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IMPACTS OF FLUVIAL LAND FORM EVOLUTION AND GLOBAL CHANGE IN URBAN ENVIRONMENTS

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Abstract: Understanding of the character of urban environments, which have been increasingly embraced by geomorphological research in the last four decades, has progressed to the way in which they are currently perceived. For fluvial geomorphology it is necessary to understand the palimpsest inherited from long-term evolution under pre-urban conditions. This includes understanding the way urban hazards arise, appreciating the diverse consequences of short-term land form changes influenced by human activity, and contemplating the nature and implications of management methods in relation to future global changes including those instigated by changed urban hazards.

Key words: urban geomorphology, palimpsest, urban channel changes, urban management methods, global change

INTRODUCTION

There have been many changes in the research focus of geomorphology and physical geography during the career of Leszek Starkel. One major change is that human activity is now embraced, its impact and significance, stimulating research on urban environments which were largely ignored by geomorphologists until 40 years ago. Although representing just 2% of the Earth's land surface, 29% of global population lived in urban areas in 1950, by 2009 this had increased to 50% and it is projected to reach 69% in the future. Human impact has been the subject for an increasing geomorphological literature (e.g. Goudie, 1986; Gregory and Walling, 1987; Goudie and Viles, 1997; Szabo et al., 2010), a separate field of anthropogeomorphology has been identified, it has been suggested that the Noosphere is a sphere of the Earth dominated by human action, the Anthropocene is now conceived as a new geological period, and the environmental impact of cities can be expressed as 'ecological footprint' (see <http://www.gdrc.org/uem/footprints>) being the amount of land required to sustain them. Six levels of intensity of anthropogenic impact, or hemeroby, have been suggested ranging from ahemerobic (natural ecosystem) to metahemerobic (artificial ecosystems) (Csorba, 2010, after Bastian and Schreiber, 1994).

Considering the human impacts on river channel geomorphology (Gregory, 2006) a number of reviews of urban processes and associated environmental effects have been published (e.g. Chin, 2006; Chin et al., 2011). Ecological research on urban environments was initially pursued separately from geomorphological investigations, but the ‘Urban Stream Syndrome’ proceeded towards a more integrated way of including geomorphic and hydrologic alterations to streams as well as the consequent deterioration of stream biogeochemical function and aquatic trophic structures (Walsh et al., 2005b). However in recognizing twenty six key research questions in urban stream ecology (Wenger et al., 2009) just one (number 9 What are channel geomorphic responses at different stages of urbanization, are the responses predictable, and do urban streams eventually reach a new stable state?) is primarily geomorphological although eight others have geomorphological significance.

This paper summarizes, from a fluvial perspective, the relevant characteristics of urban environments (1), ways in which urban areas have been superimposed on pre-urban conditions creating urban hazards (2), short term land form changes induced by urbanisation (3), leading to management implications including future global change (4).

1. URBAN ENVIRONMENTS

It was suggested that physical geography including geomorphology is much needed in an urban setting because cities are analogous to karst topography with sewers performing the function of limestone cave systems (Bunge, 1973). Urban environments can be viewed as assemblages of land forms (Gregory, 2010) with six pertinent characteristics comprising location, character as a physical system, networks, fabric, processes, and attributes including scenic quality. Creation of urban systems entails transfer of materials in or out of the area, so that for four study areas in Spain and Argentina, human activity is presently the main contributor to landform modification with the ‘human geomorphic footprint’ expressing the new landform creation and mobilization rate (Rivas et al. 2006). The seminal paper by Wolman (1967) established the way in which urban areas affect channel processes and has significantly influenced (Gregory, 2011) numerous studies of urban river channel adjustments subsequently undertaken (e.g. Gregory, 2006; Chin, 2006).

Building upon ways in which the geomorphology of urban areas has been investigated (see Gregory 2010) the current geomorphological perception of such areas necessarily refines some assumptions held in the past:

(a) Urban areas are sometimes still visualized as an extreme at one end of a fluvial process spectrum whereas other perceptions are of urban areas as a distinctive environment. This dichotomy may reflect the diversity of urban areas, and whether humid and arid areas are viewed in the same way.

