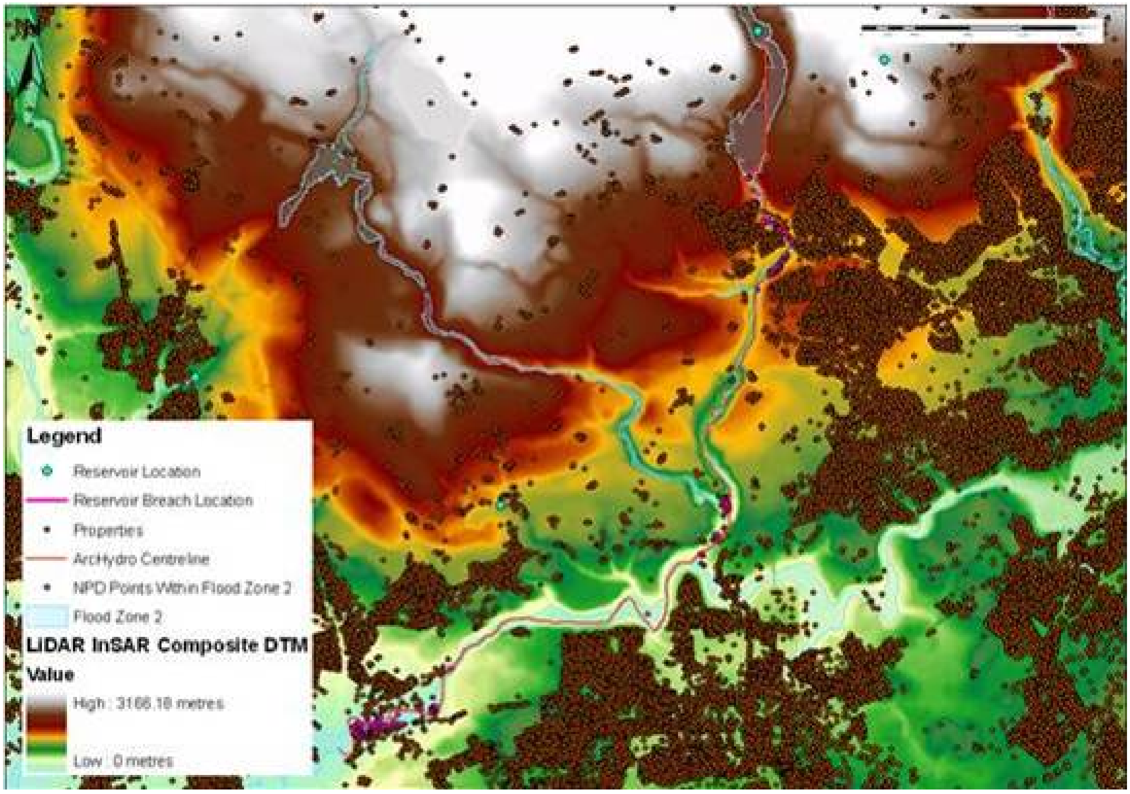


Figure 4.4 - High Level Screening method Flood Zone 2 buffering

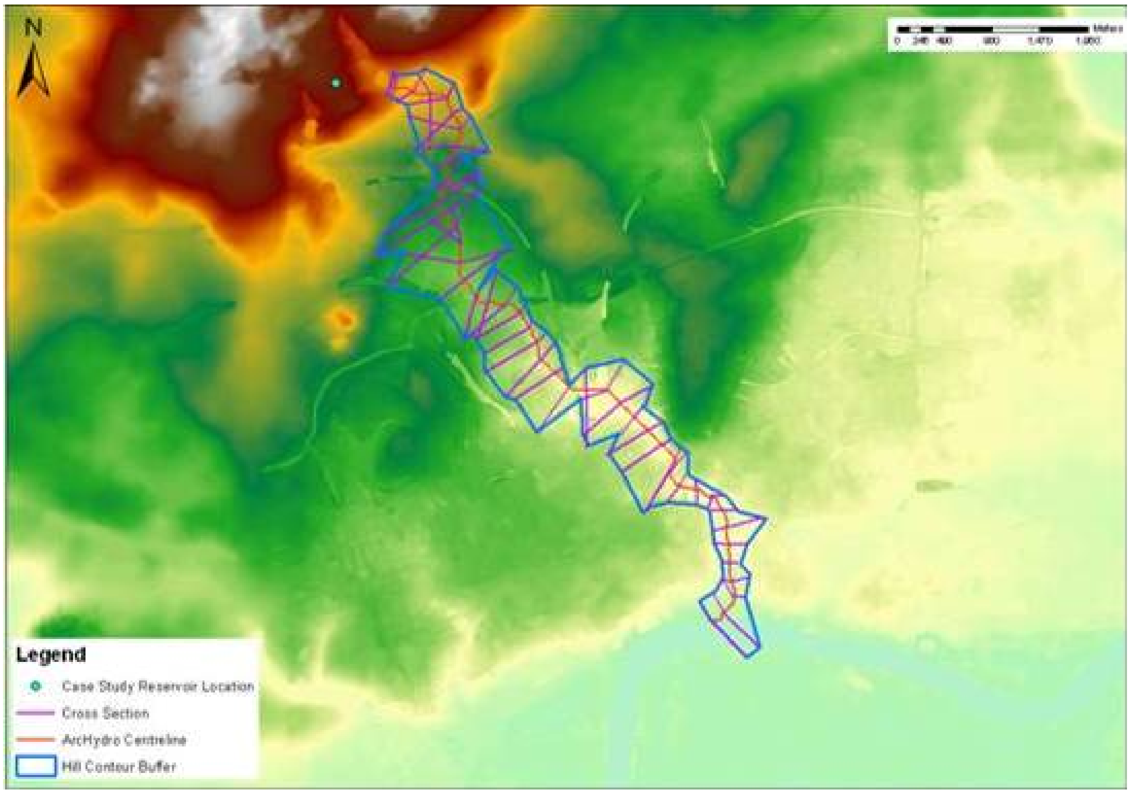


Figure 4.5 - High Level Screening method hill contour buffering

Once equipped with the buffers from each of the three different techniques outlined above the number of properties falling within the inundated extents could be extracted. This was achieved using the Ordnance Survey's Address Layer 2 dataset This analysis could be carried out to extract the number of points within other datasets representing for example, cultural heritage sites or critical infrastructure. Similarly, areas intersecting with datasets represented by polygons such as Sites of Special Scientific Interest (SSSI) could be identified. For datasets represented as polygons, it would be possible to identify whether or not they are present within the expected inundation extent, and the percentage of the polygon area inundated. Examples of the results obtained from this analysis are included in Appendix A of this report.

Overview

The overall advantage of this method is that it does not require many data inputs as no hydrographs are required. Essentially the only information required is the reservoir and breach locations.

The disadvantages of the High Level Screening method were numerous. Carrying out the method for the case study sample was time consuming and subjective. Informed judgement was required at all stages, reducing the possibilities available for automation. To carry out the High Level Screening method for one case study was more time consuming than setting up and running six different hydrographs per reservoir using the Intermediate method.

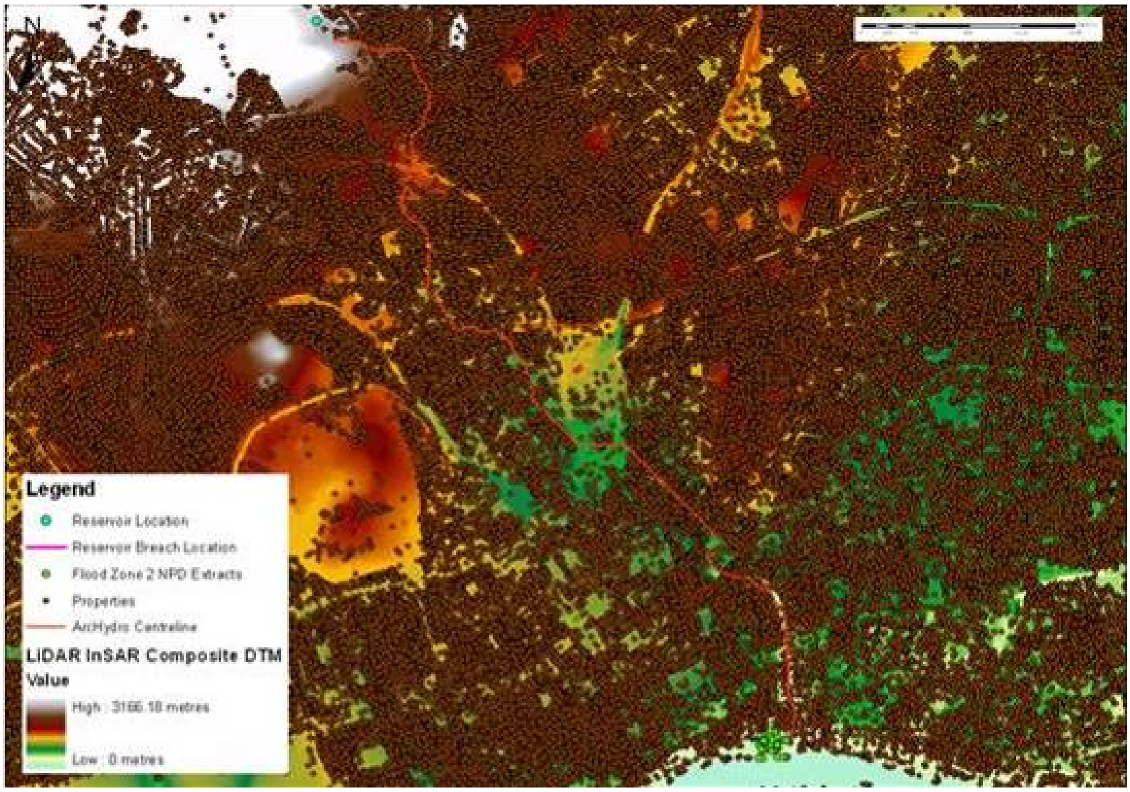


Figure 4.6 - High Level Screening method Flood Zone 2 problem

As demonstrated in Figure 4.2 above the use of a different DTM produced very different drainage path routes. This would result in a very different flood inundation area being produced and thus very different risk assessment results. As the availability of DTMs across England and Wales is variable the consistency of the results obtained using the High Level Screening method is therefore questionable.

More manual intervention was required than anticipated in order to buffer and extract property counts. Specific problems included difficulties in delineating urban areas in heavily urbanised areas (illustrated in Figure 4.3 above).

The flood zone buffering technique was flawed by an absence of flood zone data in the vicinity of some reservoirs. This is illustrated in Figure 4.6, where it can be seen that the flood centreline passes through a heavily urbanised area, but only a very small number of properties fall within the flood zone (shown in green at the bottom of the figure).

In addition, it was difficult to pick out cut-off points in the flood zone data, especially where tributaries are present, to create refined buffered outlines.

Buffering using hill contouring techniques also proved problematic. Where cross sections were spaced at 50 and 100 metre intervals there was a significant amount of overlapping of the cross-sections making it very difficult to differentiate between cross sections and to create the buffered outline. This created a significant amount of dog-legging of the buffered outline. At a 200 metre spacing cross sections were found to be too far apart and the buffer created was too crude, cutting across the channel in some cases. The buffered outline created varies according to the cross section spacing selected (illustrated in Figure 4.7).

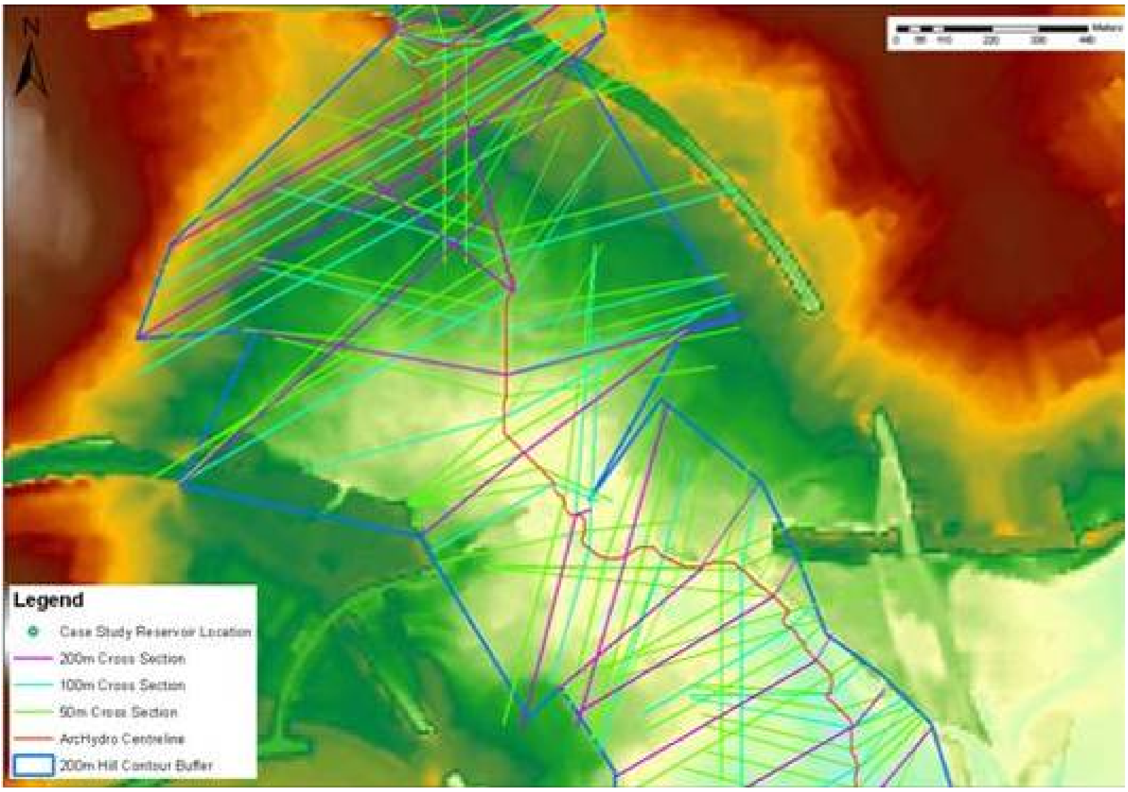


Figure 4.7 - High Level Screening method hill contour buffering problem

The problems outlined above emphasise the subjectivity involved in creating flood inundation area buffers based upon drainage pathways. This has a significant impact upon the estimated number of properties at risk and other data extracted for input to the risk assessment process. When comparing the buffers and drainage paths generated using the High Level Screening method with those from the Intermediate method gross over estimates were immediately apparent. This is illustrated in Figure 4.8 which clearly shows that the High Level method drainage line has been cut at a point a significant distance further downstream than the Intermediate method model results indicate to be the downstream limit of the flood inundation area.

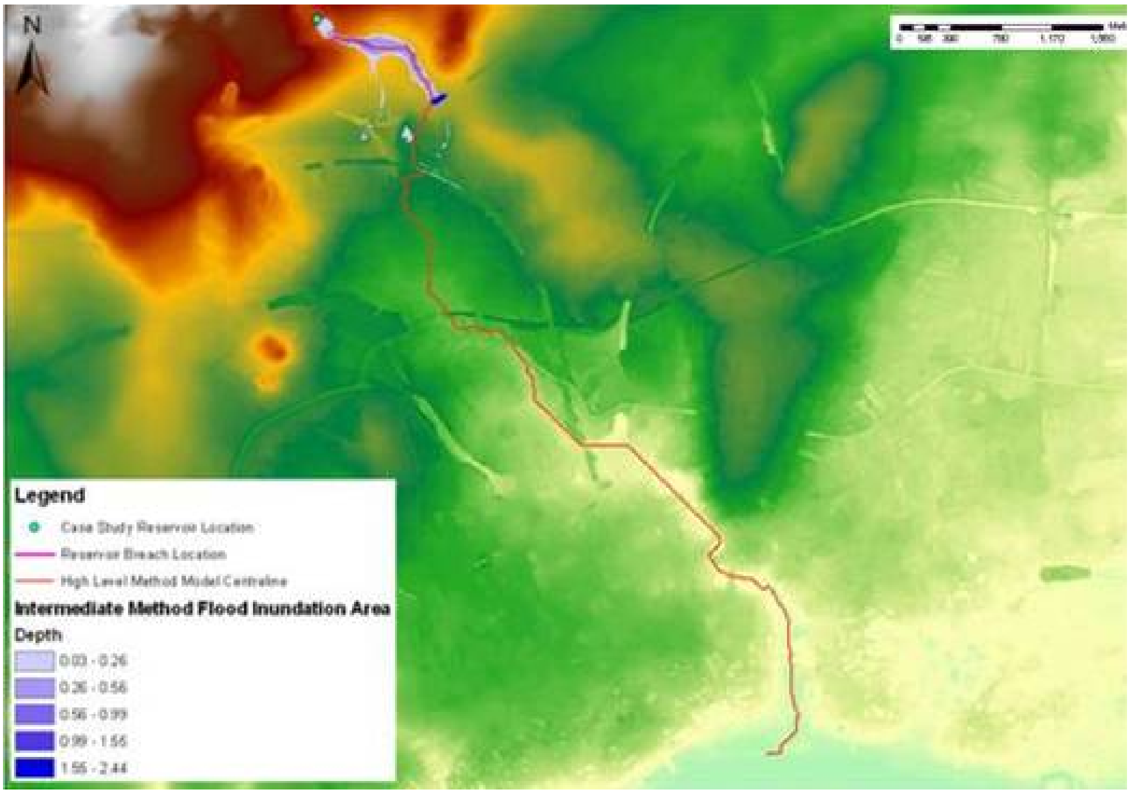


Figure 4.8 - Comparison between High Level Screening & Intermediate method model domains

A comparison of the results obtained from the property counts from the flood zone and hill contour buffering techniques emphasises the problem of subjectivity in creating buffered outlines, showing significant differences in the number of properties identified as 'at risk' using different methods. This is demonstrated in Table 4.2 below:

Table 4.2 - Comparison of results from Flood Zone 2 and hill contour buffering

Breach Reference	Number of Properties Flood Zone 2	Number of Properties Hill Contour Buffer
U5002_NW_1	2272	1059
U5004_NW_1	339	738
U5004_NW_2	348	721
U5004_NW_3	348	679
U5006_TH_1	231	29568

It must be noted that this technique does not specifically take account of reservoirs which may fail in cascade since reservoir volume is not considered in the assessment.

4.2.3 Intermediate method

The data input requirements for this method are as follows:

- DTM
- Reservoir location
- Breach location
- Dam breach hydrographs for selected reservoir volumes
- Defined model domain

The DTM used for the purposes of this study was the LIDAR InSAR Composite DTM processed to a 5m resolution. This was selected as it provides the most up to date information available.

The Intermediate method involved several discrete activities to provide the necessary data for input to the 2D modelling software. The first task was to identify breach locations for each of the case study reservoirs. This was carried out with reference to the DTM, Ordnance Survey (OS) 1:10,000 Scale Mapping, and Google Earth Imagery. These datasets were used to identify the toe of the dam or other suitable low point to position the breach line to best represent the worst-case breach location. Two out of the ten case study reservoirs required multiple breaches.

The second task involved defining the model box domain for each breach location. The model box domain represents the area of DTM extracted and used for modelling purposes. This is specified in such a way as to ensure that the potential flood inundation area is entirely within the model domain. This is achieved using informed judgement and generally adjustments are required after initial model runs.

The final task involved in model set up is to define hydrographs for input to the model. As discussed in Section 3.3, a set of generic hydrographs was used to represent reservoirs with a volume of 2,500m^3, 5,000m^3, 7,500m^3, 10,000m^3, 12,500m^3 and 15,000m^3. These were calculated using the empirical method for embankment dams proposed by Froehlich, D. C, (1995), as implemented in the NRIM Specification (Evans et al, 2009). This ensures consistency with the NRIM project. These hydrographs are represented in Table 4.3 and Figure 4.9 below.

Table 4.3 – Dam breach hydrographs used

Volume (m³)	Dam height (m)	Flow at Start of Breach Q_o (m³/s)	Peak Flow Q_p (m³/s)	Flow at End of Breach Q_e (m³/s)	Time at Start of Breach T_o (s)	Time of Peak Flow T_p (s)	Time at End of Breach T_e (s)
2,500 m³	2.36	0.00	26.51	0.00	0.00	94.29	188.58
5,000 m³	2.93	0.00	42.63	0.00	0.00	117.28	234.56
7500 m³	3.33	0.00	56.29	0.00	0.00	133.24	266.48
10,000 m³	3.65	0.00	68.55	0.00	0.00	145.87	291.74
12,500 m³	3.91	0.00	79.88	0.00	0.00	156.48	312.96
15,000 m³	4.14	0.00	90.51	0.00	0.00	165.72	331.45

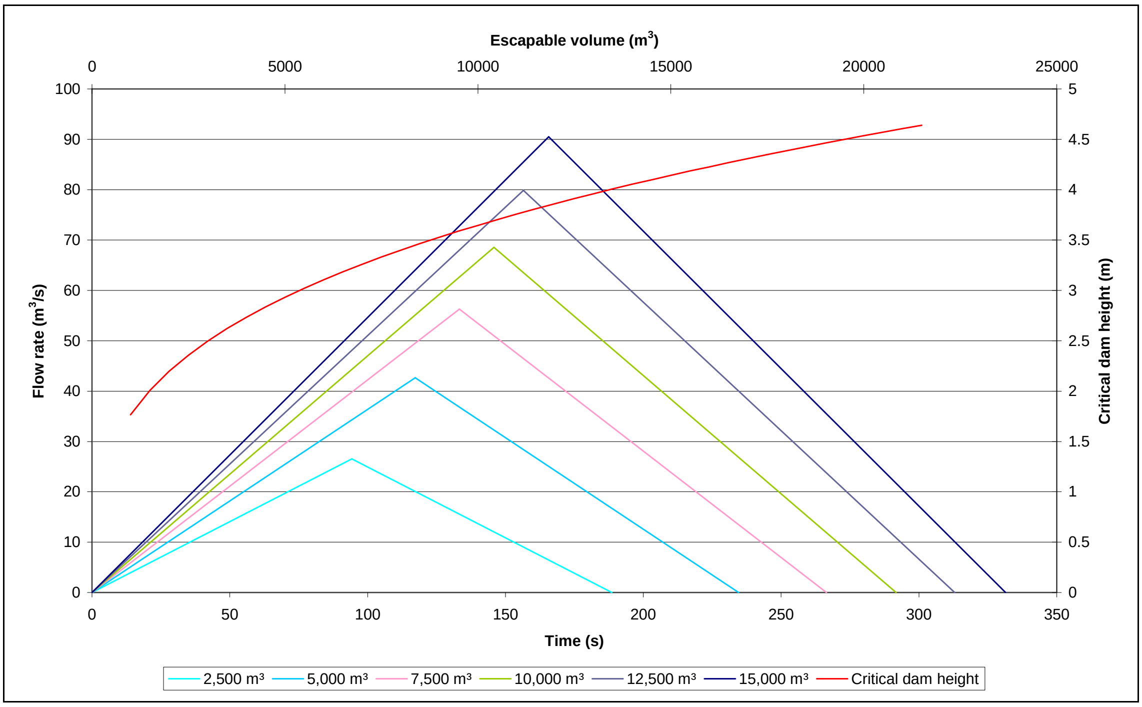


Figure 4.9 – Dam breach hydrographs used

Simulations for each of the six selected volumes were run using 2D modelling software. This was set up to output model results (depth and velocity) at two minute intervals. This time interval could be increased to five minutes to speed up both modelling and post processing and to reduce the size and quantity of output data. The model results were post processed to produce the following results at each point of interest:

- Maximum depth
- Maximum velocity
- Flood Hazard Rating
- Time of initial inundation
- Time of maximum inundation

This was carried out using ESRI ArcGIS software by spatial comparison of the dam breach inundation modelling results with the Address Layer 2 dataset. The post processed results also include combined breach results for each of the parameters listed above for multiple breach scenarios.

Although in this case the flood receptor dataset used in post-processing was the Address Layer 2, any similar GIS dataset, whether represented by points or polygons, could be used, for instance to determine whether there are any protected areas or sites of cultural heritage which fall within the predicted flood extent.

A 2D modelling approach was selected as the most appropriate modelling technique and for the purposes of this study JFLOW-GPU hydrodynamic model software was used.

Assessment of consequence

The post-processed results from all the breaches modelled have been combined into a database in Microsoft Access, from where the data has been manipulated in order to derive the Likely Loss of Life (LLOL) for each breach.

The Likely Loss of Life (LLOL) is a measure of the likely number of fatalities due to a dam breach, and has been derived as recommended in Figure 9.1 of the Interim Guide to Quantitative Risk Assessment for UK Reservoirs (Brown and Gosden, 2004). This table relates the maximum value of the product of velocity and depth at a property to the fatality rate. Two different relationships are provided, depending on whether residents have no warning or greater than 60 minutes warning. At each property the time to initial inundation has been evaluated in order to determine which relationship should be used. These relationships are illustrated in Figure 4.10.

In order to derive LLOL from the fatality rate values it has been assumed that there are 2.4 people in each inundated property. Property type has not been taken into account – every property is simply represented by a point co-ordinate and is assumed to contain 2.4 people.

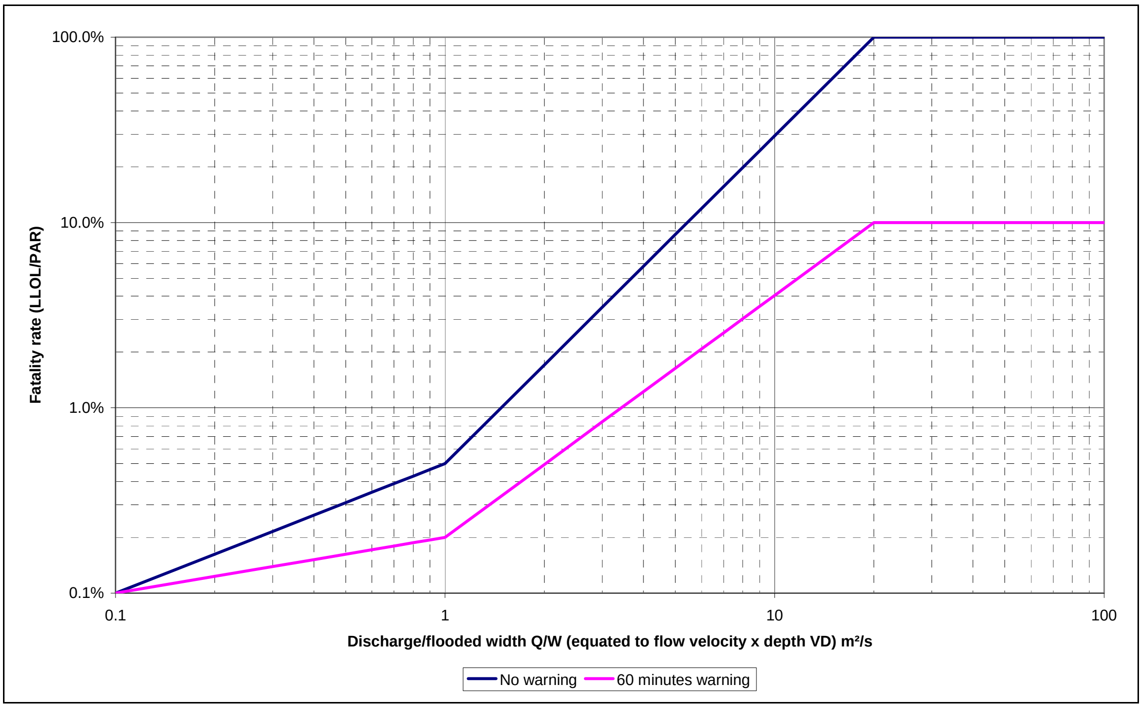


Figure 4.10 – Relationship between fatality rate and force of water suggested in the Interim Guide to QRA for UK Reservoirs

Determining the appropriate minimum reservoir volume for the Flood and Water Management Act

Figures 4.11 and 4.12 show the variation in LLOL and in the number of properties inundated with assumed reservoir volume. It can clearly be seen that for the case study sample of 10 reservoirs, downstream consequence increases as reservoir volume increases. From a similar set of results based upon a representative and statistically significant sample of all small raised reservoirs in England, it would therefore be possible to determine an appropriate minimum reservoir volume for the Flood and Water Management Act. However, in order to do this it is necessary to determine what level of risk (or what potential downstream consequence) is acceptable. It will therefore be necessary to link with Defra research study FD2641 "Scoping the process for determining acceptable levels of risk in reservoir design" to ensure that this study produces outputs that can be used for this purpose.

Reservoir U5007_TH is an outlier amongst the case study reservoirs in that it has a much greater potential downstream consequence than the other reservoirs included in the case study. This is because this reservoir is located in the middle of a very densely populated urban area. It is anticipated that if a larger sample of reservoirs were modelled this reservoir would continue to be close to the upper bound of downstream consequence, but that it would not be such an outlier compared to other reservoir locations.

