Geology-based methodologies for visualizing inland floodplains and understanding fluvial processes

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Floodplains pose a major hazard to development, largely because they naturally contain excess water when the capacity of the main river channel is exceeded. Statistical/hydrological methods can define various flooding limits, but geological maps are also valuable because they allow floodplains to be readily visualized as natural landforms occupied by distinctive deposits. Geological maps can also indicate floodable ground lying outside statistically calculated flood-risk envelopes, and they show smaller, tributary floodplains that may not have been investigated for flood-risk. Laser-based micro-topographic surveys dramatically illustrate the fluvial anatomy of floodplains and are essential for modelling and predicting the likely course of a severe flood event, thus providing information for floodplain management and planning decisions.

L'inondation des plaines constitue un risque majeur à leur aménagement, essentiellement parce qu'elles jouent le rôle de réservoir quand les capacités de rétention du lit principal de la rivière sont dépassées. Des méthodes statistiques/hydrogéologiques peuvent définir différentes limites d'inondation mais les cartes géologiques ont aussi un grand intérêt car elles permettent de visualiser aisément la géomorphologie et la nature lithologique des dépôts des plaines inondables. Les cartes géologiques sont également capables de préciser les limites des zones inondables situées à l'extérieur des périmètres fournis par les études statistiques en indiquant des secteurs inondables de superficie moins importante en relation avec les affluents. Des études de topographie de détail en utilisant le laser illustrent de façon dramatique les axes d'écoulement en plaines inondables et sont capitales pour modéliser et prévoir les traits caractéristiques d'une inondation importante, permettant ainsi de prendre les décisions qui s'imposent pour la gestion et l'aménagement des zones inondables.

Las llanuras de inundación representan un elevado riesgo para el desarrollo, fundamentalmente porque retienen de manera natural el exceso de agua cuando se sobrepasa la capacidad del cauce del río. Los métodos estadísticos/hidrológicos pueden definir diversos límites de las inundaciones, pero los mapas geológicos son también útiles porque permiten la rápida visualización de las llanuras aluviales como formas naturales ocupadas por depósitos muy representativos. Los mapas geológicos pueden indicar también los terrenos inundables que se encuentran fuera de los entornos de riegos de avenidas estadísticamente calculados y pueden indicar llanuras de inundación tributarias más pequeñas para las que puede no haberse investigado su riesgo de avenidas. Las investigaciones micro-topográficas con láser ilustran dramáticamente la anatomía fluvial de las llanuras de inundación y son esenciales para la modelización y predicción del posible curso de una inundación grave, proporcionando información para la gestión de la llanura de inundación y las decisiones de planificación.

Floodplains are flattish valley floors that provide a natural conduit and temporary storage area for water during exceptionally high flows, when the capacity of the main river channel is exceeded. Throughout Europe there are abundant recent examples of how flooding of these tracts can pose a hazard to existing development, and there is currently a major debate over the best ways to 'manage' floodplains to offset the risk that they will present if predictions of increasingly severe storm events are fulfilled. Typical questions being asked are: whether floodplains should be managed in a sustainable manner, in harmony with their environments, or whether their natural functions and processes should be subordinated in an effort to defend, at all costs, buildings and infrastructure on floodplains? Underpinning these impending decisions is an increasing body of scientific information from a wide range of disciplines (such as climatology and hydrology). This article explains why geology, and the allied science of geomorphology, should be taken into account during the complex processes that are involved in floodplain management and flood-risk assessment.

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Conceptual problems of floodplain definition

The prevalent climate of concern over flooding risk, and the plethora of initiatives that are being followed, has only served to increase confusion over what floodplains actually are. Floodplains have been defined in many ways, but in modern hydrological parlance there is often a trend to use terms such as 'flooding limit' synonymously with 'floodplain'. An example