(b) Urban areas are not uniform in character but include different degrees of imperviousness. The fabric of urban areas impedes, controls, and changes the character of fluvial processes. Such changes largely depend upon extent of impervious area, composed of buildings, roads, sidewalks/pavements and parking lots/car parks which are covered by materials such as stone, brick, asphalt and concrete. These surfaces are not rendered completely impervious: the percentage of impervious urban area, varying according to the type of land use, ranges from up to 19% in low density housing neighbourhoods to as much as 60% in high density housing areas, with commercial and industrial areas up to 90% impervious, and roads and highways up to 100% impervious (Brabec et al. 2002). In the USA, impervious urban areas have been estimated to total 110,000 km^2 (*Eos* 15 June 2004).

(c) Understanding urban processes has evolved from initial emphasis upon increased runoff, flooding and pollution, to appreciation of the effects upon river and stream channels and, rather separately, to include ecological consequences. Most recently, recognition of the holistic way in which urban processes combine has included the ‘urban stream syndrome’ which embraces not only the visible alteration of the physical form of the channel but also the consequent deterioration of stream biogeochemical function and aquatic trophic structures and other associated changes (Water Science and Technology Board 2008).

(d) To understand the geomorphology of urban areas it is necessary to appreciate the characteristics of the storm water drainage system. Integral to the process of urban development is the progressive installation of drainage systems that alter the drainage character in river basins. Within artificial drainage systems, drainage density can increase by 808% (Chin 2006). The original network of rivers and streams is complemented by systems for managing storm drainage and sewerage. Ways in which these three components are separate or combined vary from one area to another.

(e) Management methods are implemented using structures related to design frequencies for precipitation and runoff events of specific recurrence intervals, so that structures and drainage systems installed are not easily modified. Riley (1998) suggested that approximately 8 out of 10 problem situations can be traced to badly-sized or -installed culverts.

(f) Recent urban developments have tended to install separate systems of storm water and foul water drainage so that the water treatment works do not have to cope with excessive water volumes. Channelization of stream and river channels undertaken to solve flooding and bank erosion problems, which may have transferred problems downstream, have been revised by methods employing new fabric, networks and systems to modify the hydrological processes. These newer methods minimize flooding and erosion problems as well as achieving planning objectives (see below).

(g) Hydrological effects of the urban area are not limited to the urban area itself but can extend downstream where flooding, aggradation and channel change may occur.

(h) Management methods were originally dominated by the need to accelerate runoff and dispose of stormflow as quickly as possible. More recently used methods retain and release runoff more slowly because it has been shown that improving stream health involves finding ways to decrease the efficiency of water delivery from impervious surfaces (e.g. Ladson et al., 2006). It is now accepted that the urban area should be managed within the drainage basin context.

(i) A new urban drainage system is superimposed on the original 'natural' system. Within Baltimore City, 66% of all streams and 70% of streams in catchments smaller than 60 ha (1 mi^2) were buried (Elmore and Kaushal, 2008).

Such understanding of urban areas necessarily influences the way in which fluvial changes and urban management are approached.

2. THE SIGNIFICANCE OF PRE-URBAN CONDITIONS

The way in which the urban environment is superimposed on pre-urban conditions applies not just to the drainage system but to the physical environment as a whole. Palimpsest, a manuscript page from a parchment or book which has been written on, scraped off and used again, has been applied to glacial or glaciated environments where one set of conditions is superimposed on another. Griffith Taylor, as the first geomorphologist to work in the dry valleys of southern Victoria Land, Antarctica, proposed a palimpsest theory to express the multistage model whereby cirque erosion was subsequently overtaken by expanding outlet glaciers (Pickard, 1997). Palimpsest has subsequently been applied where glacial landforms are 'written' on the landscape beneath (e.g. Livingstone et al., 2008) with new landforms combined with the remnants of the original surface (see Gregory, 2010). An architectural view of cities sees palimpsests in the sense of layered environments with the layers as 'urban structure', 'urban life' and 'symbolic urbanism' placed within a multi- dimensional framework (Mubarak, 2010). Although many landscapes are palimpsests with features formed during earlier periods surviving into later ones as relicts (Favis-Mortlock and de Boer, 2003), I am not aware of palimpsest used for urban physical environment but it is an instructive analogy to use for the situation in which urban characteristics are superimposed upon a pre-existing physical environment.