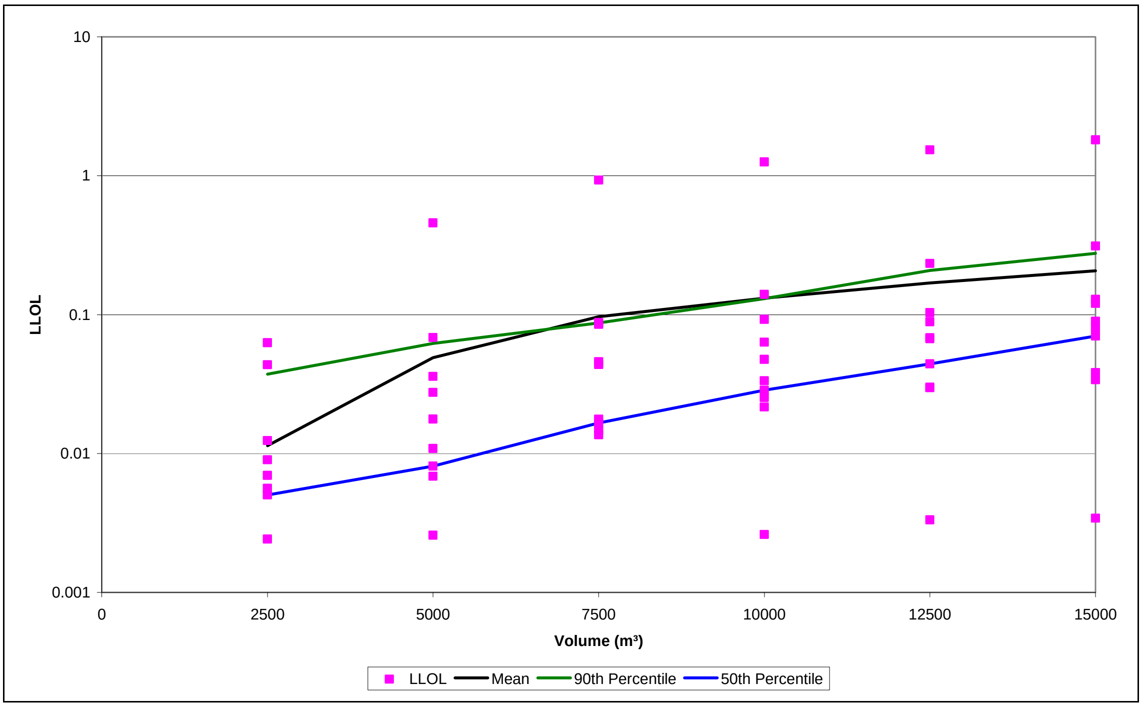


Figure 4.11 – Variation of LLOL with assumed reservoir volume

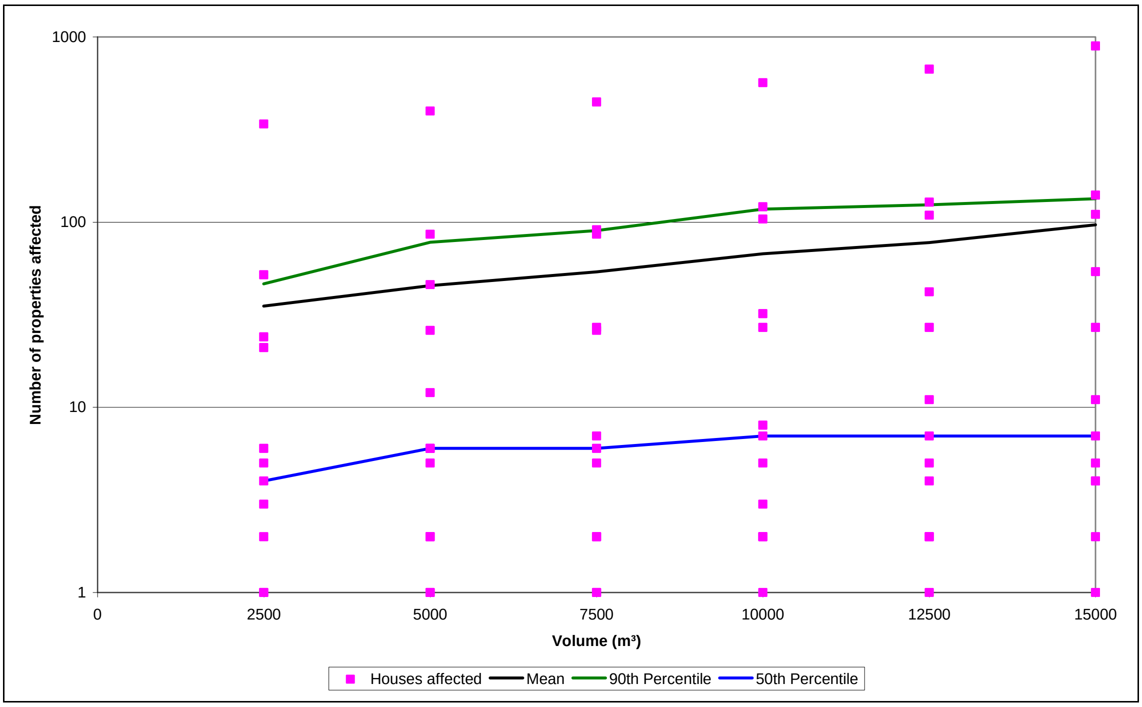


Figure 4.12 – Variation of number of properties at risk with assumed reservoir volume

Overview

This method uses simple inputs and involves very little manual intervention once the model is established. The results produced from this method are detailed and can be used to extract information based at selected points within the Address Layer 2 dataset.. This information has in turn been fed into detailed flood risk assessment tools to calculate statistics such as Likely Loss of Life (LLOL). The same process can be used to extract this information for any location represented by a point, including for example critical infrastructure, environmental protected sites and cultural data. In addition, information represented by a region could be overlaid with the flood inundation extents, for example to show whether any SSSIs are potentially affected. This analysis is automated, and the results obtained are not based upon subjective decision making.

The method facilitates detailed analysis of the intrinsic risk posed by individual reservoir locations, but because reservoir-specific parameters are not used it cannot produce individual risk assessments in accordance with the Flood Risk Regulations 2009. In order to satisfy this it would be necessary to model reservoir-specific hydrographs in line with the Detailed method. However, the results from the Intermediate method would allow the risk-based allocation of resources by prioritising reservoir locations based on their potential downstream consequence.

The most significant disadvantage of this method is the number of model runs required (six in total) for each breach to represent the different volumes of reservoir to be simulated. This produces a large quantity of data to be managed through both the modelling, post-processing and analysis stages.

This can be easily managed by setting up model log spreadsheets to record the modelling status of each reservoir.

More specifically, the results for some case study reservoirs were found to be characterised by flow back into the subject reservoir as shown in Figure 4.13 below:

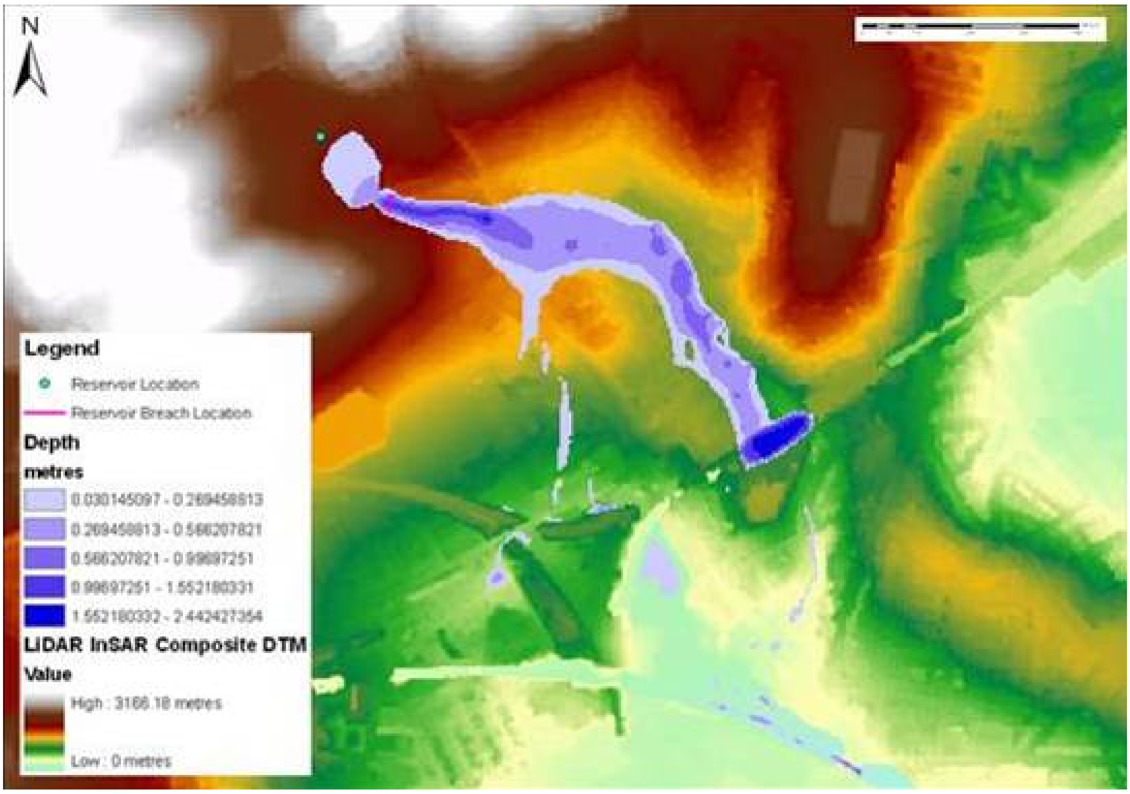


Figure 4.13 - Model results showing flow back into the reservoir from the breach location

This can be easily overcome by simply stamping subject reservoirs into the dtm to a significantly raised height. This is considered to be of particular importance for the purpose of modelling the reservoirs included in the remit of this study owing to the relatively small volumes of water involved.

Finally, this method does not specifically take account of cascade scenarios. However, it is considered that owing to the range of volumes considered in the modelling process the breach of any reservoirs in cascade downstream of the subject reservoir would be accounted for implicitly by the higher volumes simulated.

4.2.4 Detailed method

The data input requirements for this method are as follows:

- DTM
- Reservoir location
- Breach location
- Dam breach hydrograph using individual reservoir parameters (may be obtained from desk study or site visit or be provided by reservoir undertaker)
- Defined model domain

In these case studies all reservoir data has been obtained through a desk study. It would potentially also be possible to obtain all the necessary information by conducting a site visit or requesting the information from the reservoir undertaker. However, in both cases it would be necessary to first determine the ownership of the reservoirs, based only upon the reservoir location. This may be possible through use of Land Registry shapefiles, but it would be labour and time intensive and may present data licensing problems. In addition, once ownership has been determined, obtaining information will depend on the co-operation of the reservoir undertaker, either in allowing access to conduct a site visit or in providing the data directly. This may be a particular problem as the reservoirs in question have not historically been covered by reservoir safety legislation, meaning owners may be reluctant to co-operate and there is no means by which a site visit may be demanded under law.

For each of the 10 case study locations an attempt has been made to identify the following reservoir information using the DTM, Ordnance Survey (OS) 1:10k mapping and aerial photographs:

- Dam height
- Surface area
- Reservoir volume (inferred based on dam height and surface area)
- Dam construction type
- Whether the reservoir is impounding or non-impounding

The following sections summarise the results of this analysis for each of these parameters.

Dam height

For each case study reservoir the composite DTM was viewed in a GIS software package and an attempt made to determine the dam height by drawing cross-sections through the reservoir embankment. The results of this analysis can be seen in Appendix D. For some reservoirs this was straightforward, as the dam was well represented in the DTM, with a well-defined toe and crest. However, for some reservoirs, particularly those with extensive tree coverage, the dam location was not clear in the DTM, meaning that it was either not possible to ascertain the dam height, or the difference between the values obtained by different operators was very significant.

Table 4.4 below illustrates the variability of the data obtained. It can be seen that in some cases there is a good correlation between the dam height estimates produced by the different users. However, in other cases there is a 50% discrepancy between results or else no dam height could be identified at all. Estimating dam height using the DTM is a somewhat subjective process, requiring the user to exercise their judgement to define the location of the dam crest and toe. In addition the proportion of reservoirs for which it was not possible to obtain a dam height estimate is high, indicating that this method is unlikely to produce a complete data set. Given the critical role of dam height in calculating the reservoir volume and determining the breach hydrograph, it is considered that the data accuracy of this method is not satisfactory.

Table 4.4 – Dam height information obtained from desk study

Reservoir Name	**Dam Height (m)**		
	User 1	User 2	Variation
	DTM	DTM	
U5001_NW (East)	5	5.1	0.1
U5001_NW (West)	5.5	3.5	2
U5002_NW	6	7.5	1.5
U5003_NW	6	5.4	0.6
U5004_NW	6	5.3	0.7
U5005_SO (Upper)	9	-	n/a
U5005_SO (Lower)	Not clear	-	n/a
U5005_SO (Side)	Not clear	-	n/a
U5006_TH	Embankment shown on OS maps but hard to find in dtm. Position of toe is unclear.		
U5007_AN	Not clear	-	n/a
U5008_NW	-	7.3	n/a
U5009_NW	-	10.5	n/a
U5010_NW (Middle)	-	4	n/a
U5010_NW (East)	-	3	n/a
U5010_NW (West)	-	4	n/a

Surface area

Three data sources were utilised to provide estimates of reservoir surface area. Using GIS software, a polygon was manually drawn around the reservoir extent shown on the following data sources:

- DTM
- OS 1:10,000 scale maps
- Aerial photographs of the reservoir site

For the limited number of reservoirs in the case study this process was carried out manually, but it would be possible to automate by integrating it with the process for locating reservoirs described in Section 4.2.1. The results of this analysis are shown on Table 4.5 below.

Measurement of surface area from aerial photographs proved problematic as tree cover around the reservoir edges tended to mask the true surface area, potentially resulting in the surface area being underestimated.

Measurement using OS maps and using a slope analysis of the DTM yielded results which correlate well with each other and which appear not to be significantly affected by user subjectivity. However, as discussed in Section 4.2.1, it has been found that some reservoirs are not represented as completely flat areas within the DTM. A comparison between DTMs shows that the waterbodies are represented as flat areas within the NEXTMap Britain DTM, whereas in the LIDAR Composite DTM they tend not to be well represented. It is therefore proposed that the NEXTMap DTM be used for the purpose of measuring reservoir surface area.

The surface area obtained from this technique will be the surface area of the reservoir at the time the data was collected, and may not be a true reflection of the reservoir surface area at top water level (for instance if the reservoir was drawn down on that day)

Table 4.5 – Reservoir surface area information obtained from desk study

Reservoir Name	Surface Area (m^2)						
	User 1			User 2			Variation
	OS Map	DTM	Aerial photo	OS Map	DTM	Aerial photo	
U5001_NW (East)	11455	10746	8450	11310	11410	9210	3005
U5001_NW (West)	8034	7670	4400	7595	7540	5232	3634
U5002_NW	2300	2526	2240	2235	1850	2320	676
U5003_NW	8668	7453	6408	8650	8045	6990	2260
U5004_NW	10813	9545	-	10620	11130	10570	1585
U5005_SO (Upper)	11650	10080	12388	-	-	-	2308
U5005_SO (Lower)	4746	5231	4558	-	-	-	673
U5005_SO (Side)	11074	10208	7106	-	-	-	3968
U5006_TH	13755	11951	9765	13680	14400	11310	4635
U5007_AN	14522	10414	-	-	-	-	4108
U5008_NW	-	-	-	12270	12760	8680	4080
U5009_NW	-	-	-	30920	25630	26900	5290
U5010_NW (Middle)	-	-	-	-	40340	-	n/a
U5010_NW (East)	-	-	-	-	16890	-	n/a
U5010_NW (West)	-	-	-	-	22490	-	n/a

Reservoir volume

The reservoir volume is critical in determining the dam breach hydrograph, and can have a significant effect on the downstream consequences of reservoir failure. As mentioned previously, it is not possible to measure reservoir volume directly from the sources available. If reservoir volume is to be estimated it is therefore necessary to make an assumption about the relationship between volume, height and surface area.

The absolute upper bound on reservoir volume would be to assume that the reservoir has vertical walls and a flat bottom, and is given by

$$V = HA$$

However, this is considered to be unrealistically conservative for small reservoirs, which are likely to be shallow and have a sloping bed. The upper bound adopted is therefore:

$$V = \frac{HA}{2}$$

Analysis of the data held on reservoirs registered under the Reservoirs Act 1975 shows that a lower bound on reservoir volume is approximately

$$V = \frac{HA}{4}$$

This analysis also shows that the median and mode of the relationship between volume, height and surface area occur at approximately

$$V = \frac{HA}{3}$$

The above equations provide an upper bound, lower bound and best estimate of reservoir volume based on the dam height and surface area.

It can be seen from Table 4.6 that the deficiencies in the dam height and surface area data mentioned previously, combined with the different possible relationships between volume, height and area that can be assumed, give a wide range of possible volumes for each reservoir. As a result the data quality of reservoir volume information is considered to be too low even for use as an initial estimate which would be refined later.

Table 4.6 – Reservoir volume information obtained from desk study

Reservoir Name	**Reservoir volume (m³)**					
	V=H*A/2	V=H*A/4	V=H*A/3	Ratio		
	Maximum	Minimum	Best guess	Best guess to maximum	Best guess to minimum	Maximum to minimum
U5001_NW (East)	29210	10563	17557	1.7	1.7	2.8
U5001_NW (West)	22094	3850	10118	2.2	2.6	5.7
U5002_NW	9473	2775	5052	1.9	1.8	3.4
U5003_NW	26004	8651	14634	1.8	1.7	3.0
U5004_NW	33390	12647	19842	1.7	1.6	2.6
U5005_SO (Upper)	55746	22680	34118	1.6	1.5	2.5
U5005_SO (Lower)	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear
U5005_SO (Side)	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear
U5006_TH	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear
U5007_AN	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear
U5008_NW	46574	15841	27343	1.7	1.7	2.9
U5009_NW	162330	67279	97358	1.7	1.4	2.4
U5010_NW (Middle)	80680	40340	53787	1.5	1.3	2.0
U5010_NW (East)	25335	12668	16890	1.5	1.3	2.0
U5010_NW (West)	44980	22490	29987	1.5	1.3	2.0

Impounding or non-impounding

Impounding and non-impounding reservoirs may be expected to have different modes of failure as it is very unlikely that a non-impounding reservoir will fill such that it fails as a result of overtopping. This will influence the assumed reservoir water level at the time of failure, which has a direct impact on the escapable volume during a breach.

A number of methods to determine whether reservoirs were impounding or non-impounding were trialled. This initially involved a manual review of the OS mapping of the area to check whether any watercourses were shown to enter or leave the reservoir.

The Environment Agency's Detailed River Network (DRN) is a dataset that could be used to identify whether watercourses enter or leave the reservoir. Each river centreline located in the DRN is assigned a 'river type' attribute, one of which is 'Lake or Reservoir'. Therefore once a waterbody polygon has been identified a simple ArcGIS query technique could be used to determine whether the polygon overlaps (or comes close to overlapping) a river course with this 'Lake or Reservoir' attribute. If there is an overlap it would be assumed that the waterbody is either a lake or an impounding reservoir. If there is no overlap it would be assumed that this waterbody is a non-impounding reservoir. The completeness and accuracy of the DRN would affect the data obtained from this analysis.

Dam type

Aerial photos and OS maps were used to determine the dam construction type for a sample of the case study reservoirs. The results of this analysis are shown in Table 4.7.

It was possible to obtain limited information concerning the dam construction type for a small number of the reservoirs studied. However, the resolution of the aerial photos available and the presence of thick vegetation cover on many dams made it difficult to ascertain the dam type. For those reservoirs where the dam was clearly visible it was generally possible to identify whether a dam was an earth embankment or a gravity structure, but further information could not be extracted.

Limited information on dam construction type may be obtained through analysis of aerial photographs and OS maps, but this is a time-consuming process which cannot be automated. In addition the information obtained through a desk study is likely to be incomplete and of a low quality.

Table 4.7 – Dam construction type information obtained from desk study

Reservoir Name	Dam type	
	DTM / OS map	Aerial photo
U5001_NW (East)	Appears most likely to be embankment from OS map	Can't see on aerial photos as dam is covered by trees.
U5001_NW (West)	Appears most likely to be embankment from OS map	Can't see on aerial photos as dam is covered by trees.
U5002_NW	Appears most likely to be embankment from OS map	Appears to be earthfill embankment
U5003_NW	Not clear, but embankment slope is not shown on OS maps so appears not to be earthfill embankment. Probably gravity dam	Not clear as obscured by trees
U5004_NW	Appears most likely to be embankment from OS map	Appears to be earthfill embankment
U5005_SO (Upper)	Can't tell - no embankment shown	Outlet to reservoir can be seen if image studied closely, but dam type is unclear
U5005_SO (Lower)	Can't tell - no embankment shown	Obscured by trees, not possible to see dam structure
U5005_SO (Side)	Can't tell - no embankment shown	Possible to see a weir if the image is studied in close detail - this implies gravity dam, but uncertain
U5006_TH	Appears most likely to be embankment from OS map	Not clear as obscured by trees

Overview

Reservoir inundation modelling for this method would be carried out in the same way as in the Intermediate methodology, but using a single, site specific dam breach hydrograph rather than a set of assumed scenarios. The assessment of consequence factors (such as number of properties inundated, Likely Loss of Life, environmental impacts) would also be carried out in accordance with the Intermediate methodology. This method would allow an appropriate minimum reservoir volume for the Flood and Water Management Act to be determined using the same process as discussed in Section 4.2.3.

The overall advantage of this method is that it allows an individual dam breach consequence assessment meeting the requirements of the Flood Risk Regulations 2009 to be carried out for each reservoir. However, obtaining reservoir information through a desk study has proved time consuming and has produced data which is generally incomplete and of low quality. This is particularly the case for the reservoir volume, which is a critical parameter but which cannot be derived with an acceptable reliability, accuracy or completeness. Obtaining information by conducting site visits or requesting information from reservoir undertakers is likely to produce reliable data but will require significant resources and is unlikely to be feasible for all reservoirs (for instance where the undertaker is not cooperative).

The information obtained from the desk studies has been found to be of too low a quality for use to derive accurate breach hydrographs. An alternative approach is to use the desk study to produce an initial estimate of the breach hydrograph. Reservoirs could then be given an initial risk assessment to prioritise the allocation of resources for carrying out site visits or requesting information form undertakers. However, it is considered that the data extracted for the case study reservoirs is of too low a quality and is too incomplete even for this use (particularly because of the large range of possible reservoir volumes).

Whilst it is time consuming and expensive to identify reservoir ownership and carry out site visits or request information from undertakers, it is considered that this is the only feasible way to obtain the accurate reservoir information required in order to produce reservoir-specific breach hydrographs. If this is necessary in order to satisfy the requirements of the Flood Risk Regulations 2009 then it would be possible to use the results from the Intermediate method analysis to prioritise reservoir locations based on their potential consequence. This would allow the risk-based allocation of resources for conducting site visits.

5. Conclusions

5.1 Identification of small raised reservoirs

Following manual interrogation of a sample area of DTM it is believed that the methods outlined in section 3.1 will allow the location of waterbodies in England and Wales to be determined. It is likely to be harder to identify whether these waterbodies are raised above ground level, but the method outlined is considered to give the best available estimate of this without conducting site visits to every waterbody. It is noted that waterbodies are enforced as completely flat in the NEXTMap Britain DTM, but are not in the LIDAR Composite DTM. For this reason it is proposed that the NEXTMap Britain DTM be used for this purpose.

The following specific issues with the methodology have been identified:

- Some small reservoirs will be not be identified due to not being represented as flat in the DTM, or due to not being included in the OS Master Map 'water' theme layer (for instance if newly constructed, covered or not normally filled with water)
- Flat features in the DTM that are not waterbodies will also be identified. It is anticipated that use of the OS Master Map 'water' theme to cross-check the results will filter out most of these.
- The methodology is not expected to identify service reservoirs (as they are often buried) and flood storage areas (as they are often empty). However, data on these assets are held by water utility companies and by the Environment Agency and it is anticipated that this information could be obtained for this study.
- Using the DTM it will only be possible to make an estimate of whether a waterbody is raised above normal ground level. As a result the final list of reservoirs obtained will contain some waterbodies that are not raised reservoirs and will also incorrectly omit some that are raised reservoirs
- This method will identify reservoirs in England and Wales that are not registered under the Reservoirs Act 1975 (i.e. those with a capacity of less than 25,000m^3). It is not possible to accurately filter the list further to include only, for instance, those with a capacity of less than 10,000m^3

It is considered acceptable that the method for determining whether a waterbody is raised above ground level is only indicative. This is because it is likely that where waterbodies are assessed and flagged as high risk these will be investigated further and any waterbodies not within the remit of this study will then be identified and removed from further consideration.

It is also considered acceptable that this method will identify all reservoirs with a capacity of up to 25,000m^3. For the purposes of determining the minimum reservoir volume for the Flood and Water Management Act this is not a problem as typical reservoir locations are not anticipated to vary significantly with volume. Furthermore, if reservoirs above 10,000m³ in capacity are identified and their consequences of failure are subsequently assessed, this will provide a useful starting point for further study once these reservoirs are registered with the Enforcement Authority.

5.2 High Level Screening method

The reasoning behind the High Level Screening method was that it should be a simple and fast screening tool to provide a comparative measure of the consequence of failure of different reservoir locations. This could be used to focus further efforts on those locations with the greatest consequence of failure. However, the methodology has been found to be time consuming and more subjective than anticipated with informed judgement being required at all stages, reducing the possibilities for automation. Applying the High Level Screening method to one case study reservoir was more time consuming than setting up and running all six scenarios for each case study using the (more refined) Intermediate method.

The High Level Screening method has the advantage that it does not require many data inputs as no hydrographs are required, but this is compromised by the high level of user input required. In addition, the results from this method cannot be directly linked to reservoir volume in order to compare the relationship between storage volume and consequence of failure

The following specific issues with this method were identified:

- The use of a different DTM produced very different drainage path routes. This would result in a different flood inundation area being produced and thus different risk assessment results. This problem does not apply when carrying out 2D modelling.
- More manual intervention was required than anticipated in order to buffer and extract property counts. Specific problems included difficulties in delineating urban areas in heavily urbanised areas.
- The flood zone buffering technique was flawed by an absence of flood zone data in the vicinity of some reservoirs.
- It was difficult to pick out cut-off points in the flood zone data, especially where tributaries are present, to create refined buffered outlines.
- Buffering using hill contouring techniques proved problematic. The buffered outline created varied significantly according the cross section spacing selected.
- Subjective assessments are required at many stages in the process. This has a significant impact upon the estimated number of properties at risk and other data extracted for input to the risk assessment process. When comparing the buffers and drainage paths generated using this method, with those from the Intermediate method gross over estimates are immediately apparent.

- The technique takes no account of reservoirs which may fail in cascade and the additional risk posed by the breach of reservoirs downstream of the subject reservoir.

5.3 Intermediate method

The Intermediate method uses simple inputs and involves very little manual intervention once the model is set up. The results produced from this method are detailed and can be used to extract information at selected points within the flood inundation area, for example at every property inundated. This information has in turn been fed into detailed flood risk assessment tools to calculate statistics such as Likely Loss of Life (LLOL). The process can be used to extract this information for any location represented by a point, including for example critical infrastructure, environmental protected sites and cultural data. In addition, information represented by a region can be overlaid with the flood inundation extents to show whether these areas are potentially inundated. This analysis is automated, and the results obtained are not based upon subjective decision making.

The advantages of this approach are as follows:

- Allows reuse of existing modelling and consequence calculation tools developed during Phase 1 of the NRIM project
- 2D modelling outputs give high quality maps of depth and velocity over the course of a simulation that allows a suite of 'maximums' to be generated (e.g. flood extent, depth, velocity, hazard, time of initial and maximum inundation). Maps of these variables can be used as a basis for more detailed FRAs/consequence assessments.
- Model set-up, execution and post-processing are fully automated and highly efficient using 2D modelling software such as JFLOW-GPU, Infoworks RS or TuFLOW. Post Processing software can be written according to the format of the output results using coding such as C#, .NET, Java or other programming languages.
- Can be used to model multiple breaches
- Provides evidence for the minimum threshold volume without requiring collection of reservoir data or relying on poor-quality sources.
- Provides a starting point and ranked list of reservoir locations for a more detailed analysis (if inundation modelling is to be carried out for all reservoir locations).

The main issue with this methodology is that because only generic hydrographs are modelled, further work would be required in order to produce individual risk assessments for each reservoir. In addition, the following specific problems were encountered during the case study trial:

- The number of model runs required (6 in total) for each breach produces a large quantity of data to be managed through both the modelling, post processing and analysis stages. However, this can be easily managed by setting up model log spreadsheets to record the modelling status of each reservoir.

- The results for some case study reservoirs were found to be characterised by flow back into the subject reservoir. This can be overcome by simply stamping subject reservoirs into the dtm to a significantly raised height. This is considered to be of particular importance for the purpose of modelling the reservoirs included in the remit of this study because of the relatively small volumes of water involved.
- This method does not specifically take account of cascade scenarios. However, because of the range of volumes considered in the modelling process the breach of any reservoirs in cascade downstream of the subject reservoir would be accounted for implicitly by the higher volumes simulated.

5.4 Detailed method

This method is intended to be used to produce individual risk assessments for small raised reservoirs. It uses the same dam breach modelling methods as in the Intermediate method but uses reservoir-specific information to derive individual breach hydrographs for each reservoir. The principal advantage of this method is that it allows individual risk assessments which fully meet the requirements of the Flood Risk Regulations 2009 to be produced. In addition, because individual hydrographs are produced for every reservoir it allows cascade failures to be modelled explicitly.

The advantages of this approach are as follows:

- Allows reuse of existing modelling and consequence calculation tools developed during NRIM Phase 1
- 2D Modelling software such as JFLOW-GPU, Infoworks RS and TuFLOW output high quality maps of depth and velocity over the course of a simulation that allows a suite of ‘maximums’ to be generated (e.g. flood extent, depth, velocity, hazard, time of initial and maximum inundation).
- Model set-up, execution and post-processing are fully automated and highly efficient within 2D Modelling software such as JFLOW-GPU, Infoworks RS and TuFLOW.
- Can be used to model both multiple breach and cascade scenarios.
- Provides evidence for the minimum threshold volume
- Provides risk assessment for all identified reservoirs based on specific reservoir details.

However, it has been found in the case study trial that the necessary reservoir information is very hard to acquire for the following reasons:

- The collection of reservoir data through site visits or requests for information from reservoir undertakers is likely to be labour intensive and relies heavily upon the co-operation of undertakers. In addition this will require reservoir ownership to be determined based on only the reservoir location

- The collection of reservoir data through a desk study is labour intensive and produces poor quality data

Obtaining reservoir information through a desk study has proved time consuming and has produced data which is generally incomplete and of low quality. This is particularly the case for reservoir volume, which is a critical parameter but cannot be derived with an acceptable reliability, accuracy or completeness. It is therefore concluded that a desk study is not a satisfactory way to obtain this information.

The only reliable way to obtain specific reservoir information is to identify reservoir owners and to contact them to either arrange a site visit or to request the information directly. However, experience from the NRIM project has proved this to be a very time consuming task, even where the contact details of reservoir undertakers are known and where undertakers are already aware that their reservoir(s) are covered by statutory legislation.

6. Recommendations

Experience gained through the case studies and the NRIM project has shown that individual reservoir parameters (dam height, storage volume etc) are likely to be both costly and time consuming to acquire, and may be of questionable accuracy. In contrast reservoir locations, ground topography and details of receptors are relatively easy to obtain and are generally of a good quality.

For inundation mapping, there is sufficient data available to identify the breach location that is likely to result in the worst-case consequences of failure and to model any generic breach hydrograph at this location to find the impacts. It is much harder to make an assessment of the most likely breach location and to derive the corresponding specific breach hydrograph for that location as the information required is difficult to obtain and of poor quality.

It is anticipated that there will be a large number of small reservoirs requiring a risk-assessment. Therefore, in formulating the methodologies preference has been given to techniques which can be automated and which require minimal user input and judgement. From experience gained during the NRIM project, the manual collection of reservoir data was a labour-intensive exercise and had a high cost associated with it. The use of automated methods also improves consistency as it reduces scope for individual user judgement.

The High Level Screening method has been shown to be significantly more time-consuming and subjective than anticipated. It delivers outputs that are considerably less useful than the other proposed methodologies but may be more costly to implement. It is therefore recommended that this methodology is not developed further.

The Intermediate method uses simple inputs and produces detailed results that can be used to provide an evidence base for the lower limit on reservoir volume for the Flood and Water Management Act. This method cannot produce individual risk assessments for each reservoir but it provides a detailed assessment of the level of risk of each reservoir location, which may be used to facilitate the risk-based allocation of resources for further study.

The collection of the information necessary in order to carry out specific risk assessments in line with the Detailed method has proved to be difficult. The information cannot be obtained with sufficient accuracy from a desk study so it would be necessary to carry out site visits or request the information from reservoir undertakers. This proved a time consuming and costly operation in the NRIM project, and for this study it would be necessary to establish ownership and obtain contact details for undertakers. This is likely to add an additional cost.

It is recommended that for the purpose of establishing a minimum volume for the Flood and Water Management Act a representative sample of reservoir locations should be identified and the consequences of failure assessed using the Intermediate method. To ensure that the varying topography and land use with England and Wales is properly represented this sample should be geographically dispersed.

It is not known what size a representative sample is likely to be as there is no accurate information available on the number of reservoirs smaller than 25,000m³ in England and Wales. However, Hughes et al, 2004, carried out a GIS-based assessment of the number of waterbodies in Great Britain. This study did not differentiate between natural waterbodies and raised reservoirs, but found a total of 17,941 waterbodies greater than 0.02 ha in area in England and Wales. There are currently approximately 2100 reservoirs registered under the Reservoirs Act 1975, leaving approximately 15,800 natural waterbodies or raised reservoirs smaller than 25,000m³. For the purposes of budgeting if it is then assumed that 1/3 of these waterbodies are raised reservoirs then this gives a figure of approximately 5,000 raised reservoirs. Based upon this figure it has been assumed for the cost estimates that a sample of 1000 reservoirs is likely to be sufficient.