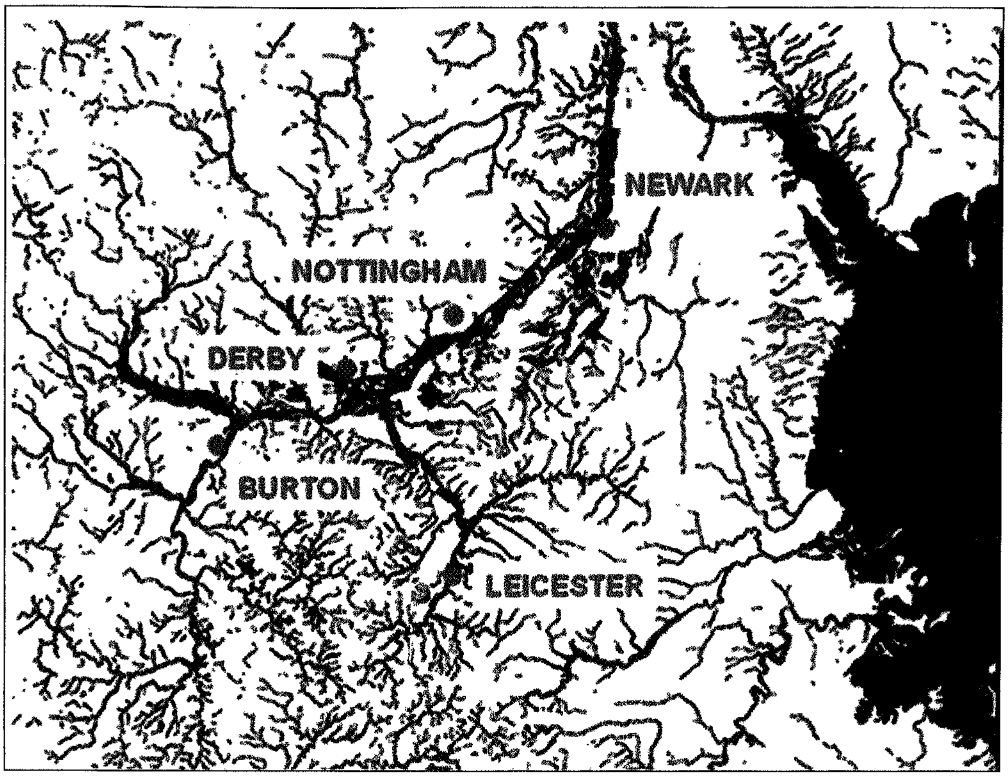

Figure 1. Distribution of floodplain alluvium in the East Midlands, UK. Extracted from DIG-MapGB (BGS digital geological map of Great Britain).

of such terminology can be found in the UK government's paper for England: 'Development and Flood Risk' (Planning and Policy Guidance Note No. 25). This maintains that the limits of the floodplains are "*based on the approximate extent of floods with a 1% annual probability of occurrence for rivers……… under present expectations or, where this is greater, the extent of the highest known flood*". With this combined statistical and historical approach there can be any number of different 'floodplains' represented in a single river valley (or coastal tract), depending on the excess limit chosen. This introduces problems for those not familiar with statistical methods who are seeking to envisage and understand floodplains. Here, we suggest that to assist public perceptions of the floodplain and its limits, as well as a catalyst to geoscientific studies relevant to floodplain management, it may be equally important to *visualize the floodplain as a natural physical entity*.

Visualizing floodplains on geological maps

Geologists (and geomorphologists) would suggest that statistically calculated flooding limits simply constitute probability envelopes within the wider context of the natural, or geological, floodplain. Floodplains are seen as distinctive landforms, the boundaries of which can be constrained by observation and which directly relate to fluvial geomorphological processes. The limits of the geological floodplain can be systematically surveyed on the ground, and are thus easy to visualize and depict on maps. In addition, a distinctive suite of Quaternary deposits defines the floodplain tract. Such deposits can be identified on the ground and it is now possible to demonstrate their distribution by utilizing new-generation airborne techniques, such as LiDAR, as outlined below. In Europe, the results of this work are the geological survey maps, commonly available digitally as well as in the more traditional hardcopy formats, which are the principal, and in most cases, only record of floodplain geology (Fig. 1).