Inherited environmental characteristics can significantly influence contemporary urban fluvial processes in 4 ways. **First**, inherited morphological and ecological characteristics including landform, especially slope and surface materials, can be influential and together with natural ecosystems provide a framework affecting the pre-urban hydrology. Landform and ecology combine in urban wetlands which have experienced rapid change with urbanization in Wuhan, China (Xu et al., 2010). Inherited characteristics provide the site conditions which should be evaluated prior to urbanization but were often ignored in many parts of the urban tropics which spread across unstable terrain conditions, such as floodplains, coastal swamps, steep slopes, or sand dunes, so that near active plate margins and tropical cyclone belts consequential problems could be magnified (Gupta and Ahmad, 1999). **Second**, the processes existing prior to urbanisation have an influence upon how they can be amplified by urbanisation. Thus existing flashy hydrological regimes may be amplified more rapidly than the more restrained hydrological responses of temperate areas. However urban effects are not always substantial and in Puerto Rico stream hydrology was equally flashy in streams draining forested and urbanized watersheds (Ramírez et al., 2009). Thus, **thirdly**, the urban response needs to be considered in relation to the characteristic geopatterns and processes inherited in different world zones. Although the transformation of the terrestrial biosphere into anthropogenic biomes (anthromes) are responsible for a variety of novel ecological patterns and processes (Ellis, 2011), it has been suggested that we have limited understanding of mechanisms driving the urban stream syndrome and the variability in characteristics of the effects of urbanization across different biogeoclimatic conditions (Wenger et al., 2009).This may arise because some knowledge of responses to urbanization is based on individual and often idiosyncratic case studies (Grimm et al. 2008). However regional environmental background characteristics are pertinent for restoration procedures (see below). Within geographic regions variations in ecological responses have been suggested to reflect the type of drainage infrastructure, exactly where urbanization occurs within the catchment, the type of urban development, to which the inherited environmental characteristics should also be added.

Fourthly, inherited characteristics provide the context for urban hazards. Hazards refer to those natural processes that have the potential to damage human property and take human lives, so that hazards associated with stream channels have necessitated a range of management responses. One way of recognizing urban stream channel hazards is in terms of urban effects, those arising from channel adjustment, and those associated with management methods (Gregory and Chin, 2002). Results have been obtained for specific areas. Thus in Eilat, Israel, the main streets of the town were designed to cope with the bulk of floodwaters, but much larger sediment-laden flows led to jumpouts and sedimentation hazards occurred producing an unplanned semi-natural drainage network temporarily resurrecting portions of the pre-urbanized alluvial fan (Schick, 1995). In the UK historical effects, while potentially large for small areas, are not significant for large river basins, although for storm water flooding within the urban environment flood hazard is inadequately defined so that new methods are needed to assess and manage flood risk (Wheater, 2006). Following results from a study of basins in Indiana key drivers for urban stream channel hazards were found to be stability or instability

Table 1 Urban fluvial hazards

Area affected	Urban hazards	Possible /management response/ remedial action
Surface of urban area	Localised temporary flooding- runoff>drain capacity, Jumpouts,	Increase design discharge for structures, introduce retention measures including detention basins, storm water drainage systems
	Pollution of runoff-from roads, point sources	Legislation, enforce regulations
	Sediment accumulation- from building construction, floods	Sustainable measures, preclude erosion
Stream and river channels: within urban area	Overbank flooding – runoff from impervious areas Blockage at culverts, bridges Scour – higher bed mobility along channel, downstream from crossings, below culverts, behind revetment, at bridge piers, Bank erosion – reduced bank stability	Channelization, channel clearing, resectioned and straightened channels Bank protection including concrete, rip rap Check dams, Infilling and grading sections and crossings
Stream and river channels: downstream of urban area	Channel incision – gullying Aggradation – high sediment loads along channel, above crossings, buried structures, debris accumulation, Channel pattern change – single to multi-thread	

and the recognition of areas susceptible to hazard, so that methods could be devised for recognizing locations of channel instability (Doyle et al., 2000). A channel classification method, applied to basins in Fountain Hills Arizona, can be used to identify urban channel hazards (Gregory and Chin, 2002), and for ecological changes Wenger et al. (2009) identify stressors which are partly related to risks and hazards. Hazards affecting fluvial processes in urban areas can be thought of as those affecting the urban area generally, those affecting the stream and river channels, and those having effects beyond the urban area, as outlined in Table 1.