For the purpose of meeting the requirements of the Flood Risk Regulations 2009 it is recommended that the Intermediate method be carried out on all reservoir locations identified. The results from this analysis will show the general level of risk of each reservoir location and will provide a means for the risk-based prioritisation of resources for further study. Ownership may then be established and undertakers contacted for those reservoir locations highlighted through this method as potentially posing a significant risk. It should be noted that for all reservoirs with a capacity of greater than 10,000m³ the Flood and Water Management Act requires reservoir undertakers to register with the Enforcement Authority, and subsequently supply relevant information to them. Assuming that the level of compliance with this aspect of the law is high, it is anticipated that it will only be necessary to establish ownership and contact undertakers where there are reservoirs that are not registered under the Act which have been shown to have a potentially significant consequence of failure. This process is illustrated in Figure 6.1.

To develop and test the methodology for risk assessment thoroughly it is recommended that a trial study be carried out. This would involve a more detailed case study analysis of the proposed methodology, followed by production of a detailed specification to ensure consistency.

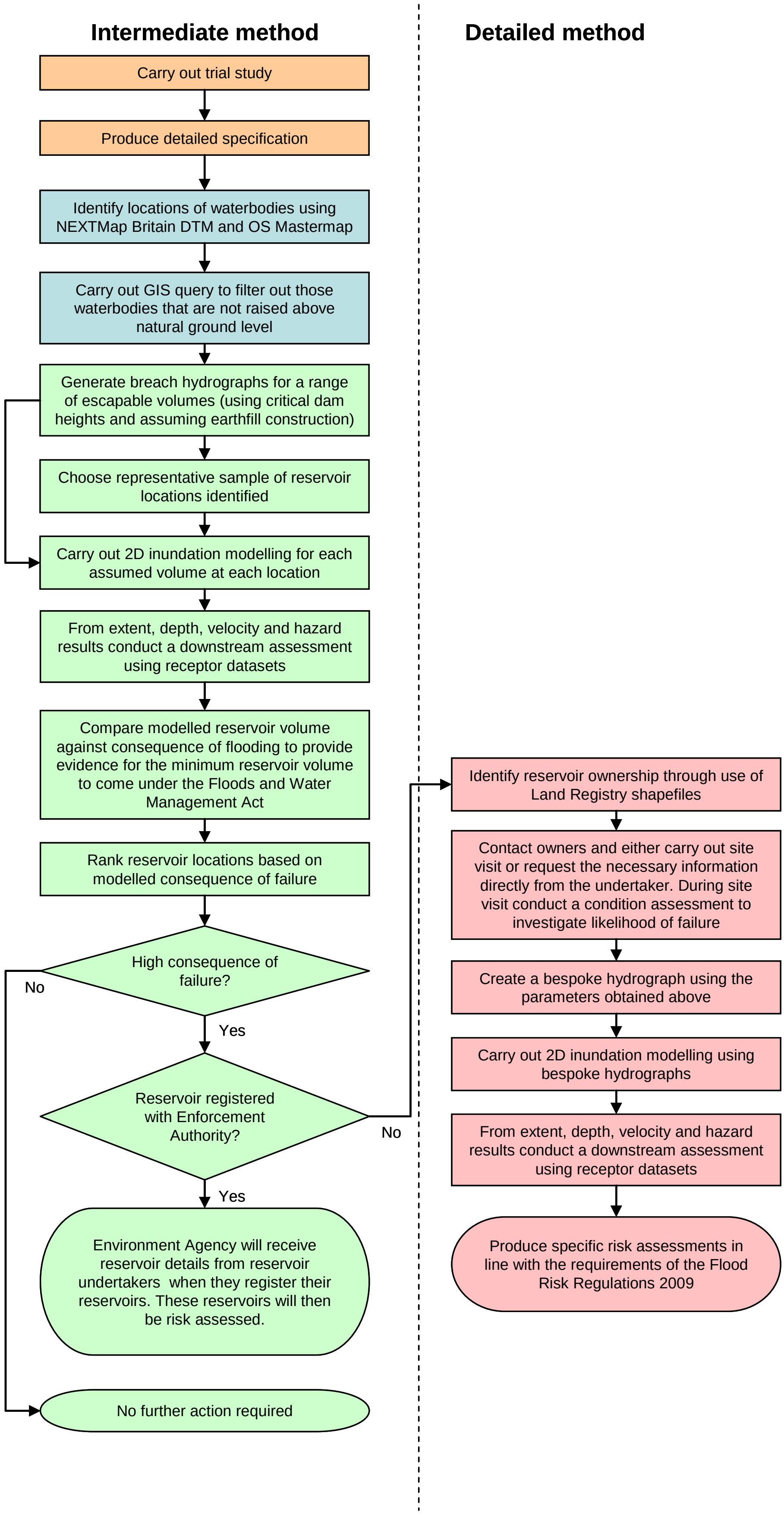


Figure 6.1 – Flow chart of recommended risk assessment methodology

7. Cost estimates

The cost estimates provided below are based on our recommendation that the Intermediate method be implemented.

7.1. Identification of small raised reservoirs

The estimated cost for locating small raised reservoirs within England and Wales is based upon the following processes being carried out. It should be noted that, as discussed in Section 4.2.1, this method will identify reservoirs with a capacity of less than 25,000m³, not just those smaller than 10,000m³.

Table 7.1 – Breakdown of tasks required to locate small raised reservoirs

Step	Locating waterbodies
1	Automated Slope Analysis – to identify flat areas.
2	Refine slope analysis results, using automated toolkits in ArcMap, based upon geometry query to exclude all long thin polygons picked out representing watercourses (as opposed to waterbodies).
3	Query of Master Map to extract waterbodies
4	Intersect results from Steps 2 & 3
5	Get height of polygons/waterbodies using NEXTMap DTM
6	Buffer polygons/waterbodies and attribute points with DTM height for every cell along the buffer line. This will be done using automated toolkits to be coded in ArcMap. This will require testing to establish suitable size of buffer to use.
7	Exclude all waterbodies where X% of points are above the level of the waterbody. This will be done using automated toolkits to be coded in ArcMap. This will require testing to establish suitable cut off % to use.
8	Exclude all reservoirs within Environment Agency National Reservoirs Database (above 25,000m3). This will be done using toolkits in ArcMap.
9	Verify remaining polygons using OS 10K mapping and Google Earth Satellite Imagery. This will be done manually.

The estimated cost for completing this task is £10,000. This is a preliminary estimate for budgeting purposes only and would need to be reviewed and refined against a defined scope.

7.2. Risk assessment

It is recommended that a trial study be carried out prior to implementation of the proposed methodology. This would carry out a more thorough testing of the methodology on a case study sample and produce a detailed specification for the main study. The estimated cost for completing this trial study is £25,000.

The estimated costs for carrying out the main study are set out below.

The estimated cost per reservoir modelled using the Intermediate method is based upon the following being carried out for each reservoir modelled:

Table 7.2 – Breakdown of tasks required to carry out Intermediate method

Flood Inundation Modelling
Develop and execute JFLOW-GPU models for 6 volumes for 1000 small reservoirs.
Checking initial model results.
DTM Edits
Re-run models as required
Check and finalise final model results
Deliverables 1 - Flood Inundation Mapping
Convert model outputs to ESRI GRID format
Execute GIS routines to produce inundation variables in ESRI Shapefile format
Check and finalise final mapped outputs
Deliverables 2 - Consequence Analysis
Execute GIS routines to produce consequence analysis assessments
Check final consequence analysis assessments
Produce collated analysis of the downstream impact assessments
Carry out assessment of Likely Loss of Life, number of properties inundated, number of protected areas inundated and number of sites of cultural significance inundated for each reservoir location
Produce charts showing variation of consequence factors with reservoir volume
Deliverables 3 - Reporting
Execute routines to produce PDF extent maps
Check production of final PDF extent maps

The estimated cost per reservoir for carrying out the above is £175 (based on 1000 reservoirs being modelled).

In addition to this the following fixed cost items would be required:

Table 7.3 – Breakdown of fixed cost items for the Intermediate method

Project Management
Meetings and project management
Data Management
Management of the large amount of data produced
Flood Inundation Modelling
Upload and prepare 2009 Composite DTM
Deliverables 2 - Consequence Analysis
Develop GIS-based routines for downstream impact assessment / consequence analysis
Deliverables 3 – Reporting
Develop XML, ArcMap and PDF routines for automated production of PDF extent maps
Produce written report

The estimated fixed costs are as follows:

- Meetings and project management = £25,000. Note that this is highly dependant on the amount of stakeholder engagement required.
- Other one-off costs = £15,000

The total estimated costs for modelling 1000 reservoirs are summarised below. This is a preliminary estimate for budgeting purposes only and would need to be reviewed and refined against a defined scope.

Table 7.4 – Breakdown of total estimated costs

Step	Estimated cost
Trial study	£25,000
Modelling and mapping of 1000 reservoirs	£175,000
Project Management	£25,000
Other fixed costs	£15,000
Total	**£240,000**

8. References

Brown A. J. and Gosden J. D., 2004. Interim Guide to Quantitative Risk Assessment for UK Reservoirs. London: Thomas Telford Publishing

Evans, et al. (2009c). National Reservoir Inundation Mapping – Specification. A report prepared by Mott MacDonald Ltd for the Environment Agency. June, 2009, Ref: 247474/01/F

Froehlich, D. C. (1995). Peak outflow from a breached embankment dam. Journal of Water Resources Planning and Management, American Society of Civil Engineers, 121(1), 90–97.

Hughes A. et al. (2000). Risk Management for UK Reservoirs. Construction Industry Research and Information Association (CIRIA) Research project report C542.

Hughes A. and Wanner T., (2009). Methodology for Prioritising Dams for ‘Offsite’ Emergency Plans, Defra research study.

Hughes M. et al (2004) The Development of a GIS-based inventory of standing waters in Great Britain together with a risk-based prioritisation protocol; Water, Air and Soil Pollution: Focus, No 4, p73-84

Udale-Clarke et al. (2005) Flood risk assessment guidance for new development, Phase 2, Framework and guidance for assessing and managing flood risk for new development – full documentation and tools. R & D Technical Report FD2320/TR2. London: Defra.