In detail, geological maps show that the lowest-lying tracts in the floodplain correspond to the extent of *alluvium*, which represents the clay, silt, sand and gravel deposits laid down by fluvial processes, such as meander migration, channel switching and overbank flooding of the modern river channel. Many larger floodplains include additional areas of raised, sandy ground adjacent to and contiguous with the alluvium outcrops. These areas represent a slightly older development of the floodplain, which was abandoned following the most recent episode of base level lowering and incision of the main stream. In the UK they are generically known as the 'first terrace' or the *'floodplain terrace'* (Fig. 2a). Depending upon its height, the floodplain terrace may be partly or wholly inundated during extreme flood events and so, adopting a precautionary approach to flood hazard assessment, it should logically be included within the modern floodplain system. Therefore, the natural geological limits of the floodplain are taken at the break in slope that marks the back-edge of the alluvium or floodplain terrace, and the change to rising ground behind this. Older and higher river terraces, which are commonly perched on a 'step' consisting of bedrock, are not considered to be part of the floodplain. Boreholes can be useful for identifying alluvium or terrace deposits in urban areas, and for clarifying their composition and physical properties at depth.

The relationship between geology and surface inland flooding

To test whether geological maps can provide a suitable earth-science framework in which to consider the extent and effects of flooding, the British Geological Survey (BGS) commissioned an aerial survey across a large part of the River Trent, in England, during a major flooding event that occurred early in November 2000.