Understanding inherited characteristics and the palimpsest of an urban environment superimposed upon a dynamic situation which has continued to evolve is required as a basis for management and for restoration when employed, which is considered (4 below) after reviewing short term fluvial landform adjustments.

3. SHORT-TERM LANDFORM CHANGES

A paper by Wolman (1967) provided the first explicit link between urban processes and consequential channel changes. It not only introduced a model which has been extensively cited but it combined ideas, some assembled from strands developing at the time others that were new, which have had fundamental influences on the development of aspects of fluvial geomorphology. In some ways it was ahead of its time –with some strands immediately pursued to be completed before others could be explored, but it also contributed to changing the ways of thinking that influenced geomorphology in succeeding decades (Gregory, 2011). Results from many subsequent papers have been summarized (e.g. Gregory, 2006; Chin, 2006; Chin and Gregory, 2009; Chin et al., 2011), so that Table 2 details the progression made. Although the ideal way of identifying changes to urban channels is by continued monitoring (e.g. Leopold, 1973; Leopold et al., 2005) this has seldom been practicable so that space time substitution has often been employed (e.g. Hammer, 1972).

In the no change model urbanization does not produce changes either within or downstream from the urban area (Table 2) because the incoming urban drainage was thought sufficient to modify the river discharge but insufficient to change the channel capacity in a detectable way. The channel change model involves increased bed and bank erosion leading to substantial channel adjustments within the urban area,

Table 2 Processes and changes in urban river channels

Model	Changes within urban area	Changes downstream of urban area	Examples
No change	No channel adjustments because runoff insufficiently increased or small relative to magnitude of flow along main channels or shear stress not sufficient to overcome strength of banks as in bedrock channels		Kang et al., 2010
Original	Channel discharges modified due to augmentation from urban area but no channel change	Altered channel-forming discharges may induce channel enlargement	
Channel change	Discharge modified and sediment discharge also changed so that channels adjust	Channels enlarged by scour or can be reduced with alluviation	Hammer, 1992;
	Variations in channel adjustment shown within urban areas, including degrees of channelization	Recognition of several types of channel change	Gregory, 2002; Gregory and Chin, 2002;
	Channels changed in character, including incision of channels and gullying, development of channels in dambos		Neller,1989; Whitlow and Gregory,1989
Increased flow velocity	Flow velocities increased, especially through channelized reaches as roughness decreased and slope increased	Peak discharges increased so that channels can adjust especially as enlargement	
Discharge accommodation	Where channel changes occur producing enlarged channels greater peak flows can be accommodated with progressive effects on overbank flooding		Faulkner, 1998
Sediment model	Where building activity supplies greatly increased sediment load aggradation may be associated with channel capacity decrease		

which could be changes of channel capacity together with changes of channel width, width-depth ratio, and planform characteristics. This model has progressed with results from investigations which identified channel changes from as much as 11 times increase in capacity to decreases to 0.2 capacity. Subsequent research has focused within urban areas on where the adjustments take place including reference to storm water entry points (Gregory, 1978), road crossings (Chin and Gregory, 2001, 2005), stable and unstable channels (Doyle et al., 2000), and the character of urbanization (Roberts, 1989). This has meant that surveys have been made to identify types of channel, including degrees of channelization, throughout the urban area (e.g. Gregory et al., 1992; Doyle et al., 2000; Gregory, 2002). An increased flow velocity model applies when channel modifications by channelization induce higher channel slopes and reduced roughness. A discharge accommodation model results from a different frequency of overbank flows downstream of the urban area, arising not only from the hydrological effects of urbanization but also because of the way in which the altered channel capacity accommodates discharges – the increased flood frequency typical of urban areas is modified and possibly moderated through what is actually negative feedback. This scenario can mean that downstream of an urban area, the frequency of overbank flows first increases due to greater urban runoff but, at a later stage, enlarged channels can accommodate larger discharges so the frequency of overbank flows is moderated. This model has been insufficiently explored despite mention by Leopold and Maddock (1954), being outlined by Hirsch (1977) and investigated by Faulkner (1998). Finally a sediment model can be identified where large amounts of sediment may produce aggradation and smaller channels, whereas if sediment sources are not available or have been protected by engineering works, then scour can result. In either case, a different frequency of overbank flows may occur downstream, involving further changes of channel capacity.