Appendix A. High Level Screening method outputs

Figure A1 – U5001_NW – High Level Screening method results

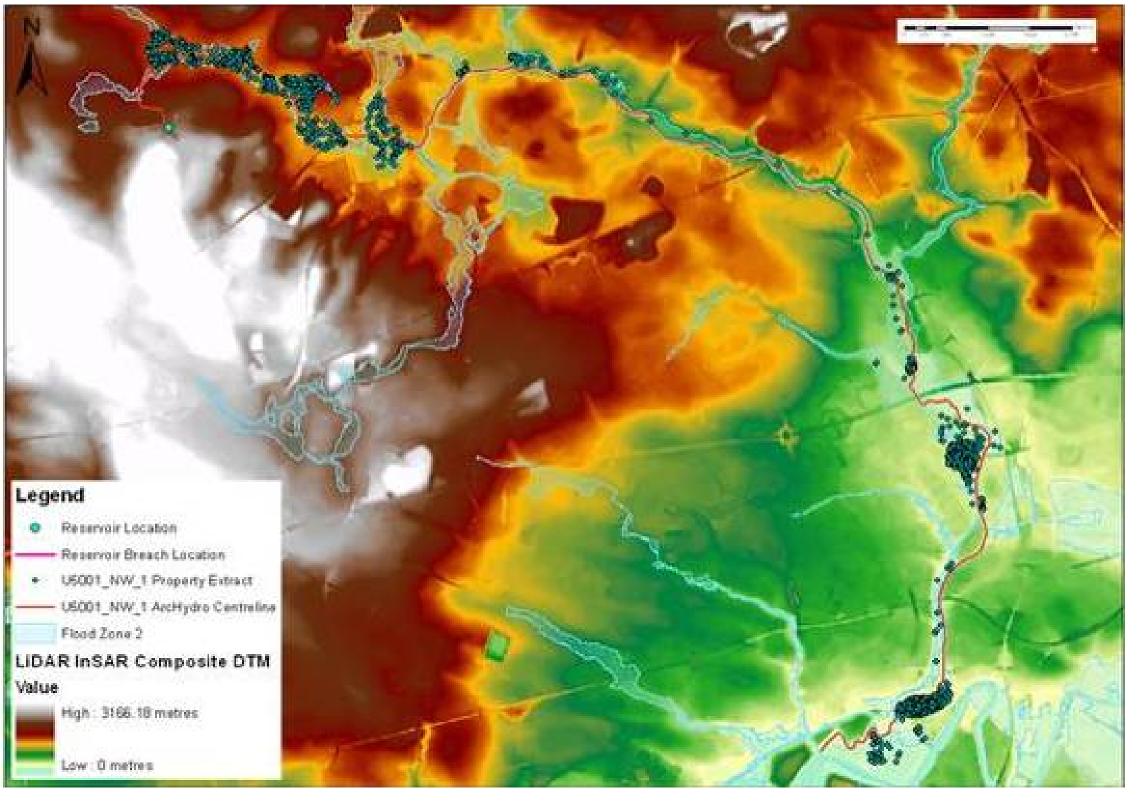


Figure A2 – U5002_NW – High Level Screening method results

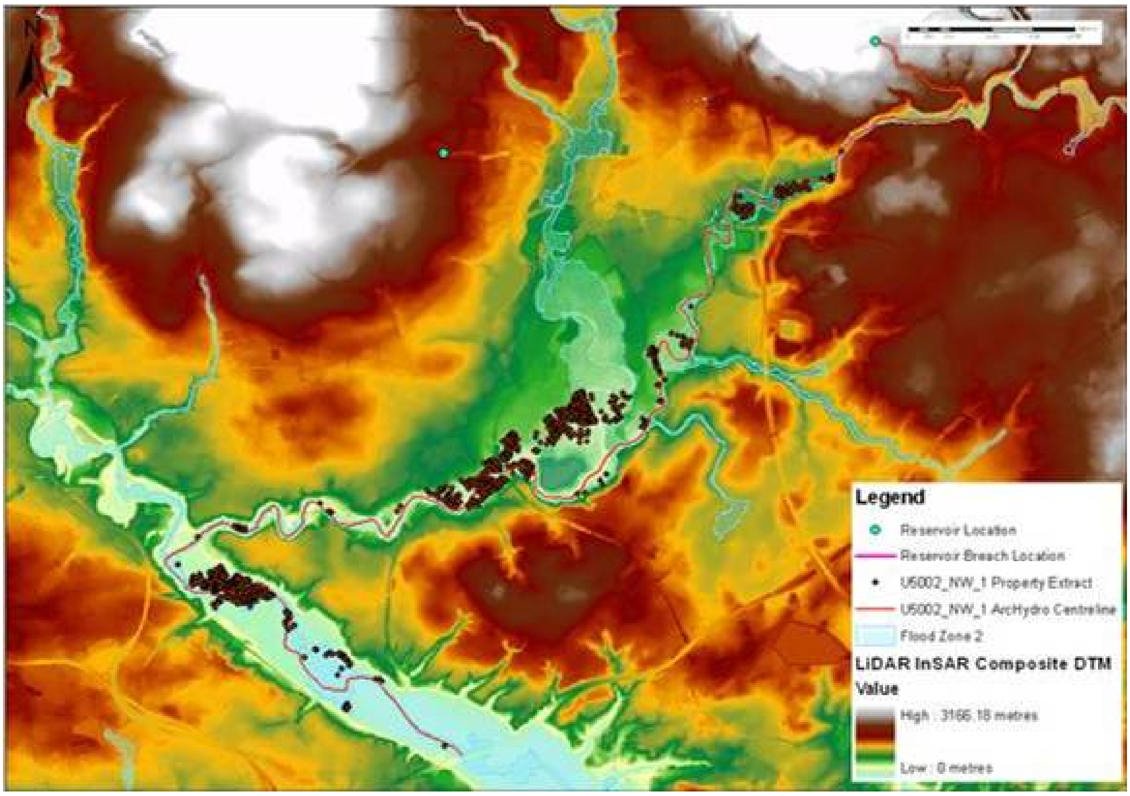


Figure A3 – U5003_NW – High Level Screening method results

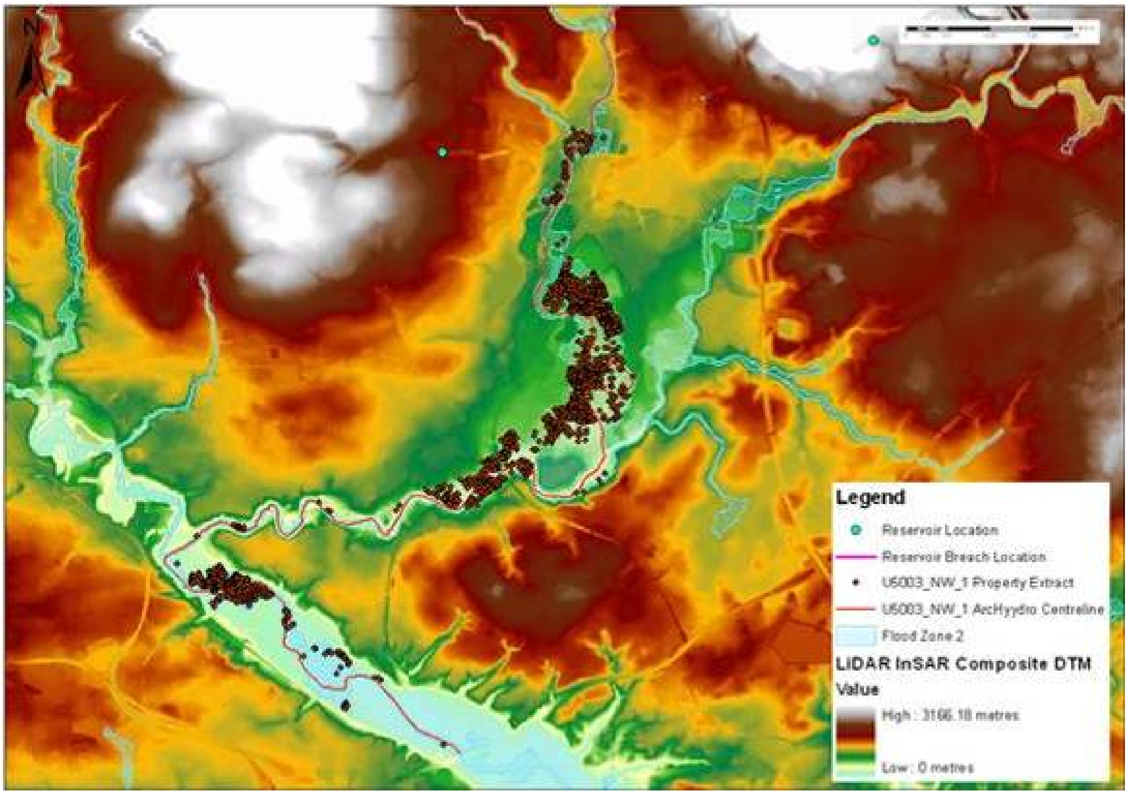


Figure A4 – U5004_NW – High Level Screening method results

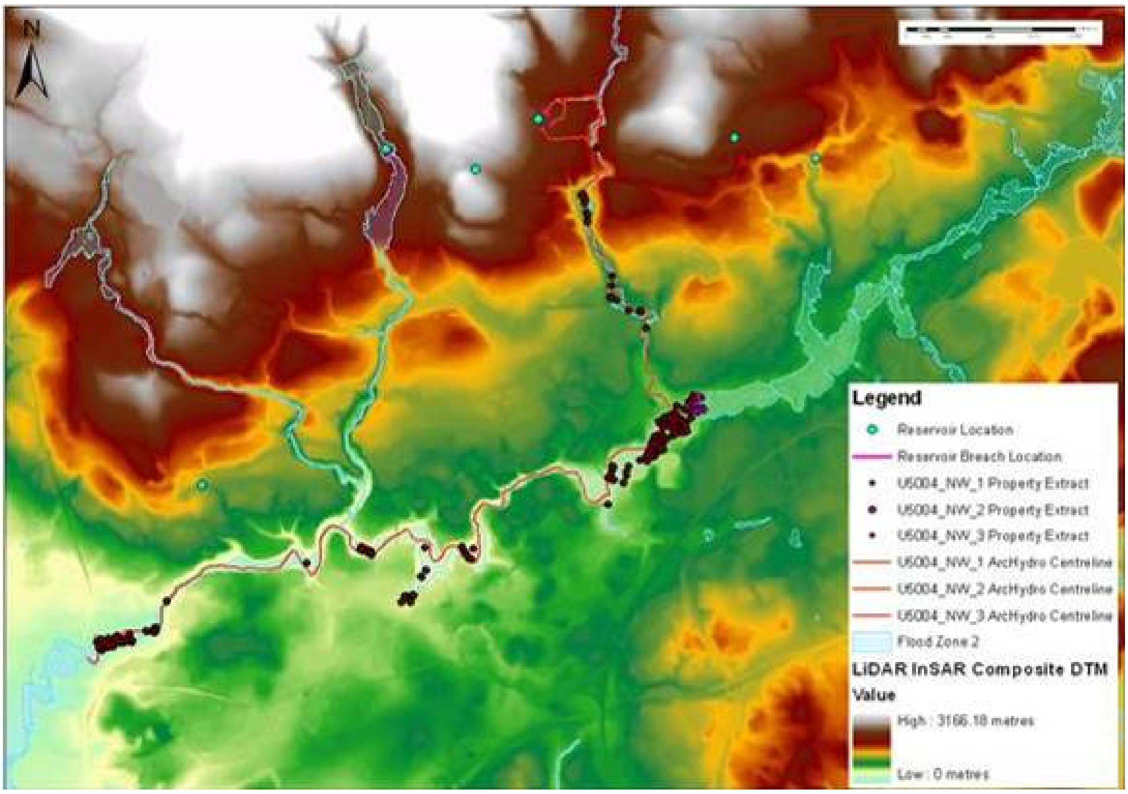


Figure A5 – U5005_SO– High Level Screening method results

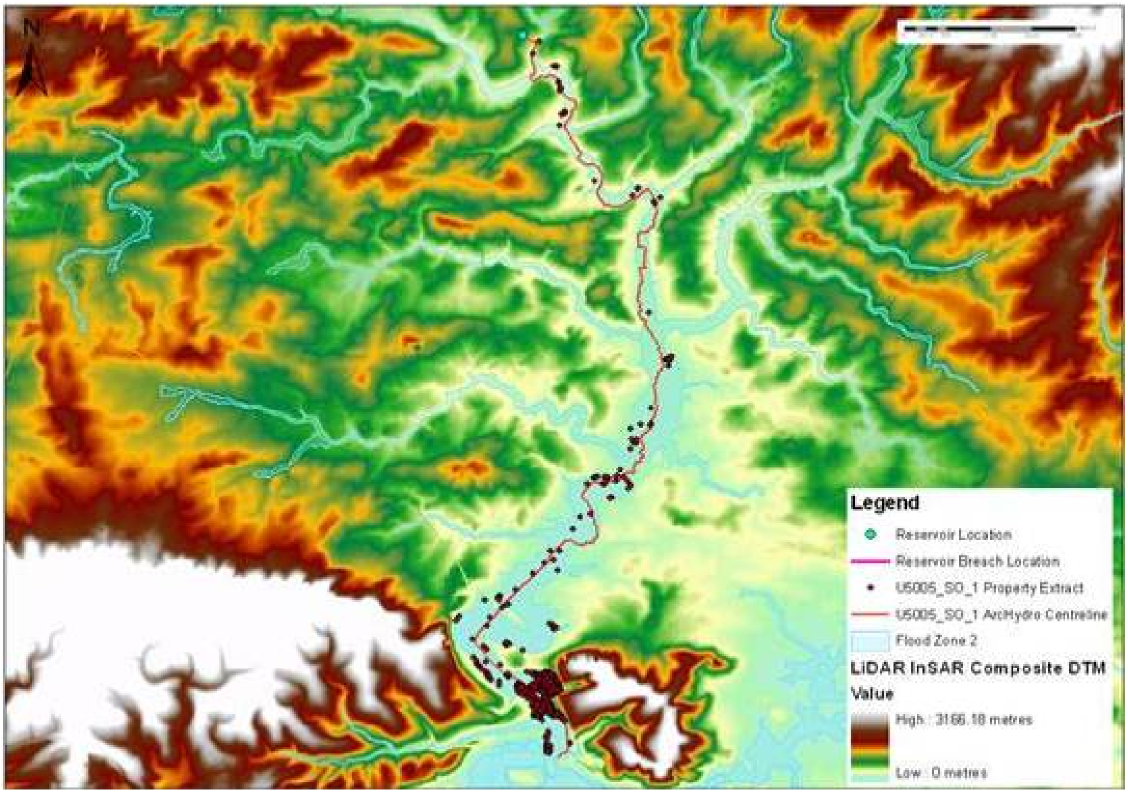


Figure A6 – U5006_TH – High Level Screening method results

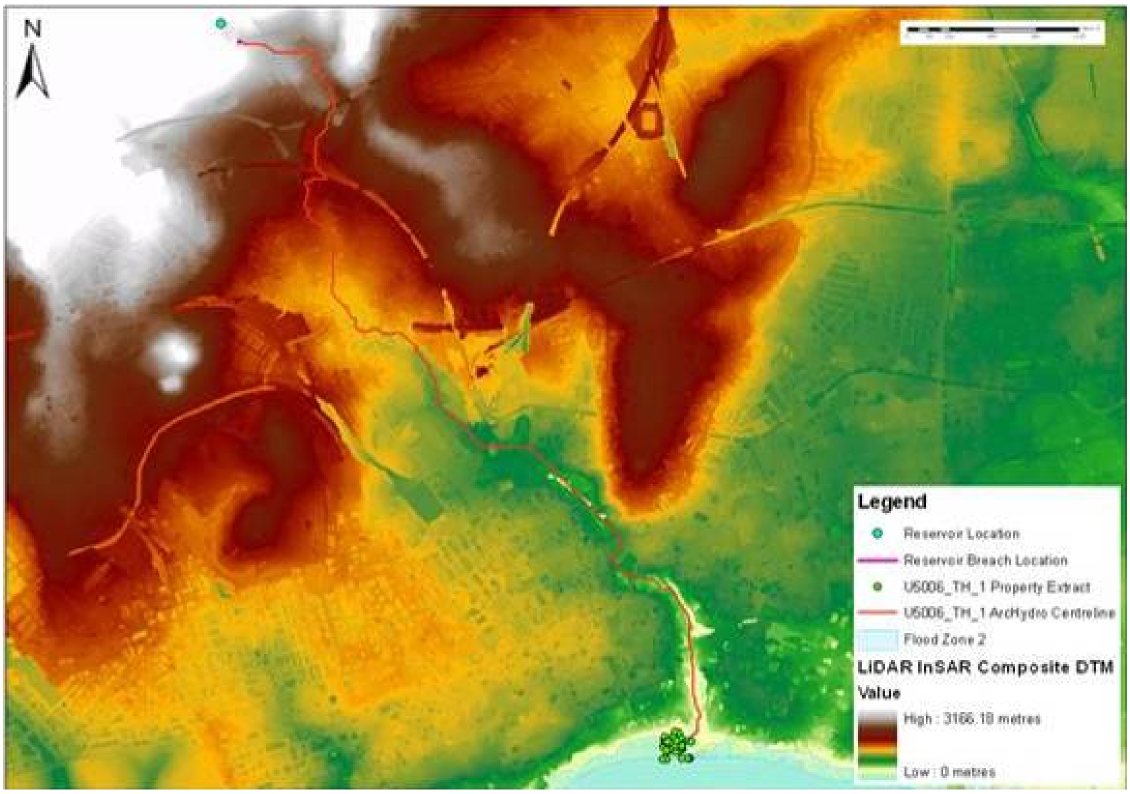


Figure A7 – U5007_AN – High Level Screening method results

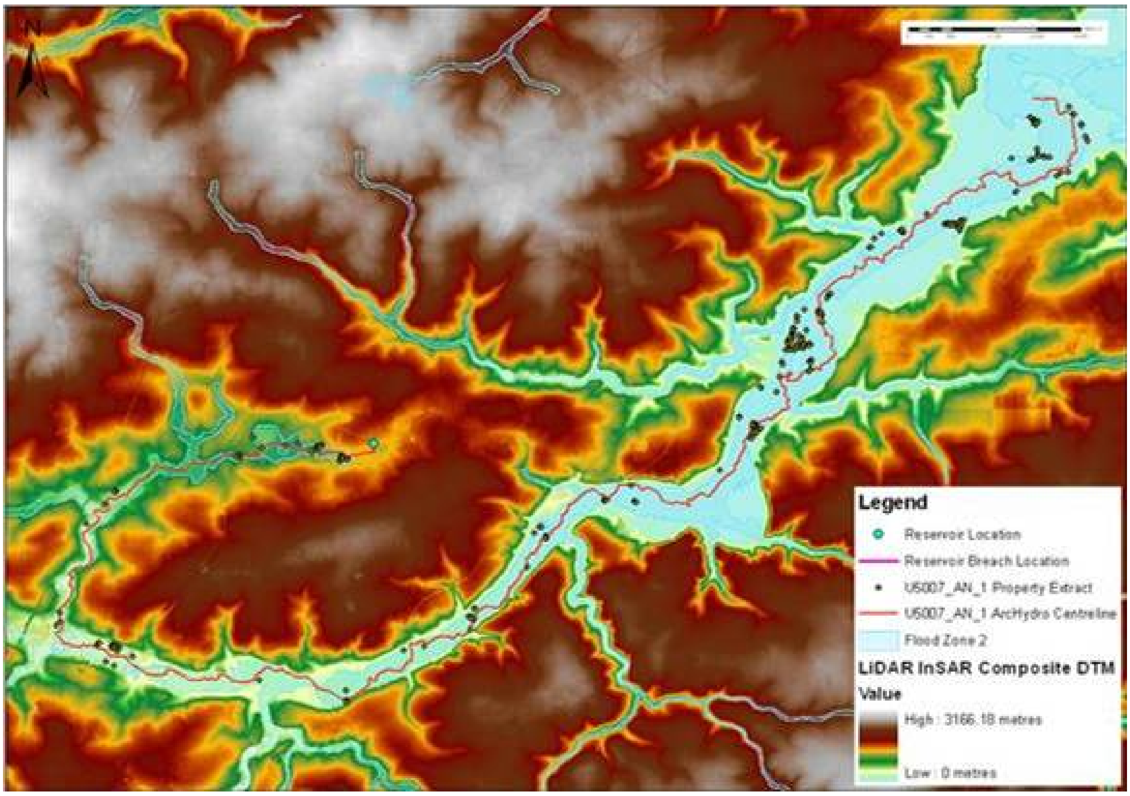


Figure A8 – U5008_NW – High Level Screening method results

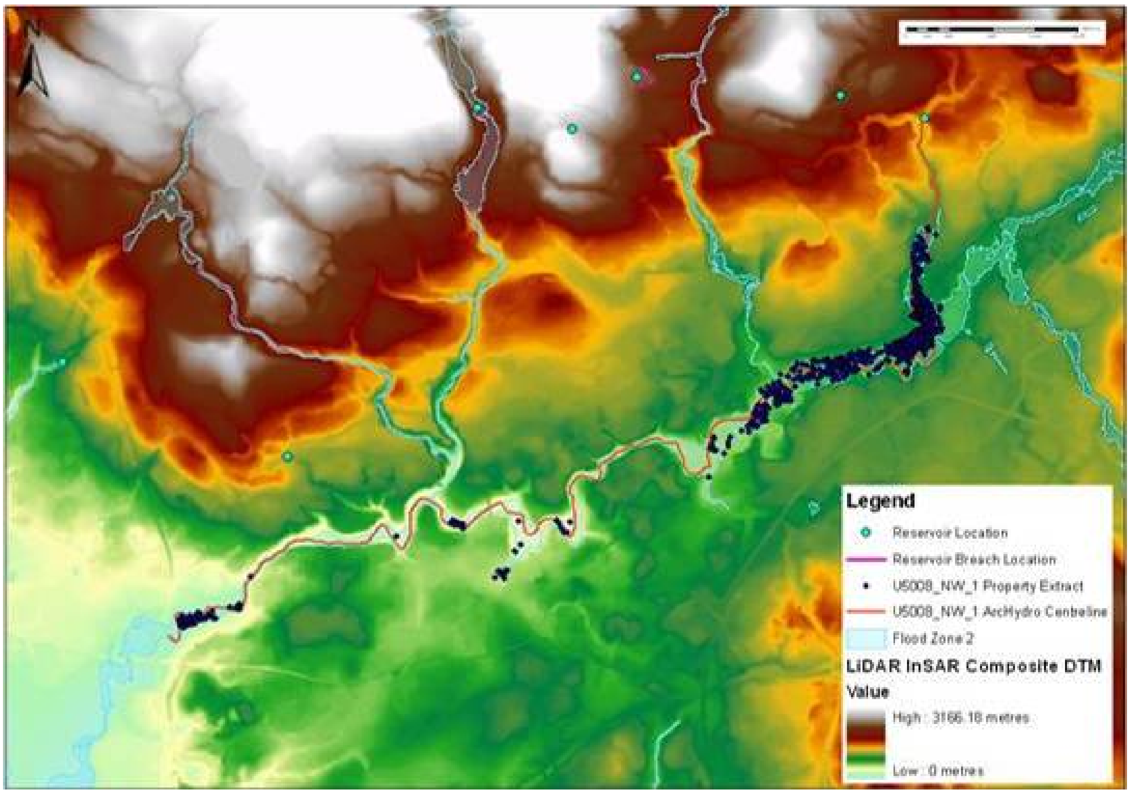


Figure A9 – U5009_NW – High Level Screening method results

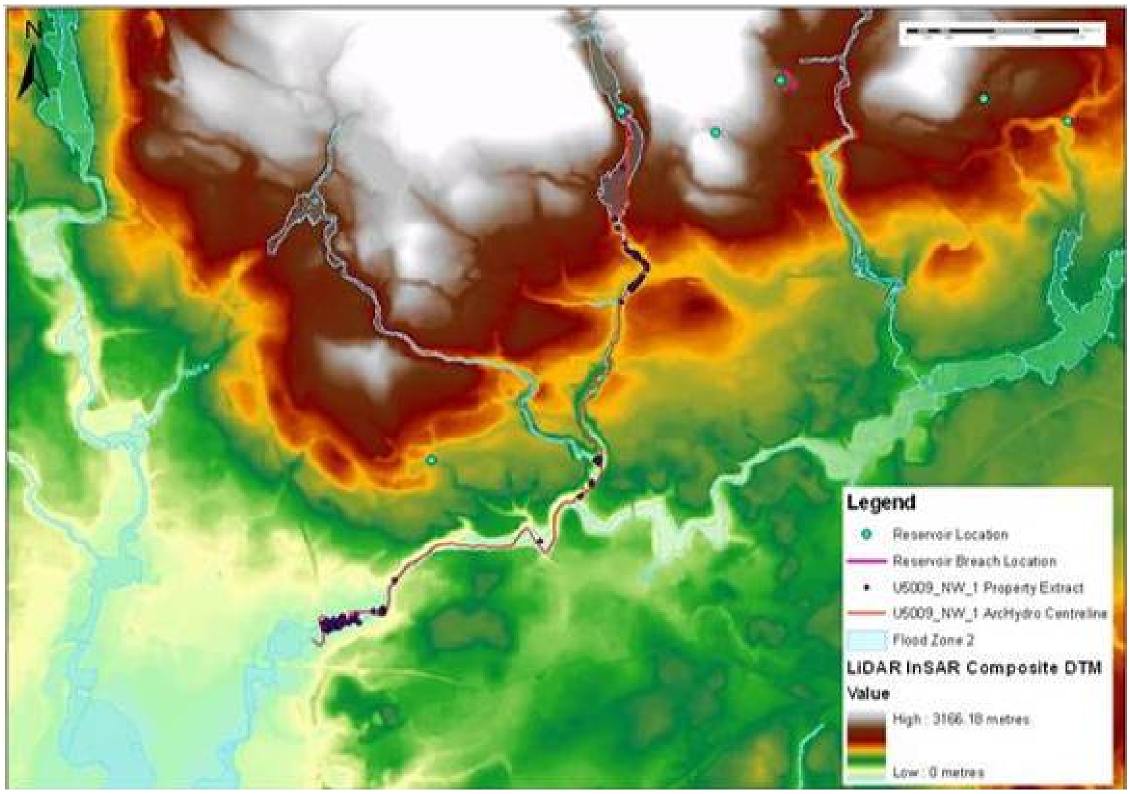


Figure A10 – U5010_NW – High Level Screening method results

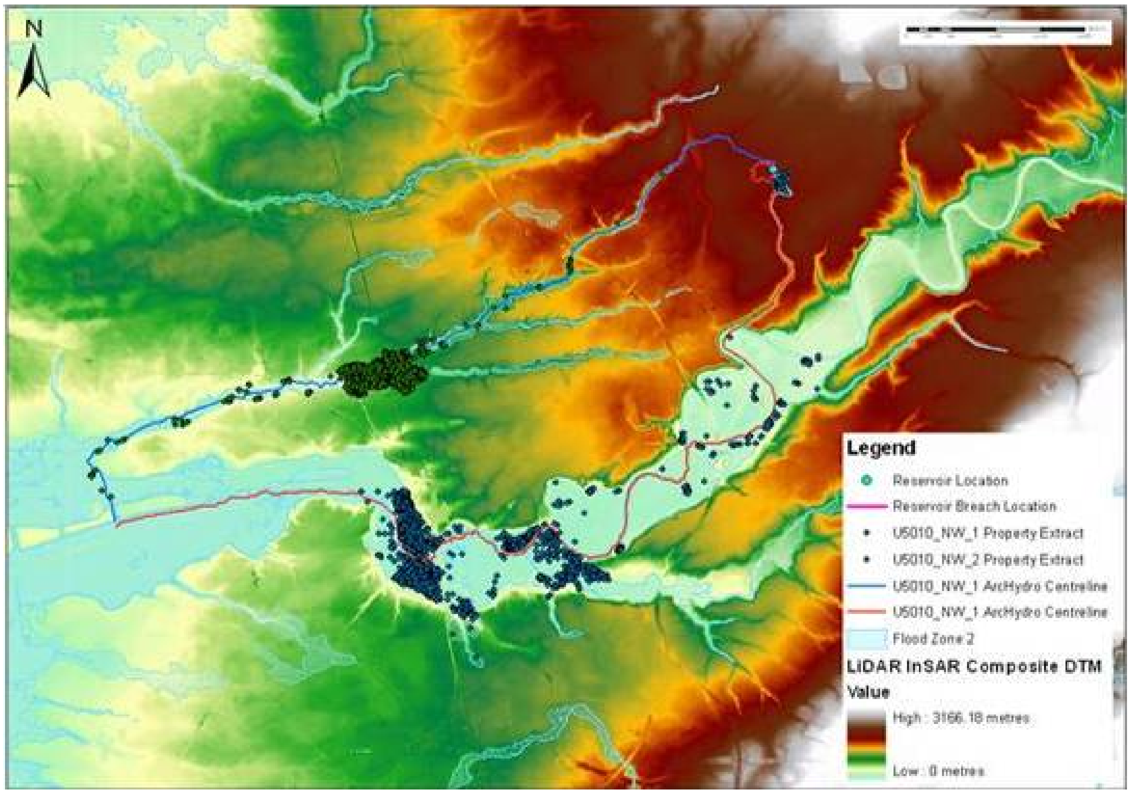


Figure A11 – Example map showing intersect of High Level Screening method Flood Zone 2 results with SSSI dataset

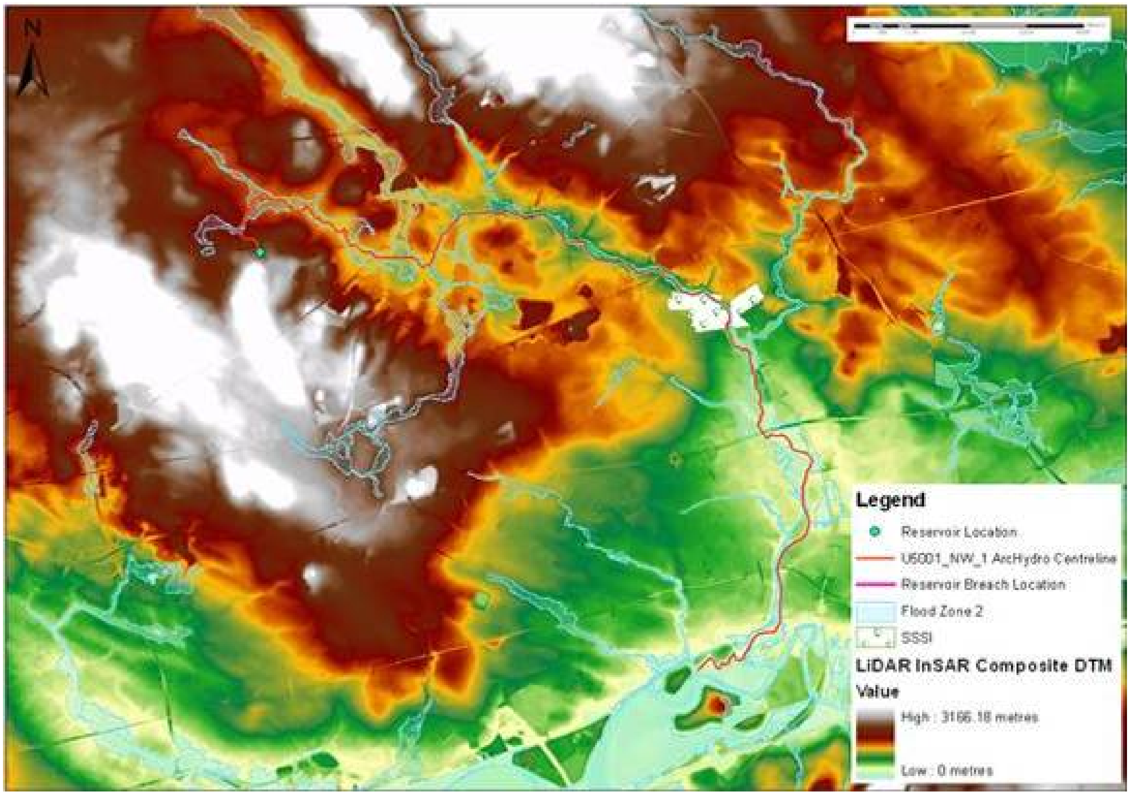
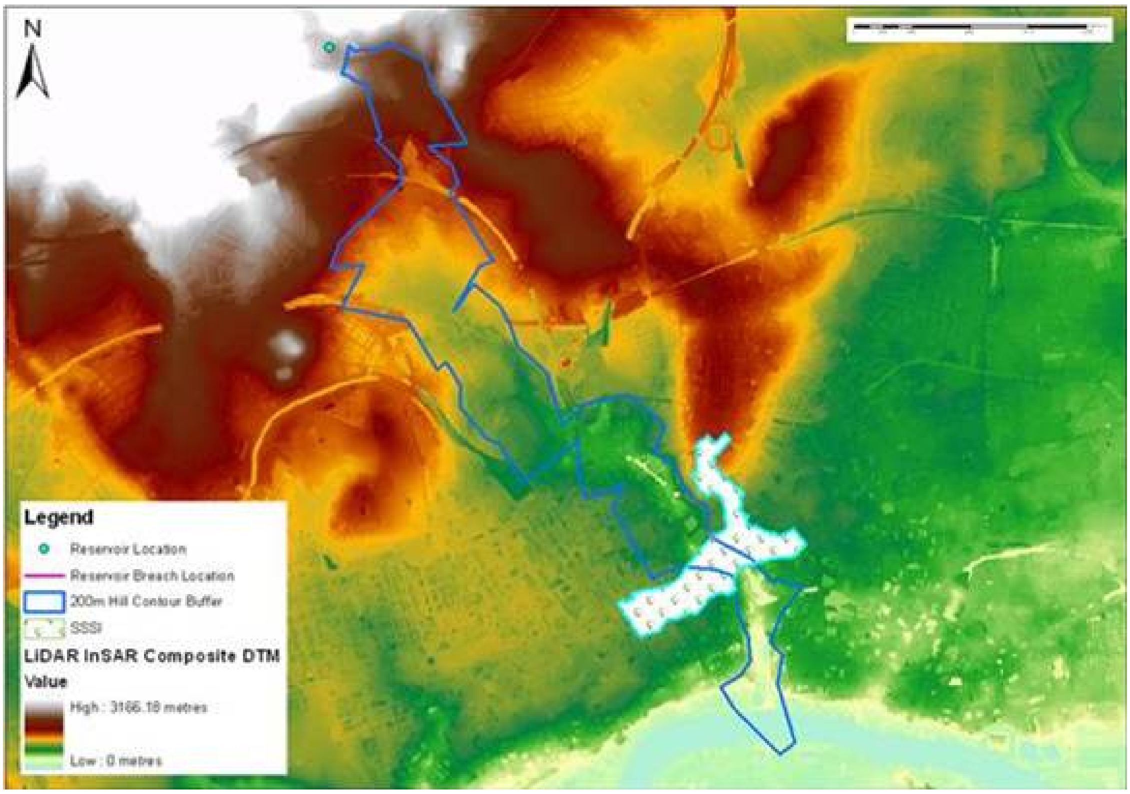


Figure A12 – Example map showing intersect of High Level Screening method hill contouring results with SSSI dataset



Appendix B. Intermediate method mapping outputs

Please note that wet islands separated from the main inundation area would be cleaned for final maps. These are the result of post processing out shallow flooding of less than 0.01m