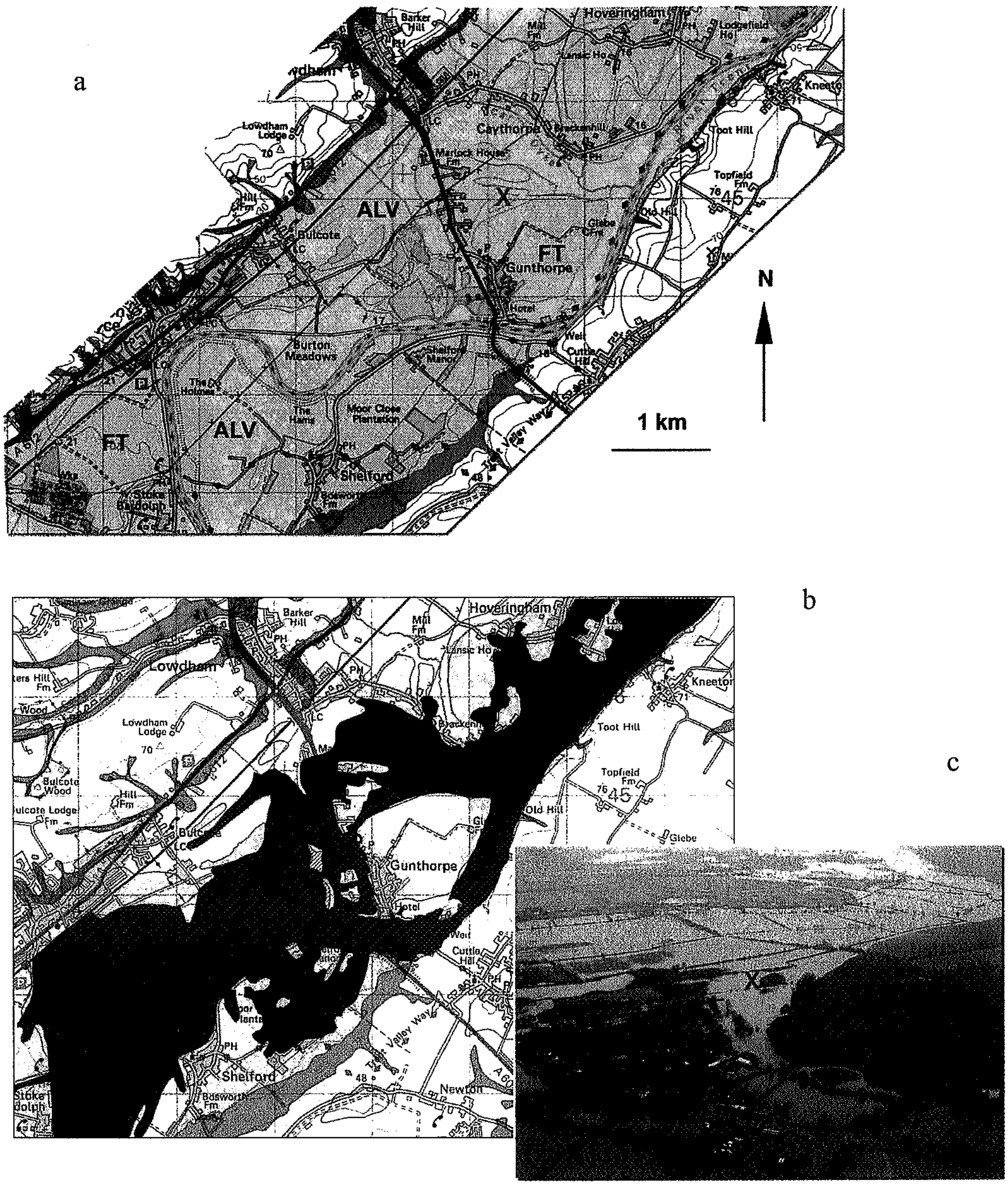

Figure 2 a. Simplified Quaternary geology of the River Trent floodplain 9 km east of Nottingham. The 'geological' floodplain is defined by outcrops of alluvium (ALV) and floodplain terrace (FT). Direction of river flow is towards the north-east.

b. The same map, showing the observed inundation extent (blue areas) of the November 2000 flood. Note that the floodplain terrace outcrops represent flood-retardant areas, and that some tracts of alluvium were also not flooded.

c. Aerial photograph of the flooding, viewed towards the NE, with location point (x) also shown on Figures 2a and b. Topography © Crown copyright. All rights reserved NERC100017897/2005.

It was found that large tracts of the alluvium, and the lower, degraded parts of the flood-retardant areas occupied by the floodplain terrace, were inundated (Figs 2b, c) during an event estimated by the UK Environment Agency to have a 1-in-35 year return period. Other parts of the floodplain alluvium, and in particular the higher ground occupied by the floodplain terrace, remained dry. Such areas, however, could be at risk from flooding during more severe events, such as the 100 year, or 1% flood. Recent statistical estimates of the 1% flood limit suggest that about 80% of the geological floodplain shown in Figure 2a would be inundated, in which case the remaining outcrops of alluvium or floodplain terrace lying outside of this may be indicating areas that would be at risk during, say, a 200 or 300 year flood event. In the UK there are many smaller, tributary floodplains (Fig. 1) for which statistical flood risk assessments may never be carried out. For these tracts of ground, the principal indication of floodplain extent, and hence of potential flood hazard, will be the geological maps showing floodplain deposits, perhaps in conjunction with local historical and anecdotal evidence of flooding.

Options for sustainable floodplain management

The flooding issue has stimulated much research into the scientific and societal aspects of floodplains. In the UK, organizations such as DEFRA (Department for the Environment, Food and Rural Affairs) and the Environment Agency are leading the development of strategies to manage floodplains better. The flood management options range from direct intervention ('hard engineering'), such as the construction of flood banks (particularly in existing urban areas), the re-routing of the main channel and excavation of flood reservoirs, to more natural 'soft' measures such as improved farming practices, afforestation of the catchments, and 'managed retreat'.

The 'managed retreat' option is mainly designed for non-urban locations. It involves the removal of artificial defences, allowing floodwaters to more readily occupy the lower-lying parts of the floodplain. This option aims to return the floodplain to its natural storage capabilities, thus reducing the eventual flood peak and mitigating the