This sequence of interpretations (Table 2) indicates why understanding of urban channel adjustments requires appreciation of the inherited characteristics of the urban area, adoption of a more holistic view and also consideration of ecological changes. These have been the focus of the urban stream syndrome describing the consistently observed ecological degradation of streams draining urban land, with symptoms including a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology, reduced biotic richness, and increased dominance of tolerant species (Walsh et al., 2005b). Downstream changes can be complicated by other influences such as those below dams, demonstrated downstream of the 9.5 km^2 Watts Branch in Maryland monitored for 41 years (see Leopold, 1973; Leopold et al., 2005), where some channel change results were questioned as a result of interference from mill dam effects (Walter and Merritts, 2008). There is no single pattern of channel adjustment which applies to all urban areas and the range of models in Table 2 demonstrates the basis for the diversity which can occur.

4. MANAGEMENT IMPLICATIONS AND FUTURE GLOBAL CHANGE

Proposing ideas for design with nature (McHarg, 1992) applied to city planning and management, McHarg (1996, p. 91) noted that geomorphologists had not been involved with urban planning to the level that they could, or should, have been. As research on urban fluvial geomorphology has developed since 1967, sufficient results have now been achieved to show how geomorphology can contribute to the management of urban fluvial systems (Chin and Gregory, 2009). However this requires knowledge of ways in which the hydrology of urban areas and their fluvial networks are now managed. Whereas earlier methods aimed to remove runoff from urban areas as rapidly as possible, problems arising have prompted search for other methods to manage urban fluvial networks which can be thought of in five groups:

Land-use planning – *to determine where to locate urbanization* including Integrated basin Management (*locate urban areas according to their potential impacts on the basin*), Smart growth (*minimize impact of urban sprawl on runoff and systems affected by runoff processes)*

Retention of precipitation – *to reduce runoff production* including Rainwater harvesting (*rain from roofs to tank storage*), Road surface detention, Disconnect roof areas from storm water drain systems, Rain gardens on housing plots (*encourage infiltration and pollutant removal*), Reduce impervious area (*allow more infiltration*), Flat roofed houses and roof detention

Delay of runoff – *to reduce rate at which urban runoff is transmitted and conveyed* including Underground storage reservoirs (*slow release of stormwater*), Collection of water on roof gardens, brown roof, green roof, Downpipes on to pavements and roads (*not directly connected to stormwater drainage system*), Soakaways, Filter drains (*linear trenches of permeable material*), Minimise connections between impervious surfaces, Permeable pavement, Detention ponds, Balancing ponds, Infiltration basins, Bioretention areas, Infiltration trenches, Water Conservation structures, Sustainable urban drainage systems (SUDS), Low impact development techniques (LID), or water sensitive urban design (WSUD)

Management of effects in the urban area – *to mitigate likely consequences of urban drainage* including Separation of foul water and storm water systems, Restoration of baseflows (*groundwater cultivation by construction that facilitates infiltration),* Reduce channel velocities and accommodate or delay pollutant loads, Permeable revetment, Swales (*shallow vegetated channels*), Excavation of pools, Plunge Pools, Channel restoration or rehabilitation, Increase residence time in channels, Set backs from the channel, Filter strips (*drain water from impermeable areas and filter out silt*), Sediment traps in channels, Preservation of wetlands, floodplains, tree cover (*increases infiltration and reduces storm runoff*), Daylighting (*excavation of culverted or buried streams)*

Planning for downstream consequences (*to minimize downstream effects)* including Total Catchment Management, Zoning and ordinances to preserve open spaces, Channel management including channelization where necessary, Protection of stream corridor, Education (*to preclude or restrict dumping of debris in channels*),