Figure B1 – U5001_NW – Intermediate method results 5000m^3 volume

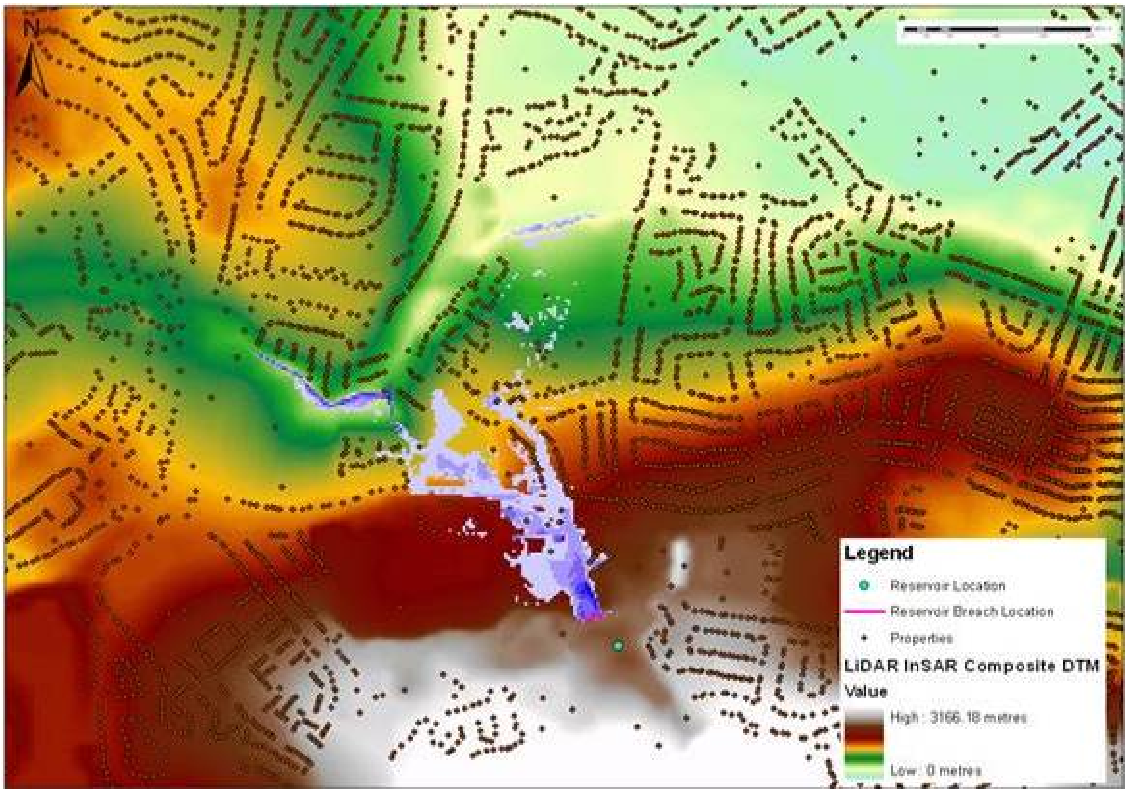


Figure B2 – U5001_NW – Intermediate method results 10000m^3 volume

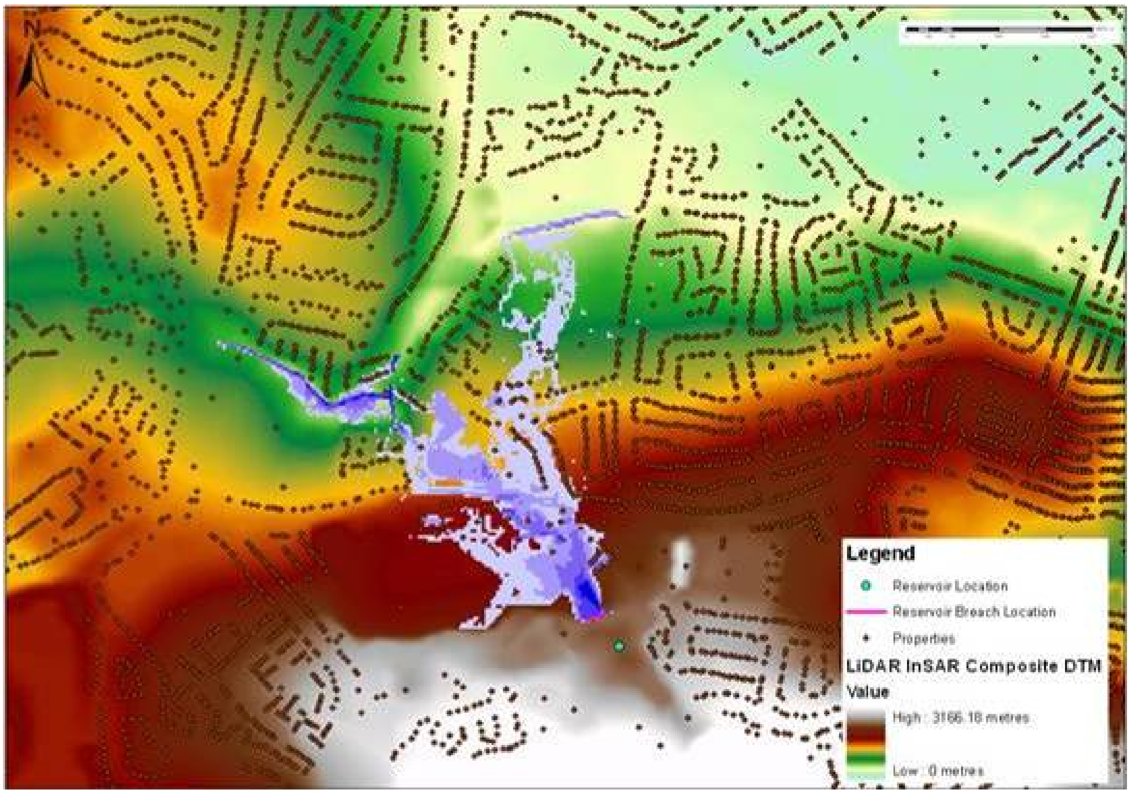


Figure B3 – U5001_NW – Intermediate method results 15000m^3 volume

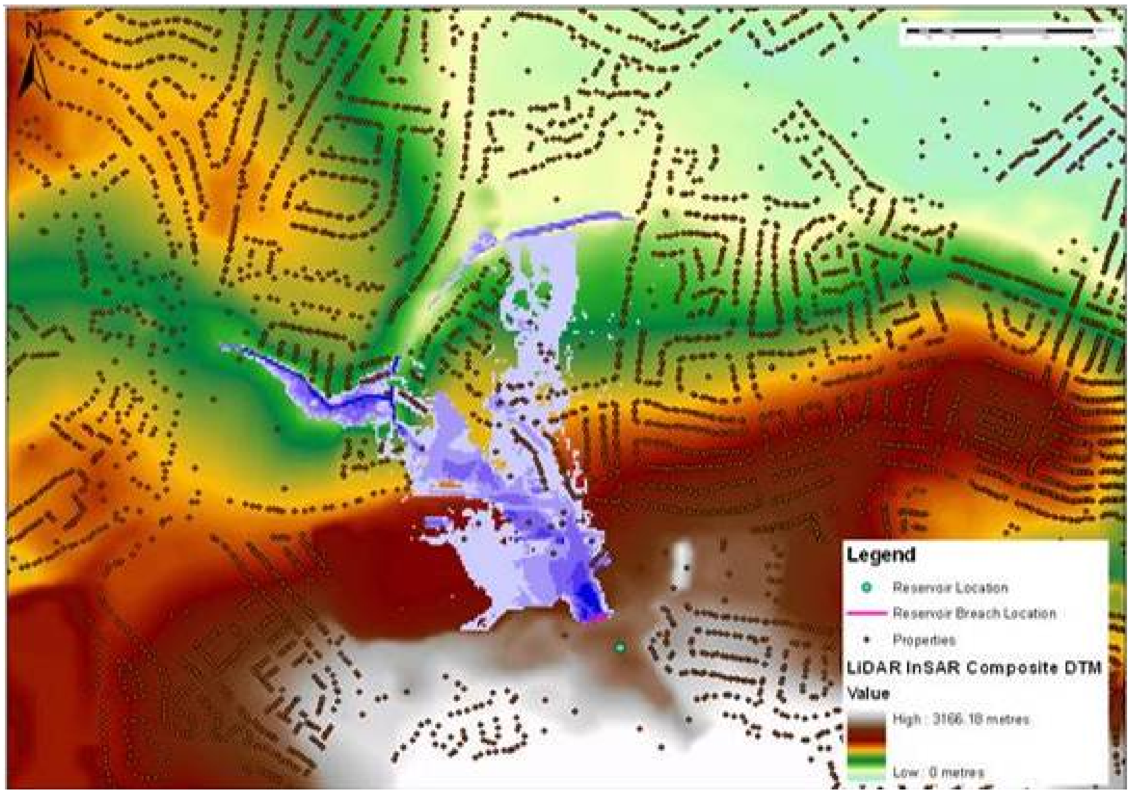


Figure B4 – U5002_NW – Intermediate method results 5000m^3 volume

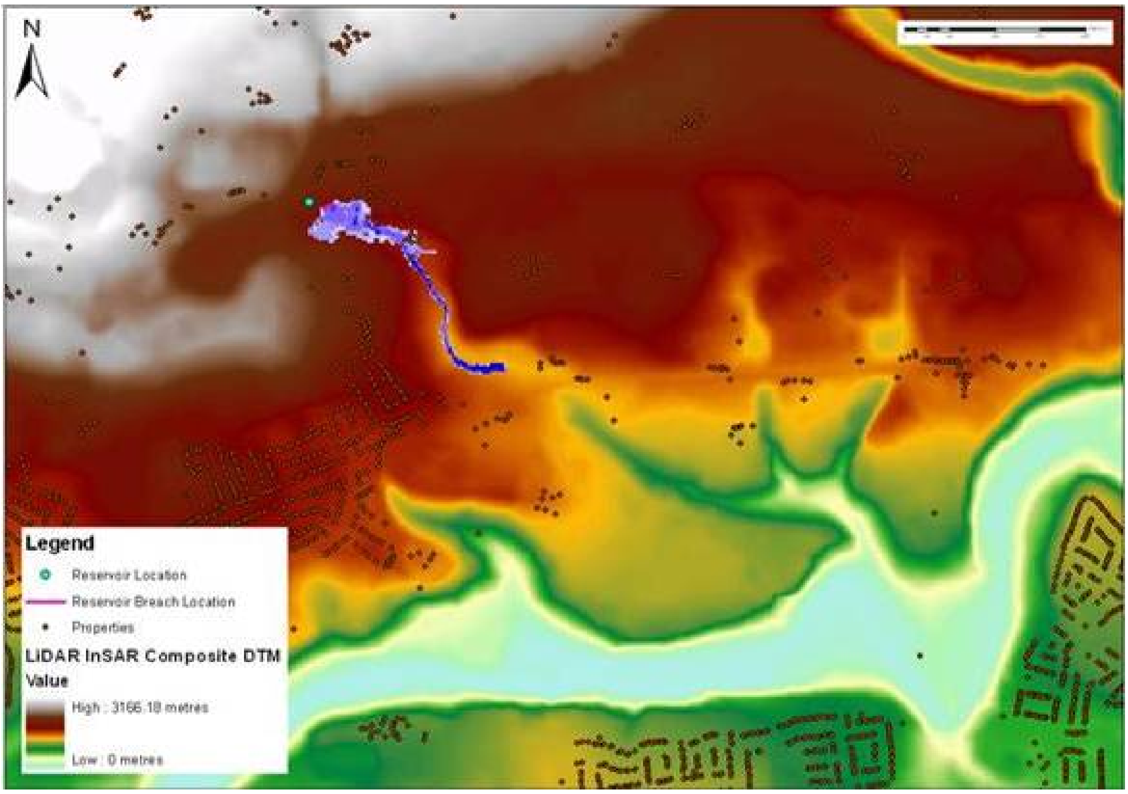


Figure B5 – U5002_NW – Intermediate method results 10000m[3] volume

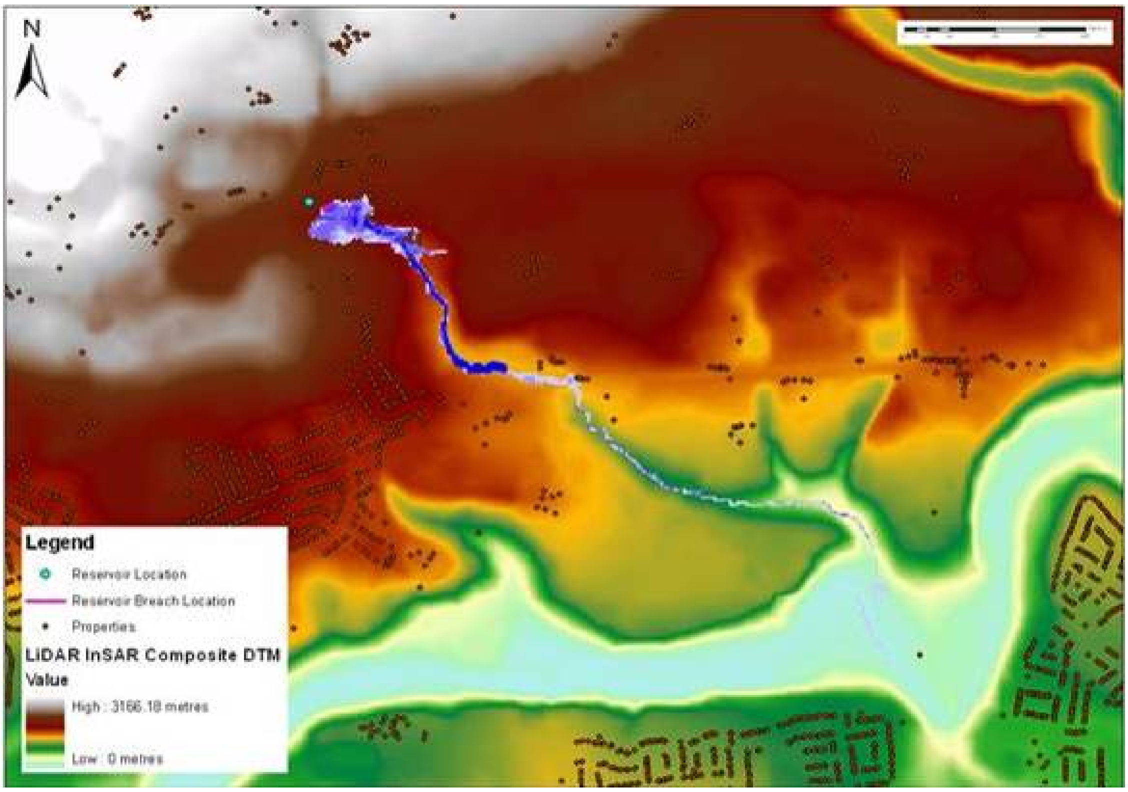


Figure B6 – U5002_NW – Intermediate method results 15000m[3] volume

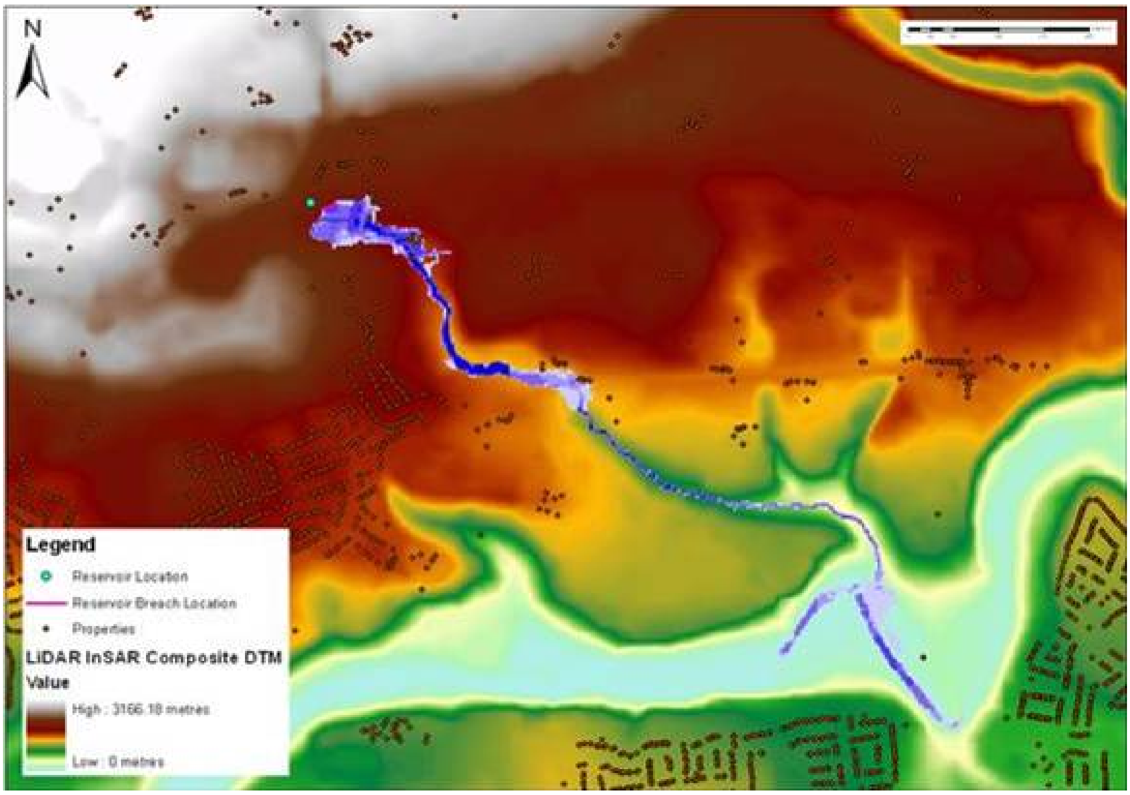


Figure B7 – U5003_NW – Intermediate method results 5000m^3 volume

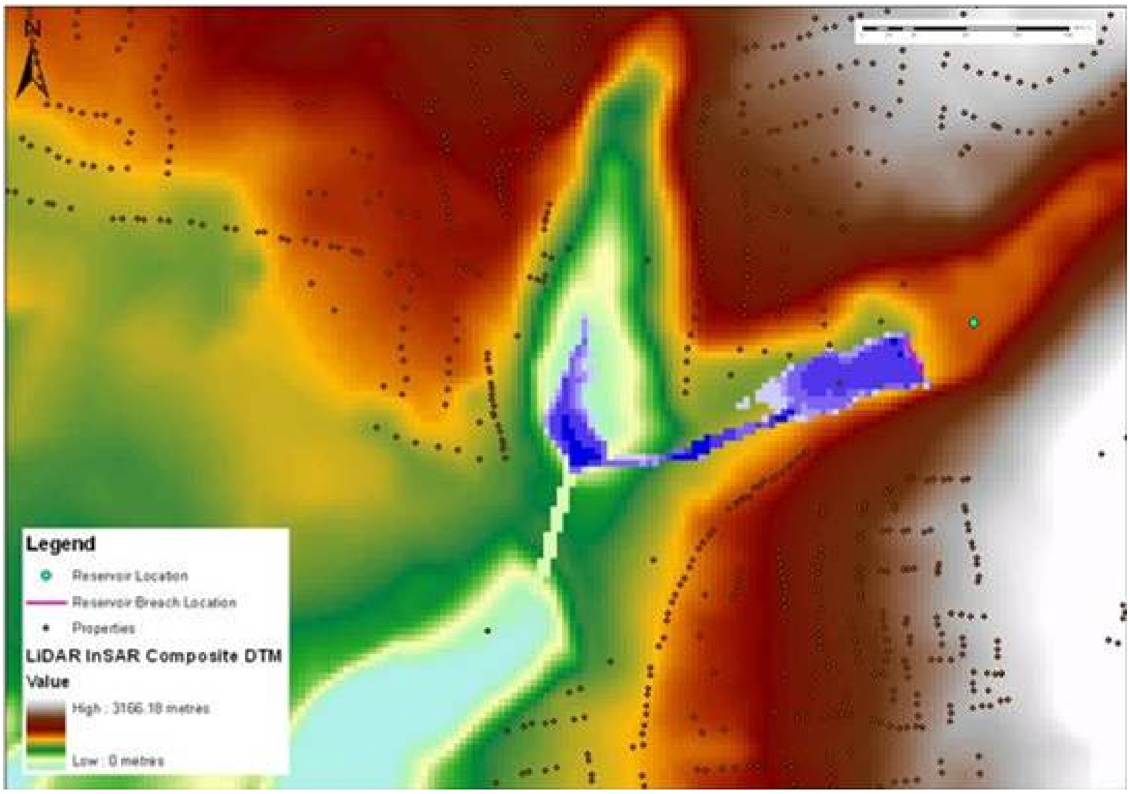


Figure B8 – U5003_NW – Intermediate method results 10000m^3 volume

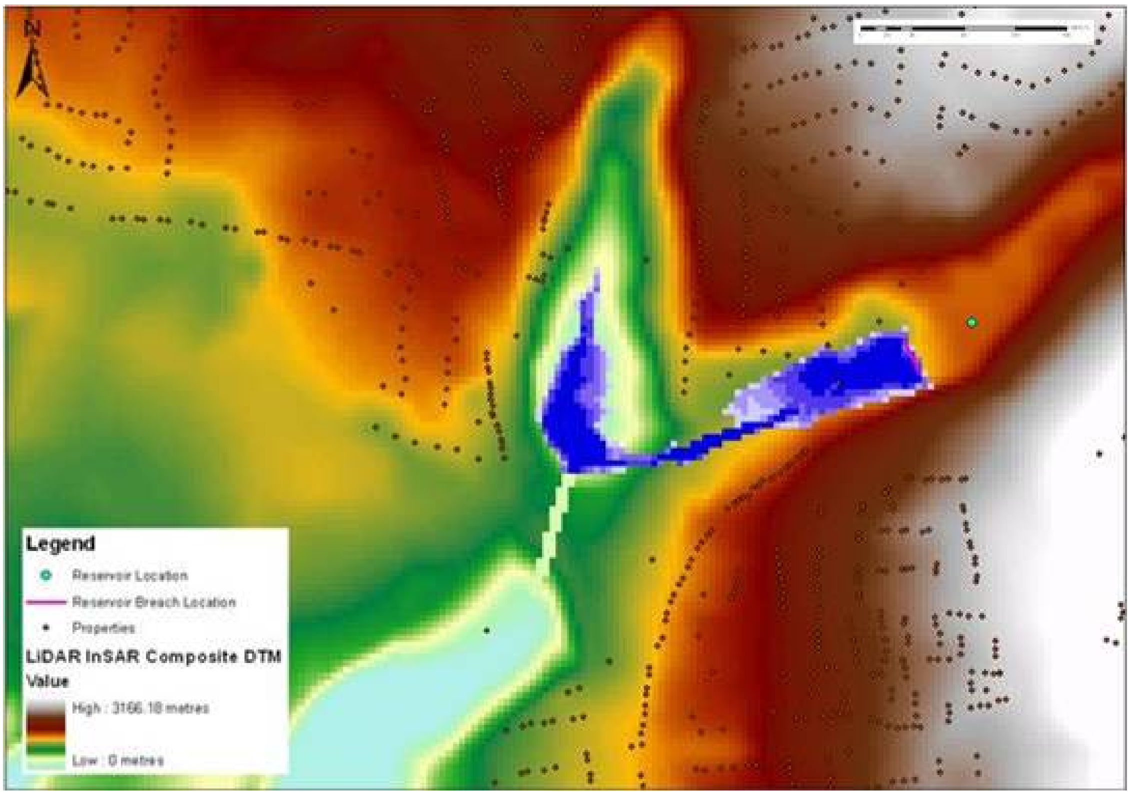


Figure B9 – U5003_NW – Intermediate method results 15000m^3 volume

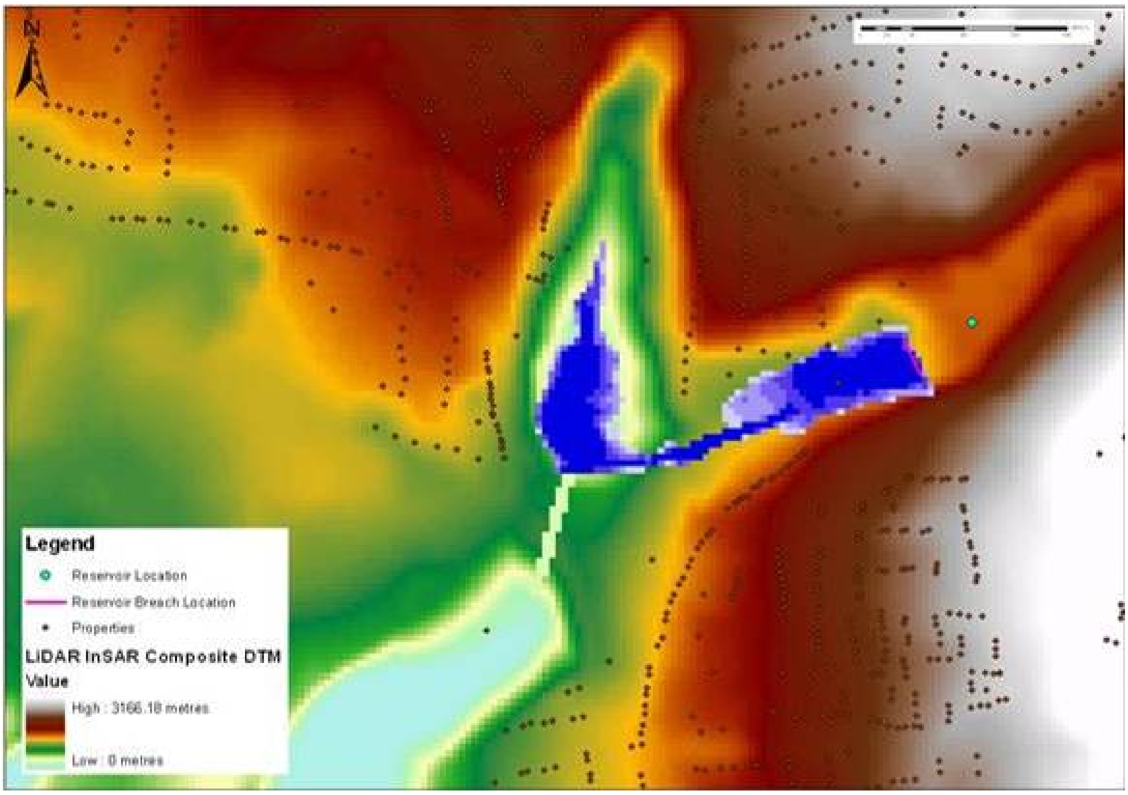


Figure B10 – U5004_NW – Intermediate method results 5000m^3 volume

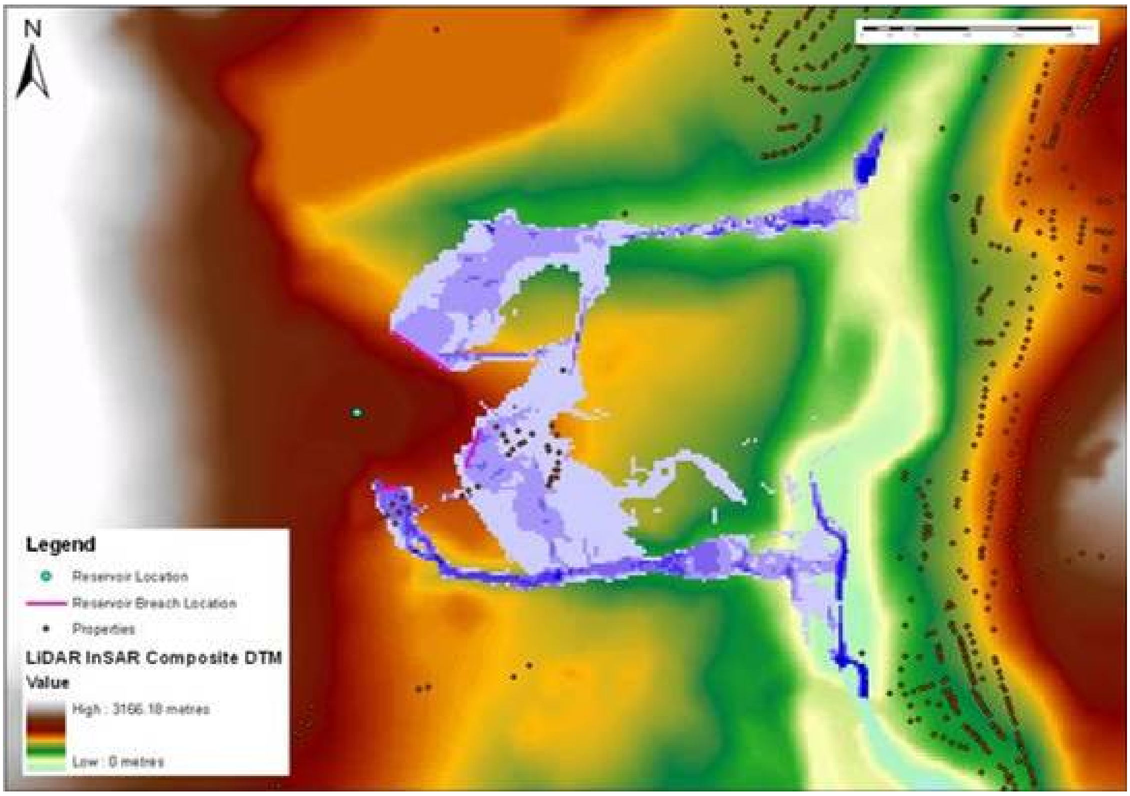


Figure B11 – U5004_NW – Intermediate method results 10000m^3 volume

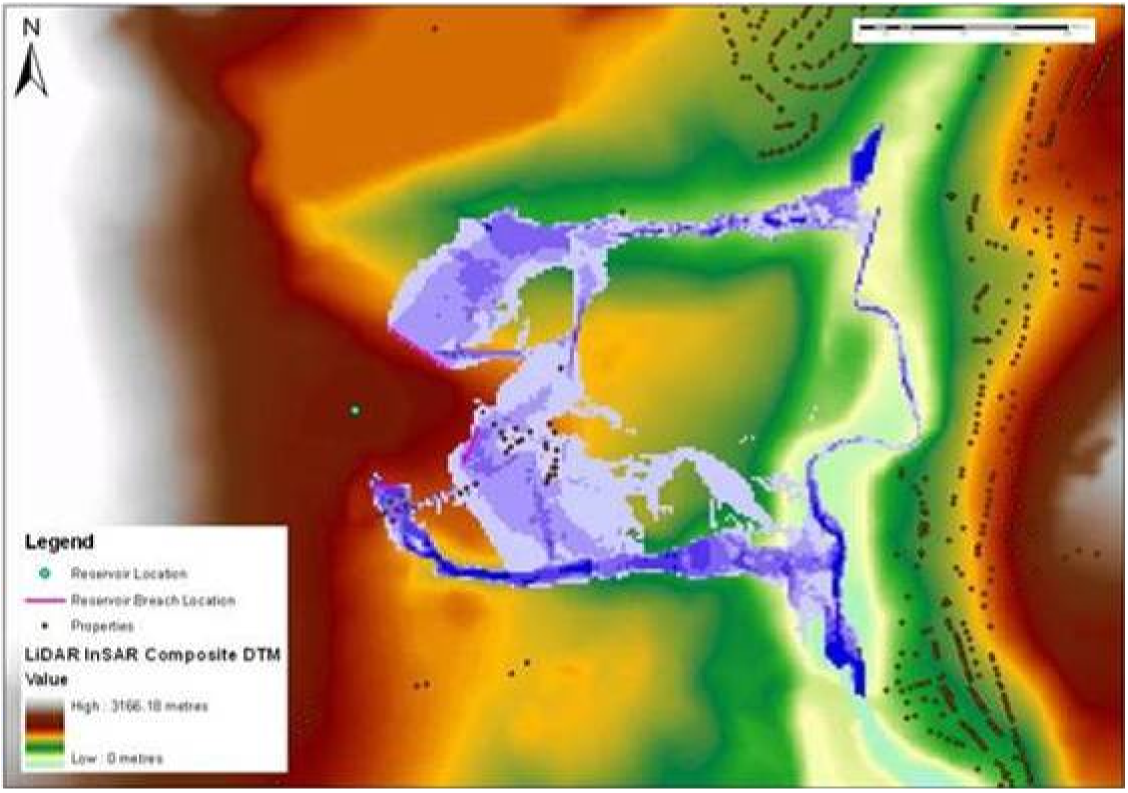


Figure B12 – U5004_NW – Intermediate method results 15000m^3 volume