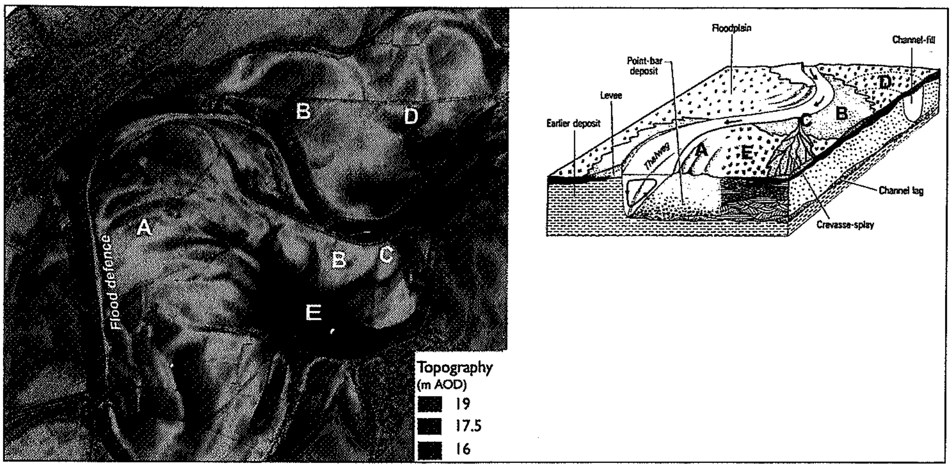

Figure 3. Airborne laser image (LiDAR method) showing the micro-topography and main alluvial elements of the Trent floodplain for the southern part of Figure 2a, with colour-enhanced contouring at 50 cm intervals. The block diagram (from Collinson, 1978) shows the fluvial elements within a floodplain bordering a typical meandering channel, with letters indicating their equivalents identified on the LiDAR image.
Source: LiDAR data © UK Environment Agency. BGS reprocessed image © NERC. All rights are reserved by the copyright proprietors.

damaging effects of flooding downstream. A second advantage is that it would create, or re-create, original fluvial habitats and ecosystems, such as seasonal wetlands, which have all but disappeared from many embanked floodplain tracts that have been 'reclaimed' for arable farming and other purposes. If sustainable management scenarios are adopted, however, it will be necessary to assess the fluvial response of the river system at times of flood, for a range of possible scenarios.

Understanding fluvial processes on floodplains

Although standard geological maps visualize the natural floodplain and its limits in broad outline, they cannot provide the type of high-resolution analysis of fluvial processes and fluvial domains that is necessary to inform planners and developers about how the floodplain will respond to severe climatic events. To achieve this, geological maps can be considered in conjunction with accurate ground elevation models provided by the new-generation LiDAR techniques of micro-topographical surveying. These elevation models (Fig. 3) can have a vertical height resolution of as little as 15 cm., sufficient to detect subtle topographical changes that characterize floodplains, which commonly have a height range of between 1 and 3 m. The topographical features revealed by LiDAR surveys will include river terraces and also erosional and depositional elements related to the modern alluvium; therefore, they form the basis for the interpretation and analysis of different domains within the entire fluvial system (Fig. 3).

The features outlined by the topographical model (Fig. 3) can be used to predict the water flow paths, and the progressive development of the flood, if defences were breached or removed and the floodplain allowed to revert to its natural state in a 'managed retreat' scenario. The model, which shows arcuate gravel ridges (at A), predicts the northwards migration of the main meander, with consequent erosion of its outer bank. At high peak flows, water from the trunk stream will overflow its levee via crevasse channels (C) that have been cut into the levee (B). The first area to be extensively inundated will be the natural, low-lying flood basin (E). The flood basin, therefore, functions as a natural storage area. It would also be a suitable area for wetlands restoration, were this to be considered as part of a floodplain management option. The LiDAR image can also be used to predict ground conditions on the floodplain, important when constructing flood defences. The point-bar complex (A) will mainly consist of sand and gravel; the levees (B) laminated silt and silty clay; and the flood basin (E) and abandoned channel (D) may be expected to contain layers of highly compressible material such as peat or organic-rich clay.

Conclusions

Geological maps at suitable scales can be used to portray the extent of floodplains as natural physical entities. They complement statistical calculations of flooding limits, produced by flood modelling. In addition, they can show areas of ground that may flood but that may not be revealed by the outlines determined by probabilistic methods, which are dependant on arbitrary choices of return period. In smaller river systems that have not been the subject of statistical hydrological studies, a geological map is frequently the most readily accessible record for showing the location of floodplain boundaries. Geological maps should, therefore, be included in any GIS-based flood-risk assessment, as a backdrop to layers that might include land-use and statistically calculated flood outlines. In conjunction with high-resolution, laser-based topographical surveys, the fluvial anatomy of floodplains can now be precisely determined. Using this imagery, the sciences of fluvial geology and geomorphology have much to contribute to studies that seek to model the development of a flood, and the response of the floodplain to severe flooding events.

Acknowledgements

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