Such specific methods available for modifying the hydrological impacts of urbanisation can be applied collectively as components of particular approaches which include:

- **Sustainable drainage systems (SUDS)** aim to manage runoff flow rates, reduce the impact of urbanization on flooding, protect or enhance water quality, serve the needs of the local community in environmentally friendly ways, provide habitat for wildlife in urban watercourses and, where appropriate, encourage natural groundwater recharge (Herrington Consulting, 2006);
- **Smart growth approaches** to land-use management can minimize impact on long-term runoff, as illustrated in the analysis of long-term hydrological impact to minimize runoff increase in Indiana and Michigan (Tang et al. 2005);
- A **watershed permitting approach**, rather than one dictated by political boundaries, has been advocated (NRC 2008). This requires an entirely new permitting structure that puts authority and accountability for storm water discharges at the municipal level, including additional actions, such as conserving natural areas, reducing hard surface cover (e.g., roads and parking lots), and retrofitting urban areas with features that hold and treat storm water;
- **Low impact development (LID)** or **water sensitive urban design (WSUD)** are decentralized storm water management tools, offering more sustainable solutions to storm water management at a watershed scale although seven major impediments to sustainable urban storm water management have been identified (Roy et al., 2008).

Discussion of how to proceed with appropriate management activities given our current incomplete understanding of the urban stream syndrome has been undertaken in relation to research in urban stream ecology (Wenger et al., 2009). Results from 47 geomorphological studies (Chin and Gregory 2009) underline the amount of variation from one area to another and illustrate four types of problem in utilizing predictions of change in management. First, urban channel adjustments can cause variable problems, including channel enlargement, incision, instability, or where the capacity of the existing storm water drainage system is exceeded. Second, a holistic multi-faceted approach is often needed to ensure that management methods do not have inadvertent consequences elsewhere in the urban area or downstream. Third, geomorphological interpretations may be needed explicitly in channel management, with the amount of channel change and its location included in river management strategies (Gregory et al., 1992). Fourth, some explicit recommendations for stream management are area-specific, reflecting inheritance (section 2 above). Information on spatial scale and patterns of urbanization may be essential to understanding and successfully managing urban streams (McBride and Booth, 2005). Roy et al. (2009, p. 910) have called for stream ecologists and managers to work together to use up-to date scientific knowledge and tools to create effective ecological solutions for maintaining stream functions in this urbanizing world (Roy et al., 2009, p. 910). Chin and Gregory (2009) used the explicit management recommendations made in empirical studies from a range of world areas, together with results of previous research, to provide a checklist protocol that can aid decision-making by river managers.

Restoration is a particular method of management of the fluvial system associated with urban areas. Many urban areas can now be managed by adaptive management using techniques listed above. However, in some locations, restoring streams and rivers is desirable with management activities of storm water management, bank stabilisation, channel reconfiguration and riparian replanting integral to river restoration projects according to Bernhardt and Palmer (2007). They suggest that restoration of urban streams is both more expensive and more difficult than restoration in less densely populated catchments, so that to be effective, urban stream restoration efforts must be integrated within broader catchment management strategies. Riley (1998) visualized urban stream restoration as requiring anticipation of stream responses to conditions and changes in the watershed and the channel.

Restoration has been envisaged in several ways reflected in a range of terms (Downs and Gregory, 2004, 240–241), ranging from making the river appear as natural as possible (naturalization), restoring it to some former condition, or assisting the river to adapt to a new environment (rehabilitation; e.g. Booth et al. 2004). Each approach requires consideration of what is a natural river (Wohl and Merritts, 2007) appropriate for a particular location. In addition urban stream rehabilitation projects have to consider the interaction between geomorphology, hydrology, ecology, water quality, economic, community and political considerations (Findlay and Taylor, 2006). Although channelization has been used extensively in urban areas, more environmentally-friendly restoration techniques have been recently employed, including daylighting underground culverts to resurrect streams on the surface. Analysis of Urban River Survey data from 143 channel reaches in three European rivers demonstrated the varied character of urban rivers and their differential potential to respond to rehabilitation efforts, which rely not only on a scientific understanding of form and process within urban river systems but also on the support of urban communities and integration within urban design and planning (Gurnell et al., 2007). Restoration approaches are now being undertaken more holistically and specific investigations have focused on how catchment and storm water design can save the stream (Walsh et al., 2005a).