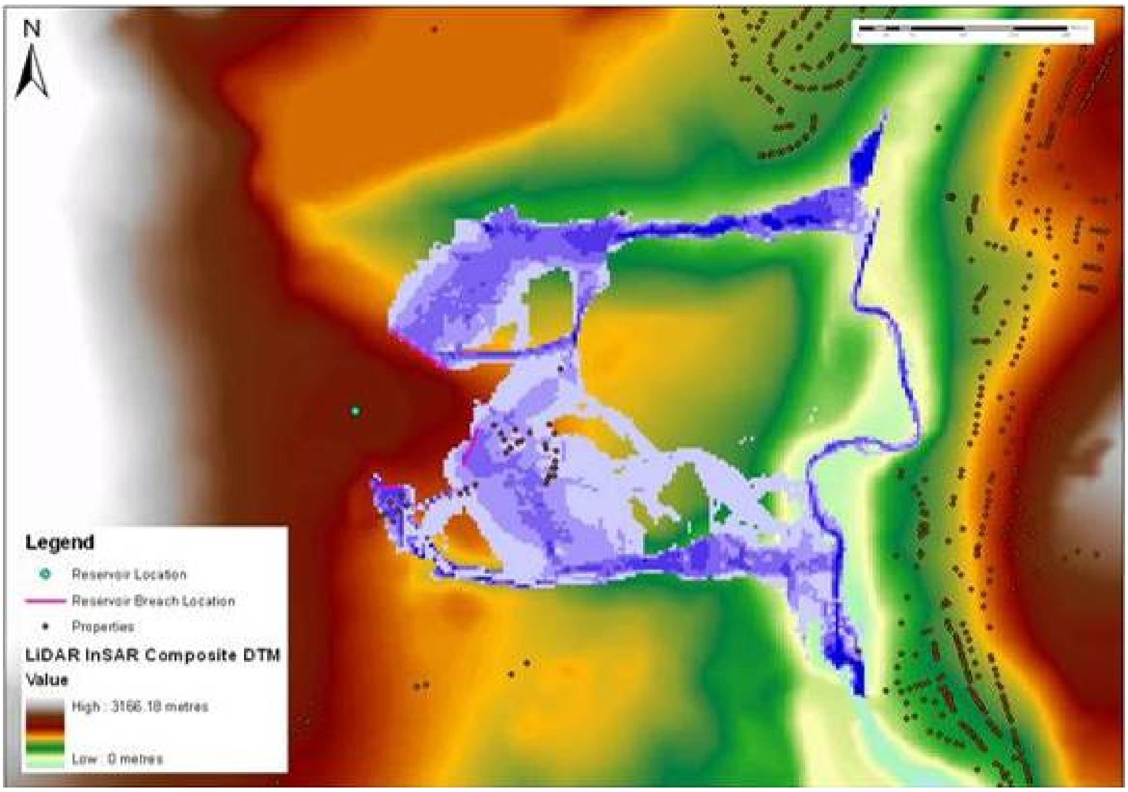


Figure B13 – U5005_SO – Intermediate method results 5000m^3 volume

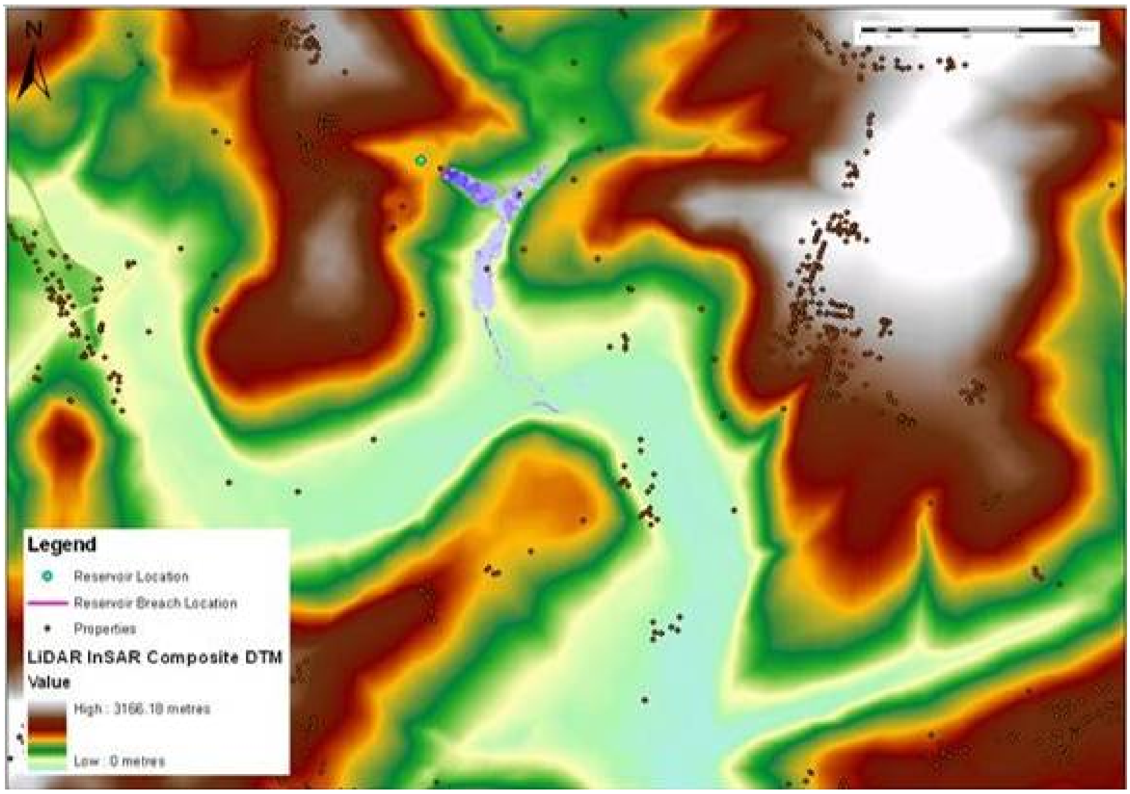


Figure B14 – U5005_SO – Intermediate method results 10000m^3 volume

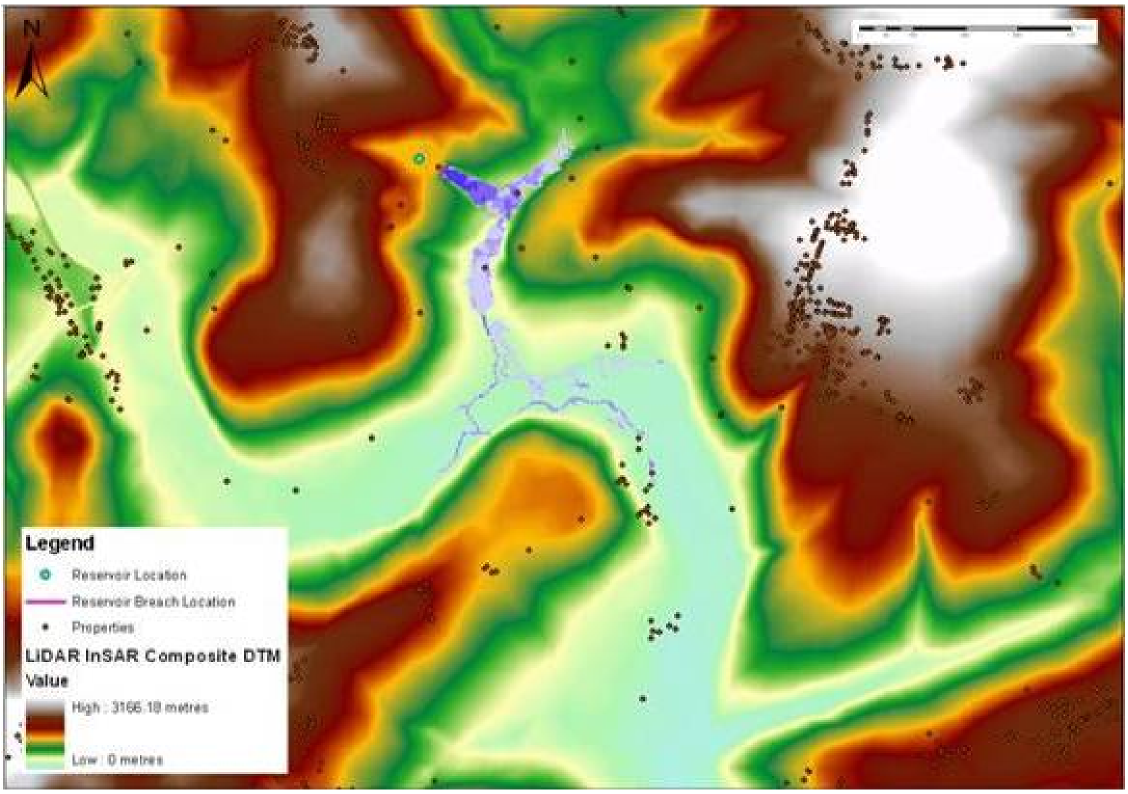


Figure B15 – U5005_SO – Intermediate method results 15000m^3 volume

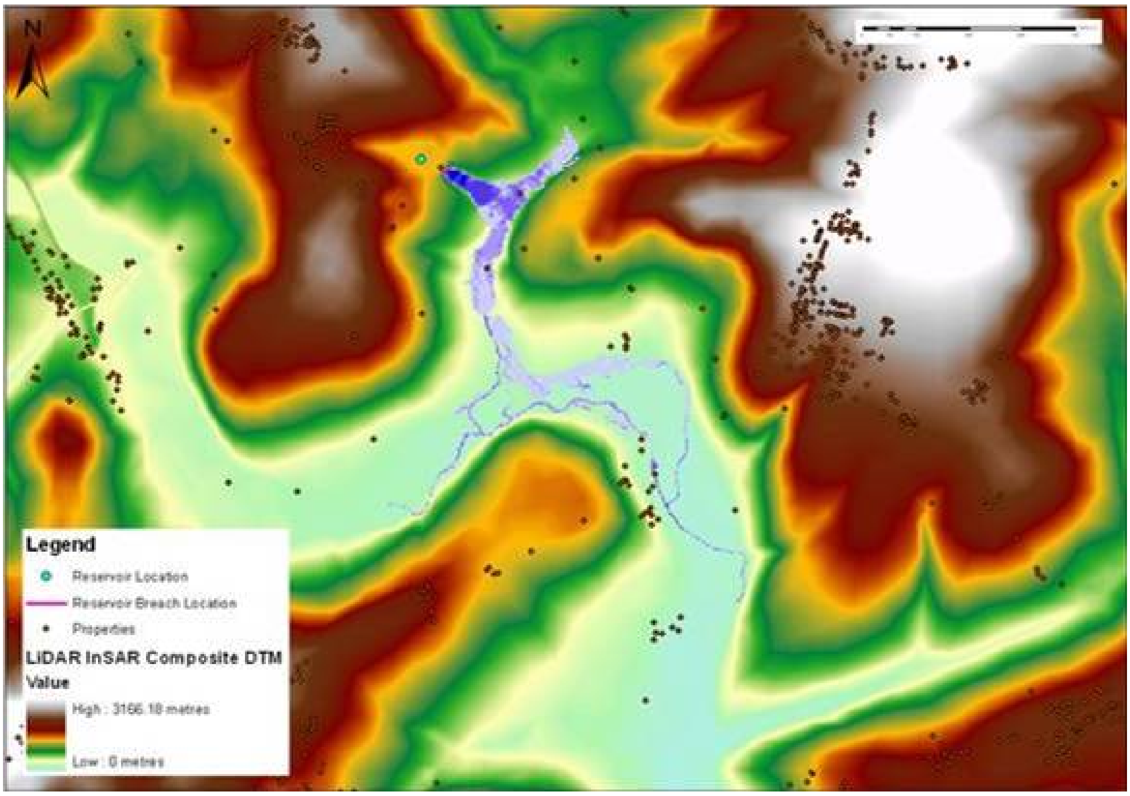


Figure B16 – U5006_TH – Intermediate method results 5000m^3 volume

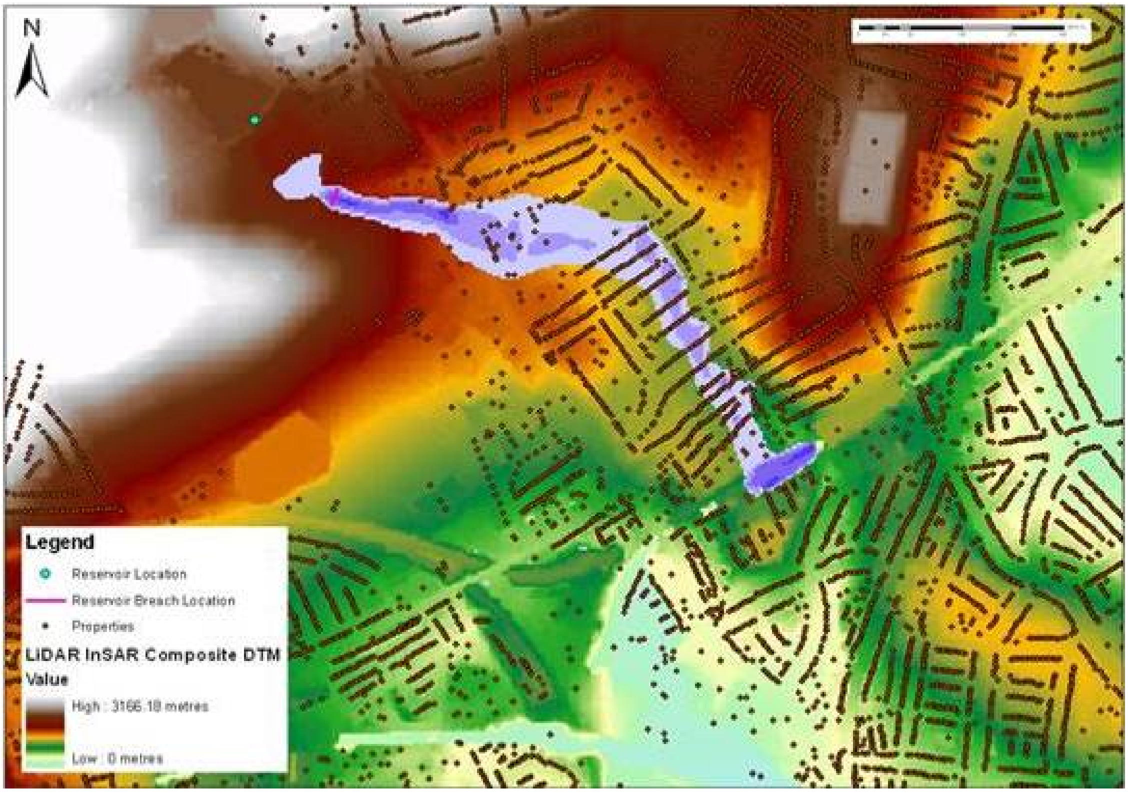


Figure B17 – U5006_TH – Intermediate method results 10000m^3 volume

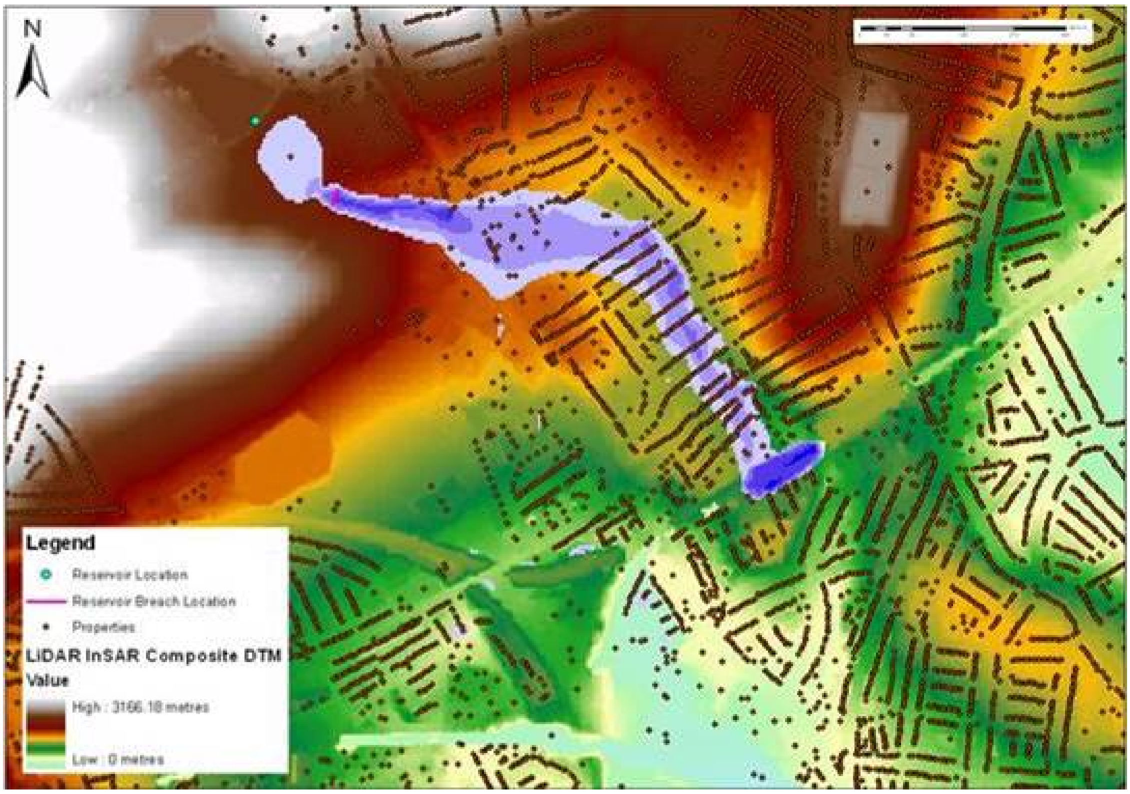


Figure B18 – U5006_TH – Intermediate method results 15000m^3 volume

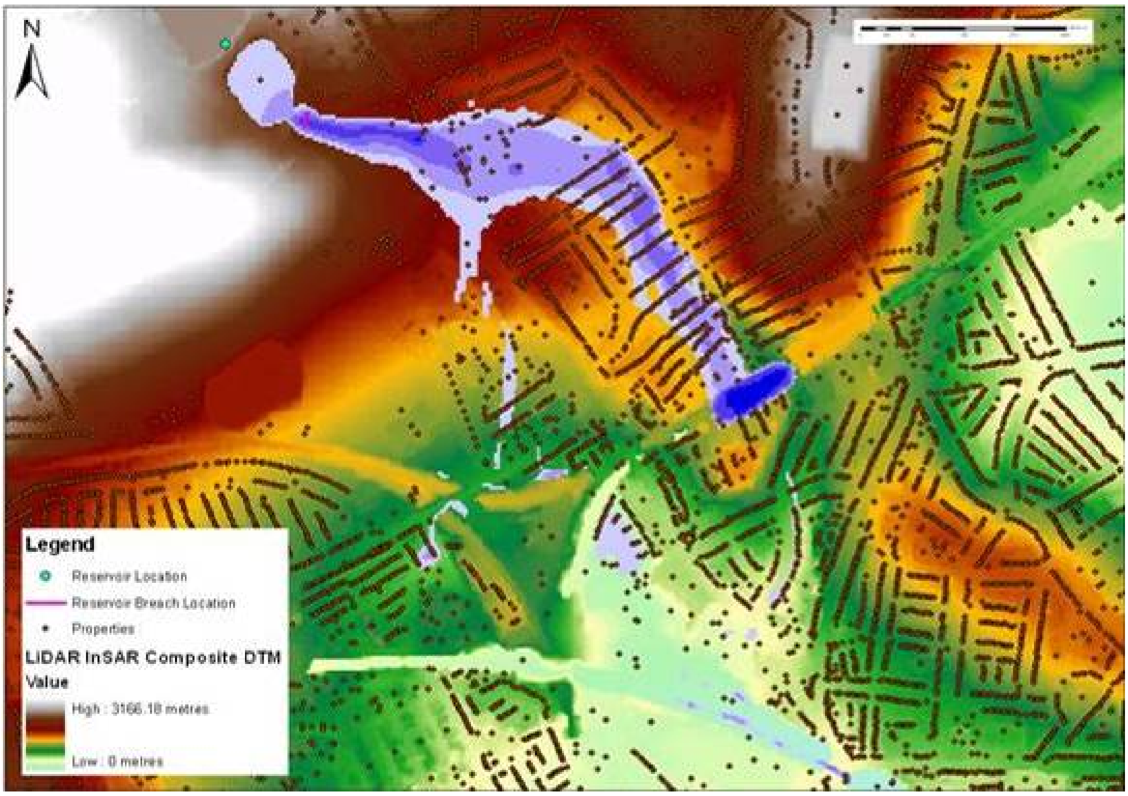


Figure B19 – U5007_AN – Intermediate method results 5000m^3 volume

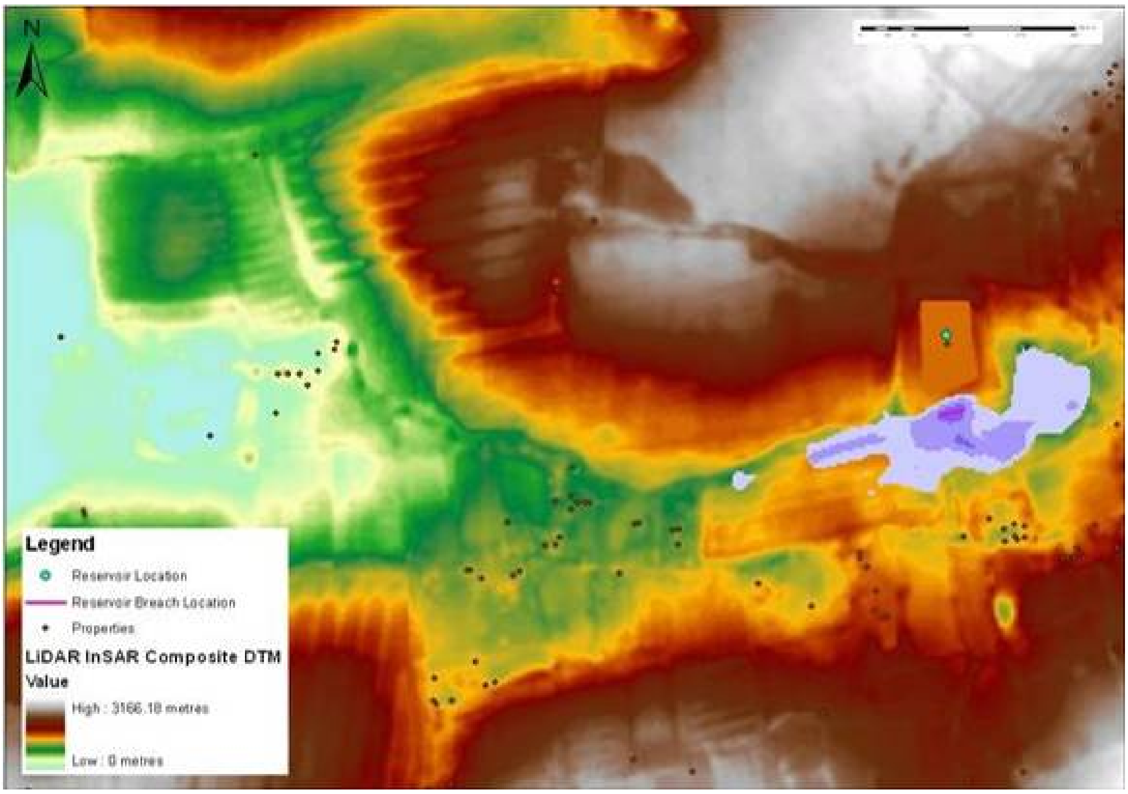


Figure B20 – U5007_AN – Intermediate method results 10000m^3 volume

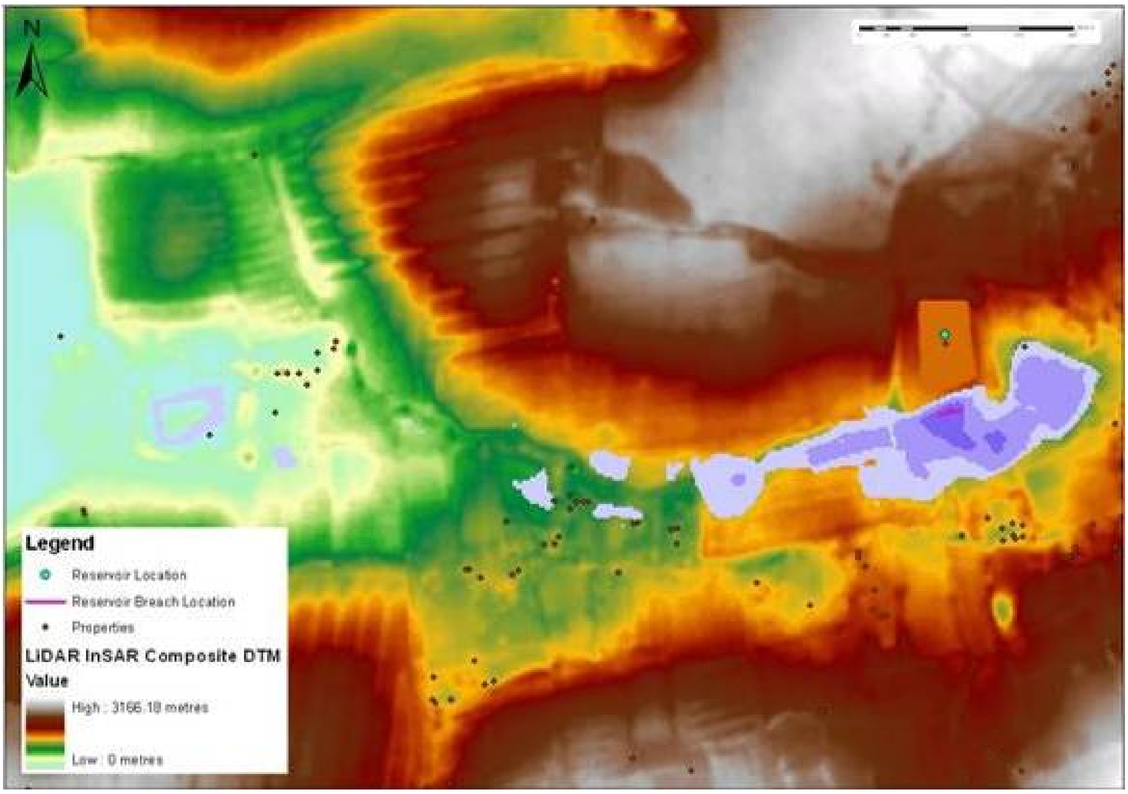


Figure B21 – U5007_AN – Intermediate method results 15000m^3 volume

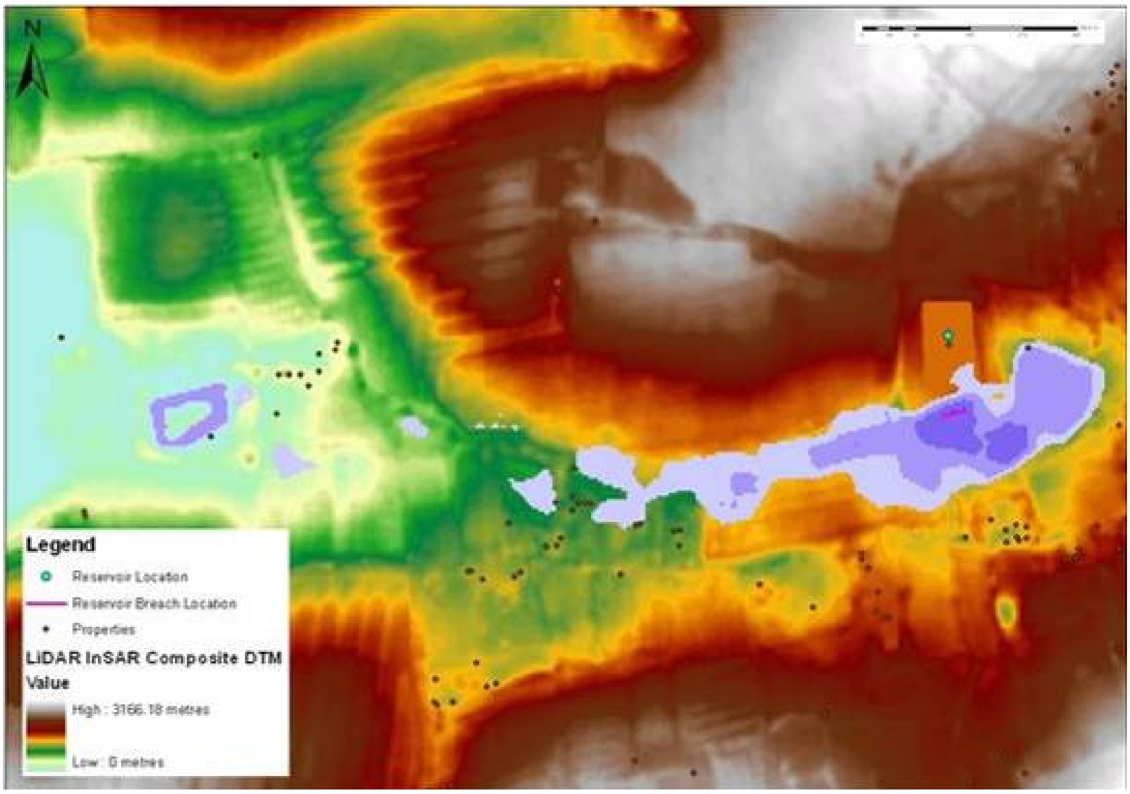


Figure B22 – U5008_NW – Intermediate method results 5000m^3 volume

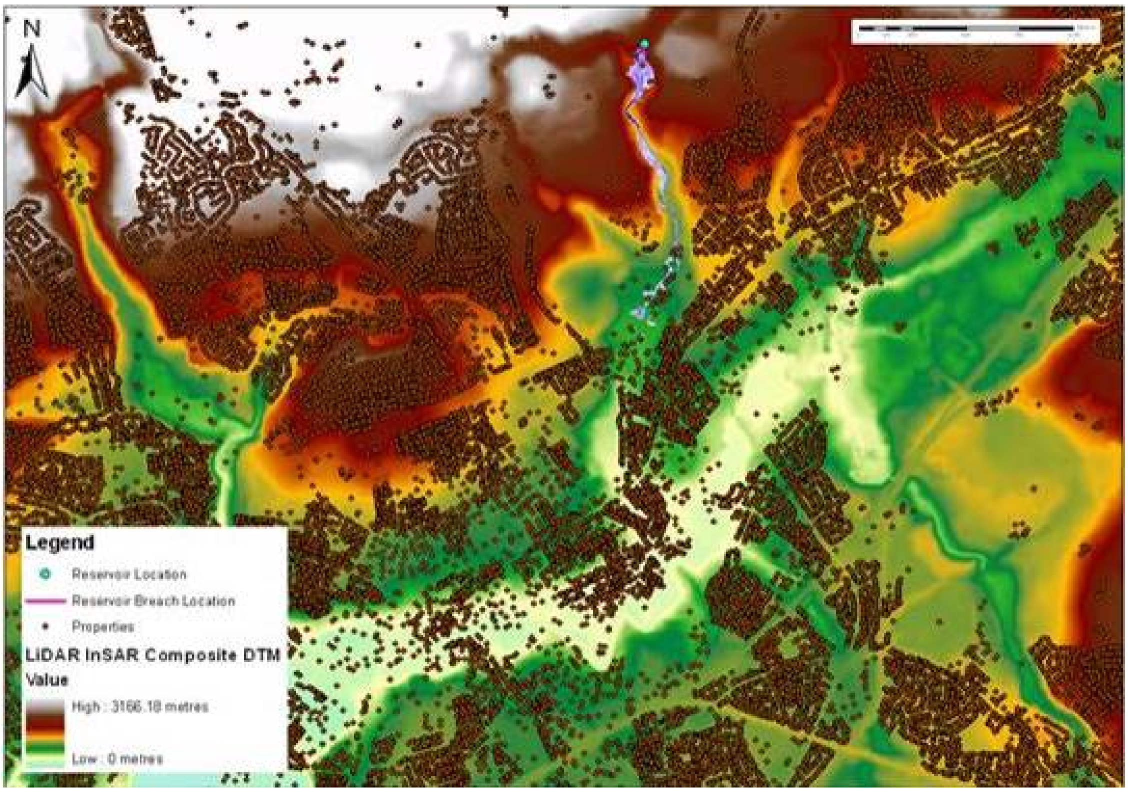


Figure B23 – U5008_NW – Intermediate method results 10000m[3] volume

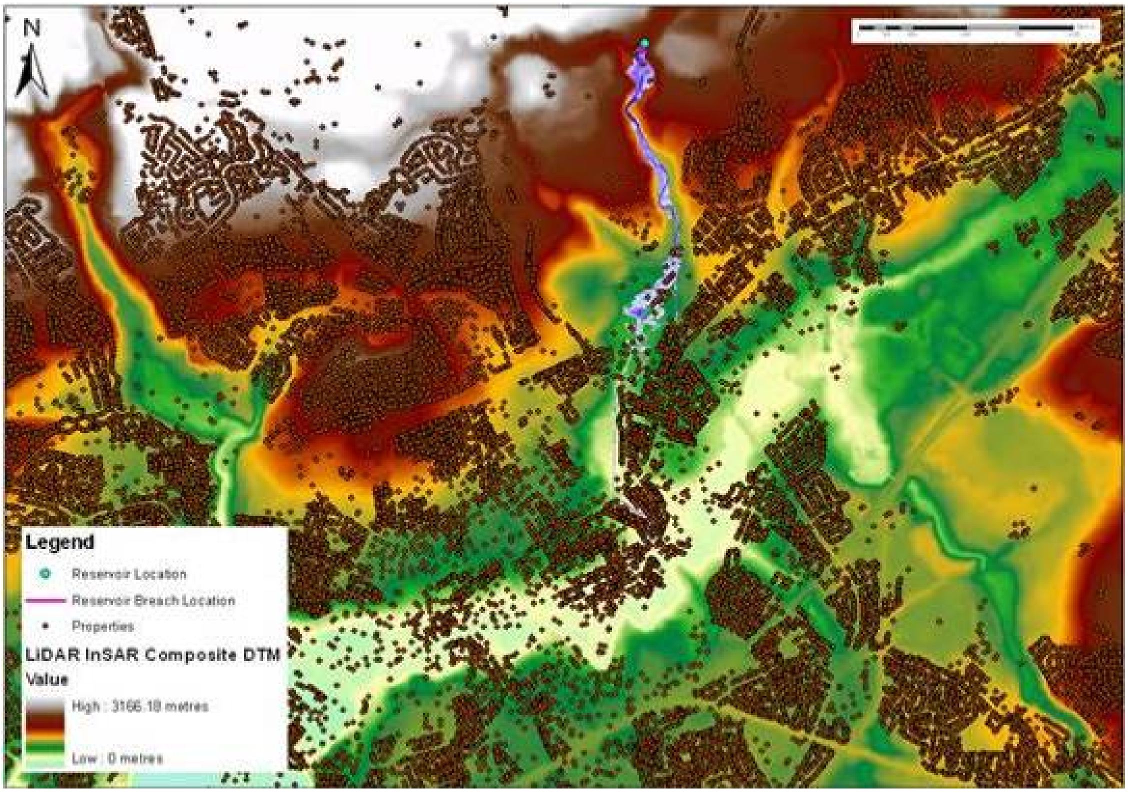


Figure B24 – U5008_NW – Intermediate method results 15000m[3] volume

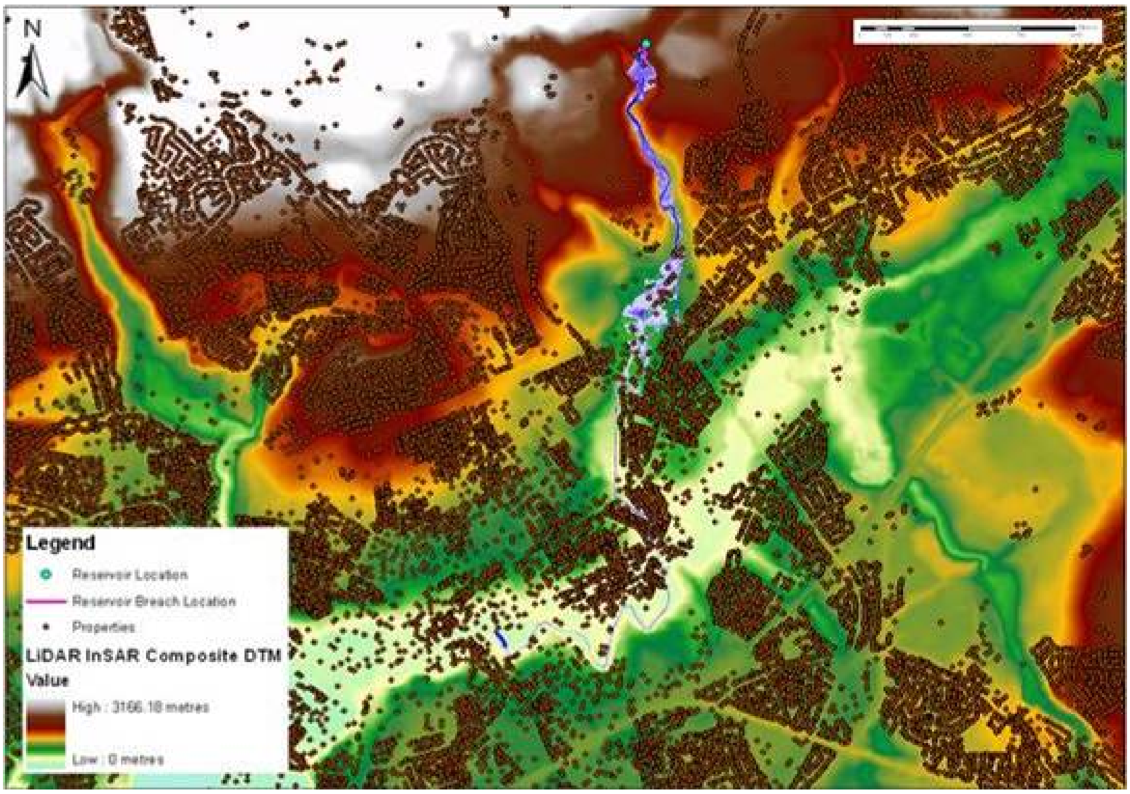


Figure B25 – U5009_NW – Intermediate method results 5000m^3 volume

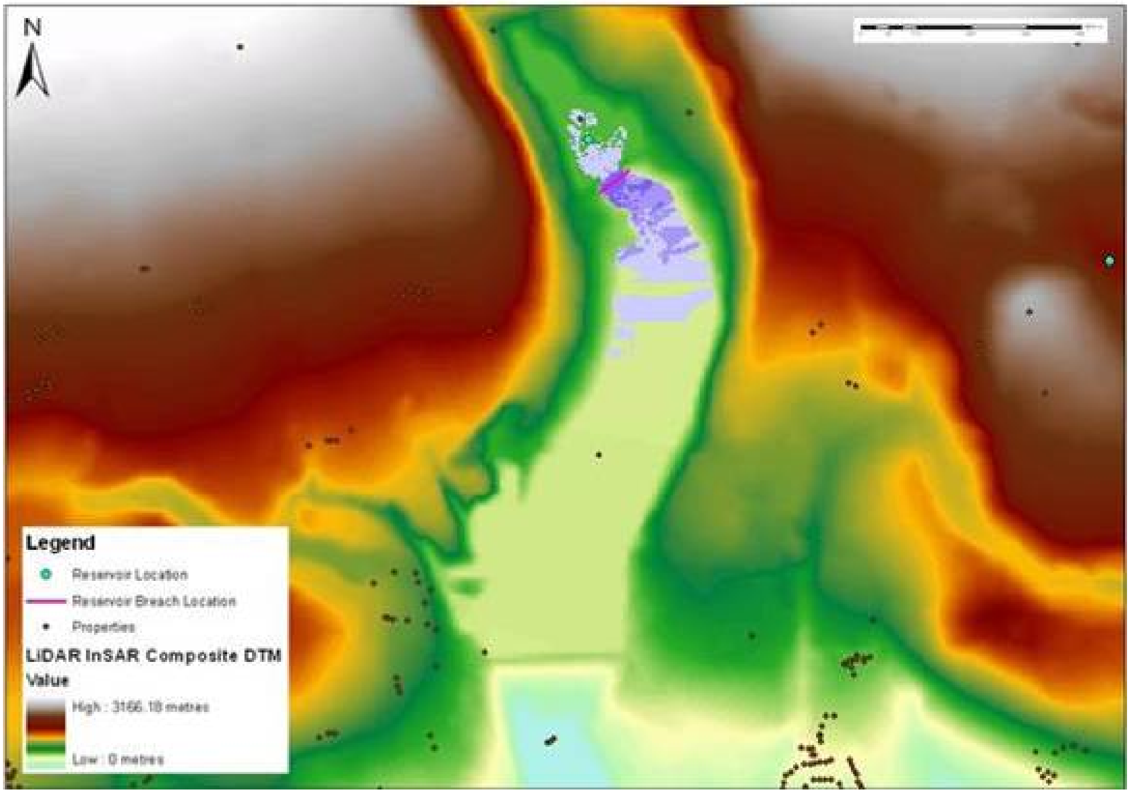


Figure B26 – U5009_NW – Intermediate method results 10000m^3 volume

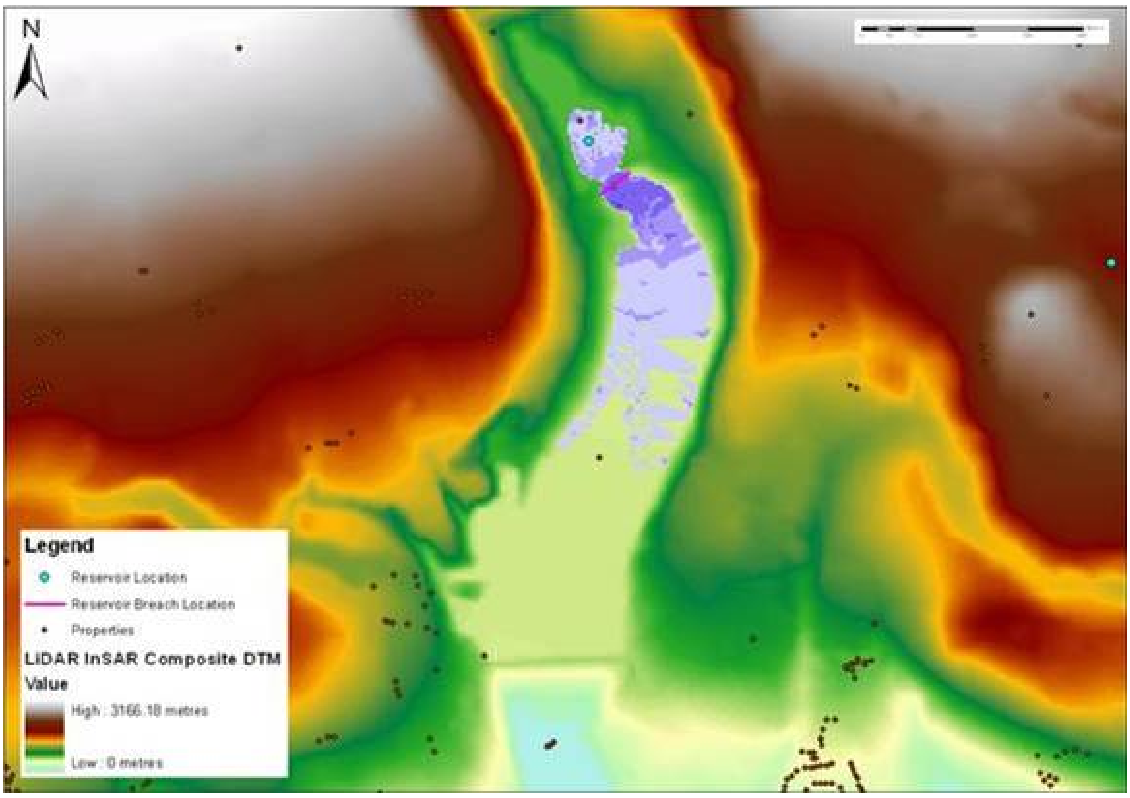


Figure B27 – U5009_NW – Intermediate method results 15000m^3 volume

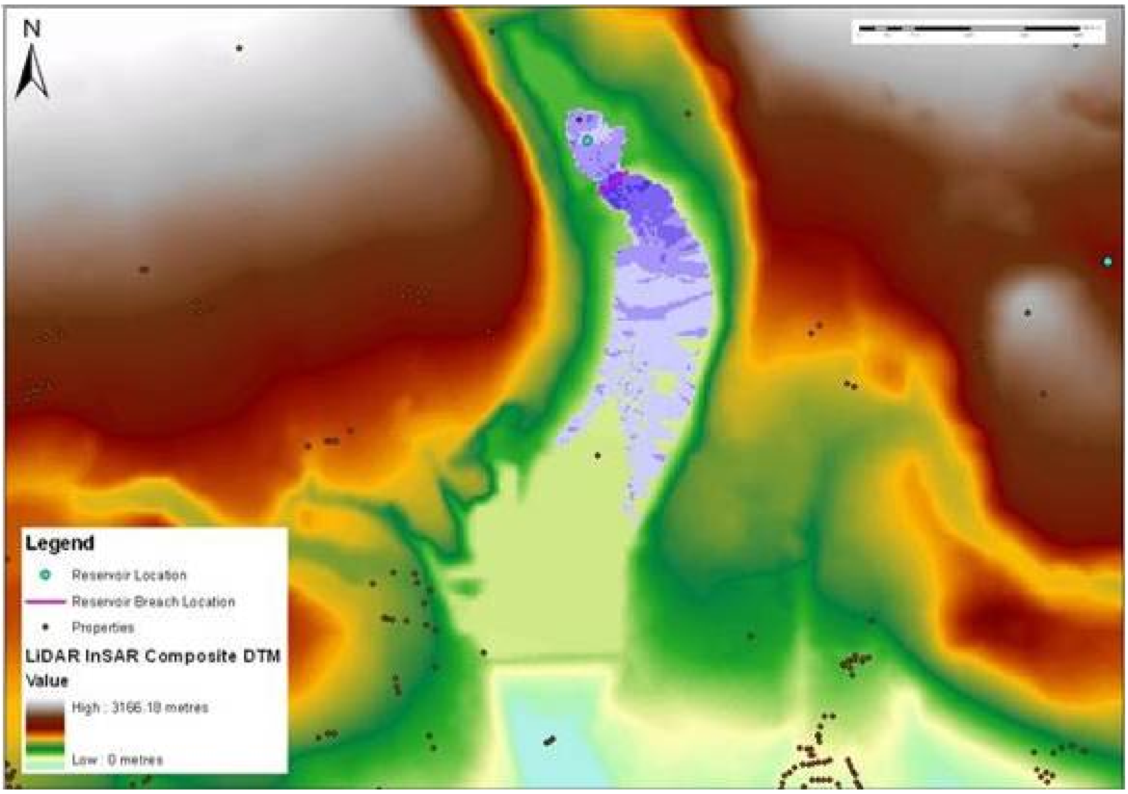


Figure B28 – U5010_NW – Intermediate method results 5000m^3 volume

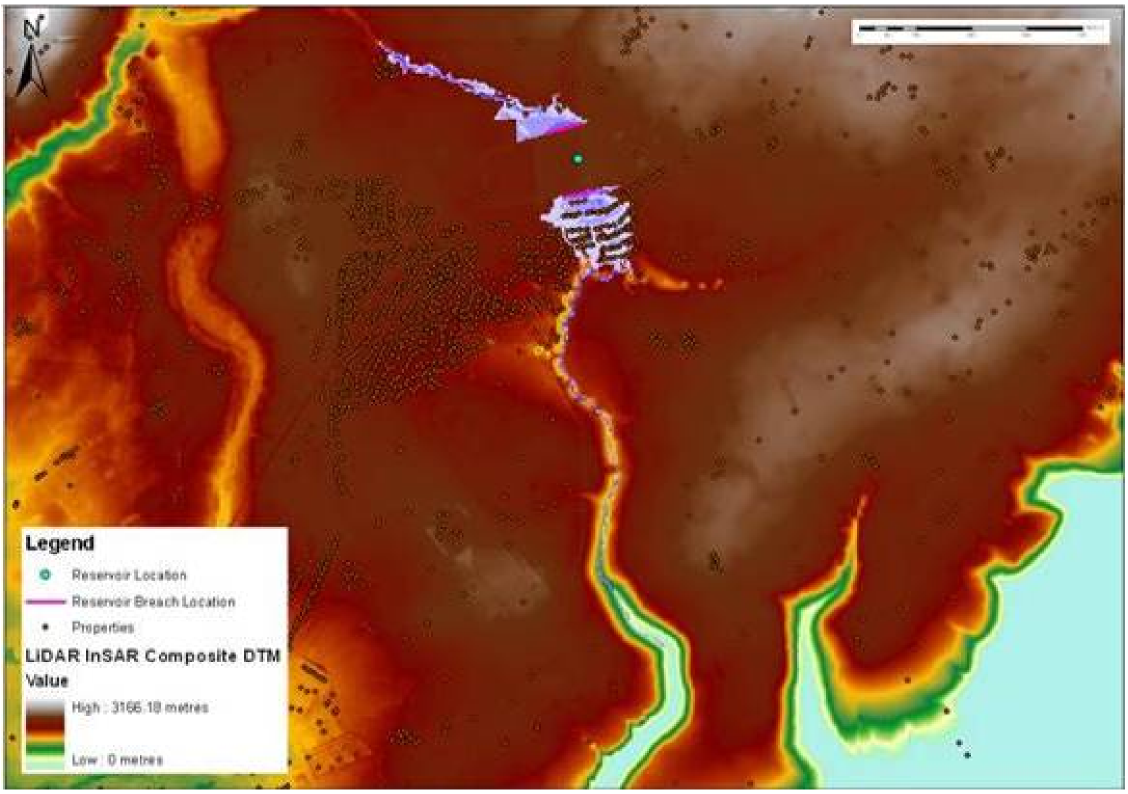


Figure B29 – U5010_NW – Intermediate method results 10000m^3 volume

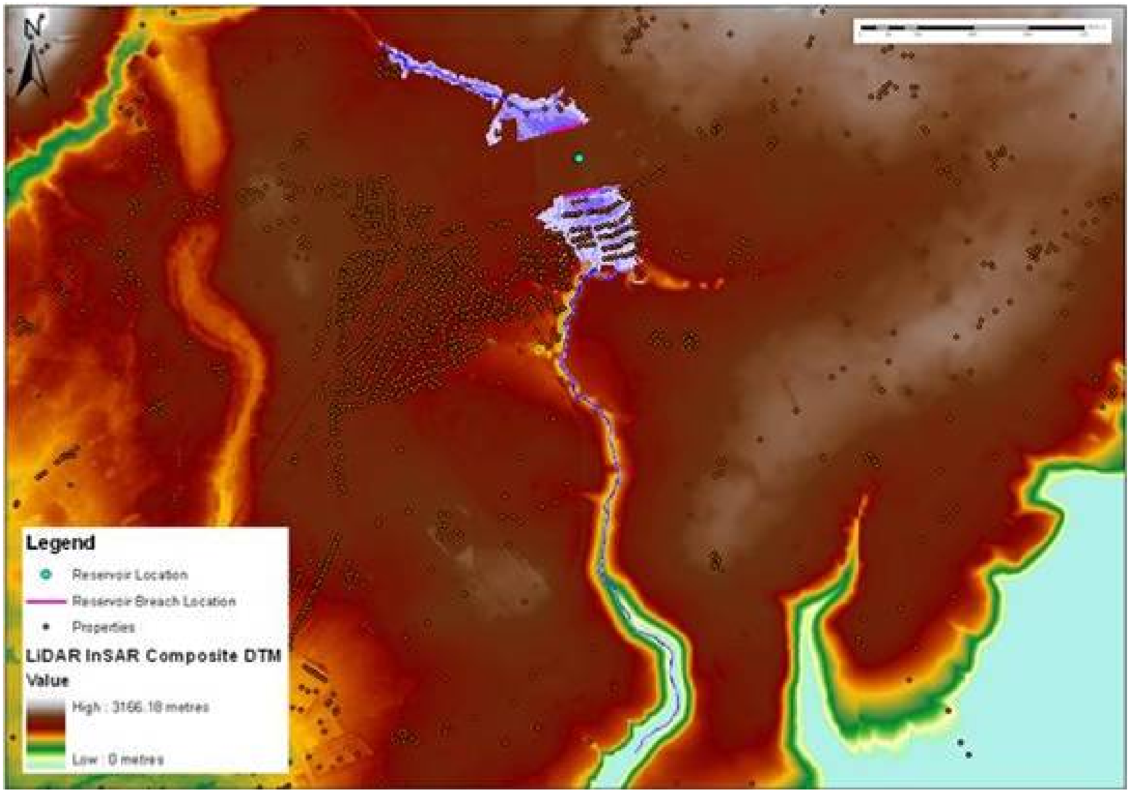


Figure B30 – U5010_NW – Intermediate method results 15000m^3 volume

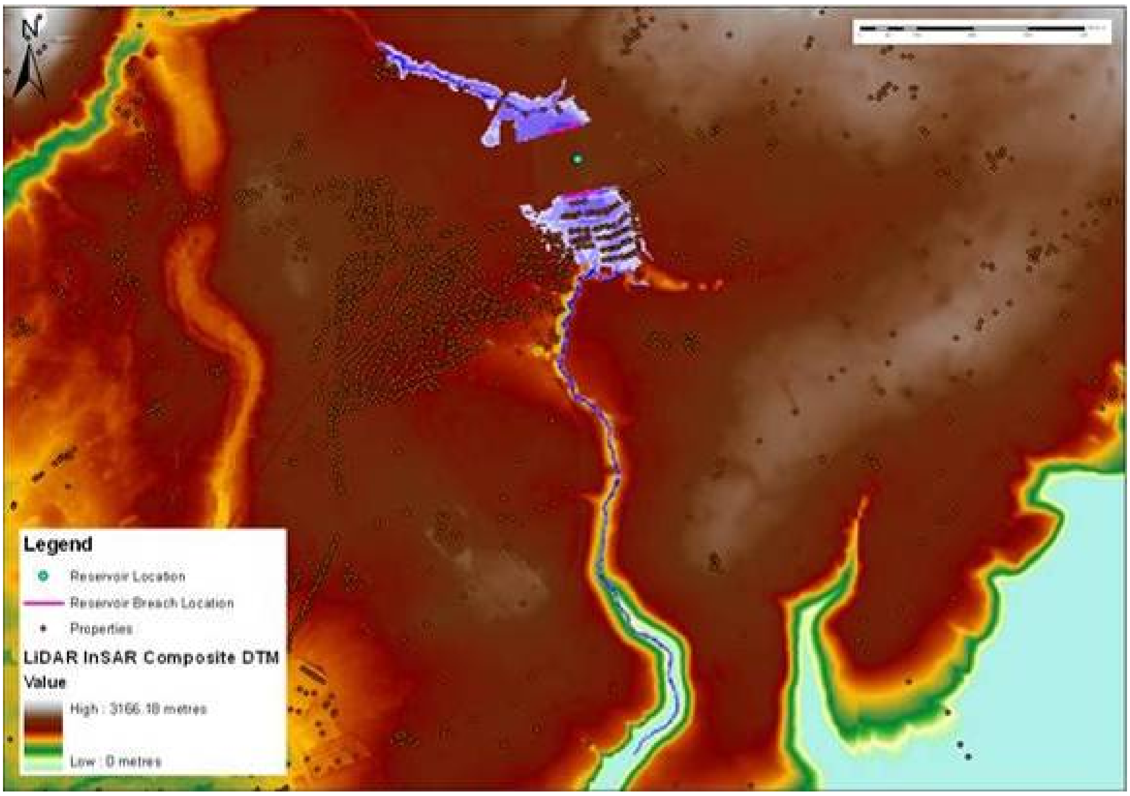
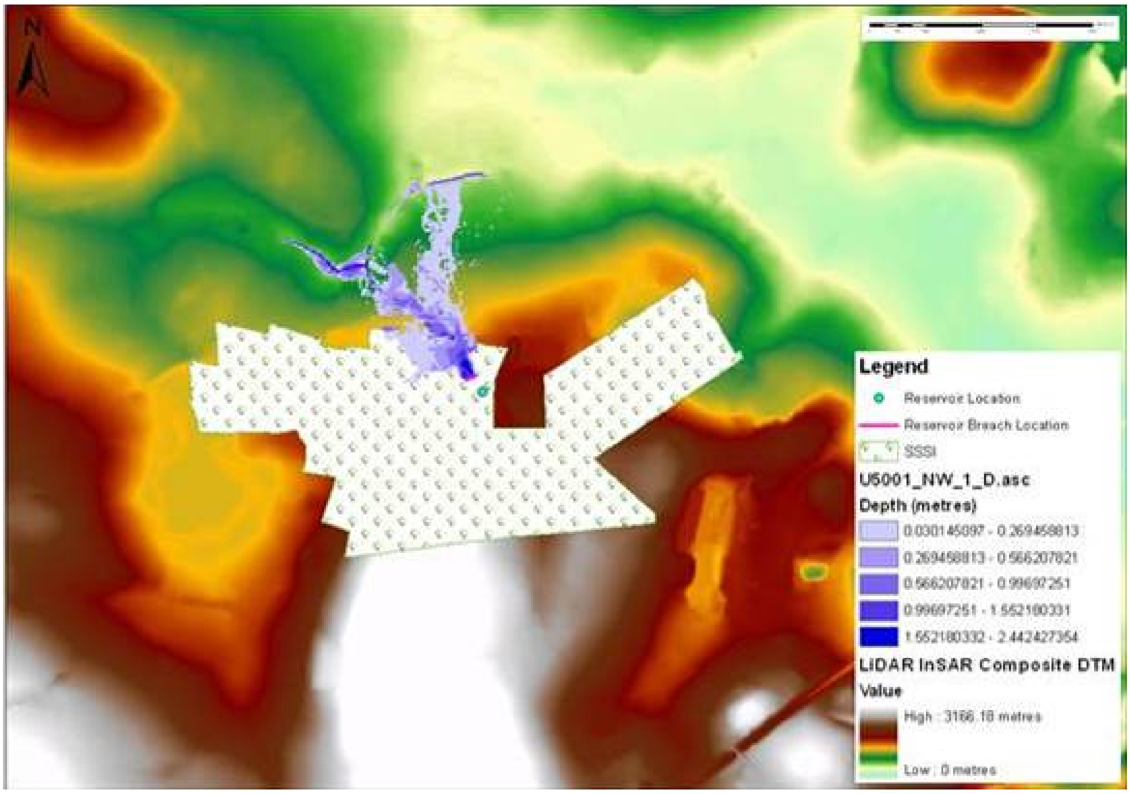


Figure B31 – Example map showing intersect of Intermediate results with SSSI dataset



Appendix C. Intermediate method downstream impact assessment

Figure C1 – Variation of LLOL with assumed reservoir volume for all case study reservoirs

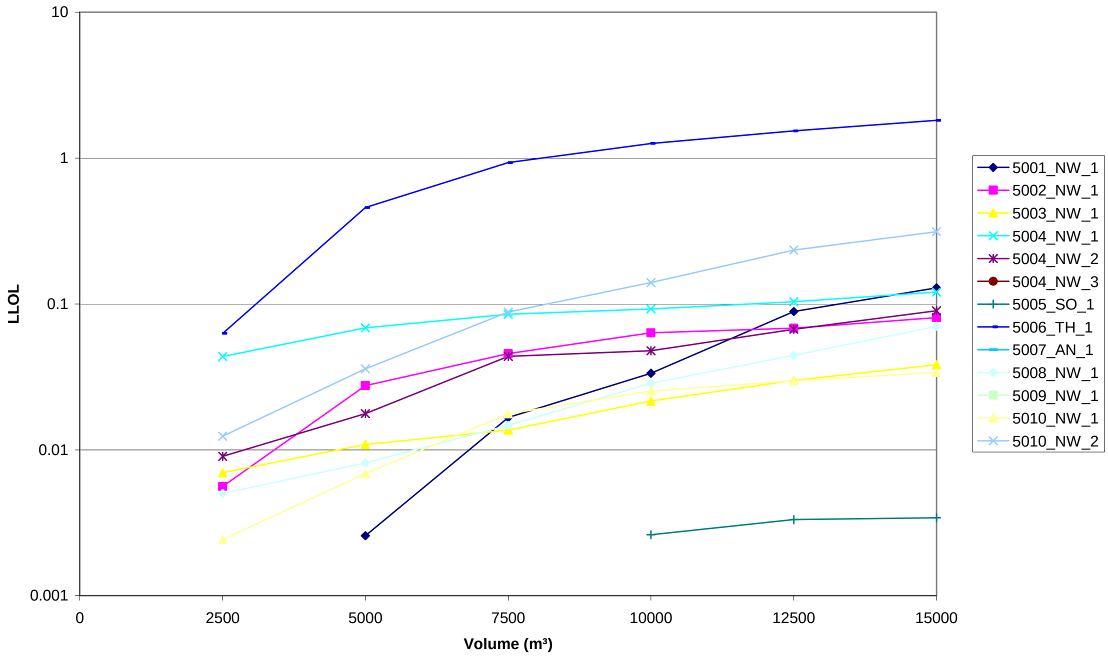


Figure C2 – Variation of number of properties affected with assumed reservoir volume for all case study reservoirs