Fluvial geomorphology has embraced the study of urban river systems and their adjustments, has progressed to consider the significance of contemporary management methods including the restoration agenda, but also needs to consider future global change with the implications of a high CO_2 world. Comparatively few scenarios for future geomorphological change have been developed although it has been suggested generally that we might develop ‘Earthcasts’ analogous to weather forecasts, of both gradual changes and extreme landscape-changing events (Murray et al., 2009). Five broad groups of issues to which geomorphologists are particularly able to contribute (Gregory and Goudie, 2011) are elaborated for the context of urban fluvial geomorphology in Table 3. It must not be assumed that answers are easy to obtain for the topics suggested in Table 3 but at least developments in urban fluvial geomorphology now mean that appropriate questions are being formulated. Outputs from General Circulation Models (GCM’s) require transfer functions to specifically model new hydrological temporal sequences and thence the likely magnitude and frequency of peak and low flows. A further transfer function is then required to relate specific process events to land form including river channels. In any location proximity to thresholds is very important and determines the sensitivity (Downs and Gregory 1995) of the urban system and its resilience.

It is apparent that there is no one outcome scenario of global change, that inherited conditions in world zones may affect the proximity to threshold conditions, and in some sensitive areas new scenarios could occur offering geomorphologists opportunities to contribute to the design of the Anthro-

Table 3 Possible effects of a high CO_2 world

Potential contribution of geomorphological research in relation to future global change	Potential effects in urban areas	How such consequences may translate into environmental hazards
Evaluating the consequences of outputs from GCM's for earth surface processes and dynamics	Frequency of peak discharges and extreme events changed Length of period between storm events changed	Increased flood frequency Overbank floods Mass movements
Consequences changed processes could have for the land surface	Extent of urban and overbank flooding greater or smaller Low flows could alter Channels could change in cross section and in planform	Failure of channel banks Scour and deepening of channels Aggradation
What new process domains could be created	Channel metamorphosis within and downstream from urban areas Variations according to world zones e.g. in Arctic changes in amount of permafrost	Channel erosion New gully cycles initiated Channel incision Avulsion and changes of channel planform
How landscapes may have different degrees of sensitivity and resilience	Thresholds may be exceeded so that flooding is more extensive than previously. Channels in urban areas could be affected by different hydrological events generated upstream	Some flood events have greater extent and impact than those produced by urban influence

pocene under new conditions in a high CO_2 world.

CONCLUSION

It was suggested in the introduction that geomorphology and physical geography have changed over the last 50 years to include consideration of human activity and the characteristics of urban areas and our understanding of processes in urban areas has evolved significantly during the last 4 decades so that 9 features of that perception are now identifiable. Envisaging the urban area as a palimpsest where the urban characteristics are superimposed on the landform and process systems affords a valuable means of approaching urban fluvial geomorphology and can be a basis for visualising urban hazards as illustrated in Table 1. Adjustments of river channels consequent upon urban processes have engaged a significant amount of research, the different conceptual models are outlined in Table 2, and it is evident how the considerable variation in response from one area to another may be affected by inherited characteristics. Whereas management methods originally concentrated upon removing urban runoff as rapidly as possible the consequences, both within and downstream from urban areas, led to the development of methods associated with land use planning, with retention of precipitation, with delay of runoff, with management of effects in the urban area and with planning for downstream consequences. Such methods are applied collectively in schemes which include Sustainable drainage systems, Smart growth approaches, watershed permitting approach, low impact development or water sensitive design.

In the light of such advances in understanding research can now focus upon the ways in which further changes may occur as a consequence of global change in relation to a high CO_2 world and some opportunities are indicated in Table 3. Although, as McHarg (1996, p. 91) suggested geomorphologists had not seized research opportunities as they could have done in the past, changes in the focus of the discipline and in the research now achieved enable future fluvial geomorphology to be more directly involved with management methods and their significance.

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