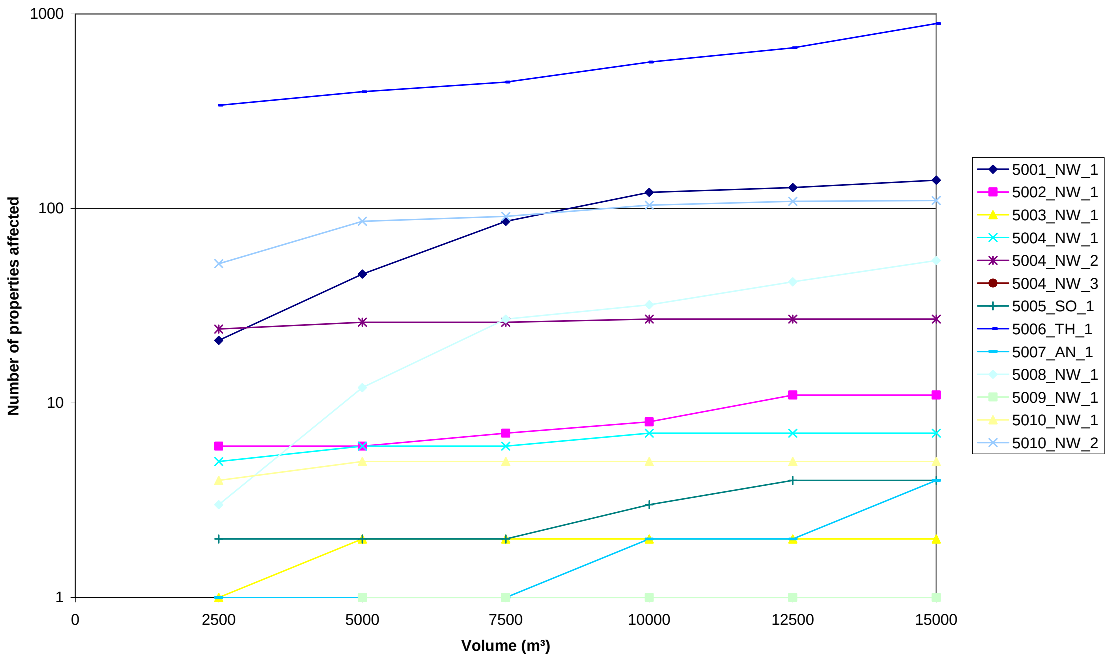


Figure C3 – Variation of LLOL and number of properties at risk for U5001_NW

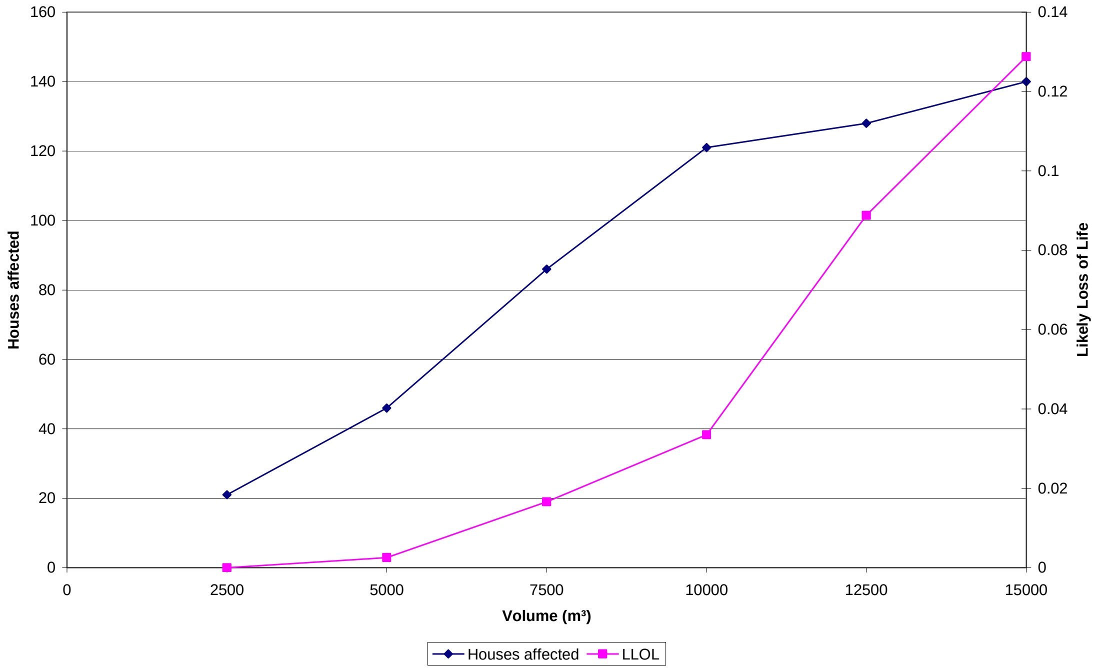


Figure C4 – Variation of LLOL and number of properties at risk for U5002_NW

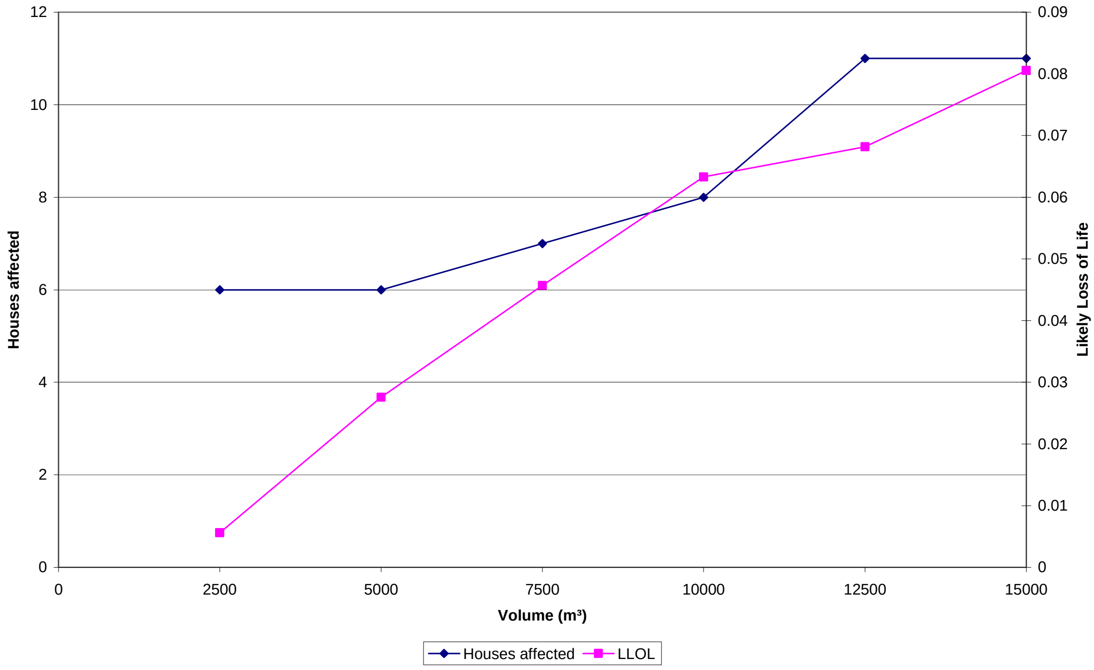


Figure C5 – Variation of LLOL and number of properties at risk for U5003_NW

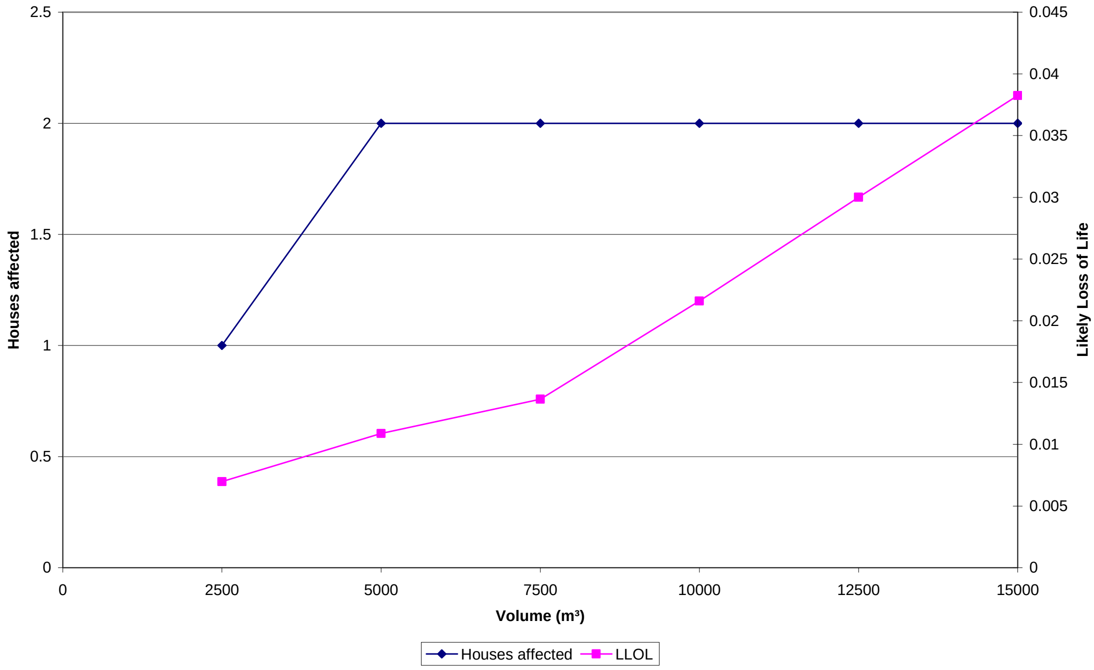


Figure C6 – Variation of LLOL and number of properties at risk for U5004_NW

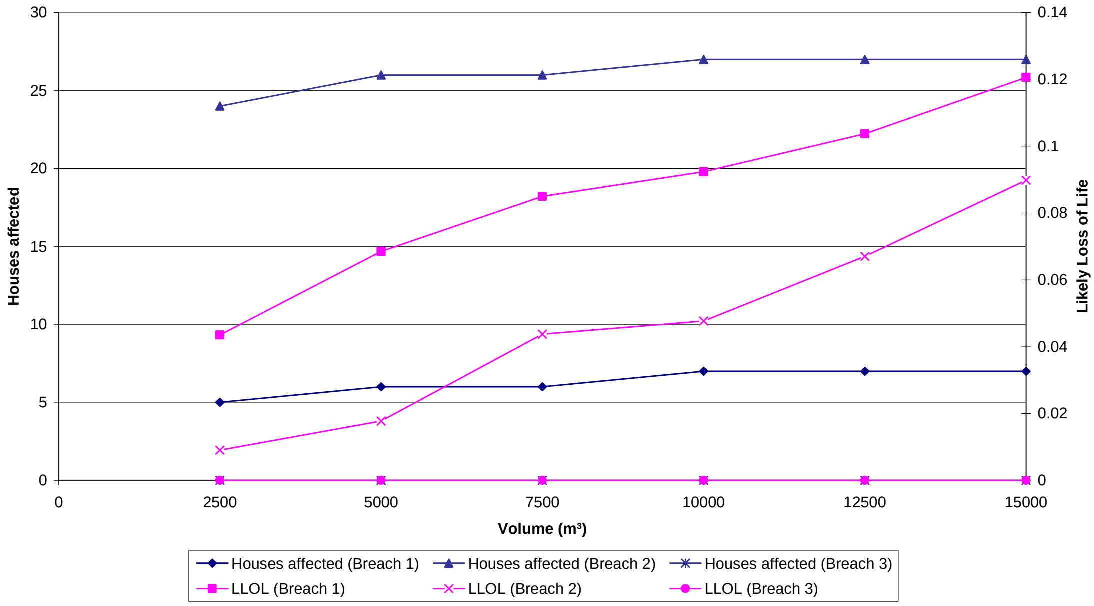


Figure C7 – Variation of LLOL and number of properties at risk for U5005_SO

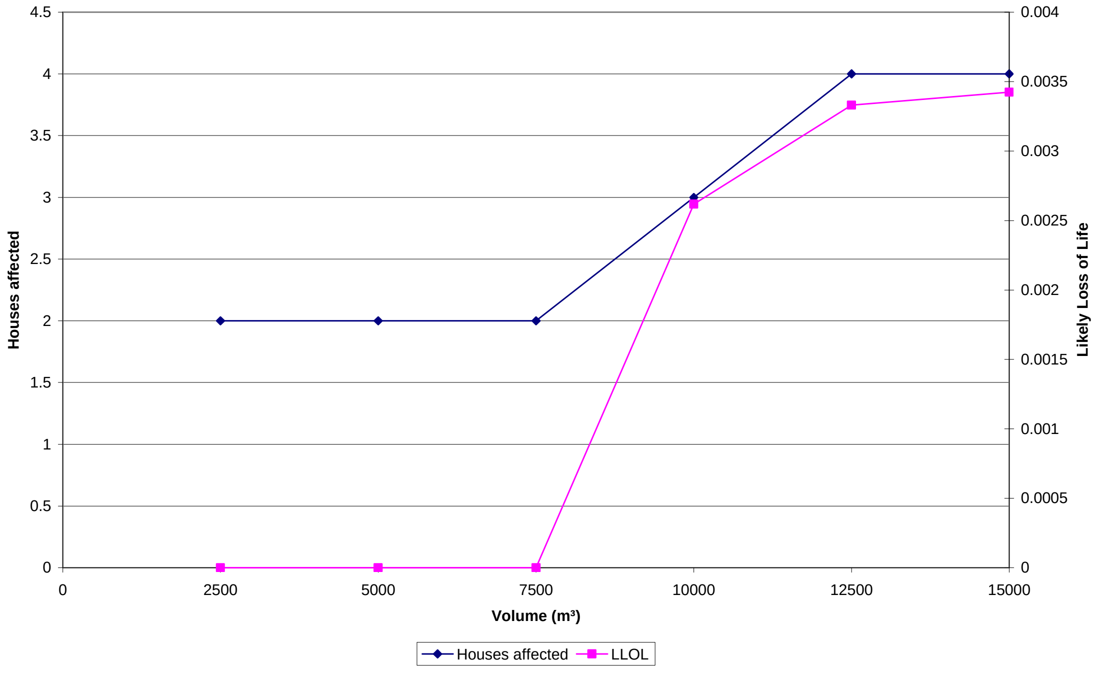


Figure C8 – Variation of LLOL and number of properties at risk for U5006_TH

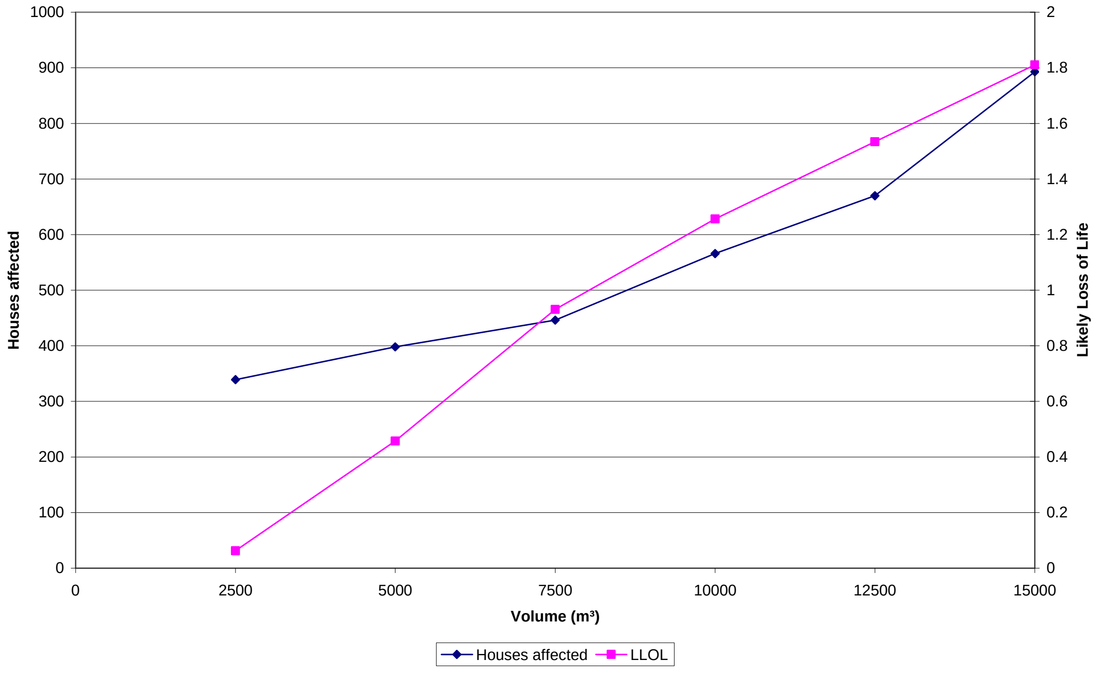


Figure C9 – Variation of LLOL and number of properties at risk for U5007_AN

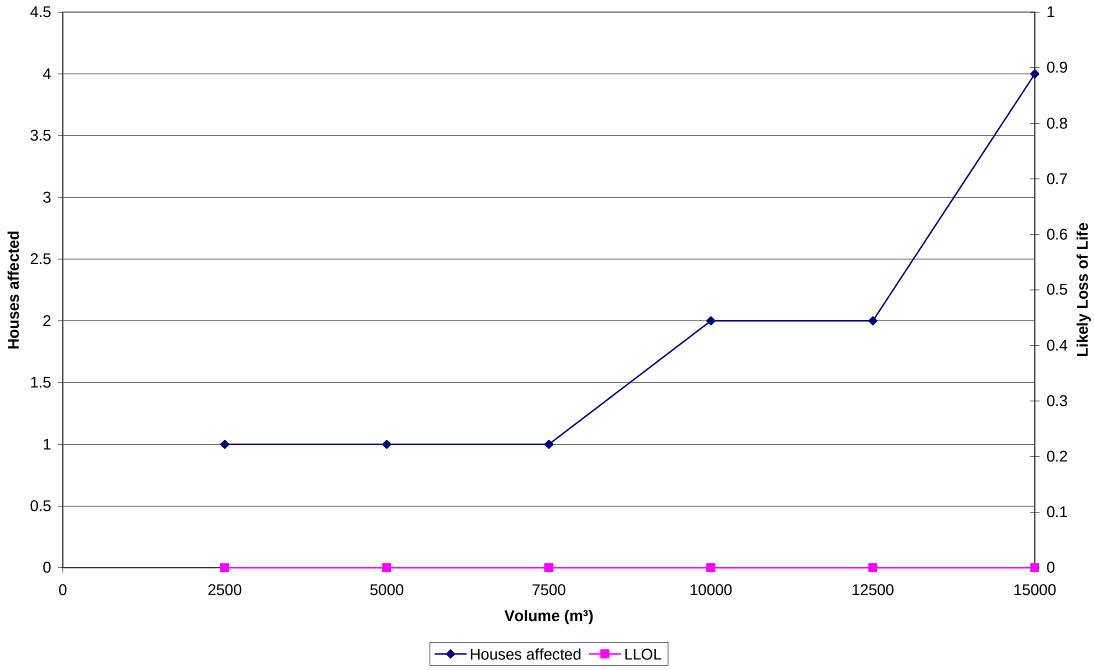


Figure C10 – Variation of LLOL and number of properties at risk for U5008_NW

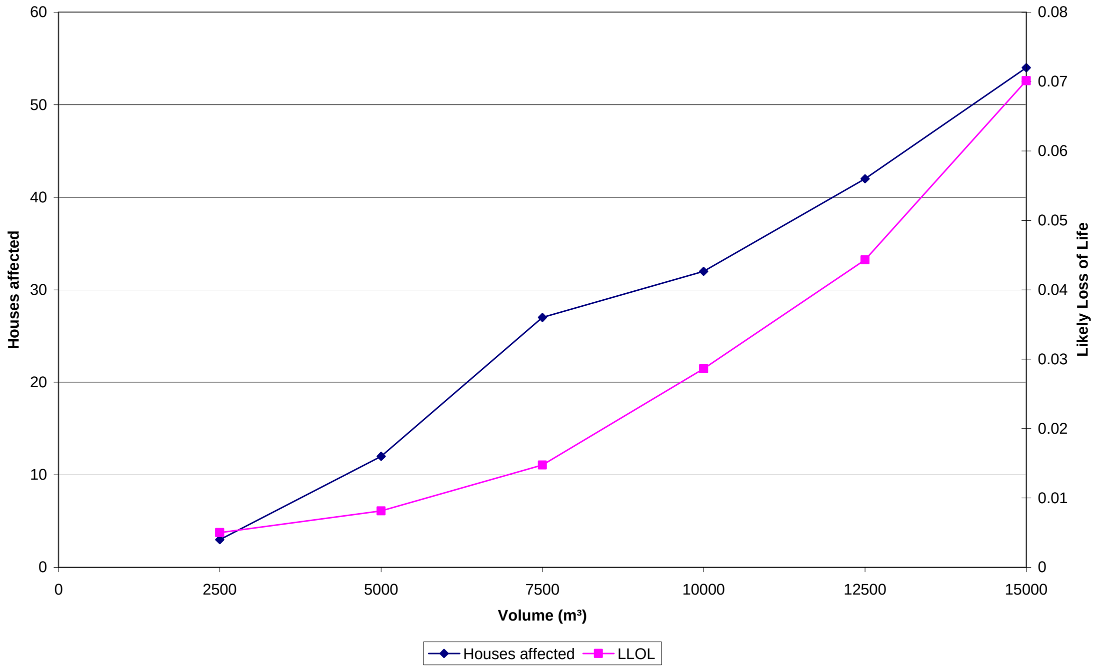


Figure C11 – Variation of LLOL and number of properties at risk for U5009_NW

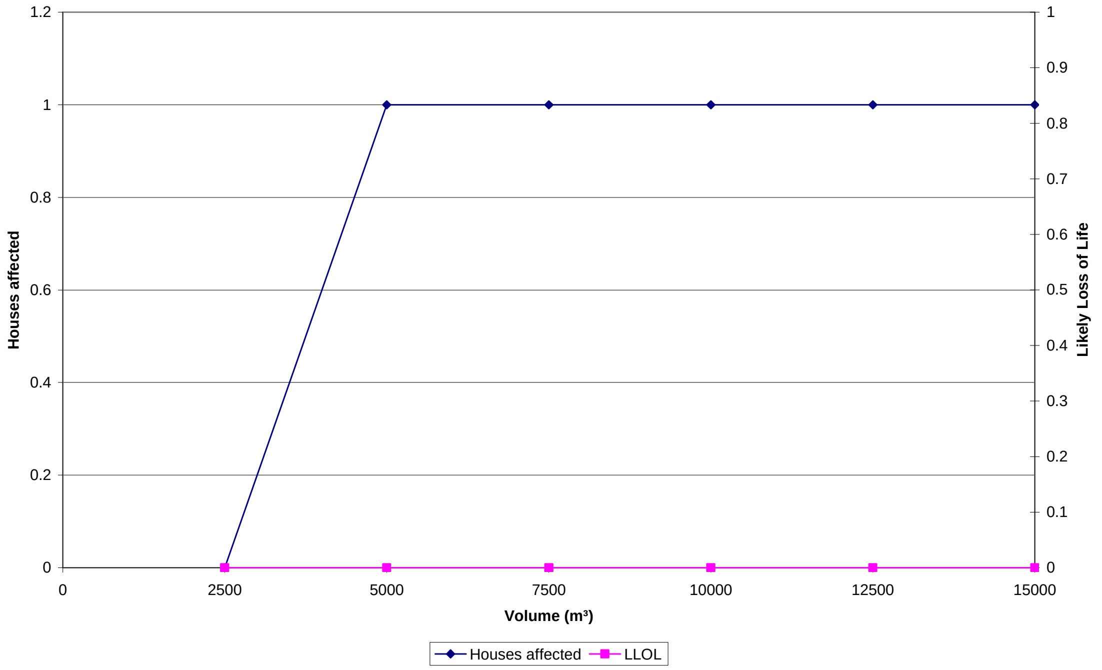
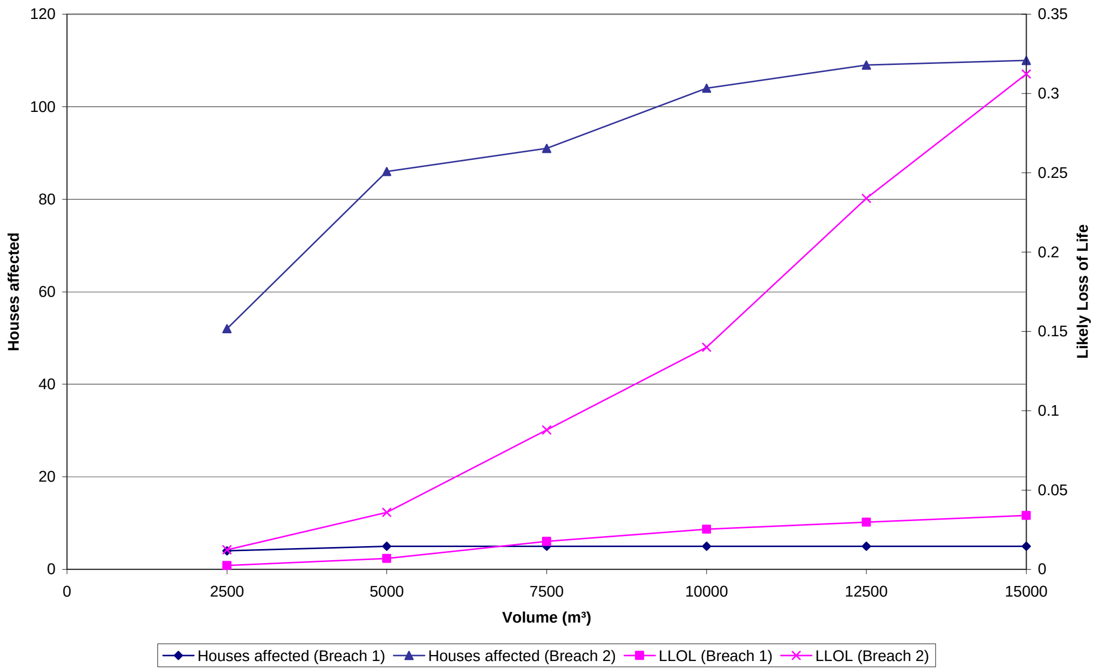


Figure C12 – Variation of LLOL and number of properties at risk for U5010_NW



Appendix D. Detailed method data collection

Figure D1 – View of U5001_NW in GIS software to find dam height and surface area

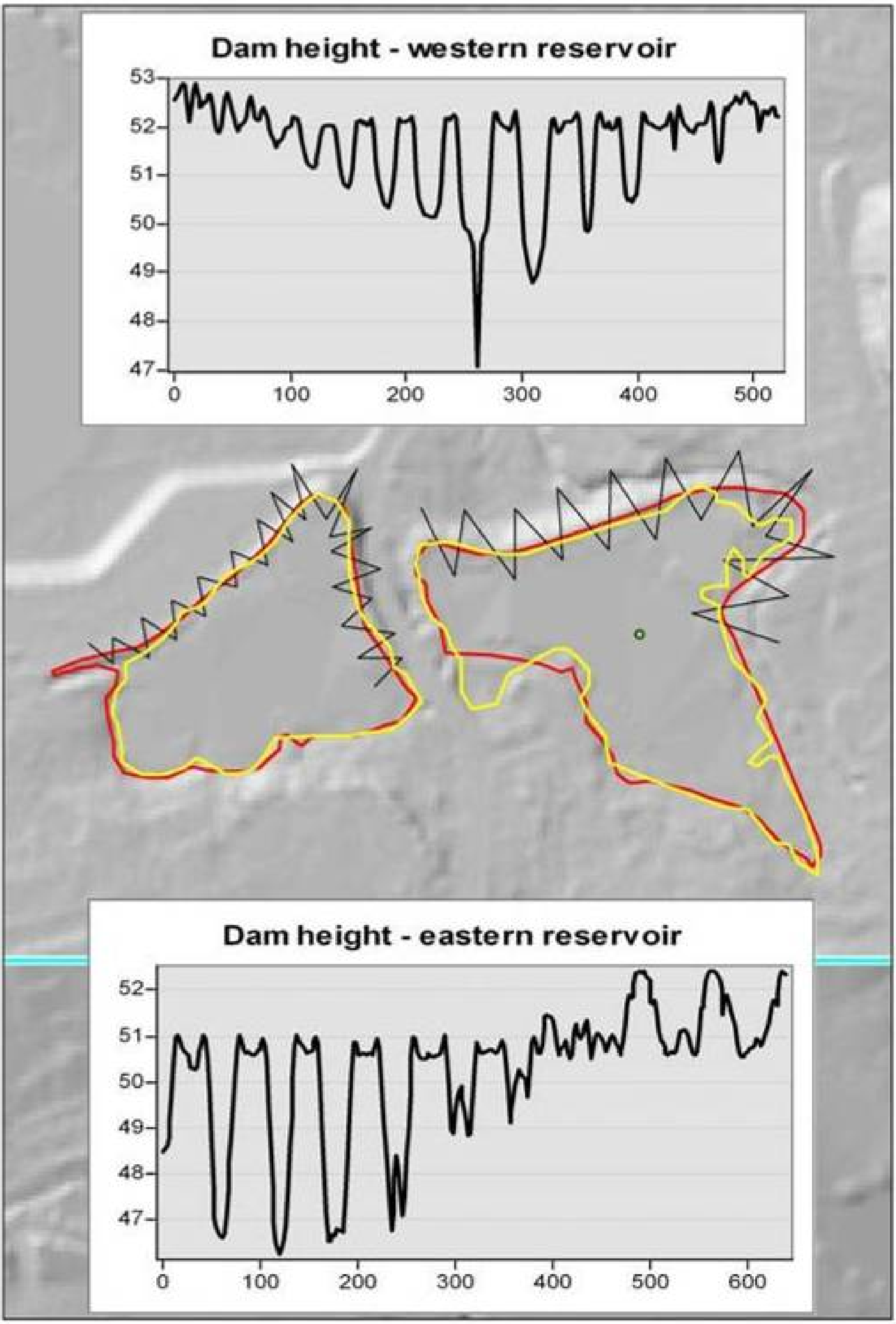


Figure D2 – View of U5002_NW in GIS software to find dam height and surface area

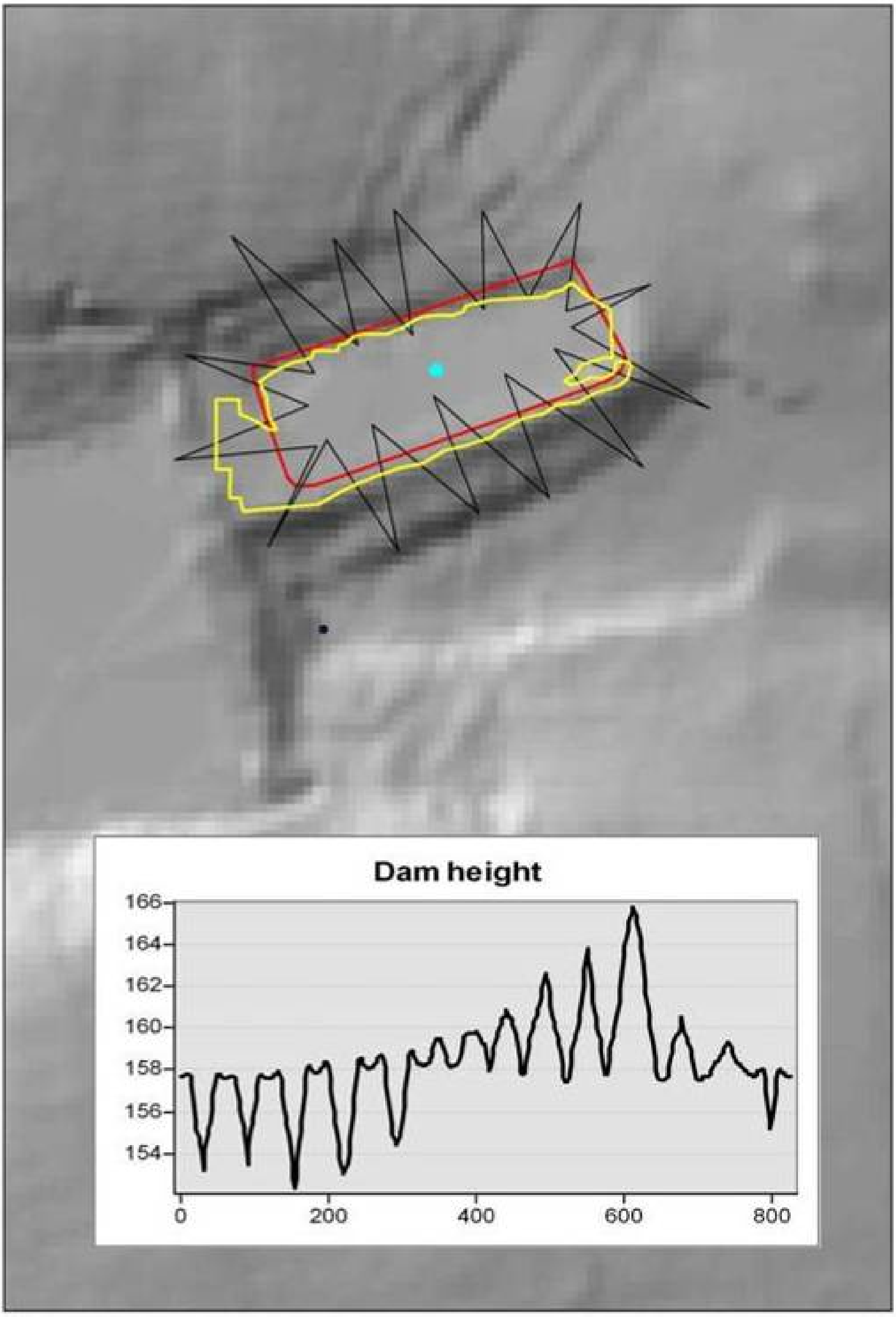


Figure D3 – View of U5003_NW in GIS software to find dam height and surface area

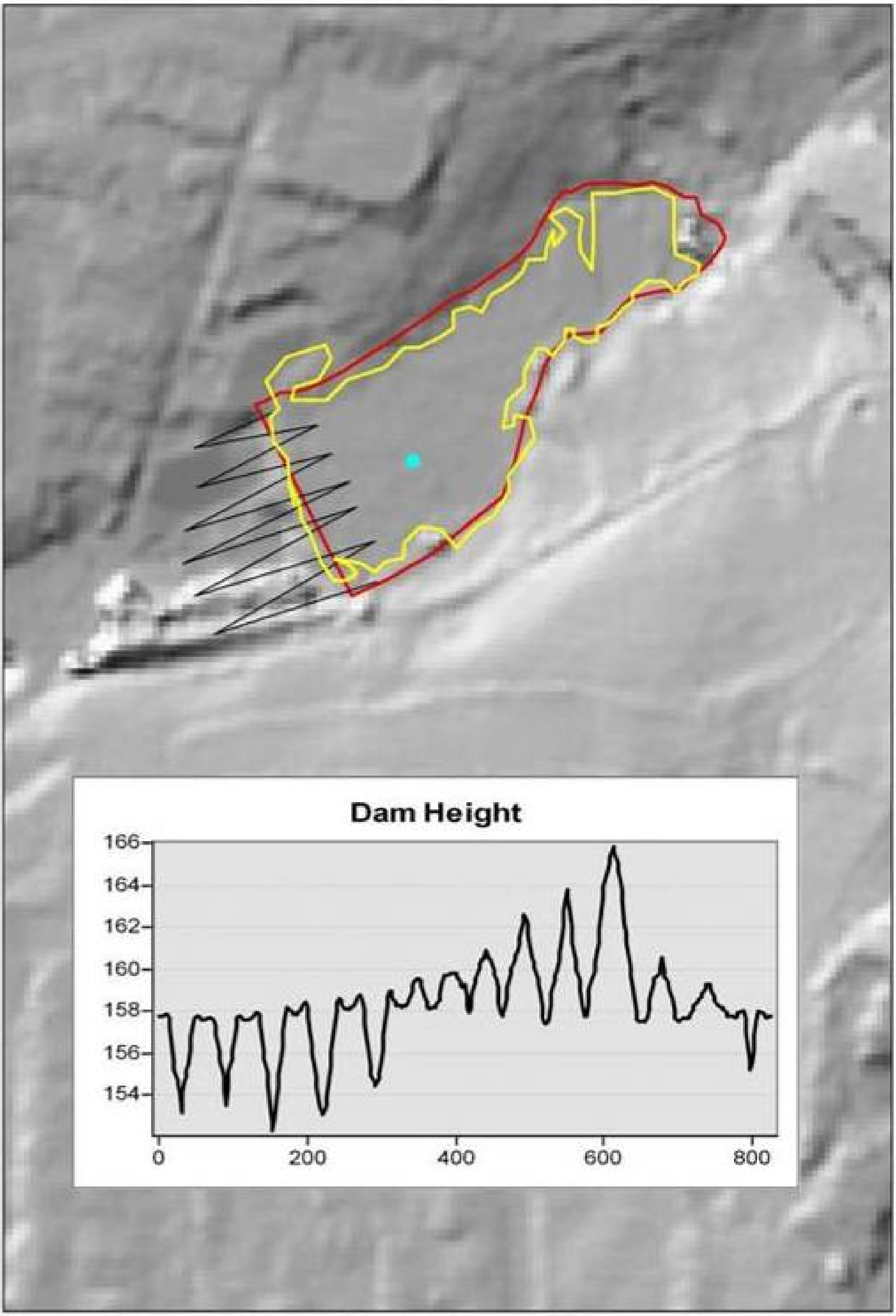


Figure D4 – View of U5004_NW in GIS software to find dam height and surface area

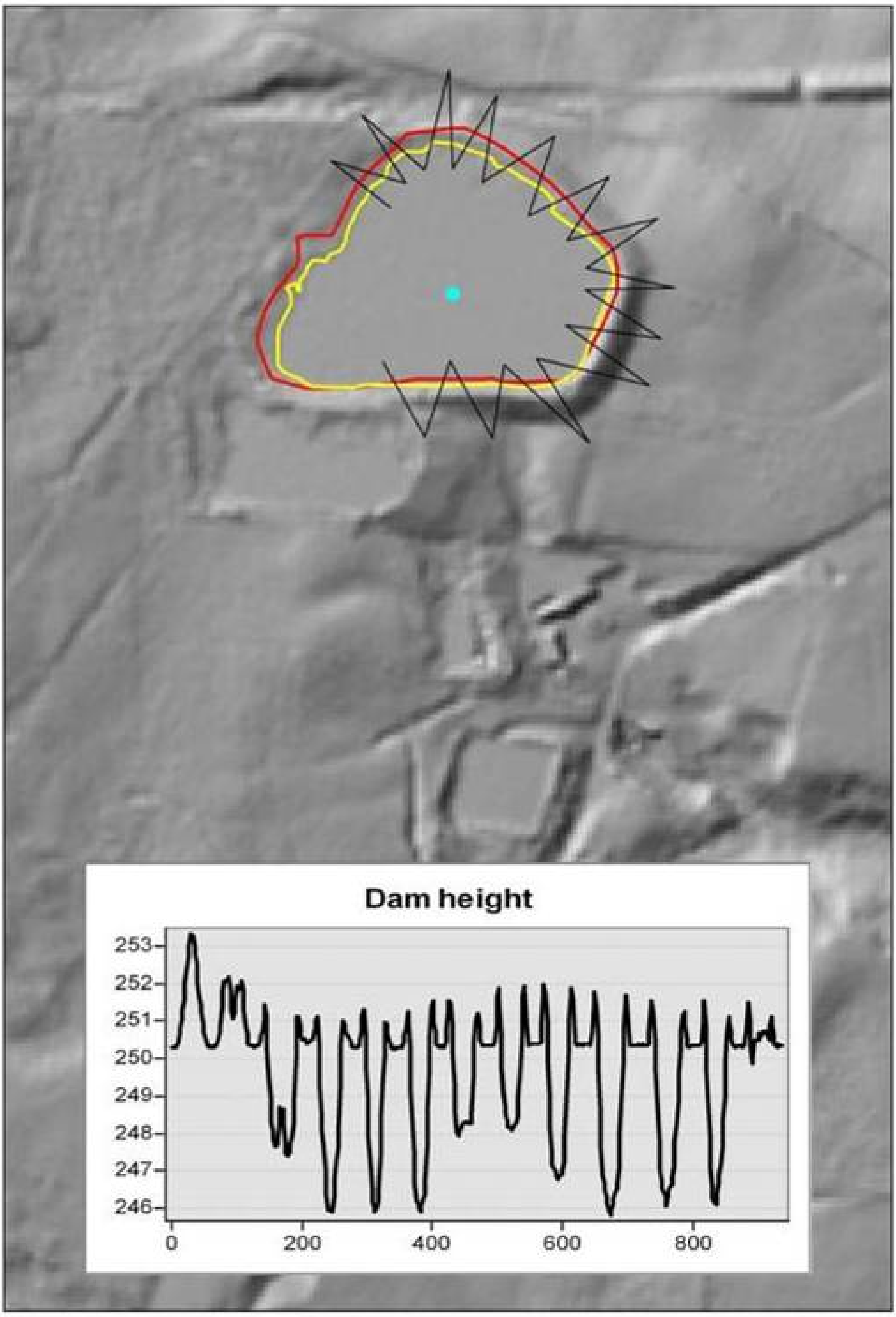


Figure D5 – View of U5005_SO in GIS software to find dam height and surface area

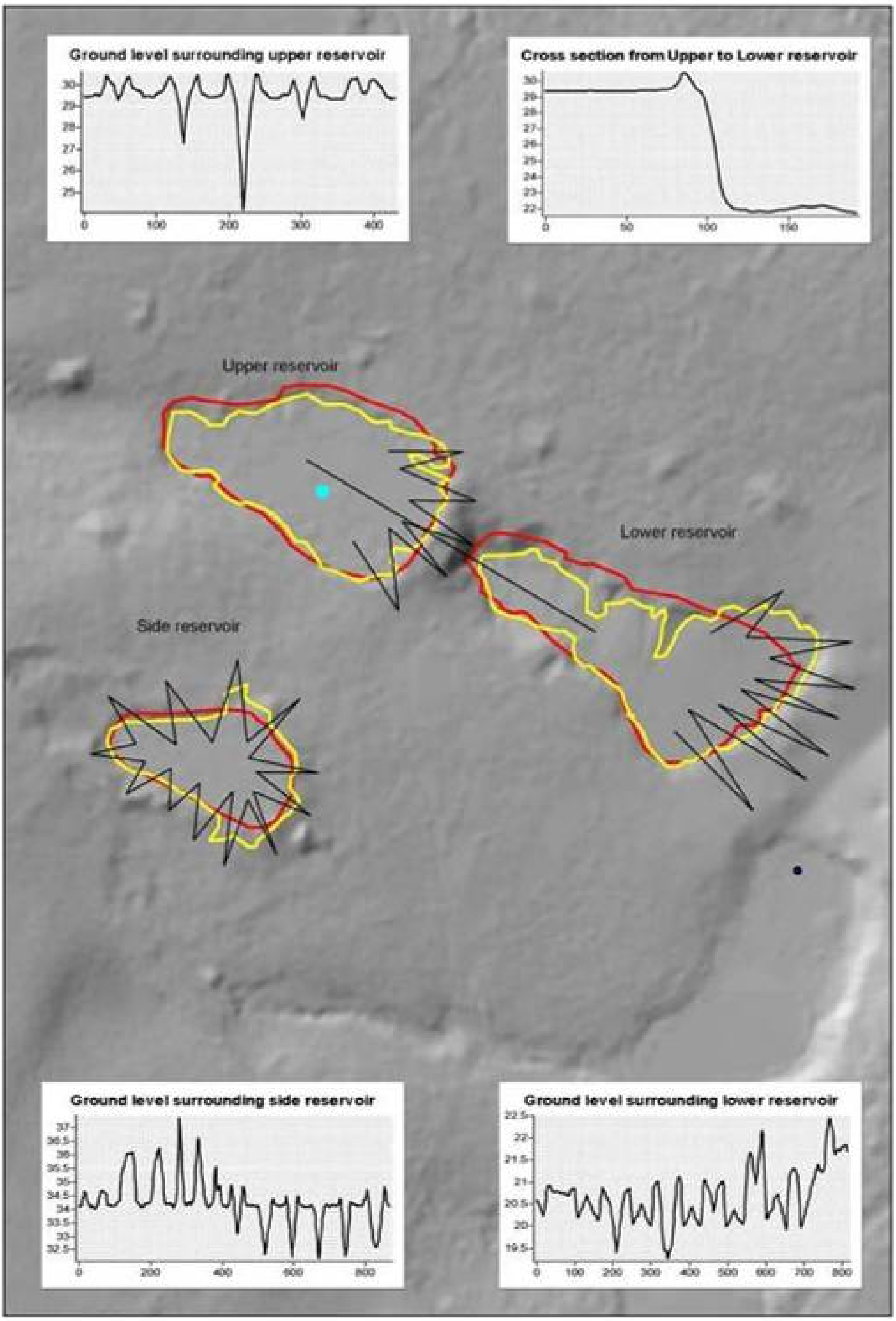


Figure D6 – View of U5006_TH in GIS software to find dam height and surface area

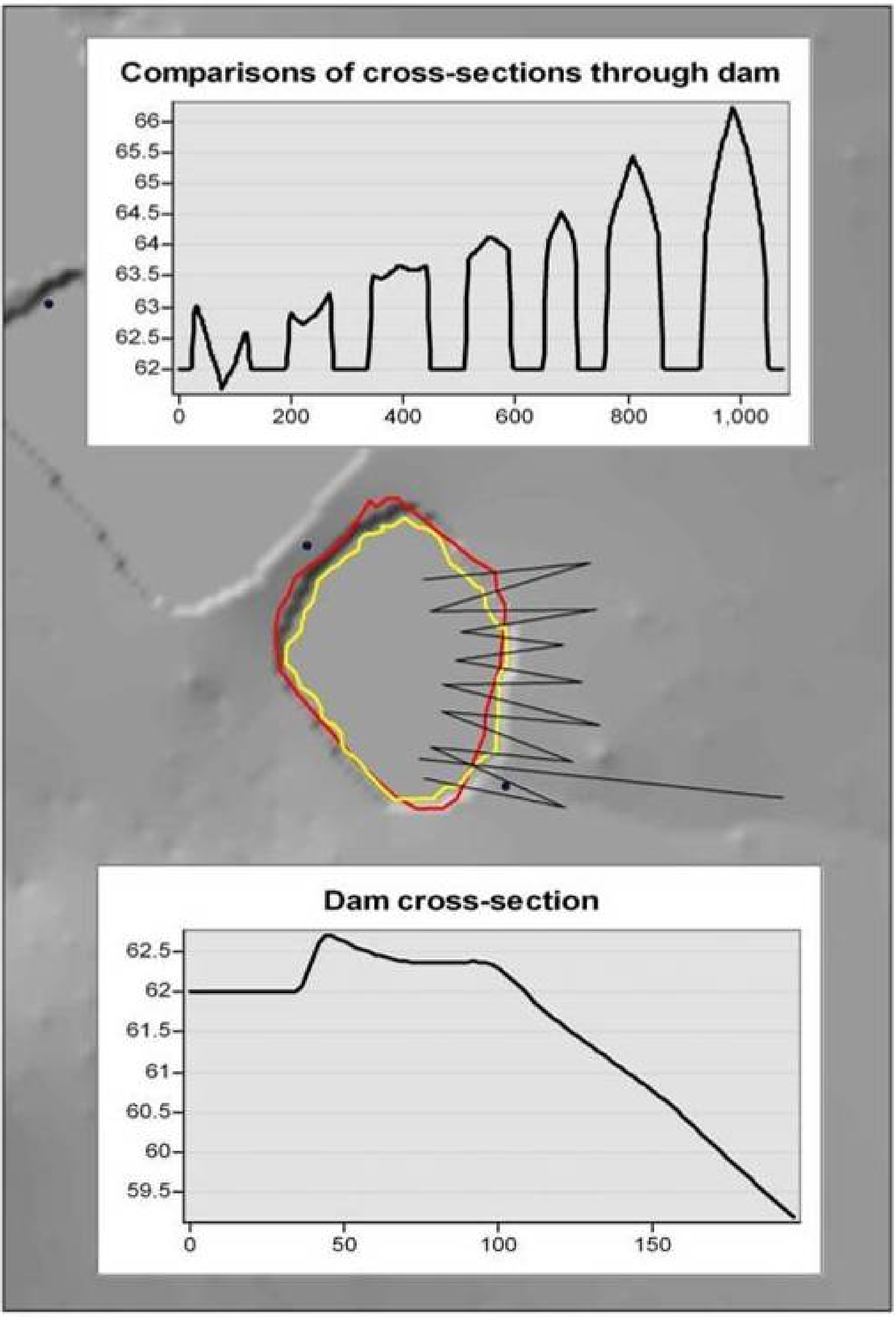


Figure D7 – View of U5007_AN in GIS software to find dam height and surface area

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